Modern Physics Letters A
Vol. 32, No. 36 (2017) 1730033 (13 pages)
© World Scientific Publishing Company
DOI: 10.1142/S0217732317300336

World Scientific
www.worldscientific.com

On the violation of the invariance of the light speed in theoretical investigations

A. Chubykalo*,‡, A. Espinoza*, A. Gonzalez-Sanchez*,† and A. Gutiérrez Rodríguez*

*Unidad Académica de Física, Universidad Autónoma de Zacatecas,
A.P. C-580, Zacatecas, México

†Departamento de Investigación, Universidad Popular Autónoma del Estado Puebla,
21 Sur 1103, Col. Santiago. C.P. 72410, Puebla, México

‡achubykalo@yahoo.com.mx

Received 14 September 2017
Accepted 27 September 2017
Published 3 November 2017

In this review, we analyze some of the most important theoretical attempts to challenge the invariance of the light speed postulated by the Special Theory of Relativity (STR). Most of those studies, however, show that STR has great stability with respect to various kinds of modifications in its axioms. This stability probably is due to the fact that in these modifications there is no so much a violation of the physical postulate of the invariance of the speed of light, as its mathematical expansion in the form of making resort to a more general affine space. In these modifications, we refer to more general transformation groups, including scale transformation of the speed of light and time $c' = \gamma c$, $t' = \gamma^{-1} t$.

Keywords: Invariance of the velocity of light.

PACS Nos.: 03.50.-z, 03.50.De

1. Introduction

In 2005, the scientific community solemnly commemorated 100 years of the publication of the Special Theory of Relativity (STR) as a remarkable profit of the human intellect.[32,38] In relation to the fundamental character of this theory and its enormous influence on the physical conception of the world, in general, in the literature with enough regularity have arisen, arise and, as we suppose, in the future will continue to arise, works that discuss its axiomatic and the perspective to exist outside the STR borders. In this review, we will stop mainly in the works, in which the possibility of the violation of the postulate of the invariance of the light speed is studied. For pure mathematical simplicity we have denoted the magnitude 3×10^{10} cm/sec with the symbol c_0. By the symbol c, we understand that the light speed can take a continuous spectrum of values.

2. From Classical to Relativistic Physics

Ritz (1908), Comstock (1910), Kunz (1910) and Tolman (1910) deemed[21,22] that the Euclidian geometry is realized in nature, and that light speed is equal to 3×10^{10} cm/sec only with respect to the emission source and that it does not depend on the state of the transmitter medium. The theories based on this hypothesis habitually denominate spill theories.[21,22] In this case, light speed c from the moving source is, according to the Galilean theorem of addition of speeds, the vector sum of the light speed c_0 from the motionless source and the speed of displacement of the source v

$$c = c_0 + v\,, \tag{1}$$

In a systematic form, the version of the electrodynamics, based on the hypothesis (1), was constructed by Ritz. In the Ritz theory, the second (Galileo-invariant[31]) pair of Maxwell equations is conserved[21,22]

$$\nabla \times \mathbf{E} + \frac{1}{c_0}\frac{\partial \mathbf{H}}{\partial t} = 0\,, \qquad \nabla \cdot \mathbf{H} = 0\,, \tag{2}$$

as a result of which, the electric field $\mathbf{E}$ and the magnetic one $\mathbf{H}$ can be expressed by well-known form through the scalar potential φ and the vector potential $\mathbf{A}$: $\mathbf{E} = -\nabla\varphi - (1/c_0)\partial_t \mathbf{A}$, $\mathbf{H} = \nabla \times \mathbf{A}$.[21,22,29] In correspondence with the hypothesis (1) the magnitudes φ and $\mathbf{A}$ are then, chosen in the form of retarded potentials[21,22]

$$\varphi(x,t) = \int \frac{\varrho(x',t')}{r} d^3x' \qquad \mathbf{A}(x,t) = \int \frac{\mathbf{j}(x',t')}{r} d^3x'\,. \tag{3}$$

Here, $\mathbf{x} = (x, y, z)$ is the observing point at the moment t, and $\mathbf{x}' = (x', y', z')$ is the point of location of the electrical charge at the moment $t' = t - r/(c_0 + v_r)$, ϱ is the density of the charge, v its velocity, $\mathbf{j} = \varrho\mathbf{v}$ is the electrical current density, $r = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$ is the length of the vector from the observing point r to the point (x', y', z') where the charge v_r is the projection of the charge velocity in the direction of the vector[21,22] $\mathbf{r}, d^3x' = dx'\,dy'\,dz'$ (in the STR it would be[16,22] $t' = t - r/c_0$). The Galileo-invariant spill theories explain the Michelson–Morley experiment, but they have difficulties in the explanation of the Fizeau experiment, and they do not agree with the results of the experiments that study the influence of the velocity of movement of the emitter on the light velocity. Difficulties also arise, in the explanation of the Doppler effect and for the explanation of the interference process of the incident and reflected light beams.[21,22]

Approximately at the same time that the interpretation of the Michelson–Morley experiment was being build up, another speed addition law was set out on the basis of the motionless ether theory:[21]

$$c' = c\sqrt{1 - V^2/c^2}\,. \tag{4}$$

Here, c' is the light speed in the laboratory reference system K' that is fixed to the interferometer moving with respect to the ether, V is the speed of translation of the Earth with respect to ether K, and c is the light speed in the ether. Hereafter, we call the expression (4) as the Abraham's formula. According to Abraham there is no delay in the time and the possibility arises of discovering the Earth movement with respect to the ether that means a violation of the principle of relativity.[21] Thus, the formula of Abraham was rejected.

