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Crucial Test of Relativity Theory: Open Currents and Magnetic Model of Light

Contents

Abstract

Fundamental tests of special theory of relativity (STR) are revised. Among crucial tests of the Faraday law we consider the experiment with a nonshielded Trouton-Noble capacitor and the nonconservation of mechanical angular momentum of an isolated charged system. As a new crucial tests of Faraday's law for open currents, the induction on a coil moving with respect to a static electric charge is outlined. The magnetic model of light propagation in moving media is considered. According to this model the phase velocity of the light wave is affected by the flow but the momentum of particles (photons) is not. Thus, the Fizeau experiment does not corroborate the addition of velocities of STR. A non-interferometric experiment of the Fizeau type represents a crucial test of the magnetic model and of the speed of photons in moving media.

1. Introduction

In this paper we wish to review in a critical way some of the experiments that support the special theory of relativity (STR) and suggest some crucial tests not yet performed, but realizable with present technology. The controversial and polemic aspects of electromagnetism and STR involved in these crucial tests touch issues that are still unclear or not well understood. Some of these issues are related to the concept of nonconservation of simultaneity, necessary to fulfill the requirement that the speed of light is constant in every inertial frame. The link with the transformations of the electromagnetic (em) fields and to the paradoxes (most of which have been "solved") inherent to them, are discussed. STR cannot be claimed to represent a well understood and tested theory until these issues are clarified theoretically and tested experimentally.

Most of the controversial issues are related to the ether concept. Physicists who use the ether concept in modern physics claim to have met with adverse criticism and hostility, even where their work is directed towards advancing physics. The ether concept in question may concern the argument about Lorentz's and Einstein's interpretations of relativity, Stokes-Planck dragged ether theory, Dirac's ether in a quantum-mechanical context, or the modern ether related to cosmic background radiation. It may be that only some concepts of ether are wrong or not useful, so that clarification of the modern concept of ether may make it viable.

Our present suggestion for crucial tests of STR is not made to support some specific ether theory, nor are these tests to be placed within a specific controversial context. Thus, to begin with, we discuss briefly in Sec. 2 a group of experiments of electromagnetism related to STR, some of which have been considered elsewhere [1] – [4]. For these we point out, from a qualitative point of view, their range of validity and their limitations. As a result of our analysis, we show that the traditional experiments do not corroborate *directly* and/or *completely* the notion of nonconservation of simultaneity and transformation of the em fields of STR.

Of particular interest are two new proposed experiments. One is the test of the Faraday law of induction for *open* circuits or *open* currents. This law has been tested in its integral form for alternating, time-varying fields only, such as alternating current in a coil (closed current). There are no reference frames where the em fields are static. However, according to STR a static, nonuniform electric field in the laboratory frame may be seen as a time-varying magnetic field (open current) for a coil in motion. This experiment has never been performed and represents a test of the law of induction, which in this case may be used to corroborate (or not) the transformations of the em fields of STR.

Furthermore, in revising the experiment of 1851 by Fizeau for the light speed in a moving medium, we find that, contrarily to what has been believed for more than a century, this experiment provides corroboration of the speed of the phase of the light wave but not that of the light particle (photon), so that it does not corroborate the addition of velocity foreseen by STR [4]. This result is quite important because Fizeau's experiment seems to be the only one dedicated to test the relativistic addition of velocity. A new experiment of the Fizeau type, capable of measuring the speed of photons in moving media, is outlined. This experiment represents a crucial test of the relativistic addition of velocity.

2. Qualitative analysis of new crucial tests of STR

Seeking here for new crucial tests of STR, we consider some aspects of the relativistic interpretation of classical electrodynamics that need corroboration and also point out a common misconception about the Fizeau experiment, which is taken as a proof of the addition of velocities of STR.

a) Within the context of ether theories based on the so called Tangherlini Transformations (TT) [5], practically all the optical tests of STR can be interpreted equally well by using the TT or the Lorentz Transformations (LT) of STR [6] – [12]. Both the TT and LT transformations foresee length contraction and time dilation and are special cases of the general transformations [9]

$$x' = a(x - vt), \quad y' = by, \quad t' = dt - \varepsilon x. \qquad (1)$$

LT are recovered from (1) by setting

$$a = d = \gamma = \left(1 - v^2/c^2\right)^{-1/2},$$

$b = 1$, and $\varepsilon = \gamma v/c^2$, while TT correspond to $a = d^{-1} = \gamma$, $b = 1$, $\varepsilon = 0$. Actually, transformation (1) with $\varepsilon = 0$ are denoted as Generalized Galileo Transformations [10]. The main difference between the Generalized Galileo Transformations and the LT is that the former conserve simultaneity of events while the LT do not. We can see this from the corresponding transformations of time from a reference frame S to a moving frame S′, which are respectively

$$t' = d\,t \qquad\qquad t' = \gamma\left(t - \frac{v}{c^2}x\right). \qquad (2)$$

Thus, the main difference is related to the last term of Eq.(2), $\gamma\, xv/c^2$, which in STR implies the violation of simultaneity in order to assure the constancy of the speed of light c. Optical experiments that provide a null result, such as the Michelson-Morley experiment, can be interpreted by STR as due to the invariance of c, and by ether theories with TT ($d = \gamma^{-1}$) as due to the Lorentz-Fitzgerald contraction of the moving interferometer arms. Analogously, tests involving time dilation, such the decay rate of moving μ mesons, are equally well interpreted using transformations (2) in the two cases.

For theories based on the Generalized Galileo Transformations, time dilation and length contraction are real effect due to absolute motion with respect to the ether. For STR these effects surge as a consequence of relativity of motion and violation of simultaneity. Supposing that the luminiferous ether does not exists, since the invariance of c requires the violation of simultaneity, the null results of the Michelson-Morley experiment and other optical experiments on the speed of light in vacuo that confirm the constancy of c, are indirect corroborations of the nonconservation of simultaneity. However, it is worth recalling that these optical experiments can be interpreted, besides by the TT, also by ether theories of the Stokes-Planck type [13] that involve an ether at rest with massive bodies.

Thus, it turns out that optical tests performed so far can be equally well used to support STR or the above mentioned ether theories, so that from a qualitative point of view, these tests cannot be considered as decisive or crucial tests of STR.

b) Nevertheless, the dependence on x of t' in the last of Eq.(2) implies that the em fields of Maxwell's equations transform in STR quite differently from what ether theories or classical electrodynamics not based on STR would predict. The LT provide a space-time symmetry: x depends on t, and t depends on x. In the relativistic interpretation of electromagnetism, this symmetry is also called duality and corresponds to the symmetry of electric and magnetic phenomena: moving electrified bodies produce magnetization, and moving magnets produce electrification. How well has this symmetry of Maxwell's equations been tested? We believe that it has been tested only partially, as the following arguments indicate.

Let us consider as an example the STR transformation of the four-potential (Φ,$\mathbf{A}$)

$$\Phi' = \gamma\left(\Phi - \frac{v}{c}A_x\right),\ A'_x = \gamma \left(A_x - \frac{v}{c}\Phi\right),\ A'_y = A_y,\ A'_z = A_z. \qquad (3)$$

In the transformation of the scalar potential Φ, it appears the term $(v/c)A_x$, implying that magnetized bodies in motion produce electrification. Thus, according to STR a moving magnet appears as electrically polarized, an effect that is due to nonconservation of simultaneity. Classical electrodynamics not based on STR would not use the LT but rather Generalized Galileo Transformations (1) with $\varepsilon = 0$, so that simultaneity is conserved and the term $(v/c)A_x$ is not present. It follows that nonconservation of simultaneity can be tested by testing the transformations of em fields. A dedicated test of this effect, the inverse Rowland experiment that will be discussed elsewhere, is needed to discriminate STR from alternative electrodynamics theories.

