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Studying The Foundations Of The Theory Of Relativity In General Education Schools

Shokhidakhon Yakubova

Associate Professor of Physics, Fergana State University, Fergana,

Republic of Uzbekistan

Abstract – This article analyzes the methodology for studying the main ideas and scientific provisions of the special theory of relativity in general education schools. Einstein's postulates, Michelson's experiment and Lorentz transformations are discussed.

Keywords – Theory Of Relativity, Einstein's Postulates, Lorentz Transformation, Michelson's Experiment.

Physics education as an integral part of secondary education contributes to the achievement of the general pedagogical goal of the school, ensuring that students master the basics of academic disciplines, develop their thinking and creative abilities, and form their scientific outlook. The formation of knowledge in physics is interconnected with the study of various physical theories. Theories in physics include general theory of relativity, classical and quantum mechanics, solid state physics, electrodynamics, special theory of relativity and structure of matter, physics of the nucleus and elementary particles [1].

The special theory of relativity is a theory in the physics of space-time, that is, a theory that describes the universal space-time properties of physical processes. Einstein extended the principle of relativity to electrodynamic phenomena, which, firstly, made it possible to describe almost the entire range of physical phenomena from a unified position, and secondly, it made it possible to explain the results of Michelson's experiment [2].

In a secondary general education school, the basics of physics are studied, and the course should always be modern and at the same time elementary. Its modernity is a requirement of life. After all, physics is steadily developing, its technical applications are expanding and changing, and young people must be prepared for work in the field of science and technology, in production.

According to the new program, it is planned to study in general education schools a certain range of issues of the particular theory of relativity. In essence, the school considers a number of the most important provisions of this theory: the final speed of propagation of interactions and the limiting nature of the speed of light in a vacuum, the dependence of the mass of a moving body on the speed of movement, the relationship between energy and mass [3].

The nature and sequence of presentation of educational material are determined by the idea of expanding and generalizing the laws of mechanics to relativistic movements. Thus, for the study of relativistic dynamics, a traditional way for classical dynamics is proposed: the basic laws of dynamics are considered as postulates, from which the entire content of relativistic dynamics follows. The idea of including classical mechanics in the theory of relativity as a particular limiting case is emphasized and developed in all questions of the topic. This contributes to the formation of a scientific worldview: all parts and sections of physical science are a single whole; the basic laws of nature in the process of the development of science do not cease to be true, turning out to be special cases of more general laws [4].

A. Einstein in his works, devoted to the development of the special and general theory of relativity, formulates the principle of relativity as the invariance of the laws of certain processes in all reference frames, emphasizing that “in all inertial coordinate systems, the laws of nature have the same form”. He calls this position "the special principle of relativity", i.e. special theory of relativity [5].

The dynamics in this presentation does not require a mandatory preliminary presentation of the kinematic part of the theory of relativity, since it uses the usual concepts of velocity and acceleration and its conclusions are not discussed for transitions from one inertial system to another. This well-known independence of dynamics frees us from consideration in the kinematic part of the preparatory questions for the presentation of the dynamics, so that the volume, content and sequence of the presentation of the kinematic part can be determined independently.

When determining the volume and content of the kinematic part, we proceed, first of all, from the meaning of kinematics in terms of worldview. Einstein's postulates form the basis of the theory. Most clearly and at the same time quite fully reflect the new in the understanding of spatio-temporal relationships, information derived from the postulates about the measurement of length and time. These questions, together with the formula for the addition of Einstein's velocities, constitute, in our opinion, the main content of the kinematic part of the educational topic.

The topic "Foundations of the theory of relativity" provides for a consistent presentation of the main ideas and scientific provisions of the special theory of relativity; here the postulates of Einstein, the principles of kinematics and dynamics of the special theory of relativity are analyzed.

The generally accepted scheme of presentation of the kinematic part of the special theory of relativity is as follows: Michelson's experiment, Einstein's postulates, Lorentz coordinate transformations and the effects and consequences arising from them. To implement it in school teaching, it is necessary to introduce a coordinate method for describing movement. Since students are not very familiar with this method, serious difficulties arise when deriving and discussing Lorentz transformations. Therefore, it is possible to justify attempts to present the main conclusions of kinematics without using the Lorentz transformations. On the other hand, Lorentz coordinate transformations underlie the entire theory of special relativity. We offer two options for studying the kinematic part of the theory of relativity. The first option is based on Lorentz transformations. The second option involves the use of the concept of a space-time interval, which retains its value in all inertial systems [6].