In 1961, the formula (4) was rediscovered once again by Rapier,[63] who considered the hypothesis of the existence of Lorentz-invariant completely entrained ether. The accomplishment of the Rapier formula is obtained if, in the expression (4), the new annotations $c \to C_{xy}$, $c' \to C$ are introduced, and then solving with respect to the variable C_{xy}. In this case, the magnitude of the light speed in the reference system, fixed in the ether, needs to be interpreted as a universal constant C, and the expression $1/\sqrt{1 + V^2/C^2} = \alpha_{xy}$ as the coefficient of refraction of the ether.[51,62] Then for the observer in the laboratory reference system the light speed is equal to

$$C_{xy} = \frac{C}{\alpha_{xy}} = C\sqrt{1 + V^2/C^2}\,. \tag{5}$$

The refraction coefficient α_{xy}, according to Rapier, reflects the kinematical characteristics of the ether and corresponds to a certain modified principle of relativity. In order to prove the validity of the expression (5), the author proposed to use the Cherenkov effect supposing that in the case of the modified principle of relativity the cosine of the Cherenkov angle of radiation for an extreme-relativistic particle will be equal to $1/n$ (n is the refraction coefficient of medium). In the STR case it will be equal to zero.[62] Furthermore, it was expected that the speed addition square-law (5) could be observed in radio-communication and astrophysical phenomena in relation to superluminal movement when $V \to \infty$.[62]

In 1963, Romain[63] obtained the violation of invariance of the light speed, starting off from the condition of invariance of the null 4-interval in the cylindrical coordinates system $c'^2\,dt'^2 - dx'^2 - dr'^2 - r'^2\,d\theta'^2 = 0 \to c^2\,dt^2 - dr^2 - r^2\,d\theta^2 = 0$ (the axis of symmetry is the x-axis).

$$x' = \alpha\frac{x - Vt}{\sqrt{1-\beta^2}}\,; \qquad r' = \alpha r\,; \qquad \theta' = \theta\,; \qquad t' = \frac{\alpha}{\gamma}\frac{t - \frac{xV}{c^2}}{\sqrt{1-\beta^2}}\,. \tag{6}$$

Here, α, $\gamma = c'/c$, $\beta = V/c$ are the group parameters, V is the speed of propagation throughout the x-axis of the reference system K' with respect to K, furthermore, $\lim\alpha = \lim\gamma = 1$ for $V \to 0$. The author interprets the parameters α and γ as the relation of the units of scale of the measurements, for example, if $c' = 1 \times 10^9$ km/h and $c = 3\times10^{10}$ cm/sec, then formally $c' \neq c$ and $\gamma = (1/3)\times10^{-1}$ (km/cm)(sec/h). This circumstance does not carry new physical phenomena, and can be eliminated by using a standard system of units, where the length is measured in cm and the time in sec. The proposed interpretation by Romain showed the inconsistency on the attempts of the revision of the STR used by the president of the National Academy of Sciences of Spain, Palacios[60] on the basis of the election of the scale parameter α in the form[22] $\alpha = \sqrt{1-\beta^2}$ for $\gamma = 1$. Palacios (and many others) supposed that the parametrization chosen by him, which goes back to the pioneering work of Voigt,[71] allows to eliminate the relativistic effect of the time retardation and to construct a theory, alternative to the STR, consequent and concordant with the experiment.

Once again and for a third time, formula (4) appeared in publications in 2001.[10] This time, the basis to study the condition of invariance was taking the 4-interval in the form

$$s^2 = c'^2t'^2 - x'^2 - y'^2 - z'^2 = c^2t^2 - x^2 - y^2 - z^2 = \text{invariant}\,, \tag{7}$$

where the light speed c' is constant but not necessarily equal to c. The transformation spacetime-light speed formulas were obtained, in agreement with the results of Romaní,[64] that conserve the expression (7)

$$x' = \frac{x - Vt}{\sqrt{1 - \frac{V^2}{c^2}}}\,; \qquad y' = y\,; \qquad z' = z\,;$$
$$t' = \gamma^{-1}\frac{t - \frac{Vx}{c^2}}{\sqrt{1 - \frac{V^2}{c^2}}}\,; \qquad c' = \gamma c\,. \tag{8}$$

The velocity addition theorem was formulated and the expression of the invariant action integral was constructed. The invariance of Maxwell equations, and that of the motion equations of charged particle in the electromagnetic field, with respect to the induced transformations were proved. In addition, instead of the known invariants of the STR (proper time, which we designated as t, the rest mass m_0, the Planck's constant $\hbar$) new invariants of the theory are introduced: the product ct, the energy of rest m_0c^2, the product hc for the invariable properties of the electrical charge $e' = e$. The synchronization of clocks located in different places by means of the transposition of a master chronometer was realized $t(x) = t(0)$, where K_0 is a certain privileged reference system. One demonstrated that in this case, $c_0 = \sqrt{1 - V^2/c^2}$, and that if $c't' = ct$ (t' and t are proper time intervals), $m_0'c'^2 = m_0c^2$, $\hbar'c' = \hbar c$, $e' = e$, then the magnitude $\gamma = c'/c$ allows the interpretation of a parameter of the scale transformations. So, the reformulated STR which is based on the introduced invariants, explains the same set of experimental facts as the STR.[10]