Conversely, in the transformation of the vector potential $\mathbf{A}$, it appears the term $(v/c)\Phi$. This implies that moving electrified bodies ("open" or convection currents) produce magnetization. According to the transformation of em fields of STR, that can be derived from (3), a static electric field $\mathbf{E}$, produced by charges at rest in the laboratory frame S, is seen as both an electric field $\mathbf{E}'$ and a magnetic field $\mathbf{B}'$ in a frame S′ moving with velocity $\mathbf{v}$ with respect to S. Moreover, the covariance of Maxwell's equations for STR surges after the introduction of the convection current $\rho\mathbf{u}$, the displacement current $\partial\mathbf{E}/\partial t$ and the interpretation of the Faraday law in differential form. However, Faraday's law of induction is tested experimentally for closed circuits only, and not for open currents such as a convection current $\rho\mathbf{u}$.

In the usual tests of Faraday's law of induction, the magnetic flux variation is produced by charges circulating in closed circuits or loops. In closed circuits, negative charges (electrons) move with respect to the ions of the neutral conductor at rest. The motion of the charged particles occurring in a loop, or closed circuit, identifies a privileged reference frame: that of the conductor at rest.

Interpreting Faraday's law in differential form, Maxwell represented it by the equation

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}.$$

However, Maxwell's ether theory and STR implies that the $\mathbf{B}$ field may be produced by charges in motion (open currents $\rho\mathbf{u}$) even when they are not circulating in closed circuits or loops. A part from Rowland's experiment [14] which provides only qualitative results, it is this step from closed to open circuits the one which has not been verified quantitatively. This fact leads to seek for a new test of the Faraday law in differential form, where $\mathbf{B}$ is produced by open currents $\rho\mathbf{u}$.

c) A test on the locality of the induced emf has been proposed in relation with the Trouton-Noble (TN) experiment [1]–[3]. This test is recalled here because we are dealing in general with the tests of Faraday's law in differential form. Briefly, the

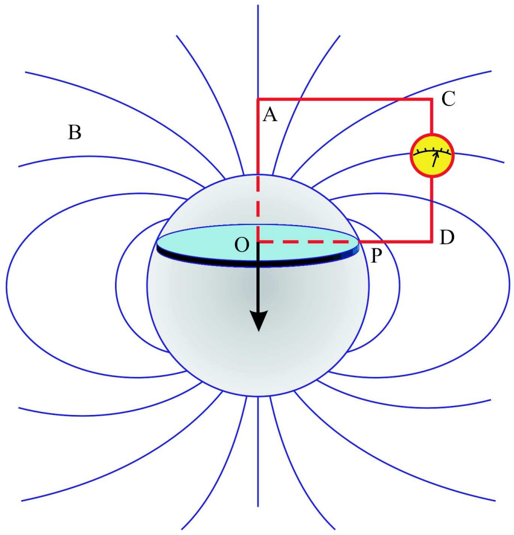

Fig. 1. A section of the Earth, perpendicular to its rotation axis, mimics a Faraday's disk. A simplified scheme of the lines of the magnetic field **B** of the Earth are drawn, assuming cylindrical symmetry and neglecting the asymmetric components of **B**. According to the standard interpretation of special relativity, the field lines of a rotating magnet do not rotate and the emf is induced on the rotating portion OP of the closed circuit OACDP. A test charge placed on the surface of the Earth feels the effective local electric field $\mathbf{E}_{eff} = \mathbf{v} \times \mathbf{B}$, where $\mathbf{v}$ is the tangential velocity of the Earth's surface at the location of the laboratory. A charged capacitor of the Trouton-Noble type, experiencing this field, tends to rotate to align the charged plates in the direction of the field.

point is the following: The Earth, which possesses a magnetic field, is rotating about its axis with angular velocity ω, as shown in Fig. 1. According to the standard interpretation of the Faraday disk rotating together with in the cylindrical magnet producing the magnetic field, the emf force is induced in the disk and is due to the effective field $\mathbf{v} \times \mathbf{B}$ that is seen by the part of the rotating disk possessing tangential velocity $\mathbf{v}$. A section of the Earth can be thought of as mimicking a giant magnetized Faraday disk, and a nonshielded TN charged capacitor placed on the Earth should feel this effective field leading to a positive result for this test.

As mentioned above, in the transformation of the scalar potential Φ appears the term $(v/c)A_x$, due to nonconservation of simultaneity and implying that moving magnetized bodies produce electrification. The effective field $\mathbf{v} \times \mathbf{B}$ foreseen by STR corresponds to the electrification felt by the charges of the nonshielded TN capacitor moving with velocity $\mathbf{v}$ with respect to the magnet. Classical electrodynamics not based on LT and STR interprets $\mathbf{v}$ as the velocity relative to the field lines. If the field lines are rotating together with the magnet (in this case, the Earth), $\mathbf{v} = 0$ and the effective field is zero. Thus, for this TN experiment, a null result is foreseen by electrodynamic theories alternative to STR, and this crucial test can discriminate STR from rival em theories.

With respect to the idea of testing the effective field $\mathbf{v} \times \mathbf{B}$ with a TN capacitor, it should be mentioned that in the early TN experiments the respective apparatus or capacitors were shielded from external fields so that those experiments could not detect the effective field $\mathbf{v} \times \mathbf{B}$ and a null result is to be expected.

The traditional historical Trouton-Noble experiment was performed originally to corroborate Maxwell's ether theory. Charges (those of the TN capacitor) moving with respect to the ether form a current (open current) that produces a magnetic field. A moving charge would feel this magnetic field and a force would be acting on it producing a torque on the TN capacitor. Since this torque was not observed, it was assumed that there was no motion with respect to the ether, i.e., there was no ether. Ironically, this null result can be interpreted also as a proof that open currents do not produce a magnetic field! Thus, other tests involving open currents are potentially possible crucial tests of STR.

d) Always within the context of testing the Faraday law in differential form and STR, we consider convenient to recall here that the effect of the Faraday law of induction on a charged isolated system is associated to the violation of the conservation of the mechanical angular momentum of the isolated system. This aspect of electromagnetism, discussed in detail in Ref. [3], is here summarized as follows: Faraday's law of induction between closed circuits is well verified experimentally. When the current varies in a circuit, it induces an emf and a current in another closed circuit. In this case there is no violation of the mechanical linear and angular momentum: the action and reaction principle holds [15].

But does the current varying in a circuit produce a force $-c^{-1}q\partial_t\mathbf{A}$ on an isolated charge q? This is what Maxwell's equation and STR foresee, but there are no dedicated experiments that corroborate the theory. In the test described in Ref. [3], the magnetic moment of a small magnet, surrounded by a spherical distribution of charge, varies in time (Fig. 2). It follows that the force $-c^{-1}q\partial_t\mathbf{A}$ acting on the spherical charged shell produces a torque on the isolated system with the consequent violation of its mechanical angular momentum. Thus, this test can be considered

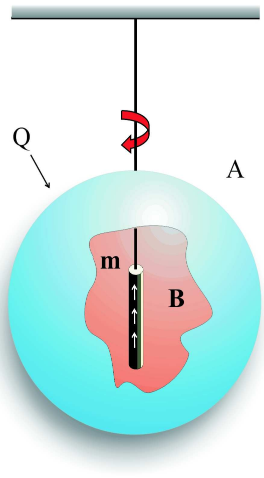

Fig. 2. Testing Faraday's law by verifying the nonconservation of the mechanical angular momentum of an isolated system. A magnetic dipole **m** (a small rod magnet) with its moment pointing in the vertical direction is placed at the centre of a charged spherical shell. The total charge Q of the shell is in the presence of the magnetic field **B** and vector potential **A** of the rod magnet. The whole system is suspended by a thin vertical torsion fiber. If **m** varies with time (or if the shell is discharged through the conducting suspension fiber) the em angular momentum of the system varies. By Faraday's law of induction in differential form, an azimuthal force $-c^{-1}q\partial_t\mathbf{A}$, tangent to the surface of the shell, is applied to the charge q on the shell and the corresponding torque acts on the system. Since there is no reaction torque on the magnet, the mechanical angular momentum of the isolated system is not conserved.

