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Significance of the Sagnac Effect

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SIGNIFICANCE OF THE SAGNAC EFFECT: BEYOND THE CONTEMPORARY PHYSICS

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CONTENTS

I. THE PARADIGM

A. Analytical Viewpoint

During the historical development, the notions of electrodynamics and the theory of light have become complicated complexes of concepts [1]. And what is more, nowadays they are incomplete, or in the worst case wholly confusing. The laws

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of electrodynamics in their present form are not valid in rotating and deforming systems in general [2]. These turbulent notion complexes—which are inadequate for the inner connections, as verified by experiments, measurement results, and certain electrodynamical states and processes—have to be broken open, disintegrated, and then disjoined. Henceforth, we must search for those genuine, pure, and simple electrodynamical ideas that can be joined in an imminent natural and adequate manner. Consequently, progress can be achieved only by careful analysis.

Some of the unsolved problems in contemporary electrodynamics draw attention to deeper (more profound) evidence, new ideas and new theories or equations. The aim of this historical introduction is to find the deeper evidence and new basic concepts and connections. The guiding principle is the investigation of light propagation.

B. Profound Evidence and Connections

The childhood of optics was in ancient religious Egypt. The first survived written relics of the optics originates from antique Greek science. Euclid was regarded as one of the founders of geometric optics because of his books on optics and catoptrics (catoptric light, reflected from a mirror).

The geometric description of the light propagation and the kinetics description of motion were closely correlated in the history of science. Among the main evidence of classical Newtonian mechanics is Euclidean geometry based on optical effects. In Newtonian physics, space has an affine structure but time is absolute. The basic idea is the inertial system, and the relations are the linear force laws. The affine structure allows linear transformations in space between the inertial coordinate systems, but not in time. This is the Galilean transformation:

$$x' = x + x_0 + vt, \qquad t' = t + t_0 \tag{1}$$

This is a law of choice for any motion equation.

The revolution in physics at the end of nineteenth century was determined by the new properties of light propagation and heat radiation. However, there remain many unsolved problems in these fields [2].

The laws of sound propagation in different media include the concept of ether, which is the hypothetical bearing substance of light and electromagnetic waves.

II. HISTORICAL OVERVIEW

A. The Main Experiments

The first measurement for the determination of velocity of sound was made by Mersenne in 1636. In 1687 Newton gave a rough formula for the velocity of sound. It was further developed by Laplace in 1816, based on the adiabatic changes of states for gases. In 1866 Kundt constructed the so-called Kundt tube, which can determine the velocity of sound in liquids and solid materials. He found that the velocity of sound grows because of the solidity of bearer materials. In the framework of classical mechanics, this observation inspired the notion that ether is an extremely solid substance.

The first attempt to determine the speed of light was made by Galileo in 1641. Descartes assumed an infinite speed of light based on the unsuccessful Galilean measurement.

In 1676, after 20 years of observation of the motion of Jupiter's Io moon, Römer published his result about the speed of light, which was calculated as $c = 220{,}000$ km/s [3].

In 1727 Bradley performed a much more precise experiment to determine the speed of light. His measurements were based on the aberration of stars, and the results of these measurements closely approximated today's values.

Arago was the first to measure the speed of light under laboratory conditions [4]. This measurement gave the Bradley's value for the speed of light. In 1850 Arago's followers Foucault [5], and Fizeau [6] proved that the speed of light is higher in air than in liquid. These measurements closed down the old debate in the spirit of the wave nature of light. In that time this seemed to verify the concept of ether as the bearing substance of light.

The first experimental investigation for the magnitude of change in light speed in moving media was made by Fizeau in 1851 [7]. His experiment proved that the velocity of the propagation is greater in the direction of motion of the medium than in the opposite direction; that is, the light is carried along with the moving medium. This theory was developed and confirmed by Michelson and Morley in 1886. In 1926 Michelson developed the Foucault's rotating-mirror experiment. The result of Michelson's experiment [8] is $c = 2.99769 \times 10^8 \pm 4 \times 10^5$ m/s [where c is (longitudinal) speed of light].