The transformation law for the light velocity in the Abraham's form[21] and also the mathematical results of Ref. 10 have been reconstituted by many authors, to some extent e.g. Loiseau,[52,53] Di Jorio,[43,44] Marinov,[55] Hsu,[41,42] Sjödin,[69] Mamaev,[18,19] Russo.[67,68] From these fundamental researches, the ones by Hsu[42,43] closely coincide with the work by Kotel'nikov.[10] In those works, instead of the integral of the action cS,[10] the action in the form S/c is chosen, where S is the action of the STR type.[16] Due to this choice invariants of the theory have been changed. Instead of the rest energy m_0c^2, the electric charge e, the product $\hbar c$ rest mass m_0, the ratio of a charge to the light velocity e/c and the ratio of the Planck's constant to the light velocity $\hbar/c$ became invariants. But this circumstance has not affected the gist of the researches. As well as the work[10] the Hsu's publications represent a rejigger version of STR.[42]

In 1972, Kirzhnitz and Chechin[6] in order to give an explanation of the anomaly in the spectrum of the ultrahigh energetic cosmic rays (5×10^{19} eV) passed the limit of the Lorentz-symmetry by mean of the change-over from the space of Minkowski to the space of Finsler.[66] These authors rewrote the well-known relativistic relation $\mathcal{E}^2 - c_0^2\mathbf{p}^2 = m^2c_0^4$ like $\mathcal{E}^2 - c_0^2\mathbf{p}^2 = m^2c_0^4/f(v^2/c_0^2)$, where v is the velocity of the particle, and $f(v^2/c_0^2)$ is the positive homogeneous function of the zero degree. Eventually, the moment and the energy take the form of $= m\mathbf{v}/\sqrt{(1 - v^2/c_0^2)f(v^2/c_0^2)}$, $\mathcal{E} = mc_0^2/\sqrt{(1 - v^2/c_0^2)f(v^2/c_0^2)}$ which becomes the formulae of STR when $v \ll c_0$. If $v \to c_0$, then the momentum and energy tend to infinity, but according to another law than SRT. This was the explanation of the spectrum shape of cosmic rays of ultrahigh energies. For us, in this work the example of the transition from Minkowski to the Finsler space is important. Recall that in this space the element of the arc is defined by the expression $I = \int_{t_1}^{t_2} F(x, \dot{x})$, where F is the function of spatial variables x and their first derivatives with respect to the scalar parameter t; F must be a positive defined homogeneous function of the first power of the variable x: $F(x, k\dot{x}) = kF(x, \dot{x})$, $k > 0$, or according to the well-known Euler's theorem $\dot{x}(\partial F/\partial x) = F(x, \dot{x})$. Besides, the condition $F(x, \dot{x}) = F(x, -\dot{x})$ must be satisfied. If $F(x, dx) = \sqrt{g_{ij}(x)dx^i\, dx^j}$, $F(x, -dx) = F(x, dx)$, and $F(x, k\, dx) = kF(x, dx)$, the Finsler space becomes the Riemann space which in turn goes into the Minkowski space with $g_{ij} = \mathrm{diag}(+, -, -, -)$. Thus, in the Finsler space not only the coordinates x in the metric coefficients are present, but also components of the velocity, if the parameter t is interpreted as time. As a result, spatial–temporal transformations converting the metric in itself become more general: $x' = x'(x, \dot{x})$ rather than punctual ones, such as, in the Minkowski space[6] $x' = x'(x)$. The set of points x' correspond to the point with coordinates x depending on the values of the derivatives $\dot{x}$. Accordingly, the theory formulated in such a space is modified.[6]

As another example, we will focus on the lectures of Logunov.[17] In contrast to the above-discussed works[10,41,43,64,69] in which a violation of invariance of the speed of light was carried out in the framework of the invariant relation $c't' = ct$ in the pseudo-orthogonal Minkowski space, in Ref. 17 the violation of invariance of the speed of light is produced by the transition from the pseudo-orthogonal space to the affine spacetime. As a result, it was shown that 4-interval of the Minkowski space $ds^2 = c_0^2\, dT^2 - dX^2 - dY^2 - dZ^2$ with the metric $g_{ik} = \mathrm{diag}(+, -, -, -)$, $i, k = 0, 1, 2, 3$ by mean of the linear transformations

$$T = qx + pt\,, \qquad X = ax + bt\,, \qquad Y = y\,, \qquad Z = z\,, \tag{9}$$

allows the mapping on the four-dimensional affine space with the metric

$$ds^2 = g_{00}\left[(dx^0)^2 - \left(\frac{c_0}{c_1} + \frac{c_0}{c_2}\right)dx^0\, dx^1 + \frac{c_0^2}{c_1 c_2}(dx^1)^2\right] - (dx^2)^2 - (dx^3)^2\,, \tag{10}$$

where $x^{0,1,2,3} = (c_0 t, x, y, z)$, $g_{00} = p^2 - b^2/c_0^2$; c_1, c_2 are the velocities of light in the positive and negative directions of x-axis in the affine frame of reference which we denote by K_A. As it happens in the affine space, these velocities are different, $c_1 \neq c_2$. The values of c_1 and c_2 are associated with metric coefficients by means of the relations

$$c_1 = c_0 \frac{-g_{01} + \sqrt{g_{01}^2 - g_{00}g_{11}}}{g_{11}}; \qquad c_2 = c_0 \frac{-g_{01} - \sqrt{g_{01}^2 - g_{00}g_{11}}}{g_{11}}. \tag{11}$$