crucial because is simultaneously a test of Faraday's law in differential form, of STR and of the nonconservation of the mechanical angular momentum of an isolated system.

e) The new crucial test of the Faraday law in differential form and of STR, that we propose and describe in detail in Sec. 3 (see Fig. 3), is the following: Consider a set of static electric charges in frame S. These charges produce an electric field **E**. If a coil moves with respect to S, it will see a time-varying $\mathbf{B}'$ field in its rest frame S′. Hence, an electromotive force (emf) will be induced in the coil according to Faraday's law applied in S′. Now, an important point is the following: Can this induced emf be justified from the point of view of frame S where there is only a static **E** field? We do not know theoretical justifications for the induced emf. However, we believe that a test of this emf is crucial because it is capable of demonstrating if open currents (the charges seen moving in frame S′) produce (or not) a magnetic field and the related magnetic induction, as implied by STR.

f) Another experiment definitely worth revising, which is erroneously considered to confirms the addition of velocities of STR, is that performed by Fizeau in 1851. This experiment, designed to measure the speed of light in a moving medium, succeeded in corroborating Fresnel's ether theory. The outcome was later considered to support the relativistic addition of velocities. However, this experiment is based on an interferometric technique and a comparison with similar techniques used for effects of the Aharonov-Bohm type, indicates that what has been measured is the phase velocity rather than the particle (photon) velocity [4]. Thus, surprisingly, the Fizeau experiment does not corroborate the addition of velocities of STR. We do not know other dedicated experiments on addition of velocities and, thus, outline a crucial test that may achieve this purpose in Sec. 4 (Fig. 4).

Summarizing, we have considered several tests that support STR. Do these tests corroborate in a definitive way that STR is a well understood and tested theory? Unfortunately, this is not the case because, even after 100 years of STR, there are several aspects of the theory that have not been tested directly. Besides tests mentioned above such as the nonshielded Trouton-Noble experiment and the violation of mechanical angular momentum, we emphasize in this paper two crucial aspects: the Faraday law of induction for open currents and the addition of velocities for particles.

An experiment on the Faraday law of induction for open currents would validate (or not) the STR assumption that a static electric charge produces a magnetic field and associated induction in a moving frame, i.e., that open or closed currents play the same role in electrodynamics.

The repetition of a Fizeau type experiment that measures the speed of photons would validate (or not) the relativistic assumption that phase and particle speeds in moving media are the same, i.e., would validate (or not) the addition of velocities of STR. These two tests are considered in detail in the next Sections.

3. Testing Faraday's law for open currents

Let us consider a static charge distribution in frame S, which produces an electric field **E**. For our purposes it is convenient to consider a parallel plate charged capacitor with voltage difference V applied to the plates separated a distance d, as shown in Fig 3.

A coil moving with velocity $\mathbf{v}$ is made to pass through the capacitor. According to STR, in the rest frame of the coil the charge distribution in relative motion produces a magnetic field $\mathbf{B}' \simeq \mathbf{v} \times \mathbf{E}/c^2$ (MKSA system).

Faraday's induction law in the frame of the moving coil reads

$$emf = \oint \mathbf{E}'_{eff} \cdot d\mathbf{x} = -\frac{d}{dt} \int_S \mathbf{B}' \cdot d\mathbf{a}, \qquad (4)$$

implying that an emf force is induced in the coil while this passes through the capacitor and the magnetic field $\mathbf{B}'$ varies from zero to its maximum value.

Why should one doubt that this emf is induced in the coil? The point is that magnetic fields are generally produced by currents circulating in closed circuits or loops. In the rest frame of a conducting circuit, electrons move with respect to the ions of the conductor. The relative motion of electrons with respect to the ions forms a neutral current that generates a magnetic field. In their motion, electrons are bound to a closed path by the constraints of the conductor, and it turns out that a loop, or closed current, defines a privileged reference frame. On the contrary, there are no experiments showing that an isolated charge in uniform motion (open current) is equivalent to a conduction current that produces a magnetic field. Thus, the law (4) has not been tested for the case of a an isolated charge distribution moving with respect to the coil.

However, it may be claimed that the Rowland experiment of 1876 [14] indicates that isolated moving charges produce a magnetic field. Rowland used a circular parallel plate capacitor that was charged and set spinning about its axis of symmetry. By placing a magnetic needle near the rotating capacitor, Rowland observed qualitatively a small deviation of the needle that he attributed to the effect of the magnetic field produced by the charges of the capacitor in their circular motion. Some objections to Rowland's experiment are the following. In Stokes-Planck ether type theories the Earth is a local privileged frame where the ether is at rest [13]. In this case the charges of the capacitor are moving with respect to the ether and according to Maxwell they produce a magnetic field. But Rowland experiment does not prove the reciprocal effect that, if a charge is fixed on the Earth, an observer moving with respect to it experiences a magnetic field because of the relative motion. Moreover, in Rowland's experiment the charges move in circular motion due to the constraints of the rotating capacitor. A privileged frame for this motion is established, as in the case of charges moving in the closed circuit of a conductor.

In conclusion, there is no experimental evidence that a charge in *uniform* motion produces a magnetic field or that a stationary charge produces magnetization for a moving observer. Furthermore, the historical experiments of the Rowland type provide only qualitative results and do not corroborate the functional dependence of the magnetic field $\mathbf{v} \times \mathbf{E}/c^2$ on $\mathbf{v}$ and $\mathbf{E}$. In view of all these arguments, we believe that the result of Rowland experiment on the magnetic field produced by moving charges needs corroboration.

Considering this problem from a theoretical point of view, is there a way to predict in frame S the result implied by Eq.(4) without resorting to use the transformations of STR? This problem presents some similarity with one discussed in the literature consisting of a current loop moving in the presence of a static electric field [16]. According to STR, the presence of the magnetic field in the rest frame of the current loop gives rise to a torque on the loop that sets it rotating. For the problem discussed in the literature, one wished to justify, as seen from frame S, the existence of the torque on the loop when moving in a static electric field. This torque has never been observed experimentally in part because this test is not easily realizable with present technology. However, it would be important to be able to describe this effect in the reference frame of the laboratory within the context of present theory. This task was accomplished [16] considering a neutral current loop made of nonconducting oppositely charged sliding ropes. The origin of the torque was justified as due to the action of the electric field on the charges of the loop that gives rise to internal stresses in the charged ropes. Application of the cardinal equations of dynamics shows that associated to these internal stresses there is a momentum flow when the loop is moving and its variation give rise to a force perpendicular to the ropes with a resulting net torque on the loop, a situation analogous to that of the Right-Angle Lever paradox by Tolman, widely discussed in the literature [17].

We tried to translate and apply the arguments about the torque on the loop mentioned above to the present problem, but have been unable to come up even with a qualitative justification of the result implied by Eq.(4). Therefore, as far as we know, from the point of view of an equivalent coherent description in frame S, in the present literature there is no theoretical justification of the induction foreseen by Faraday's law of induction (4) applied in the rest frame of the coil.

We are left now with the evaluation of the emf (4) to check that this test is realizable with present technology.