B. The Turning Point: Michelson–Morley Experiment

In 1867 Maxwell published his book on electromagnetism [9]. Maxwell's work has a basic importance, not only in the electromagnetism but also in optics. It also provided a common frame of reference for the propagation of electromagnetic and light waves.

The Maxwell equations are valid only in the unique inertial coordinate system, but they are not invariant for the Galilean transformation (1). This means that the Maxwell equations do not satisfy the requirements of classical equation of motion. This problem was apparently solved by the introduction of the concept of ether, the bearing substance of light. The challenge was to determine ether as the unique inertial system, or earth's motion in this ether.

Maxwell in another work [10] raised the question as to whether the translation motion of the earth relative to the ether can be observed experimentally.

An electromagnetic inertial system could be found by measurement, which could be used in astronomical calculations as well. Furthermore, space must be provided for formulating an equation of motion that is less rigorous than that used in Galilean relativity theory.

Numerous unsuccessful measurements were made to determine the motion of earth in the ether. These measurements were not able to give results compatible within the framework of classical Newtonian mechanics, even though that the earth has an orbital velocity $v_o \sim 30{,}000$ m/s (where v_o is velocity of the earth to the ether). In 1887 Michelson and Morley also determined the earth's orbital velocity by their precision interferometer [11]. The updated arrangement of Michelson-Morley experiment (M-M experiment) can be seen in Fig. 1.

According to classical mechanics, the traveling times of light T for the arms d_1 and d_2 can be given as Follows:

$$T_{OAO'} = \frac{2d_1}{c}\frac{1}{1-(v^2/c^2)}, \qquad T_{OBO'} = \frac{2d_2}{c}\frac{1}{\sqrt{1-(v^2/c^2)}} \tag{2}$$

Fitting the length of interferometer's arms—according to the zero difference of traveling times (zero interference)—it is given that $\Delta T = T_{OBO'} - T_{OAO'} = 0$. Then the lengths of two arms can be determined exactly:

$$d_1 = d_2\sqrt{1-\left(\frac{v^2}{c^2}\right)} \tag{3}$$

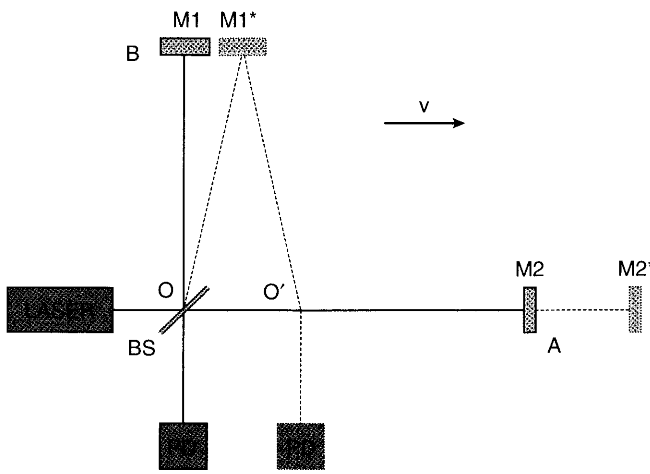

Figure 1. An up-to-date arrangement the of Michelson–Morley experiment. Here LASER means the source of light, BS means beamsplitter, M1 and M2 are mirrors on the end of arms, PD is the phase detector (interferometer), and v is the earth's orbital velocity, which is regarded as the inertial motion for short time periods.

According to classical physics, the difference of traveling times ΔT^* and the interference picture must be changed, turned around the instrument with 90°:

$$\Delta T^* = T^*_{OBD'} - T^*_{OAO'} = \frac{2}{c(1-(v^2/c^2))}\left\{d_2 - d_2\sqrt{1-\left(\frac{v^2}{c^2}\right)}\right\} \tag{4}$$

Substituting Eq. (3) into Eq. (4) and arranging, the traveling time difference for $v^2 \ll c^2$ is

$$\Delta T^* = \frac{2d_2c}{c^2 - v^2}\frac{v^2}{c^2} \tag{5}$$

Their experiments proved that the travelling-times differences did not change along the two arms $\Delta T^* = 0$ for any turning round of instrument. In other words, there was no change in phase relations or interference fringes. Thus, one might suppose that the solar system moved relative to the ether possessing a velocity that coincided with that of the orbital velocity of the earth, and, by coincidence, the experiment was carried out during a period when the earth was moving relative to the sun in the same direction as the ether. This experiments essentially contradict classical Newtonian mechanics. The Michelson–Morley measurements, which resulted in a negative outcome, have had one of the most remarkable influences on the development of twentieth-century physics. A modern setup can be seen in Fig. 2.