Michelson's experience. When studying the theory of relativity in secondary school, it is necessary to use the concept of an inertial frame of reference known to students from mechanics.

As you know, Newton considered possible the existence of absolutely resting space. Naturally, the question arose about determining the speed of motion of reference systems, in particular the Earth, in this space, that is, about the absolute speed of motion. However, any kinematic measurement of velocity presupposes the presence of a frame of reference associated with some bodies. The latter themselves can move in space. Thus, in kinematics, the relative velocity is always measured. For example, by means of astronomical observations, the speed of the Earth's movement relative to the Sun and stars, taken as stationary, is determined. It would be possible to determine the absolute speed of motion of the system provided that the physical phenomena in the system depend on the absolute speed of its motion. But Galileo's principle of relativity, which establishes the equality of all inertial systems in relation to mechanical phenomena, makes it impossible to determine the absolute speed using mechanical phenomena.

Newtonian mechanics studies the motion of bodies at low speeds, i.e. in cases $\upsilon << c$. ($c \approx 3 \cdot 108$ m/s). In this case, a single time or time count is adopted in all reference systems. In classical mechanics, Galileo's principle of relativity is taken as a basis, i.e. the laws of dynamics in all inertial reference frames are fulfilled in the same way [7].

Let us recall Galileo's theory of transformations. It allows you to calculate the coordinates and speed of two bodies relative to each other, which move relative to inertial reference frames K and K'. In a particular case, the frame of reference K 'moves along the X-axis of the frame of reference K (Fig. 1). In this case, Galileo's transformations with respect to a fixed frame of reference will be written in the following form:

$$x = x' + u\,t x = x' + u\,t_{,}\ y = y'y = y'_{,} z = z'z = z'_{,} t = t't = t'_{.} \tag{1}$$

In the initial case (t = 0), the axes of the two systems coincide. According to Galileo's transformations, when passing from one frame of reference to another frame of reference, the velocities will be

$$u_x = u'_x + u, u_x = u'_x + u, u_y = u'_y u_y = u'_{y,}\ u_z = u'_z . u_z = u'_z . \tag{2}$$

The acceleration of the body in all reference frames will be the same:

$$a_x = a'_x a_x = a'_{x,}\ \ a_y = a'_y a_y = a'_{y,}\ \ a_z = a'_z a_z = a'_{z.} \tag{3}$$

This means that Newton's second law $\vec{F} = m\vec{a}\vec{F} = m\vec{a}$ in classical mechanics in the transition from one inertial frame of reference to another frame of reference retains its shape.

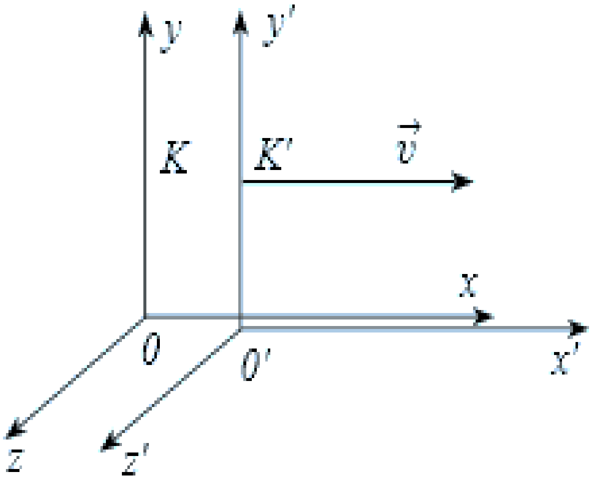

Fig. 1. Graph for explanation of Galileo's theory of transformations

On the basis of Maxwell's theory, the speed of propagation of electromagnetic waves in all inertial reference frames is the same and equal to the speed of propagation of light in vacuum [8].

The independence of the speed of light from the frame of reference or the speed of motion of reference bodies was experimentally proved by A. Michelson and E. Morley.

With the development of the Maxwell-Lorentz electromagnetic theory at the end of the 19th century, electromagnetic phenomena, in particular the propagation of light, were associated with absolutely resting space. It was assumed that light propagates in absolute space at a constant speed. In this case, according to the speed addition formula of Galileo $u = u' + v$ the influence of the annual motion of the Earth in orbit on the speed of propagation of light in different directions on the surface of the Earth can be expected. For the experimental detection of this effect, the American physicist Michelson set up an experiment in 1881, which was then repeated several times in various versions.