The maximum variation of the flux induced in the coil is

$$\Delta\Phi = \int_S \mathbf{B}' \cdot d\mathbf{a} = \frac{\mathbf{v}}{c^2} \mathbf{E}\, S = \frac{\mathbf{v}}{c^2} \frac{V}{d}\, S \qquad (5)$$

while the time it takes for the coil to enter and reach

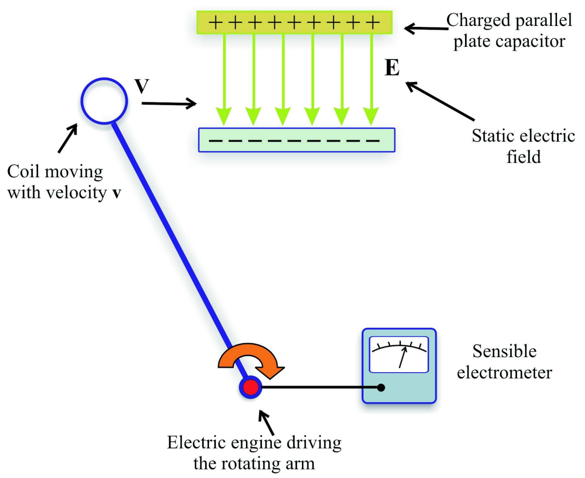

Fig. 3. The reciprocal Rowland experiment as a test of "open" currents and Faraday's law in differential form. A coil, fixed at the extremity of a rotating arm, moves with velocity $\mathbf{v}$ in the laboratory frame. A stationary parallel plate capacitor is placed in such a way that, when the arm passes by, the coil is located between the parallel plates. According to relativity theory, if the capacitor is charged and the electric field between the plates is $\mathbf{E}$, the coil experiences a time-varying magnetic induction field $\mathbf{B}' = -\mathbf{v} \times \mathbf{E}/c^2$. The magnetization experienced by the coil, eventually produced by the charges of the plates comoving with the capacitor, is evidence of the existence of convection or "open" currents. The emf induced in the coil, which would corroborate the validity of Faraday's law for open currents, may be detected by a sensible electrometer.

the centre of a capacitor with linear dimension l is

$$\Delta t = \frac{l}{2v}. \qquad (6)$$

To detect the emf we propose an arrangement of the type described in Fig. 3. The parallel plates of the capacitor sandwich the circumference of a spinning wheel or the extremity of a rotating arm where a small coil is fixed. The coil will move trough the capacitor at the speed $v = \omega R$, which is the tangential speed of the arm extremity. The coil is connected electrically to the fixed axis of rotation by some sliding contacts near to it and the electric contacts close the circuit on an electrometer. In order to decrease the electronic noise arising from the sliding contacts, the speed at the center should be minimized with respect to the tangential speed by choosing R as big as possible. We suggest $R = 50cm$ and $\omega = 50rev/s$ for this experiment. The area of the coil linking the magnetic field can be taken as $S \simeq 0.5\, l^2$, i.e., a half of the capacitor area with $l = 5cm$. It follows that, with $V = 10^5 Volts$ and $d = 1cm$, the maximum emf induced in the coil is

$$emf = \frac{\Delta\Phi}{\Delta t} = 2\frac{v^2}{c^2}\frac{V\,S}{d\,l} \simeq 1 \times 10^{-9} Volts. \qquad (7)$$

Modern electrometers have sensibility of as much as $10^{-12}V$. Therefore, result (7) should be measurable with a sensitive electrometer.

Since the coil move in circular motion in the presence of the magnetic field $\mathbf{B}_E$ of the Earth, there will be an emf induced by $\mathbf{B}_E$. As a way to get rid of this effect that masks the one we seek to measure, one could shield the apparatus with a permeable material. In this way the intensity of $\mathbf{B}_E$ inside the shield will be strongly reduced. Another way is to monitor and record the emf induced by $\mathbf{B}_E$ on an oscilloscope when $\mathbf{E} = 0$, and then subtract it from the output when $\mathbf{E} \neq 0$. In this way only the sought for effect of $\mathbf{E}$ will appear in the output. Actually a combination of both shielding and signal subtraction may prove more effective.

4. Phase and photon velocities in the Fizeau experiment

In this and in the following Sections we point out why the magnetic model of light propagation in moving media forms the basis for a crucial test of STR. In order to do so, we need to recall the physics involved in the Fizeau experiment and its relation to the quantum effects of the Aharonov-Bohm type.

At the time of Fizeau's experiment, theories were developed to account for the actual mechanism of the propagation of light waves in the hypothetical ether in terms of its mechanical and elastic properties. Some of the experiments were conceived for the measurement of the velocity of the Earth relative to the ether, such as in the Michelson-Morley experiment performed later. The theory of propagation of light waves in an elastic solid, was developed by Poisson in 1828. Poisson showed that both longitudinal and transverse waves could be propagated in a solid, the velocity being related to the rigidity modulus, the bulk modulus and the density of the elastic medium. Modifications of ether theories were introduced by Cauchy, Lord Kelvin, Green, and MacCullagh. On the basis of MacCullagh's ether, it was possible to interpret a wide range of optical phenomena with equations that turned out to be similar in mathematical form to Maxwell's equations.

Optical experiments, accurate to first order of v/c, were unable to detect the absolute motion of the Earth relative to the ether. These null results were interpreted in terms of Fresnel's dragging coefficient [18]. Fresnel's dragging coefficient f was used also in interpreting Fizeau's experiment on the velocity of light in moving water. Dragging of light by the ether was a common acceptable hypothesis among ether theories of that time. After Michelson-Morley's experiment was performed, Stokes and Planck developed an ether theory capable of accounting for the null result of the Michelson-Morley experiment by supposing that the ether was dragged locally by massive bodies such as planets, much in the same way as the Earth does it with its own atmosphere [13].

According to Fresnel [18] the speed achieved by light in a medium moving with velocity $\mathbf{u}$ is given by the Galilean composition of velocities provided that the flow $\mathbf{u}$ drags light by the fraction $f = 1 - 1/n^2$, where n is the refractive index. The velocity of light in the direction of the flow should then be $c/n + fu$, i.e.,

$$v_\phi = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right) u \tag{8}$$

as later corroborated by Fizeau [19].

The simpler interpretation of the Fizeau effect offered by STR appears to be superior. In fact, the speed (8) is nothing but the speed resulting from the relativistic composition of velocities to first order of v/c. However, the observable quantities measured in the Fizeau experiment, which lead to the traditional interpretation of this experiment, the phase velocity (wave velocity) and the particle velocity (photon velocity), are taken to be the same without justification. Because of this, we re-examine below Fizeau's experiment in relationship to what has been called the magnetic model of light propagation in moving media which relates Fizeau's effect to effects of the AB type.

The relationship between light in moving media and charged matter waves has been addressed by Cook, Feran, and Milonni [20] who suggested that light propagation at a fluid vortex is analogous to the Aharonov-Bohm (AB) effect for electron waves that encircle a localized magnetic flux [21]. In this and other quantum effects of the AB type [22], [23], [24], matter waves propagate in a flow of electromagnetic (em) origin that acts as a moving medium [24] and modifies the wave velocity. More recently, a magnetic model of light propagation has been considered by Leonhardt and Piwnicki (LP) [25]. In effects of the AB type, the propagating matter waves are dragged by the em flow but the material particles move in a field- or force-free classical path and their initial speed is not modified by the em flow.

Since the magnetic model of light propagation is based on an analogy with the effects of the AB type, both matter and light waves are described by the same formalism and the same equations of motion, suggesting that the natures of matter and light waves are closely related. Furthermore, it has been shown [26] that the interaction momentum in both the AB effect and the magnetic model has the same physical origin and is related to the momentum of the em interaction fields.

The important point is that, if the analogy between matter and light waves propagation holds, although the phase velocity of matter and light waves is affected by the flow $\mathbf{u}$, the momentum and velocity of particles (electrons and photons) is not. Thus, although the phase velocity of light propagating in a moving medium agrees with the addition of velocities of STR, according to the magnetic model of light, the momentum and velocity of particles does not, a point which has not been discussed previously in the literature.