C. The Sagnac-Type Experiments

The earth's rotation around its axis can be seen from the apparent motion of the stars. The rotation can also be observed by mechanical experiments carried out on the surface of the earth, that is, with the help of Foucault's pendulum, or by observing of the motion of a rapidly rotating gyroscope. It is important that the rotation of the earth can also be observed by closed optical experiments.

This effect was first demonstrated in 1911 by Harress and in 1913 by Sagnac, so it is now often called the *Sagnac effect.* Sagnac determined a rotation by a closed optical instrument [12]. Sagnac also fixed an interferometer onto a rotating disc. A flowchart of the basic arrangement of the essential features in the Sagnac experiment is shown in Fig. 3.

It is clear that the rotation occurs relative to the carrier of electromagnetic waves; this is the observed rotation relative to the ether.

This measurement was improved by Michelson and Gale in 1925 using the earth instead of rotating disk [13].

In 1926 the Michelson–Gale experiment was confirmed by Pogány [14], who determined the surface velocity of the rotating earth by a closed optical

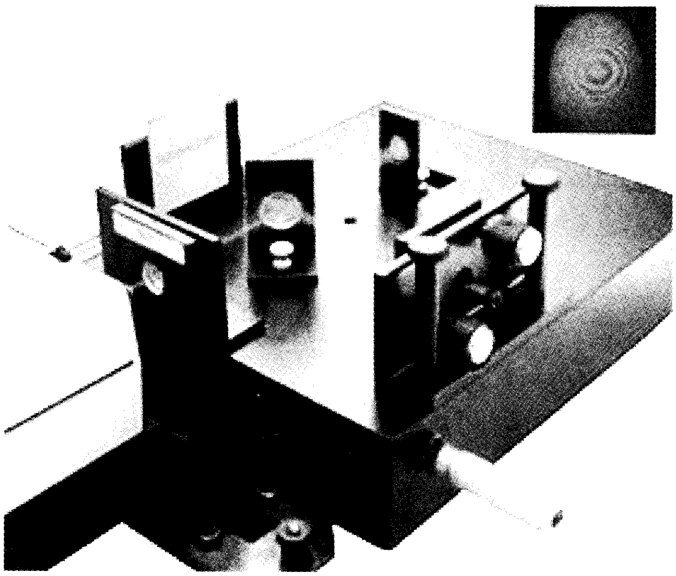

Figure 2. An up-to-date setting of a M-M-type experiment.

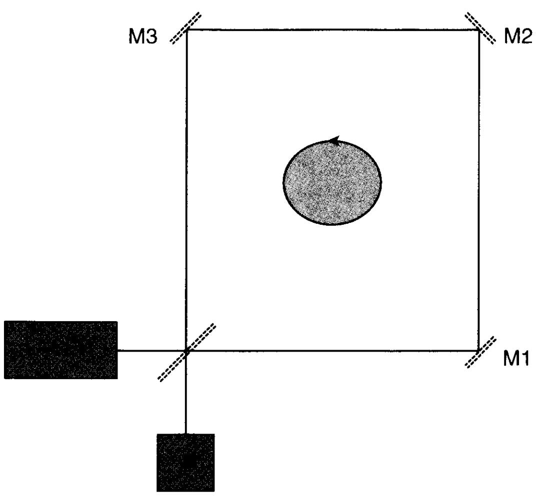

Figure 3. Arrangement of Sagnac the experiment. Here, LASER represents the source of light, the first mirror is a beamsplitter, M1–M3 are mirrors on the end of arms, and I represents the interferometer.