As a result, $c_1 + c_2 = -2c_0 g_{01}/g_{11}$, $g_{01} = g_{10} = -g_{00}c_0(c_1 + c_2)/2c_1c_2$, $g_{02} = g_{20} = g_{03} = g_{30} = 0$, $g_{11} = g_{00}c_0^2/c_1c_2$, $g_{22} = g_{33} = -1$. The affinity is manifested in the difference of the angle between axis $x^0 = ct$ and axis x^1 and $90°$. Indeed, following Ref. 21 and introducing the direction vectors of the axes of the system K_A in the form $\mathbf{e}_0 = (1, 0, 0, 0)$, $\mathbf{e}_1 = (0, 1, 0, 0)$, $\mathbf{e}_2 = (0, 0, 1, 0)$, $\mathbf{e}_3 = (0, 0, 0, 1)$, we find that $\cos(\mathbf{e}_0\mathbf{e}_1) = \mathbf{e}_0\mathbf{e}_1/\sqrt{\mathbf{e}_0^2\mathbf{e}_1^2} = g_{01}/\sqrt{g_{00}g_{11}} = -(c_1 + c_2)/2\sqrt{c_1c_2} \neq 0$, where it is considered that $\mathbf{e}_1\mathbf{e}_2 = g_{01}$, $\mathbf{e}_0^2 = g_{00}$, $\mathbf{e}_1^2 = g_{11}$. Like the Lorentz transformations, in the pseudo-orthogonal space in the affine space, there exist their analog which are obtained by transmuting the square of the interval (10) into itself during a transition to the variables t', x', y', z':

$$x' = \frac{x + Vt}{\sqrt{1 + \frac{V}{c_1}}\sqrt{1 + \frac{V}{c_2}}}; \qquad y' = y; \qquad z' = z; \qquad t' = \frac{\left(1 + \frac{V}{c_1} + \frac{V}{c_2}\right)t - \frac{Vx}{c_1c_2}}{\sqrt{1 + \frac{V}{c_1}}\sqrt{1 + \frac{V}{c_2}}}. \tag{12}$$

When $c_1 + c_2 = 0$, the affine metric transforms into the pseudo-orthogonal one; the speed of light becomes an isotropic speed ($c_1 = -c_2$), the Logunov transformations pass into the Lorentz ones. As a result, if one understands by the speed of light, in an affine space, a mathematical speed (i.e. the coordinate speed by Logunov, symbols[17] c_1 and c_2), then the invariance violation $c_1 \neq c_2$ in electrodynamics can be accomplished without contradiction with experiments. The corresponding theory is a reformulation of STR.

The transition to the nonlinear theory with broken invariance was implemented by Fushchich.[39] The corresponding equations are as follows:

$$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{H}, \qquad \frac{1}{c}\frac{\partial \mathbf{H}}{\partial t} = -\nabla \times \mathbf{E}, \qquad \nabla \cdot \mathbf{E} = 0, \qquad \nabla \cdot \mathbf{H} = 0, \tag{13}$$

where the propagation velocity of the electromagnetic field c is determined by the formula

$$c = c_0\sqrt{1 - \frac{(\mathbf{E}^2 - \mathbf{H}^2)^2}{4\rho^2} - \frac{(\mathbf{EH})^2}{\rho^2}}. \tag{14}$$

Here, $\rho = (\mathbf{E}^2 + \mathbf{H}^2)/2$ is the energy density of the electromagnetic field. From Eq. (14) it follows that the velocity of propagation of the field in Eq. (13), depends on the energy density of the electromagnetic field, does not exceed the speed of light $c_0 (c \leq c_0)$ and coincides with the value of c_0 only when, $\mathbf{E}^2 - \mathbf{H}^2 = 0$, $\mathbf{EH} = 0$.

3. The Connection with the Problem of Superluminal Motions

The question of the existence of superluminal motions (with speeds $v > 3 \times 10^{10}$ cm/sec) has been a subject for wide discussions in contemporary theoretical and experimental physics. Superluminal motions explicitly already appeared in the works of Ritz (for e.g. see Refs. 20, 21 and 28) and Rapier.[63] As long as the Galilean velocity addition law is still a test for checking the hypotheses of superluminal motions, the formula of Rapier (5) in one or the other interpretation, has not been tested experimentally. At least, the authors of this work do not know any publication on this topic.

In 1946, Blohintzev[2,3] drew attention to the possibility of formulating a field theory which admits superluminal ($v > c_0$) propagation of interactions, outside the light cone in the space-like region[16] $s^2 = c_0^2 t^2 - \mathbf{x}^2 < 0$ and applied it to the description of the field "inside" an elementary particle distributed in a certain spacetime region the size of $s_0 = \sqrt{c_0^2 t^2 - \mathbf{x}^2} \sim 10^{-13}$ cm.

Meanwhile, Kirzhnitz[5] built the model of a particle with an anisotropic mass tensor $M^\mu_\nu = \mathrm{diag}(m_0, m_1, m_1, m_1)$ and momentum, $p^\mu = M^\mu_\nu v^\nu$, with $\mu, \nu = 0, 1, 2, 3$. In this model, the case $m_0 = m_1$ corresponds to the motion of a particle with the velocity $v < c_0$ in the standard theory;[16,17,21] the variant $m_0^2 = m_1^2 = m^2 < 0$, corresponds to the motion of a particle of an imaginary mass $m = i\mu$ with a velocity $v > c_0$ and the real energy $\mathcal{E} = \mu c_0^2/(v^2/c_0^2 - 1)^{1/2}$. If $m_0^2 \neq m_1^2$ the expression for the energy becomes $\mathcal{E} = m_0 c_0^2/\sqrt{1 - (m_1/m_0)^2 v^2/c_0^2}$ from which one can see that for $m_0 > m_1$ the speed limit of a particle $v_{\max} = c_0 m_0/m_1$ also exceeds the velocity of light c_0.