All of these contrasting theoretical views could be investigated, and possibly either confirmed or refuted, by the proposed new test of photon and particle speeds, which is introduced below.

5. Wave equations for matter and light waves

5.1. Schrödinger equation for matter waves

In quantum effects of the AB type [21]– [24], a beam of interfering particles possessing em properties interacts with external em fields and potentials in a force-free (or field-free) region of space. These effects are nonlocal since there are no external forces acting locally on the particles so that an important characteristic is that, despite the em interaction, the particle momentum $\mathbf{p} = m\mathbf{v}$ and energy $E = (1/2)mv^2$ is conserved. The Schrödinger equation for quantum effects of the AB type may be written as

$$\frac{1}{2m}(-i\hbar\nabla - \mathbf{Q})^2\Psi = E\Psi \tag{9}$$

and its solution is given by the matter wave function

$$\Psi = e^{i\phi}\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,e^{i\frac{1}{\hbar}(\mathbf{p}\cdot\mathbf{x}-Et)}\,\mathcal{A} \tag{10}$$

where

$$\Psi_0 = e^{i\frac{1}{\hbar}(\mathbf{p}\cdot\mathbf{x}-Et)}\,\mathcal{A}$$

solves the Schrödinger equation with $\mathbf{Q} = 0$ and, here, $2mE = p^2$.

The em interaction momentum $\mathbf{Q}(\mathbf{x})$ is directly related [24] to the linear momentum of the interaction em fields in the form $\mathbf{P}_e(\mathbf{x}) \propto \int \mathbf{E}\times\mathbf{B}\,d^3\mathbf{x}$, which has dimensions proportional to a velocity $\mathbf{u}(\mathbf{x})$ and permeates the whole space. If $\mathbf{Q} = \pm\mathbf{P}_e$ is thought of as describing a moving fluid or a flow $\mathbf{u}$, the particles or matter waves propagate through this moving em fluid.

With $\mathbf{Q} = (e/c)\mathbf{A}$ (the Aharonov-Bohm effect), Eq. (9) is the Schrödinger equation for a charged matter wave in a magnetic field [27], where the flow $\mathbf{u}$ acts as a vector potential. For particles possessing a magnetic dipole moment $\mathbf{m}$ and moving in the presence of a field $\mathbf{E}$, we have $\mathbf{Q} = \mathbf{m}\times\mathbf{E}/c$ [22], while for an electric dipole **d** in a magnetic field **B**, we have $\mathbf{Q} = (\mathbf{d} \cdot \nabla)\mathbf{A}/c$ [24].

In seeking an analogy between the equations for matter waves and light waves, we conveniently write Eq. (9) as ($\hbar = 1$)

$$(-i\nabla - \mathbf{Q})^2 \Psi = p^2 \Psi. \qquad (11)$$

We show below that, with $p = k$ the wave vector, this equation represents also the equation for light waves, provided that **Q** is the interaction em momentum.

5.2. The wave equation for light in moving media

It is convenient to recall how the wave equation of light in slowly moving media is obtained in the context of special relativity. Here, and in the following equations, we use an approximation that keeps only those terms of lowest order in u/c. The Lorentz transform of the wave equation

$$\left[\nabla'^2 - \frac{n^2}{c^2}\partial_{t'}^2\right]\Psi = 0$$

which is written in the comoving frame of the medium, will read as follows in the Laboratory frame

$$\left(\nabla^2 - 2\frac{n^2-1}{c^2}\mathbf{u}\cdot\nabla\,\partial_t - \frac{n^2}{c^2}\partial_t^2\right)\Psi = 0, \qquad (12)$$

and its solution Ψ, is given by (in units of $\hbar = 1$)

$$\Psi = e^{i\phi}\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,\Psi_0 = e^{i\int -\frac{n^2-1}{c^2}\omega\mathbf{u}\cdot d\mathbf{x}}\,\Psi_0$$
$$= e^{-i\int \frac{n^2-1}{c^2}\omega\mathbf{u}\cdot d\mathbf{x}} e^{i\int(\mathbf{k}\cdot d\mathbf{x} - \omega\, dt)}\,\mathcal{A} \qquad (13)$$

where Ψ_0 solves Eq. (12) with $\mathbf{u} = 0$.

Since

$$\partial_t\Psi = -i\omega\Psi \text{ and } \partial_t^2\Psi = -\omega^2\Psi$$

Eq. (12) becomes

$$\left(\nabla^2 + 2\frac{n^2-1}{c^2}\mathbf{u}\cdot\nabla\, i\omega + n^2\frac{\omega^2}{c^2}\right)\Psi = 0. \qquad (14)$$

On account of the solution (13), for a magnetic model of light propagation in moving media [20], [25], in Eq. (11) we set **Q** to be equal to the Fresnel-Fizeau momentum,

$$\mathbf{Q} = -\frac{\omega}{c^2}(n^2-1)\mathbf{u} \qquad (15)$$

in agreement with Fresnel's predictions [18] and Fizeau's experiment [19]. Moreover, in Eq. (11) one sets $\mathbf{p} \to \hbar\,\mathbf{k}$ with $k = n\omega/c$, where n is the index of refraction, **k** the wave vector, and ω the angular frequency. In units of $\hbar = 1$, **k** represents the momentum and ω the energy. This position $\mathbf{p} \to \mathbf{k}$ does not represent a close physical equivalence between material particle and light. It is introduced here only to show that matter and light waves are described by a wave equation with the same form. However, although the wave equation is the same, according to the creators and supporters of the magnetic model [20], [25] and as discussed below, the Hamiltonian H_ϕ for light may not longer be the Hamiltonian H_{AB} of the effects of the AB type.

Then, after clarifying that $H_\phi \neq H_{AB}$, the wave equation (11) reads now

$$\left(-i\nabla + \frac{n^2-1}{c^2}\omega\mathbf{u}\right)^2\Psi = n^2\frac{\omega^2}{c^2}\Psi \qquad (16)$$

which, in lowest order in u/c, is identical to (14).

Thus, the standard wave equation for light in moving media, Eq. (12) or (14), takes on the form of Eqs. (16) and (11), supporting the idea of a magnetic model of light propagation in slowly moving media. We stress here that, so far, the analogy between matter and light waves stems form the fact that both obey a wave equation of the same type (11) or (16).

The wave speed (8) is obtained by using the relations $\nabla\Psi = -(k/\omega)\partial_t\Psi$ and $-i\omega\Psi = \partial_t\Psi$ in Eq. (12) which then transform it to

$$\left[\nabla^2 - \frac{n^2}{c^2}(1 - 2\frac{n^2-1}{n\,c}\mathbf{u}\cdot\widehat{\mathbf{k}})\partial_t^2\right]\Psi$$
$$= \left[\nabla^2 - \frac{1}{v_\phi^2}\partial_t^2\right]\Psi = 0 \qquad (17)$$

representing a wave traveling with speed v_ϕ. Actually, the same wave equation (12) or (17) can be derived without reference to special relativity by taking into account the polarization produced by the effective field in the moving media [28].

5.3. The interaction em momentum

This general property of Eq. (11) to describe both matter and light waves, would be corroborated if it can be shown that the Fresnel-Fizeau momentum **Q** of Eq. (15) is the variation of the interaction em momentum $\mathbf{P}_e$, as happens for all the effects of the AB type. If this is so, **Q** has the same physical origin in both cases, i.e., is given by the interaction em momentum.

In general, with T_{ik}^M the Maxwell stress-tensor, the covariant description of the em momentum leads to the four-vector em momentum P_e^α expressed as ($c = 1$)

$$P_e^i = \gamma\int\left(\mathbf{g} + T_{ik}^M\beta^i\right)dV,$$

$$P_e^0 = \gamma\int\left(u_{em} - \mathbf{v}\cdot\mathbf{g}\right)dV \qquad (18)$$

where $\beta = v/c$, $\mathbf{g} \propto \mathbf{E}\times\mathbf{B}$ and the em energy and momentum are evaluated in a special frame $K^{(0)}$ moving with velocity $\mathbf{v}$ with respect to the laboratory frame.