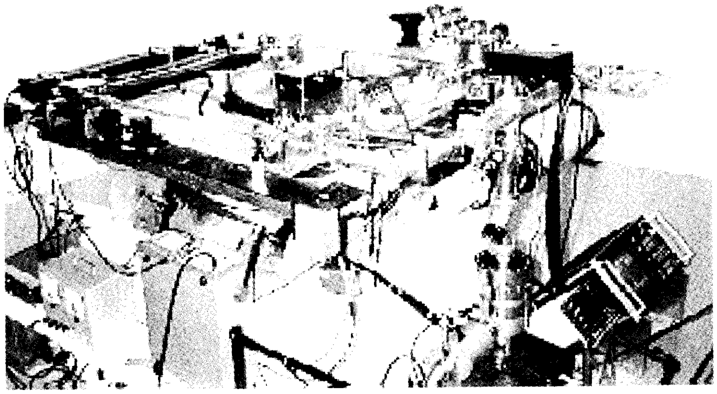

Figure 4. The CI laser-gyroscope arranged by Bilger et al. [15].

instrument, $V_R \sim 300$ m/s, in Budapest's latitude. Because of its precision, this experiment it is used in some military applications, such as in laser gyroscope techniques. It is also commonly used today in guidance and navigation systems for airlines, nautical ships, spacecraft, and in many other applications. A laser gyroscope is shown in Fig. 4.

Because of the incredible precision of interferometric techniques, this measured velocity is altogether one percent of the earth's circumference velocity derived from the orbital motion. Very-long-baseline interferometry (VLBI)—which is an exhaustively improved *Pogány* experiment—can detect $\Delta\omega \approx 10^{-9}$ in the earth's rotation.

Sagnac-type experiments are versatile and more accurate than the M-M-type experiments, which cannot detect rotation. Sagnac-type experiments demonstrated that the caused phase shift is proportional to the angular velocity ω and the measure of the enclosed surface S in a rotating system.

III. ANALYSIS OF MICHELSON–MORLEY EXPERIMENT

A. The Least-Arbitrariness Principle: The Necessary Hidden Variables

In order to explain the negative result of the M-M-type experiments, a whole series of hypotheses were proposed, all of which were eventually found to be untenable. This first explanation consists in the assumption that the ether at the earth's surface is carried along by the earth, adhering to the earth like the earth's atmosphere. This explanation became very improbable in the light of Fizeau's experiment on light propagation in media with motion. This experiment suggested that the ether is not carried along or at most is only partially carried along by moving medium [7,8].

Numerous researchers tried to determine the velocity of the earth motion to the ether by electromagnetic and optical methods. These experiments predicted that the earth with the experimental instruments always are standing in (or moving along with) the ether, which really is a tenacious contradiction of contemporary physics.

The physicists tried to solve this profound problem by the *principle of least arbitrariness or* a fortiori [2c]. This principle means the optimum relation among the introduced hidden variables, which are necessary to description of the phenomena. (This maxim is well known and accepted in the scientific community as (*Occam's razor.*)

B. The Lorentz Interpretation of M-M Experiments

Lorentz [16] and his colleagues introduced a hidden variable: the *contraction form factor* $\beta = (1 - v^2/c^2)^{1/2}$ in Eq. (3). In the case of $d_1 = d_2$, Eq. (3) provides a simple solution of this contradiction. In Eq. (5) the difference in traveling times can be eliminated if, for example, d depends on the velocity only:

$$d^* = d\beta \tag{6}$$

(where β is the contraction from factor).

Of course, in Eq. (6) the contraction form factor β is valid only in the arm that is parallel to the velocity vector. Equation (6) was interpreted by Lorentz and Fitz-Gerald as a real contraction [17]. It is important to see that in Eq. (6) the hidden parameter β is only one possible solution for the contradiction, but the result of the M-M experiment allows numerous other solutions based on the inner properties and features of the light. The M-M experiment destroyed the world picture of classical physics, and it required a new physical system of paradigms. Thus, for example, the applicability of Galilean relativity principle was rendered invalid.

One of the most important requirements for an axiomatic theory is to determine the validity-round of the laws, and to verify of the self-consistency in the theory. The M-M experiment proved that the prediction of the classical physics was not valid for light propagation, or rather, for Maxwell's theory of electromagnetism. This is an applicability limit of Newtonian physics. Beyond this limit, Newtonian physics becomes incomplete.