Throughout his life, the American physicist Albert Abraham Michelson perfected the technique of measuring the speed of light. Creating more and more complex installations, he tried to obtain results with a minimum error. In 1924-1927, Michelson developed a scheme for an experiment in which a beam of light was sent from the top of Mount Wilson to the top of San Antonio (a distance of about 35 km). For the rotating shutter, a rotating mirror was used, manufactured with extreme precision and driven by a specially designed high-speed rotor that rotates up to 528 revolutions per second. By changing the frequency of rotation of the rotor, the observer achieved the appearance of a stable image of the light source in the eyepiece. Knowing the distance between the installations and the frequency of rotation of the mirror made it possible to calculate the speed of light. The observer will see the light source if, during the movement of the light to the distant mirror and back, the octahedral prism turns by the next facet or by a multiple of n facets of the prism (Fig. 2).

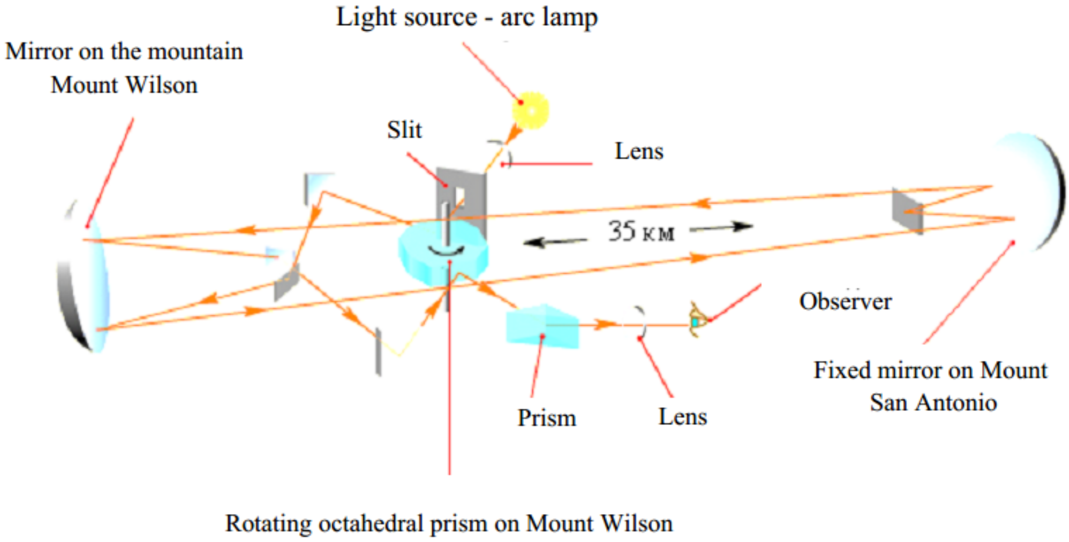

Fig. 2. Graph to explain the method for measuring the speed of light

The speed of light can be calculated using the formula: $c = \frac{8L\omega}{\pi n}$ $c = \frac{8L\omega}{\pi n}$ Michelson received the speed of light with = (299796 ± 4) km / sec. According to modern data, the speed of light in a vacuum is: c = 299792458 ± 1.2 m / s [1].

The experiment is one of the subtle and complex experiments, since the speed of motion of the Earth is small in comparison with the speed of light. The phenomenon of light interference was used to register the difference in velocities in the longitudinal and transverse directions to the motion of the Earth. However, experience did not give the expected changes in the speed of light. That is, light propagated on Earth in all directions at the same speed. The movement of the Earth did not affect the course of the electromagnetic process - the propagation of electromagnetic waves.

The result of Michelson's experiment is in sharp contrast with Galileo's law of addition of velocities. He showed that the speed of light is equal in any frame of reference, and not only in any one, privileged one. Michelson's experiment can serve as a starting point for the presentation of the theory of relativity in the school of kinematics. The approximate sequence of consideration of the issue is as follows.

The principle of relativity of Galileo is recalled and the impossibility of detecting absolute motion by means of mechanical processes is revealed. The basic idea of Michelson's experiment and its negative result are stated. The contradiction of the result of the experiment with the assumption of the existence of a privileged absolutely stationary frame of reference is emphasized. A new point of view on the negative result of the Michelson experiment and similar experiments, expressed by A. Einstein in 1905, is reported. The principles underlying the special theory of relativity are communicated. Einstein's special principle of relativity asserts the complete equality of all inertial systems in relation to all physical phenomena. The principle of independence of the speed of light from the speed of a source emitting light complements the principle of relativity. Since the limiting nature of the speed of light is associated with the second principle, it can be pointed out here with reference to experimental facts [9].