That $\mathbf{Q} = \mathbf{P}_e$ for all the effects of the AB type (save for the sign), as mentioned above, has been shown already by one of us in Ref. [24]. More recently [26], it has been proved that the Fresnel-Fizeau momentum can be calculated exactly as the variation of the interaction em fields, i.e., as the variation of the polarization em momentum due to the flow $\mathbf{u}$.

Thus, calculation of the variation of $\mathbf{P}_e$ yields

$$\Delta\mathbf{P}_e = \mathbf{Q} = (e/c)\mathbf{A},$$

for the Aharonov-Bohm effect

$$\Delta\mathbf{P}_e = \mathbf{Q} = -\omega(n^2-1)\mathbf{u}/c^2$$

for light waves in a moving medium,

corroborating the common physical origin of $\mathbf{Q}$ in the equation for matter and light waves.

6. Momentum flow of matter and light

6.1. Matter waves

So far we have considered the main properties of the equivalent wave equations (9), (11), and (16), (12) describing matter and light waves. The Hamiltonian $H_{AB} = (\mathbf{P}-\mathbf{Q})^2/2m$ of Eq. (9) can be derived from the classical Lagrangian

$$L = \frac{\mathbf{p}^2}{2m} + \mathbf{v}\cdot\mathbf{Q} \tag{19}$$

where $\mathbf{p} = m\mathbf{v}$ is the linear momentum satisfying the equations of motion

$$\frac{d\mathbf{p}}{dt} = -\frac{\partial}{\partial t}\mathbf{Q} + \mathbf{v}\times(\nabla\times\mathbf{Q}), \tag{20}$$

while (with $-i\hbar\nabla \longleftrightarrow \mathbf{P}$) $\mathbf{P} = \partial L/\partial\mathbf{v} = \mathbf{mv} + \mathbf{Q}$ is the canonical momentum. In the case of field-free or force-free effects, the rhs of Eq. (20) vanishes, so that the momentum $\mathbf{p}$ of the classical particle does not change, a result that is well established for all effects of the Aharonov-Bohm type. Moreover, for the Schrödinger equation (9), the eigenvalue E of H is constant and thus the same when $\mathbf{Q} = 0$ or $\mathbf{Q} \neq 0$. In other words, the mechanical flow of the energy and momentum carried by the moving particles is not altered by the electromagnetic flow due to the interaction momentum $\mathbf{Q} \propto \mathbf{u}$.

In the absence of any em interaction, $\mathbf{Q} = \pm\mathbf{P}_e = 0$ and the exponential term $\mathbf{p}\cdot\mathbf{x} - Et$ of Eq. (10) refers to a matter wave associated with a particle of energy $E = (1/2)mv^2$, and the wave propagates with speed $E/p = (1/2)v$ which differs from the actual speed of the particle v. Since the dynamical variable is p, the group velocity is always

$$\partial H_{AB}/\partial P = dE/dp = p/m = v.$$

If the em interaction is switched on, i.e., if $\mathbf{Q} \neq 0$, then in force-free effects of the AB type we will still have $d\mathbf{p}/dt = 0$ in Eq. (20) and the momentum and speed of the particle or group velocity is not altered.

The wave function of Eq. (10) represents a matter wave which is simply out of phase by ϕ with respect to the original wave function. However, if one wishes to write the term

$$\int(\mathbf{Q}\cdot d\mathbf{x} + \mathbf{p}\cdot d\mathbf{x})$$

in terms of the canonical momentum $\mathbf{P}$ as

$$\int \mathbf{P}\cdot d\mathbf{x} = \int (\mathbf{Q}+\mathbf{p})\cdot d\mathbf{x},$$

the phase velocity of the matter wave can be thought of as being modified by the flow $\mathbf{u}$ to become

$$v_\phi = E/P = E/(p + \mathbf{Q}\cdot\widehat{\mathbf{p}}).$$

Assuming that $\mathbf{Q}(\mathbf{x}) = -G\mathbf{u}(\mathbf{x})$, we have

$$v_\phi = v + G\mathbf{u}\cdot\widehat{\mathbf{v}}.$$

In conclusion, the interaction momentum $\mathbf{Q} = \pm\mathbf{P}_e$ is carried by the em flow interacting with the matter waves, while the particle momentum $\mathbf{p}$ keeps constant. The important point here is that even if the phase velocity of the matter wave is modified by the em interaction, the speed, momentum and energy of the particle are not.

6.2. Light waves

We consider now two possible and simple alternatives for the wave function of light waves in the magnetic model. The implications for each alternative will then be discussed.

6.2.1. An alternative wave function

In their approach to the model of light propagation, Leonhardt and Piwnicki (LP) [25] consider Eq. (16) and, for its solution Ψ, take the ansatz

$$\Psi = \mathcal{A}\,\exp\left[i\int(\mathbf{k}_\phi\cdot d\mathbf{x} - \omega\,dt)\right] \tag{21}$$

in order to obtain form Eq. (16) the relation

$$k_\phi^2 - \frac{n^2}{c^2}\omega^2 + 2\omega\frac{n^2-1}{c^2}\mathbf{u}\cdot\mathbf{k}_\phi = 0 \tag{22}$$

which they interpret to be a dispersion relation and which yields the Hamiltonian

$$H_\phi = \omega = \frac{c}{n}k_\phi + \left(1 - \frac{1}{n^2}\right)\mathbf{u}\cdot\mathbf{k}_\phi \tag{23}$$

Eq. (23) implies that the speed of the wave (or its phase velocity) $v_\phi = \omega/k_\phi$ is given by Eq. (8). The Hamilton equations

$$\frac{d\mathbf{x}}{dt} = \frac{\partial H_\phi}{\partial \mathbf{k}_\phi}, \quad \frac{d\mathbf{k}_\phi}{dt} = -\frac{\partial H_\phi}{\partial \mathbf{x}} \tag{24}$$

yield

$$\frac{d\mathbf{k}_\phi}{dt} = -\nabla\left[(1-\frac{1}{n^2})\mathbf{u}\cdot\mathbf{k}_\phi\right]. \tag{25}$$

Furthermore, in order to derive a Lorentz-type equation of motion analogous to that of material particles, LP consider the velocity

$$\mathbf{v}_\phi = \frac{d\mathbf{x}}{dt} = \frac{c}{n}\widehat{\mathbf{k}}_\phi + \left(1-\frac{1}{n^2}\right)\mathbf{u}, \tag{26}$$

which agrees with STR, and the rescaled ray velocity

$$\mathbf{w} = k_\phi \mathbf{v} = \frac{c}{n}\mathbf{k}_\phi + \left(1-\frac{1}{n^2}\right)k\mathbf{u} \tag{27}$$

to derive the Lorentz type equation of motion

$$\frac{d\mathbf{w}}{dt} = -\left(1-\frac{1}{n^2}\right)\mathbf{w}\times(\nabla\times\mathbf{u}). \tag{28}$$

6.2.2. Wave function acquiring a phase

In close analogy with the effects of the AB type we seek for a solution of the type

$$\Psi = \exp\left[i\phi + i\int(\mathbf{k}\cdot d\mathbf{x} - \omega\, dt)\right]\mathcal{A}$$

as in (13), for the wave equation Eq. (16). Substitution of Ψ into (16) yields the dispersion relation

$$k^2 - \frac{n^2}{c^2}\omega^2 = 0, \tag{29}$$

while the Hamiltonian for light rays is

$$H = H_\phi = \omega = \frac{c}{n}k. \tag{30}$$

Thus the frequency $\omega_\phi = \omega$ and the wave vector k are unchanged and still the same as in the absence of the flow $\mathbf{u}$. The only change is that of the phase of the wave function. The Hamilton equations yield

$$\mathbf{v} = \frac{d\mathbf{x}}{dt} = \frac{c}{n}\mathbf{k} \tag{31}$$

for the group or particle (photon) velocity and

$$\frac{d\mathbf{k}}{dt} = -\nabla(H), \tag{32}$$

for the light momentum. Here, the physical analogy with the AB effects (where the energy, velocity and momentum of the material particle are unchanged) is maintained.