Lorentz, Fitz-Gerald, and others were able to formally explain the lack of changing in interference fringes [1] using a hidden variable that is essentially the quotient of the theoretical and the measured results. This method, combined with the least-arbitrariness principle, obtained the optimal hidden parameter, which was satisfied by the experiment. The operator of the optimal hidden parameters used in the description of the M-M experiment is the generalized form factor, the so-called Lorentz transformation. Lorentz believed a fortiori that this operator functions in connection with the ether's wind, and that this wind is the actual cause of the assumed bodies' contractions. The merit of the Lorentz transformation is the verification for the invariance in the Maxwell equation. However, one disadvantage of the Lorentz interpretation is that the contraction is independent of the material properties of bodies.

C. The Einstein Interpretation of M-M Experiments

Einstein created a tabula rasa in his 1905 paper titled "On the electrodynamics of moving bodies" [18]. He rejected the paradigm of ether as well as the classical concepts of space and time, and founded a new physics by the exclusion of inner forces called the *special relativity theory*. He stated two axioms: (1) the principle of relativity and (2) the homogeneous and isotropic propagation of light in any inertial coordinate system of the vacuum. The homogeneous isotropic light propagation can be satisfied by the Lorentz-contracted spacetime. Of course, without the concept of physical ether, the ether wind theory is meaningless. Einstein refused the material explanation of Lorentz and Fitz-Gerald, but kept the contraction form factor β without another material interpretation. It is clear that the nonmaterial interpretation given by Einstein is high-handed, but it is still questionable that it is the least arbitrary.

It is well known that Einstein's interpretation for the Michelson–Morley-type experiments was self-consistent in mathematical sense, although he lost the genuine concepts and the traditional a priori and anthropic relations of space and time forever. With this step the science left its childhood or rather, lost its innocence. In this way Einstein created the opportunity for any extravagant interpretations of strange experiments, and so any other physical concepts, for example, the propagation theory, became illusory.

D. Interferometers: Standing-Wave Systems

As it was confirmed that the notions of electrodynamics and the theory of light propagation have become complicated complexes of concepts and they are wholly confusing. These inadequate notion complexes have to be broken open, disintegrated, then disjoined.

Let us study the M-M- and the Sagnac-type experiments without any preconceptions. We can then see that the interferometers are unable to measure the traveling times; they can measure only the interference fringes of standing waves. This means that description of the M-M experiment allows the use of the wavelengths and phases, but not the traveling times and the speed of propagation. In a strict sense, the Michelson–type the interferometers are unable to measure the velocity of propagation and traveling times in the arms. Specifically to measure traveling times, it an exact optical distance measurement theory and method would be necessary. (In connection with the restrictions of the least-arbitrariness principle in the geometric optics, the principle of least action can give the path of light as the distance.)

The fine distinction between traveling times and the shift in interference fringes may not be clear from the point of view of Newtonian mechanics, which predicts both to be changing. Finally, classical physics and the geometric optics are refuted or restricted by experience, notwithstanding the fact that these are self-consistent theories in their own right.

IV. ANALYSIS OF SAGNAC-TYPE EXPERIMENTS

A. The Classical Arrangements

Consider a disk of radius R rotating with an angular velocity ω around its axis [1,12–14]. Suppose a large number of mirrors n are arranged on its periphery in such a way that a light signal starting, say, from a point A of the periphery is guided along a path very nearly coinciding with the edge of the disk. If the disk is at rest, a signal starting at time $t=0$ from a point A on the periphery arrives back into A at a time

$$T = \frac{2\pi R}{c} \tag{7}$$

However, if the disk is rotating with a circumference velocity $v_R = \omega R$ and the light signal is moving in the direction of rotation, then, at time $T = 2\pi R/c$, it will reach a point A_0 located at the location that A had left at $t = 0$. The signal has to catch up to point A, which is moving away; the signal will reach this location at a later time T_+, so that $cT_+ = 2\pi R + v_R T_+$; therefore

$$T_+ = \frac{2\pi R}{c - v_R} > T \tag{8}$$

(where v_R is circumference velocity).