Einstein's principles, or postulates, lead to significant changes and refinements of our ideas about space and time.

Einstein's postulates. The first postulate is the principle of relativity: in all inertial reference frames, all physical phenomena proceed in the same way, i.e. according to the same laws. In other words, Galileo's principle of relativity applies to any physical phenomenon, not just mechanical processes. No physical process depends on the absolute speed of the frame of reference in space.

The second postulate is the constancy of the speed of light: the speed of light does not depend on the relative motion of the light source and the receiver. First of all, it turns out to be superfluous to assume an absolutely motionless space with some properties. The law of addition of velocities is also subject to clarification, which contradicts the constancy of the speed of light in vacuum in all directions in all inertial systems. To obtain specific conclusions from Einstein's principles according to the first version of the technique, we will consider transformations of Lorentz coordinates.

Lorentz transform. The above-mentioned law of addition of velocities is obviously incompatible with Einstein's principles. The reason for this is the transformation of the Galilean coordinates in the transition from one inertial system to another, which do not accurately reflect the real properties of space and time.

Let there are two inertial frames of reference. Let's connect with each of them a rectangular Cartesian coordinate system. For simplicity of reasoning, we will choose them so that at the initial moment of time the axes coincide and so that the relative speed of movement of the systems is directed along the axis OX (fig. 1). It follows from the drawing that for each point

$$x' = x - \upsilon t, \quad y' = y, \quad z' = z \tag{4}$$

taken for granted that

$t' = t$

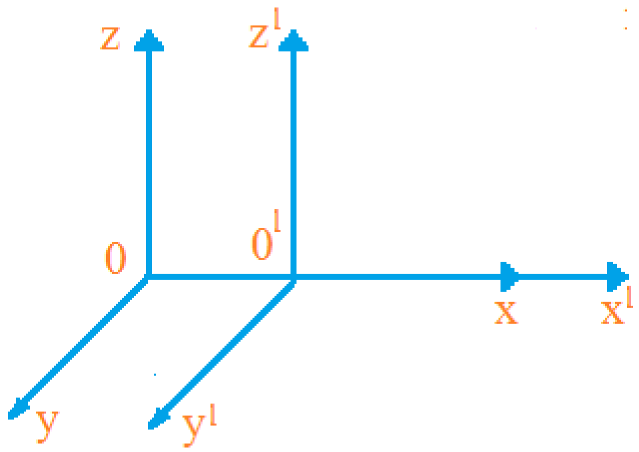

Fig.3. To the conclusion of the Lorentz transformations

These transformations are called transformations of the coordinates of Galileo. From them follows the formula for the addition of velocities, which we named above Galileo`s.

Let the material point, located at the moment of time at the origin, move uniformly along the axis OX. Then

$$\frac{x'}{t'} = \frac{x}{t} - \frac{\upsilon t}{t} \tag{5}$$

The same value of time intervals and spatial distances, their invariance with respect to Galileo's transformations

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} = \sqrt{(x_2' - x_1')^2 + (y_2' - y_1')^2 + (z_2' - z_1')^2}, \tag{6}$$

$$t_2 - t_1 = t_2' - t_1'$$

consistent with our intuitive ideas about space and time, but is in contradiction with the principles of Einstein [10]. Let a light signal be emitted from a point O at a time $t = t' = 0$ along the axis OX. For the speed of light in both systems, we obtain, respectively, the following expressions:

$$c = \frac{x}{t}, \quad c' = \frac{x'}{t'} \tag{7}$$

It can be seen from these formulas that if $t = t'$, then $c \neq c'$ (or if $c = c'$, then $t \neq t'$).

But the conclusion about the invariance of distances and intervals of time in reality has never been subjected to experimental verification, and there is no reason to take it as obvious.

So, coordinate transformations are needed, not contradicting, but following from Einstein's principles. In the introductory part, before analyzing the Lorentz transformations, it is desirable to show the incompatibility of Galileo transformations and the invariance of time intervals and distances with Einstein's principles.

In such an amazing way, the theory of relativity collected the previously scattered concepts of space, time and matter into one extraordinary simplicity and completeness of the physical picture of the world: matter and electromagnetic energy merged into one single whole, which determines everywhere and at any moment in time.