Since this result appears not to agree with the theoretical predictions of special relativity, one may be induced to dismiss a priori the magnetic model of light. However, supporters of this model may reasonably argue that there is no experimental evidence against it, as surprisingly there are no measurements or tests of the velocity of photons in moving media.

7. Consequences of the magnetic model of light

In view of the above considerations, we can emphasize the following two alternatives:

a) An interpretation of the results established by Eqs. (22), (23) and (26) suggests that the wave vector and the speed of the wave are modified to $\mathbf{k}_\phi$ and v_ϕ by the flow $\mathbf{u}$. The speed v_ϕ agrees with the predictions of special relativity and with the experimental observations of Fizeau.

In effects of the AB type the canonical momentum $\mathbf{P}$ is the sum of the momentum $\mathbf{p}$ of the particle and the momentum $\mathbf{P}_e$ of the em interaction. $\mathbf{P}_e$ is a nonlocal quantity (i.e., it is not localized on the particle) arising from the interaction of em fields or potentials that permeate the whole space. The fundamental point here is to establish if, for light waves, the additional Fresnel-Fizeau momentum $(n^2-1)\omega\mathbf{u}/c^2$ that adds to $\mathbf{k}$ in Eq. (27) is carried by the moving medium or by the light particle (photon). If the additional momentum $(n^2-1)\omega\mathbf{u}/c^2$ is localized and carried by the photon, the resulting canonical momentum $\mathbf{k}_\phi$ and the speed v_ϕ physically represent the momentum and speed of the light particle dragged by the moving medium. The original speed c/n and momentum $\mathbf{k}$ of the propagating light are modified by the flow $\mathbf{u}$, and both energy ω and momentum $\mathbf{k}_\phi$ are localized to the photon, carried by it, and transmitted with the acquired velocity $\mathbf{v}_\phi$.

However, if this is the case, the hypothesized analogy between matter and light waves and the magnetic model of light propagation in moving media does not hold because for such a model the energy and momentum of the particles are not modified by the flow $\mathbf{u}$.

Let us consider for example the propagation of light in a moving medium with characteristics analogous to those of the AB effect. In this case the velocity of the flow is such that $\mathbf{u}(\mathbf{x}) \propto \mathbf{Q}(\mathbf{x}) = (e/c)\mathbf{A}(\mathbf{x})$, where $\mathbf{A}(\mathbf{x})$ is a function that mimics the vector potential due to a solenoid. In the AB effect, charged particles coming with velocity $\mathbf{v}$ from far away and passing near the solenoid obey the equation of motion (20), and their momentum $\mathbf{p}$ is not modified because, for this field-free effect, we have $(\partial/\partial t)\mathbf{A} + \mathbf{v}\times(\nabla\times\mathbf{A}) = 0$. However, if the momentum $\mathbf{k}_\phi$ represents the momentum of the light particles, a photon propagating through the flow $\mathbf{u}(\mathbf{x}) \propto \mathbf{A}(\mathbf{x})$ modifies its momentum and velocity as implied by Eq. (25) where $\nabla(\mathbf{u}\cdot\mathbf{k}) \propto \nabla(\mathbf{A}(\mathbf{x})\cdot\mathbf{k})$ does not vanish. Thus, there would be forces acting locally on the photon and the analogy with the force- and field-free AB effect breaks down.

b) The interesting magnetic model of light propagation in moving media [20], [25] is supported by the equivalence of the Eqs. (9), (11), and (16), (12) for matter and light waves. In our interpretation we adhere to the standard interpretation of AB effects and assume that there is a physical analogy between the propagation of matter waves in an em flow $\mathbf{Q}$ and the propagation of light waves in a flow $\mathbf{u}$. The only effect of the em flow $\mathbf{Q}$ and the flow $\mathbf{u}$ is that the wave functions Ψ of Eqs. (10) and (13) differ from Ψ_0 only by a phase factor due to ϕ, while there is no effect on the momentum and energy of the particles. Generally speaking, phase factors may be removed by a suitable phase transformation without modifying the equations of motion so that phases are not *per se* physical observable quantities, but phase shifts, or better, phase shift variations are.

In tests of Aharanov-Bohm effects and in the Fizeau type of experiments, two wave functions with different phases are made to interfere and the phase shift variations are then measured. The results of these tests confirm that such a phase shift variation, corresponding to the phase factors of Eqs. (10) and (13), exists.

If the magnetic model of light propagation in moving media holds, as happens in AB effects the additional Fresnel-Fizeau momentum $(n^2 - 1)\omega\mathbf{u}/c^2$ is carried by the medium and not by the light particles. That the photon momentum does not change is assured by the fact that the relationship $\omega = kc/n$ still holds as implied by Eqs.(29) and (30) and the group velocity is given by $d\omega/d\mathbf{k} = \mathbf{c}/n$ as implied by Eq.(31).

The only thing that can be concluded from the outcome of the above mentioned interferometric tests, and in particular from that of the Fizeau experiment itself, is that the phase and the speed of the waves are modified by the flow $\mathbf{Q} \propto \mathbf{u}$. However, these interferometric tests are unable to measure the group velocity, the energy and the momentum of the particles involved.

Within the magnetic model of light propagation, the outcome of the Fizeau experiment can be interpreted as due to the phase shift arising from the shifted wave function (13) even when photons propagate in the moving medium maintaining the same original velocity and momentum. This implies that all the Fizeau type experiments based on interferometric techniques do not represent a conclusive test or a confirmation of the relativistic addition of velocities for particles. Therefore, the non-interferometric approach to the measurement of the speed of light in moving media proposed here, possesses a physical relevance not contained in the traditional Fizeau approach.

Thus, in order to discriminate between the two alternatives a) and b), it appears justifiable to suggest the repetition of the Fizeau experiment but with a non-interferometric approach, where the quantity to be measured is the group velocity or the speed of the photons in a moving medium.

8. New, non-interferometric experiment for the speed of light in moving media

We consider here an experiment capable of measuring the speed of photons in a moving medium. We are interest in showing that such an experiment is feasible and can be realized with present technology. Technical aspects and details of an experiment of this type are given elsewhere.

8.1. Determining the speed of photons in a moving medium by direct measurement of the time of flight

This method uses a device D_S that acts as a source capable of emitting a short burst of photons or pulse of light of duration τ, as shown in Fig. 4. The pulse is made to travel through the pipe with the moving fluid and, as it exits, hits a photodetector D_{ph} that is electrically connected to the source D_S. When D_{ph} is hit by the pulse of light it triggers the source D_S which emits a second light pulse that makes another trip through the pipe. Furthermore, D_{ph} (or D_S) triggers circuitry to record the number of times N a light pulse has completed a trip. Let us denote by L' the part of the path outside the pipe and t_D the time delay between the moment the light pulse hits D_{ph} and the moment D_S emits a new light pulse after being triggered by D_{ph}. A clock connected to D_{ph} measures the total time T elapsed after N trips, which is given by

$$T(u) = NL/[c/n(u)] + NL'/c + Nt_D. \qquad (33)$$

The time $T(u)$ can be compared with the time T measured in the same conditions but for the medium at rest to yield