The hypothesis of the existence of particles with imaginary mass was discussed by Terletskii,[26,27] and was Feinberg[29] who called these particles tachyons, also describing their basic properties; when $v \to \infty$, the energy of a tachyon $\mathcal{E} = \mu c_0^2/\sqrt{v^2/c_0^2 - 1}$ tends to zero. However, the absolute value of the momentum $\mathbf{p} = \mu \mathbf{v}/\sqrt{v^2/c_0^2 - 1}$ of the tachyon tends to the finite value μc_0, and if $v \to c_0$ then $\mathcal{E}$ and $\mathbf{p}$ tend to infinity. The tachyon's energy and the momentum are connected by the relation $\mathcal{E}^2 - c_0^2 p^2 = -\mu^2 c_0^4 = m^2 c_0^4$. For the magnitude μ (the absolute value of the mass) the special name "meta-mass" exists. Besides the imaginary mass, the principal distinction between tachyons and normal particles is that tachyons have no state of rest. The energy of the motionless tachyon ($p = 0$) becomes the imaginary one (i.e. $\mathcal{E} = i\mu c_0^2$).

The distinctive ingredient of the works referenced above is that all of them keep certain consistency with the STR, producing some amplification of the STR postulates rather than their violation. This amplification concerns with the assumption of the possibility of motion in the time-like region of the light cone $s^2 = c_0^2 t^2 - x^2 > 0\,(v < c_0)$, as well as in the space-like region $s^2 < 0$, where $v > c_0$;[2,6,27,30] it also concerns with attributing some tensor of mass to the particle that automatically leads to material motions in the region $s^2 > 0$, to tachyon motions in the region $s^2 < 0$, and to superluminal motions in the time-like region when

$m_0 > m_1$.[5] The variant of the theory describing the coexistence of sub-light, light and super-light particles (bradyons, luxons and tachyons) is contingently called "the extended theory of relativity".[23] Thanks to the opening here of additional mathematical and physical abilities, this trend has been studied in detail in the literature. Tachyon motions (they are also called superluminal) was studied by Bilaniuk and Sudarshan,[1] Recami,[24] Kirzhnitz and Sazonov,[7] Patty,[61] Oleinik[59] and many other authors, e.g. see Refs. 8 and 23. The electrodynamic study of superluminal motion for particles with an anisotropic mass tensor was performed by Sazonov,[24] but despite the success of the theoretical description of the superluminal motion, all attempts of an experimental detection of superluminal motions (as it is understood by the authors of this review) in the form of either tachyons, or in the form of particles with anisotropic mass were unsuccessful. There is also the opposite view, advocated by for example, Recami[23] and his co-authors,[65] Mugnai.[56] Thus, the problem of the existence or not, of superluminal motions in the real nature, still has not received a conclusive solution.

Different from the above approaches, the problem of superluminal motions in classical electrodynamics has been studied by Chubykalo and Smirnov-Rueda,[34] Chubykalo and Vlaev,[35] Chubykalo *et al.*[36,37] The Maxwell's equations have Lorentz invariance (the velocity of the electromagnetic field is finite and equal $c = c_0$) only if they are considered as a single ensemble.[30] If the Maxwell's equations are divided into subsystems, then the situation becomes different. For example, the electromagnetic fields of the first and second pair of equations[a] transform according to different representations of the Galileo group. But Galilean symmetry admits superluminal interactions. Therefore, the question of the existence of such interactions is not as simple as it appears in the Lorentz-invariant theory. With the Helmholtz vector decomposition theorem $\mathbf{A} = \mathbf{A}_1 + \mathbf{A}_2 + \mathbf{A}_3$, $\nabla \times (\mathbf{A}_1 + \mathbf{A}_3) = 0$, $\nabla \cdot \mathbf{A}_2 = 0$,[9] and changing over to the fields having extended (v-gauge) calibration $(c_0/c^2)\partial\varphi/\partial t + \nabla \cdot \mathbf{A} = 0$, the authors carried out the scope of the Lorentz symmetry. Here, $\mathbf{A}$ and φ are the vector and scalar potentials, respectively,[16] $0 < c < \infty$. This allows us to distinguish two types of vector potential: magnetic potential of the irrotational (gradient) nature $\nabla \times \mathbf{A}_i = 0$ and the rotational (solenoidal) one $\nabla \cdot \mathbf{A}_s = 0$. The first one is propagated with an arbitrary velocity c, so that $\nabla \mathbf{A}_i = (4\pi c_0/c^2)\mathbf{j}_i$, the second one with the velocity of light c_0: $\nabla \mathbf{A}_s = (4\pi/c_0)\mathbf{j}_s$ (here $\mathbf{j}_i$ and $\mathbf{j}_s$ are the corresponding current densities). Applying this technique to the electric field has allowed to treat the Coulomb field (the irrotational component of the electric field $\mathbf{E}_i = -\nabla\varphi$, $\nabla \times \mathbf{E}_i = 0$) as a separate physical entity characterized by the instantaneous velocity of propagation $c = \infty$. However, a specially devised experiment performed by Tsontchev *et al.*[70] led to the conclusion that this type of the irrotational field propagates with the speed of light c_0, the errors of measurement. Nevertheless, the theoretical possibility of instantaneous interactions

[a]The first pair $\nabla \times \mathbf{H} - (1/c_0)\partial_\mathbf{t}\mathbf{E} = 0$; the second pair $\nabla \times \mathbf{E} + (1/c_0)\partial_\mathbf{t}\mathbf{H} = 0$.[31]

has not yet received a thorough refutation, since the possibility of the existence of the irrotational magnetic component has not been investigated experimentally. For fields of type $c = c_0$, the extended (v-gauge) calibration turns into Lorentz gauge,[16] and their distribution is described by STR.