Next, the question of new coordinate transformations should be raised. But first it is necessary to clarify what is the meaning of the refinement introduced by Einstein in the measurements of time and length. The equality of systems allows you to choose physically identical length standards. In each of the reference systems, the measurement of the length of a body at rest is reduced to the imposition of a standard on the measured body. If we are talking about measuring the length of one body from the point of view of different systems, then at least in one frame of reference the body moves. Let the body be at rest in the shaded frame of reference. Its length, measured there by superimposing a standard, is equal to l'. In a non-shaded frame of reference, to measure the length of the same body, it is necessary at the same time to detect the positions of the ends of a moving body and measure the distance between the notches by superimposing a standard. Received length l and will be the length of the body in this frame of reference.

The refinements of the basic measuring operations introduced by Einstein more accurately reflect the properties of real physical space and time than those that were intuitively accepted earlier.

Let a light signal be sent along the axis OX at the moment of time $t = 0$ from coinciding origins O и O' and two frames of reference. Over a period of time t, this signal will reach a certain point A. The speed of light in the two reference systems under consideration is expressed as follows:

$$c = \frac{x}{t}, \quad c' = \frac{x'}{t'} \tag{8}$$

But $c = c'$. So

$$x = ct, \quad x' = ct'.$$

$|x = ct$ Coordinate transformations must be linear to preserve the equality of all points in space and moments of time. Means,

$$x = x' + \beta t', \tag{9}$$

where a and β are coefficients independent of x and t. This formula must also satisfy the following requirement: at any moment of time t', the origin of coordinates of a non-shaded frame of reference has a coordinate in the hatched frame of reference $x' = -\upsilon t'$. Substituting zero into the transformation for *x*, we have

$ax' + \beta t' = 0$, or $x' = -\frac{\beta}{a}t'$. Hereof $\frac{\beta}{a} = \upsilon$ and $x = a(x' + \upsilon t')$.

The inverse transformation formula is obtained by simply changing the sign at a speed:

$$x' = a(x - \upsilon t). \tag{10}$$

We now use the condition for the constancy of the speed of light c. Substituting instead of x and x', respectively, ct and ct', we get : $ct = a(c + \upsilon)t'$, $ct' = a(c - \upsilon)t$.

We multiply these equalities by the log:

$$c^2 tt' = a^2(c^2 - \upsilon^2)tt'$$. Here of $$a = \frac{1}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}$$

Therefore, the transformation law for the coordinate is represented in the following form:

$$x = \frac{x' + \upsilon t'}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}, \quad x' = \frac{x - \upsilon t}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}. \tag{11}$$

From these equalities we find for t the following expression:.

$$t = \frac{t' + \frac{\upsilon}{c^2}x'}{\sqrt{1 - \frac{\upsilon^2}{c^2}}} \tag{12}$$

Thus, the final direct and inverse transformations of coordinates that satisfy the principle of constancy of the speed of light have the form:

$$x = \frac{x' + \upsilon t'}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}, \quad x' = \frac{x - \upsilon t}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}, \quad t = \frac{t' + \frac{\upsilon}{c^2}x'}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}, \quad t' = \frac{t - \frac{\upsilon}{c^2}x}{\sqrt{1 - \frac{\upsilon^2}{c^2}}}, \tag{13}$$

$$y = y', \quad z = z'.$$

G.A. Lorentz came to these transformations before the creation of the theory of relativity from other considerations. They are called Lorentz transformations. It is easy to see that the Galileo`s transformations are the limiting case of Lorentz transformations [11]. Indeed, when $\upsilon << c$ the value $\frac{\upsilon^2}{c^2}$ can be neglected. Galileo's transformations are approximate, quite accurately describing the laws of nature at low speeds of movement of systems.

All the main conclusions of the kinematics of the theory of relativity are associated with the Lorentz transformations.

The Lorentz transformations for the frame of reference, considered in Fig.3 are written in the following form:

Table 1. The Lorentz transformations for the frame of reference

$K' \to K$	$K \to K'$
$x = \dfrac{x' + vt'}{\sqrt{1-\beta^2}}$	$x' = \dfrac{x - vt}{\sqrt{1-\beta^2}}$
$y = y'$	$y' = y$
$z = z'$	$z' = z$
$t = \dfrac{t' + {vx'}/{c^2}}{\sqrt{1-\beta^2}}$	$t' = \dfrac{t - {vx}/{c^2}}{\sqrt{1-\beta^2}}$
$\beta = \dfrac{v}{c}$	

When studying them in high school, you should first pay special attention to clarifying the essence of the very connection between shaded and unshaded quantities even before writing formulas, which can be helped by simpler Galileo transformations.

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