$$T(u) - T = \frac{NL}{c}\left[n(u) - n\right]. \qquad (34)$$

Since $n(u) = n_\phi(\mathbf{x}) \simeq n - (n^2 - 1)u/c$, we have the theoretical prediction of $n - n(u) \simeq (n^2 - 1)u/c \simeq (1.5^2 - 1) \times 10^{-7} = 1.25 \times 10^{-7}$ for a flow with a minimum speed of $3\,m\ s^{-1}$. With $n(u) = n[1 + (c/nNL)(T(u) - T)]$ from (34), the resulting measured speed difference is

$$\frac{c}{n(u)} - \frac{c}{n} \simeq \frac{c}{n}\left[1 - \frac{c}{nNL}(T(u) - T)\right] - \frac{c}{n} = \frac{c^2}{n^2 NL}(T - T(u)), \qquad (35)$$

which can be measured by measuring N and $T(u) - T$. The speed difference (35) is to be compared with the theoretical prediction provided by the speed difference $c/n(u) - c/n \simeq (1 - 1/n^2)u \simeq 1.66\,m\ s^{-1}$ for $u = 3\,m\ s^{-1}$. Supposing that the clock precision for the measurable time difference $T(u) - T$ is $\simeq 10^{-5}s$, with $L = 10\ m$ in Eq.(35) the number of iterations or round trips necessary to detect the speed difference $(1 - 1/n^2)u \simeq 1.66\,m\ s^{-1}$, should be

$$N = c^2[T(u) - T]/[L(n^2 - 1)u] \simeq 9 \times 10^{16} \times 10^{-5}/10 \times 3.75 \simeq 2.4 \times 10^{10}.$$

The time of measurement is of the order of Eq.(33) and hence it is important that the device D_{ph} possesses a fast response to light. Avalanche photodiodes and fast photomultiplier tubes can have rise times of nanoseconds in response to a light pulse. Use of such a device could shorten the experimental time considerably. Thus, assuming that t_D is less than $L/(c/n) \simeq 0.1\mu s$, the required minimum time of measurement is

$$T \simeq NL/(c/n) = 2.4 \times 10^{10} \times 10 \times 1.5/3 \times 10^8 = 1.2 \times 10^3\,s = 0.33$$

h, which is a reasonable value.

There are reasons to believe that the method proposed here can be more sensitive than the traditional interferometric approach, since interferometry is limited by the sensitivity of the apparatus and the length of the optical paths used to measure the resulting phase shift. With the method proposed here, one can essentially increase the length of the photon path indefinitely by increasing the number N of iterations or photon flights. Thus, this approach should be able to improve upon the results of traditional interferometric approaches, by providing a measurement of the speed of a burst of photons with an increased sensitivity.

In general, the conceptual physical arrangements and the experimental parameters estimated above, seem to suggest that the proposed apparatus could have enough sensitivity and stability to settle the issue in an experiment of practical duration. Therefore, we conclude that a non-interferometric approach may indeed be viable and that the quantity $c/n(u)$ is measurable with existing experimental techniques.

9. Conclusions

In our paper we have outlined some crucial tests of STR.

Among tests of electromagnetism, of particular interest are those that involve open currents or circuits. These tests are suitable to verify the Faraday law of induction in differential form.

The Faraday law of induction in differential form can be tested locally by measuring the effective field $\mathbf{v} \times \mathbf{B}$ that a charge at rest on the Earth surface would feel while comoving with the tangential rotational velocity $\mathbf{v}$ in the presence of the field $\mathbf{B}$ of the Earth (see Fig. 1). A nonshielded TN capacitor can be used as a testing device. The field $\mathbf{B}$ is produced by real (closed) currents such as those of a ordinary magnet. However, the device that tests the law of induction detecting the effective field $\mathbf{v} \times \mathbf{B}$ is not the usual closed circuit or loop where the emf is induced, but a test charge at rest on the Earth. In the nonrotating frame, the charges producing $\mathbf{B}$ form a closed current while the test charge forms an open current. Preliminary results of this test indicate a null result. Since this outcome does not favor STR we have considered in Ref. [3] a more sensible detecting device that tests the effective field $\mathbf{v} \times \mathbf{B}$ by monitoring the charge induced on the plates of a rotating capacitor by the effective field.

An analogous situation represents the test of Faraday's law via the nonconservation of the mechanical angular momentum of an isolated system. In Fig. 2 a magnet surrounded by a spherical charged shell possesses a time-varying magnetic moment. The charged shell feels the induction produced by the varying vector potential $\mathbf{A}$ and a torque is applied to the system. The charges in motion producing $\mathbf{A}$ form a closed current while the test charges on the spherical shell form an open current, which corresponds to static charges in this case. This experiment is still in a preliminary phase of realization [3].

Is there another way to test the effect of open currents? To answer this question we have proposed a test consisting of detecting the magnetic field seen by a coil moving with respect to a charge distribution fixed in the laboratory frame of reference (see Fig. 3). In this case we test the assumption of Maxwell (and STR) that a charge in uniform motion forms a convection or open current producing a time-varying magnetic field in the rest frame of the coil. This field is detected by the coil via the Faraday law of induction and the analysis performed in Sec. 3 shows that this experiment is viable.

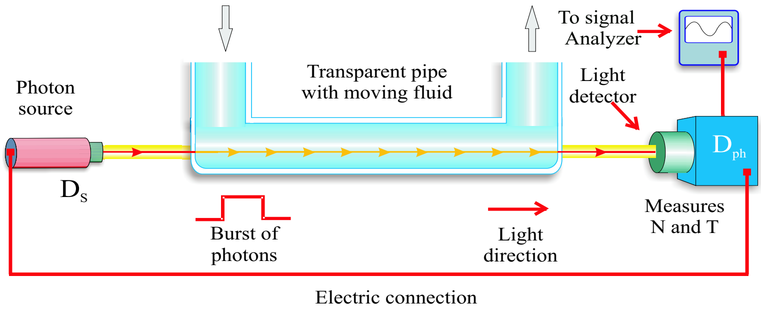

Fig. 4. A short burst of light emitted by the source D_S propagates through a transparent fluid moving with velocity $\mathbf{u}$ in a pipe of length L and then hits a photodetector D_{ph}. At this time, the device D_{ph}, which is electrically connected to the source D_S, triggers it so that another burst of light is emitted, and so on. The device D_{ph} records the number of times N a burst of photons strikes it and the total time T taken by the iterative process. Knowing the other parameters, the speed of photons is determined by measuring N and T. This experiment should be sensible enough to allow for checking the functional dependence of the photon speed as a function of the refractive index n and the flow $\mathbf{u}$.

Finally, the impact and range of validity of the Fizeau experiment has been reconsidered.

The magnetic model of light propagation in moving media implies that the phase velocity of the matter or light wave is affected by the flow $\mathbf{u}$, but that the momentum of particles (electrons or photons) is not. The traditional experiments of the Fizeau type are based on interferometric methods that measure the phase shift or phase velocity variations of the waves. Two light waves having the same frequency but with different propagation vectors or phases are compared and what is being measured can be related to the speed of the wave, which can either coincide with the speed of photons, or not. It follows that the traditional interpretation of the Fizeau experiment is incorrect because, contrarily to what has been believed for more than a century, this experiment is not suitable for corroborating the addition of velocity of STR.

Instead, with our approach we compare two signals with different frequencies that are related to two photon bursts traveling at different speeds, one propagating in the moving medium and another in the medium at rest. This non-interferometric experiment of the Fizeau type can be used to test the magnetic model and the speed of photons in moving media as a function of both n and u.

In closing, we have considered several tests of STR. Some of them are actually tests of the Faraday law of induction in differential form, while one exploits the magnetic model of light, based on an analogy between the behavior of light and particles. The new crucial tests proposed, the one discussed in Sec. 3 on the em induction in a moving coil produced by a static charge, and the test of the Fizeau type of Sec. 8 for the speed of photons in moving media, are realizable with present technology.

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