Another approach to the problem of the violation of the Lorentz invariance, which is related with the problem of superluminal motion, was proposed by Kostelecky and Samuel[33,45] within the superstring theory. In this area of mathematical physics, particles are not study as point-like particles as in quantum field theory. Instead, they are considered as one-dimensional extended objects, the so-called strings.[25] In the framework of this theory, it is postulated that the elementary particles and their interactions are the result of oscillations and interactions of objects with lengths comparable with the Planck length $l_{\rm P} = (\hbar G/c_0^3)^{1/2} \sim 10^{-33}$ cm ($\hbar = 1.054 \times 10^{-27}$ erg $\cdot$ sec is the Planck constant, $G = 6.672 \times 10^{-8}$ din $\cdot$ cm$^2 \cdot$ g^{-2} is the gravitational constant, $c_0 = 3 \times 10^{10}$ cm/sec).[58] Kostelecky and Bluhm showed that in the Big Bang model in the early stage of the Universe of the order $t_{\rm P} = l_{\rm P}/c_0 \sim 10^{-43}$ sec, the string theory allows the spontaneous breaking of Lorentz symmetry. From the point of view of the present Lorentz-invariant state of the matter, traces of this violation would have to manifest itself in the form of the existence of small residual tensor (relict) fields which should present in 3-space some selected directions violating its isotropy. As a result, the physical properties of the particles, the values of physical constants, and in particular the speed of light c will vary somewhat depending on the orientation of the laboratory frame of reference, relative to the directions of the relic fields. To assess the magnitude of these variations it must be taken into account that the Planck energy $\mathcal{E}_{\rm P} = (\hbar c_0^5/G)^{1/2} \sim 10^{19}$ GeV corresponds to the Planck length $l_{\rm P}$. For comparison, the rest energy of the proton and neutron is of the order of 1 GeV.[31] The achieved level of energy in modern accelerators do not exceed hundred GeV. Therefore, between the world of the Planck energy and the energy level of the laboratory there is a giant chasm. The variations, theoretically predicted by the theory of Kostelecky effects would be negligible: $\sim 10^{-19}$ according to Bluhm (Sunrise Professor of Physics Robert Bluhm[33]). Nevertheless, the perspectives for the development of the superstring theory are promising, and now this area has received considerable attention. Suffice it to note that superstring theory is considered the most likely candidate for the role of a unified field theory, which unify four interactions: gravitational, electromagnetic, weak and strong together; there may be a violation of CPT-invariance;[45] it is possible the proton decay under the schemes $p^+ \to \pi^0 + e^+$, $p^+ \to \pi^+ + \bar{\nu}$ with a lifetime of $\sim 10^{32}$ years.[4] Because of the importance of the string direction of a theory predictions of the author[45] within the Standard Model Extension were subjected to thorough experimental testing. This was possible because of the exceptional sensitivity of modern research techniques. In modern versions of the Michelson experiment using cryogenic optical resonators,[58] the anisotropy of the speed of light was $\Delta_\theta c/c_0 = (2.6 \pm 1.7) \cdot 10^{-15}$ or $\sim 7.8 \cdot 10^{-5}$ cm/sec. A similar result was obtained by measuring the Doppler effect by the laser spectroscopy method.[70] The experiment confirmed the predictions of the SRT within a precision of 2.2×10^{-7}. Thus, it was not possible to reach the level of amendments, predicted in Ref. 45, or with the ever-increasing precision experiments indicate isotropy of the surrounding space.

Similar problems were discussed in the paper of Glashow[40] in terms of the hypothesis of the existence in nature of some preferred reference frame. This hypothesis, like Newton's absolute time and after the creation and triumph of the SRT invariably attracts the attention of many researchers and is analyzed in many works, for example, in Refs. 54 and 55. In the paper,[40] it is assumed that such system of reference in which the rotation and translation are an exact symmetry, really exists. Its identification feature is the isotropy of the cosmic background radiation (CBR). In such theory, a violation of the Lorentz invariance is treated as corrections (perturbations) in the standard Lorentz-invariant Lagrangian. Experimental effects as in the string theory of Kostelecky and Bluhm[34,46] should be seen in the area of the Planck energy. For example, a photon could be unstable with respect to the decay $\gamma \to \gamma + \pi^0$, a vacuum Cherenkov radiation and the proton β-decay of the type $p^+ \to n^0 + e^+ + \nu$ could also be permitted. Signs of the existence of such processes could be observed in cosmic rays of ultrahigh energies.[40]

In a series of works between 2003 and 2004 carried on going beyond the Lorentz invariance by the transition to the 5-space of Finsler $V^5(t, x, c)$ without modification of the dispersion relation between momentum and energy, but by replacing $c_0 \to c = c_0\sqrt{1 + v^2/c_0^2}$ in the invariant interval ds, where v is the velocity of a particle.[47–49] These works are a continuation of the research.[11–14,46] It has been shown that $V^5(t, x, c)$ comprises two subspaces of Minkowski: one, on the hyperplane $(c_0 t, \mathbf{x})$ with the light velocity c_0, and the second one on the hyperplane $(\int c(\tau)d\tau, \mathbf{x})$ with the light velocity $c_0 \leq c < \infty$.[15,50] In the first of them the SRT is realized, in the second one by analogy with the SRT, the version of electrodynamics was built, allowing superluminal motions $v > c_0$. Unlike the SRT and the tachyon theory, time on the particle trajectory is not slowing down. The motion occurs with a real mass in the time-like region with the velocity $v < c$, the mass of the particle does not depend on its velocity. The speed of light is isotropic, so that there are no effects of anisotropy, which are characteristics of string theory of Kostelecky[45] and publications of Glashow, Mansouri–Sexl and Marinov.[40,54,55] Therefore, the proposed version of electrodynamics is consistent with the experiments of Michelson and Morley. In the works[47–50] it is shown how under the adduced relations, many experimental facts can be consistently explained while they were hitherto explained only in the SRT. For example, experiments of Michelson and Fizeau, the aberration of light, the appearance of atmospheric μ-mesons at the surface of the Earth, Doppler effect, a number of well-known experiments on the proof of the independence of the speed of light on the speed of the light source, the decay of unstable particles, production of new particles in nuclear reactors, Compton effect, photo effect. Some possible transformations and invariance are considered in

Refs. 72 and 73. In particular, here it is considered a possible dependence of the speed of light on frequency and a transformation with the correct composition law.