Now suppose that the light moves relative to the edge of the disk c_+ -according to classical physics and according to Eq. (8), in the direction of velocity

$$c_+ := c - v_R \tag{9}$$

(where c_+ is speed of light in the direction of velocity).

Suppose that the velocity of the beam is relative to the disk but that we have calculated the traveling time only and that the signal starting from A must again catch up with point A, which is moving away.

If the light signal moves in the opposite direction, it reaches A sooner that at $t = T$ as point A moves then toward the signal. In this case we find for the time at which the signal reaches A

$$T^- = \frac{2\pi R}{c + v_R} < T \tag{10}$$

or we may assume that the speed of light traveling in the opposite direction is velocity c_-:

$$c_- := c + v_R \tag{11}$$

(c_- is speed of light opposite the velocity).

In the boundary transition ($n \to \infty$), the polygon—constructed by the mirrors—becomes a circle with radius R, and the difference of the times needed to circle around the disk in the opposite direction is thus

$$\Delta T = T_+ - T_- = 2\pi R\left(\frac{1}{c - v_R} - \frac{1}{c + v_R}\right) = \frac{4\pi R v_R}{c^2 - v_R^2} \cong \frac{4S\omega}{c^2} \tag{12}$$

where $S = \pi R^2$ is the area of the disc circled round by the beams and ω is angular velocity.

Of course, according to the Section III.D, this calculation should really be carried out at wavelengths $\lambda - s$ instead of traveling times $T - s$. The Sagnac-type experiments are also standing-wave systems. Then the magnitude of shift of the interference fringes with the above ω

$$\Delta\lambda = \lambda_+ - \lambda_- = 2\pi R\left(\frac{c}{c_+} - \frac{c}{c_-}\right) \cong \frac{4S\omega}{c} \tag{13}$$

which has been confirmed by experiments [12–14] without any doubt.

Naturally this coincidence does not mean that the geometric optics added to the classical physics could be used for the exact description of the light propagation since the Michelson–Morley experiment refuted its validity forever. It is evident that there are possible new mathematical definitions for c_+ and c_- instead of the ordinary speed addition rule of the classical physics seen in Eqs. (9) and (11). These can be compatible with the experimental results as well.

B. The Relativistic Calculation

The major absurdity of the result of the Sagnac-type experiments is that the calculation was carried out by the geometric optics exclusively. Of course, the calculation should carried out using the special relativity theory exhaustively.

The validity of a physical theory depends on, among other things, the certainty and completeness by which the theory is ordered to the totality of experiences [2c]. Consequently, the special relativity theory must also be confronted with observation and experiment carried out on the physical system examined. In any given case one has to clarify the mutuality of the special relativity and the Sagnac effect. In this case, the second postulate of the special relativity theory must be satisfied; that is, the speed of light must be the same in every direction

$$c_+ = c_- = c \tag{14}$$

by definition. Substituting Eq. (14) into Eq. (13) a zero shift of interference fringes, we obtain. $\Delta\lambda = \lambda_+ - \lambda_- = 0$, which is contrary to the experiments.

This means that the special relativity theory does not predict any shift of interference fringes that is contrary to the experiments. The standing-wave approach of Sagnac-type experiments allows a freedom in the definition of c_+ and c_- instead of Eqs. (9) and (11), but the second postulate of the special relativity theory is out of this range.

Of course, the Sagnac-type experiments were not made in a perfect inertial systems. The earth's orbital motion around the sun is also a noninertial system. But the circumference velocities in both cases are extremely low, $v/c \ll 1$, and—in the first approximation—these frames of reference are almost inertial systems.

The Sagnac-type experiments proved that the circumference velocity can be detected by purely and closed optical instruments as well. The circumference velocity of the rotating earth, $v_R \sim 300$ m/s, is extremely low to the earth's orbital velocity, which is also a circumference velocity, with $v_o \propto 100 \times v_R$. In both cases, Michelson–Morley and Sagnac wanted to determine the circumference velocities. The M-M experiments were unable to determine the earth's orbital circumference velocity, but the Sagnac experiment determined the rotating earth's circumference velocity. On the basis of the Michelson–Morley-type experiments, Einstein postulated the constancy of the speed of light, so the results of the Sagnac-type experiments—with different speeds of light—contradict the special relativity theory.

In a strict sense, the classical Newtonian mechanics and the Maxwell's theory of electromagnetism are not compatible. The M-M-type experiments refuted the geometric optics completed by classical mechanics. In classical mechanics the inertial system was a basic concept, and the equation of motion must be invariant to the Galilean transformation Eq. (1). After the M-M experiments, Eq. (1) and so any equations of motion became invalid. Einstein realized that only the Maxwell equations are invariant for the Lorentz transformation. Therefore he believed that they are the authentic equations of motion, and so he created new concepts for the space, time, inertia, and so on. Within this framework the Lorentz transformation is the law of choice for the equation of motion. Sagnac's result proved that Einstein's method contradicts experience. Besides, on a deeper level it is proved that Maxwell's equations are not applicable for the slowly rotating systems. So, in an authentic theory of light, Maxwell's equations must be changed to allow for a description of rotating and deforming systems [19,20].

C. The Incompleteness of the Theory of Light

The classical theory of light—consisting in the complexes of concepts such as light propagation and interference—employs geometric optics added to classical physics and the Maxwell theory of electromagnetism. These turbulent notion complexes suffered from logical inconsistencies. [For example, the Maxwell equations are not invariant to the Galilean transformations (1) since those are not equation of motion in the mechanical sense.] This conceptual conglomeration was broken open by the Michelson–Morley-type experiments. In the present case, the incompleteness of classical light theory means that it cannot describe and explain the M-M-type experiments within the frame of the theory. For a complete, accurate description and explanation, a new theory was needed. Einstein believed the new theory to be nonclassical, and so he created the special relativity theory. The relativistic theory of light is similar in composition to the classical one, except that classical mechanics is changed to the relativistic mechanics. The relativistic theory of light—beside the explanation of the M-M-type experiments—was free from the logical problem of the classical light theory described above.

Eight years later Sagnac made a crucial experiment. The Sagnac-type experiments are broken open the complexes of concepts of relativistic light theory. Thus it became an incomplete theory since its prediction of the shift of interference is $\Delta\lambda = \lambda_+ - \lambda_- = 0$, contrary to the Sagnac-type experiments.

We need to find a complete theory of light based on more profound evidence, new basic concepts, and authentic connections.

V. SUMMARY

The complete theory of light should describe and explain the totality of experiences, that is, the M-M- and Sagnac-type experiments simultaneously.

In the spirit of the standing-wave picture of Sagnac-type experiments, this theory needs to recalculate the result of the Michelson-Morley experiment as well. In the M-M experiment there is a new unknown hidden parameter c_p, which denotes the speed of light in the direction perpendicular to the earth's velocity. The traveled path of light in the perpendicular arm $\lambda_p := 2Tc_p$ [dim{λ} = meter]. [where c_p is speed of light perpendicular to the velocity (transversal light speed)]. The difference of the paths traveled in the interferometer is

$$\delta\lambda^* = \lambda_+^* + \lambda_-^* - 2\lambda_p^* = d_2\left(\frac{c}{c_+} + \frac{c}{c_-}\right) - 2d_1\frac{c}{c_p} \tag{15}$$

It can be seen that the second postulate of special relativity theory [Eq. (14)] leads to the form

$$c_+ = c_- = c_p = c \tag{16}$$

Substituting Eq. (16) into Eq. (15), we obtain a zero interference change, corresponding to with the M-M experiment. The M-M experiments are only a limited part of the totality of experiences.

The Michelson–Morley- and Sagnac-type experiments give only two independent equations—Eqs. (13) and (15)—for three unknown hidden parameters c_+, c_-, and c_p. In the present case the incompleteness means that there are three unknown parameters for two equations. A third equation is needed in the form of a crucial experiment for the unique solutions. (Of course, this crucial experiment must be independent of the M-M- and Sagnac-type experiments.) In this manner we will be able to develop an authentic nonquantized (complete) theory of light.

After the frequent metaphysical optimism of a century ago, we again return to the fundamental questions.

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