4. Afterword

If we abstract from the early work in the field of classical physics, then the mentioned studies show that STR has great stability with respect to various kinds of modifications in its axiomatics.[33] Apparently, this is due to the fact that in these modifications it is not so much a violation of the physical postulate of the invariance of the speed of light, as its mathematical expansion in the form of making resort to a more general affine space. In other words, in these modifications the authors refer to more general transformation groups, including scale transformation of the speed of light and time $c' = \gamma c$, $t' = \gamma^{-1}t$. In the case of including in the theory of space-like area of movements, as well as physical images of string theory, making resort to the hypothesis of the existence of the selected frame of reference and including the Finsler space, there is a need of experimental verification of the consequences stemming from it. At present, these issues have not been studied enough yet.

References

1. O. Bilaniuk and E. Sudarshan, *Phys. Today* **22**, 43 (1969).
2. D. I. Blohintzev, *J. Exp. Theor. Phys.* **18**, 489 (1946), (in Russian).
3. D. I. Blohintzev, *J. Exp. Theor. Phys.* **17**, 266 (1947), (in Russian).
4. S. Ikeda, *Lett. Nuovo Cimento* **21**, 567 (1978).
5. D. A. Kirzhnitz, *J. Exp. Theor. Phys.* **27**, 6 (1954), (in Russian).
6. D. A. Kirzhnitz and V. A. Chechin, *Sov. J. Nucl. Phys.* **15**, 585 (1972); *ibid. JETP Lett.* **14**, 172 (1971).
7. D. A. Kirzhnitz and V. Sazonov, Superluminal motions and special theory of relativity, *Einstein Memorial Collected Papers* (Nauka, 1974), pp. 64–111 (in Russian).
8. L. Brillouin, *Wave Propagation and Group Velocity* (Academic Press, 1960).
9. A. N. Tikhonov and A. A. Samarscii, *Equations of Mathematical Physics* (Dover Publications, 1990).
10. G. A. Kotel'nikov, *J. Russ. Laser Res.* **22**, 455 (2001).
11. G. A. Kotel'nikov, On the symmetry of Maxwell's equations with an invariant velocity of light, preprint of the Russian Research Centre "Kurchatov Institute", IAE-2813 (Moscow, 1977), in Russian.
12. G. A. Kotel'nikov, *Int. J. Math. Math. Sci.* **31**, 149 (2002).
13. G. A. Kotel'nikov, *J. Russ. Laser Res.* **23**, 565 (2002).
14. G. A. Kotel'nikov, On the possibility of faster-than-light motion of the Compton electron, preprint of the Russian Research Centre "Kurchatov Institute" IAE-6403/1 (Moscow, 2006).
15. G. A. Kotel'nikov, *Russ. Phys. J.* **49**, 134 (2006).
16. L. Landau and E. Lifshitz, *The Classical Theory of Field* (Pergamon Press, 1975).
17. A. Logunov and A. Arepyev, *Lectures in Relativity and Gravitation: A Modern Look* (Pergamon Press, 1991), 1st English edition.
18. A. V. Mamaev, Light speed in moving inertial reference frame, *Science, Technology and Higher Education, Materials of the II International Research and Practice Conference*, Vol. II (Westwood, 2013), pp. 74–79.

19. B. Nimbuev, *Invariant Time, Serpukhov Effect and Quasar 3C 279* (1996).
20. W. Panofski and M. Philips, *Classical Electrodynamics and Magnetism* (Addison-Wesley, 1963).
21. W. Pauli, *Theory of Relativity* (Pergamon Press, 1958).
22. H. Poincaré, Sur la dynamique de l'électron, *Ions*, *Électrons*, *Corpuscules*, Vol. 2 (Gauthier-Villars, 1905), pp. 576–580.
23. E. Recami, Relativity and beyond, *Albert Einstein 1879–1979 Relativity*, *Quanta*, *and Cosmology in the Development of the Scientific Though of Albert Einstein* (Johnson Reprint Corporation, 1979), pp. 537–597.
24. V. Sazonov, *Sov. J. Nucl. Phys.* **15**, 1060 (1972).
25. http://en.wikipedia.org/wiki/String_theory.
26. Y. Terletskii, *Sov. Phys. Dokl.* **133**, 329 (1960).
27. Y. Terletskii, *Paradoxes in the Theory of Relativity* (Plenum Press, 1968).
28. J. Jackson, *Classical Electrodynamics* (Wiley, 1998).
29. G. Feinberg, *Phys. Rev.* **159**, 1089 (1967).
30. V. Fushchich and A. Nikitin, *Symmetries of Maxwell's Equations* (D. Reidel Publishing Co., 1987).
31. Yu. Shirokov and N. Yudin, *Nuclear Physics* (Nauka, 1972), pp. 18; 292–293; 304–306; 322 (in Russian).
32. A. Einstein, *Philos. Sci.* **1**, 63 (1934).
33. R. Bluhm, Breaking Lorentz symmetry, http://physicsworld.com/cws/article/print/2004/mar/10/breaking-lorentz-symmetry (2004).
34. A. Chubykalo and R. Smirnov-Rueda, *Phys. Rev. E* **53**, 5373 (1996).
35. A. Chubykalo and S. Vlaev, *Int. J. Mod. Phys. A* **14**, 3789 (1999).
36. A. Chubykalo, A. Espinoza and R. Alvarado Flores, *Phys. Scripta* **84**, 015009 (2011), doi:10.1088/0031-8949/84/01/015009; *Corrigendum-Phys. Scripta*, doi:10.1088/0031-8949/84/6/069502; *Phys. Scripta* **85**, 047002 (2012), doi:10.1088/0031-8949/85/04/047002; A. Chubykalo, A. Espinoza, R. Alvarado Flores and A. Gutiérrez Rodríguez, *Found. Phys. Lett.* **19**, 37 (2006).
37. A. Chubykalo and G. Kotel'nikov, *Electromagn. Phenom.* (*Ukraine*) **6**, 3 (2006).
38. A. Einstein, *Ann. Phys. B* **17**, 891 (1905).
39. V. Fushchich, *Sov. Phys. Dokl. Ukr.* **4**, 24 (1992).
40. S. Glashow, *Nucl. Phys. B* (*Proc. Suppl.*) **70**, 180 (1999).
41. J. P. Hsu, *Found. Phys.* **6**, 317 (1976).
42. J. P. Hsu and L. Hsu, *Phys. Lett. A* **196**, 1 (1994).
43. M. Di Jorio, *Nuovo Cimento B* **22**, 70 (1974).
44. M. Di Jorio, *Lett. Nuovo Cimento* **8**, 603 (1978).
45. V. Kostelecky, *Phys. Rev. D* **39**, 683 (1989).
46. G. Kotel'nikov, On the possibility of faster-than-light motion of the Compton electron, preprint of the Russian Research Centre "Kurchatov Institute" IAE-6403/1 (Moscow, 2006).
47. G. Kotel'nikov, On the faster-than-light motions in electrodynamics, in *Proc. XII Int. Conf. on Selected Problems of Modern Physics* (Dubna, 2003), pp. 143–147.
48. G. Kotel'nikov, On the possibility of faster-than-light motions in nonlinear electrodynamics, in *Proc. Institute of Mathematics of NAS of Ukraine*, Vol. 50 (Kiev, 2004), pp. 835–842.
49. G. Kotel'nikov, On the electrodynamics with faster-than-light motion, *Has the Last Word Been Said on Classical Electrodynamics? New Horizons*, eds. A. Chubykalo, V. Onoochin, A. Espinoza and R. Smirnov-Rueda (Rinton Press Inc., 2004), pp. 71–81.

50. G. Kotel'nikov, *Electromagn. Phenom.* **6**, 36 (2006).
51. H. Lorentz, *Proc. Acad. Sci.*, Vol. 6 (Amsterdam, 1904), pp. 809–818.
52. J. Loiseau, *Appl. Opt.* **7**, 1391 (1968), (in French).
53. J. Loiseau, *Appl. Opt.* **11**, 470 (1972), (in French).
54. R. Mansouri and R. Sexl, *Gen. Relat. Gravit.* **8**, 497; 515; 809 (1977).
55. S. Marinov, *Found. Phys.* **9**, 445 (1979).
56. D. Mugnai, A. Ranfagni and R. Ruggeri, *Phys. Rev. Lett.* **84**, 4830 (2000).
57. H. Müller, S. Herrman, C. Braxmaier, S. Schiller and A. Peterts, *Phys. Rev. Lett.* **91**, 020401-1 (2003).
58. L. B. Okun, Fundamental units: Physics and metrology, arXiv:org/abs/physics/0310069/ (see also cds.cern.ch/record/677027/files/0310069.pdf).
59. V. P. Oleinik, Faster-than-light transfer of signals in electrodynamics, in *Instantaneous Action-at-a-Distance in Modern Physics*, eds. A. Chubykalo *et al.* (Nova Science Publishers, 1999), pp. 261–281.
60. J. Palacios, *Rev. R. Acad. Cienc. Madr.* **51**, 21 (1957), (in Spanish).
61. C. E. Patty, *Nuovo Cimento B* **70**, 65 (1982).
62. H. Poincaré, *Comptes Rendus* **140**, 1504 (1905), (in French).
63. P. M. Rapier, *Proc. IRE* **49**, 1691 (1961); **50**, 229 (1962).
64. J. Romain, *Nuovo Cimento* **30**, 1254 (1963).
65. E. Recami, F. Fontana and R. Caravaglia, *Int. J. Mod. Phys. A* **15**, 2793 (2000).
66. H. Rund, *The Differential Geometry of Finsler Space* (Springer Verlag, 1959), pp. 1–5.
67. F. P. Russo, *Speculat. Sci. Technol.* **21**, 73 (1998).
68. G. Saathoff *et al.*, *Phys. Rev. Lett.* **91**, 190403-1 (2003).
69. T. Sjödin, *Nuovo cimento B* **51**, 229 (1979).
70. R. Tsontchev, A. Chubykalo and J. Rivera-Juarez, *Hadronic J.* **23**, 401 (2000).
71. W. Voigt, Ueber das Doppler'sche Pricip, *Nachr. K. Wiss. Georg-August-Universitat*, Göttingen No. **2**, 41 (1887), (in German).
72. S. N. Artekha, *Kritika Osnov Teorii Otnositelnosti* (Criticism of the Foundations of the Relativity Theory) (Izdatelstvo, 2004).
73. S. N. Arteha, *Galilean Electrodyn.* **15**, 3 (2004).