Locality and Electromagnetic Momentum in Critical Tests of Special Relativity

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Abstract

In this review of recent tests of special relativity it is shown that the electromagnetic momentum plays a relevant role in various areas of classical and quantum physics. Crucial tests on the locality of Faraday's law for "open" currents, on a modified Trouton-Noble experiment, on nonconservation of mechanical angular momentum, on the force on the magnetic dipole, and on a reciprocal Rowland's experiment are outlined. Electromagnetic momentum provides a link also between quantum nonlocal effects and light propagation in moving media. Since light waves in moving media behave as matter waves in nonlocal quantum effects, the flow of the medium does affect the phase velocity of light, but not necessarily the momentum of photons. Thus, Fizeau's experiment is not suitable for testing the addition of velocities of special relativity. A crucial, non-interferometric experiment for the speed of photons in moving media, is described.

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1 Introduction

In recent years, several experiments have been proposed that test unexamined aspects of the special theory of relativity (STR) and are realizable with present technology. We mention here only some of the experiments with which we are more familiar, such as those related to the interaction between current elements (Graneau [1], Pappas [2], Phipps and Phipps Jr. [3], Cavalleri and Spavieri [4], and Cavalleri et al. [5]), the experiments of the Trouton-Noble type (Cornille [6], Nieves and Spavieri [7], Spavieri and Gillies [8], [9]), the proposed test for the correct force on a magnetic dipole (Spavieri and Gillies [8], [9]) with the related polemic on the nonlocality of quantum effects (Boyer; Aharonov, Pearle, and Vaidman, and Spavieri [10]; Boyer [11]), the link between the Sagnac effect and Fizeau's experiment [12], and the newly proposed experiments on light wave propagation in moving media (Spavieri and Gillies [13]).

The aspects of electromagnetism, wave propagation, and STR involved in some of these tests refer to issues that are still unclear theoretically or not yet corroborated experimentally. These issues form part of a more general context that includes pre-relativistic interpretations of electromagnetism and the subsequent advances of STR over the past century. With our discussion of relevant experimental aspects of STR and proposal of new crucial tests, we do not intend to present a systematic and complete review of the experiments supporting STR because this is already partly available in most texts and in other more thorough review articles. Instead, we intend to point out particular theoretical and experimental aspects of STR that have either emerged recently or have not been discussed in the conventional literature. One of these aspects refers to the unifying role of electromagnetic momentum in several phenomena of classical and quantum physics. This and other aspects considered are of significant interest because they reveal otherwise uncovered features of STR and they establish new, unexpected important links between STR and other areas of modern physics [13], [14].

Some of the experiments we discuss are related to tests of Faraday's law of induction, and specifically for the cases where induction is either produced by convection currents (i.e., "open currents") or where the resulting induction field is observed locally with test charges. Some others refer, or are related, to optical experiments or propagation of electromagnetic (em) waves in moving media, such as in a new test of the Fizeau [15] type. Faraday's law of induction is considered here in relation to the concept of locality (or nonlocality) of em interactions. We clarify why the known tests of Faraday's law (mostly in its integral form) are not sufficient to corroborate it in its differential (local) form, and we propose a set of new experiments that test the locality of Faraday's law. In discussing the correct force on a magnetic dipole in the context of nonlocality of quantum effects [8]-[11], we consider the feasibility of a test of this force. With regard to the optical experiments, we reconsider Fizeau's experiment and its unexpected link with quantum effects of the Aharonov-Bohm type for electrons (Aharonov-Bohm [16]), magnetic dipoles or neutrons (Aharonov-Casher [17]), electric dipoles (Spavieri [18], [19], Tkachuk [20]), and electron-positron pairs (Spavieri [21]). The link is due to the similarity of the wave equations for matter and light waves and to the common origin of the em interaction described in terms of the em momentum of fields [14]. All this has led to the formulation of a magnetic model of light propagation in moving media, discussed by Cook et al. [22], Leonhardt and Piwnicki [23], and Spavieri and Gillies [13], [14]. On account of this model, we are able to point out a misconception that has been propagated within several standard texts on STR.

Most of the controversial issues discussed during 100 years of STR are related to the concept of the ether. As noted by Duffy [24], physicists who use the concept of ether in modern physics claim to have met with adverse criticism and hostility, even where their work is directed towards advancing physics, and there is no suggestion of taking science back to the concepts of yesterday. The ether concept in question may concern the argument about Lorentz's and Einstein's interpretations of relativity, the Stokes-Planck ether theory [25], Dirac's ether in a quantum-mechanical context, or the modern ether related to cosmic background radiation. There may be grounds for believing that all ether theory is lacking compared to alternative ways of interpretation. Alternatively, it may also be the case be that only some concepts of ether are obsolete, so that clarification of the modern concept of ether may still make some conceptualizations of it at least partly acceptable or useful.

Our present proposal of crucial tests of STR does not adhere to a specific alternative based on some ether theory, nor are these tests to be placed within a controversial context. Our purpose is to point out, in an objective manner, those crucial aspects of STR that have not been corroborated experimentally. Our considerations are based on the fact that the various tests and phenomenological studies supporting STR cover only a fraction or a part of the theory. There are aspects and assumptions that have not been tested directly, such as the ones discussed above. Thus, it is not simply a problem of alternative interpretations of existing phenomenology, but of corroboration and new experimental support. The new tests we propose have the aim to corroborate, complement and integrate the body of experiments on em phenomena and em wave propagation. We wish to show that in the present modern theoretical context, even after 100 years of scrutiny, STR cannot be claimed to represent a well-tested theory until these issues are clarified theoretically and examined experimentally. We believe that all these arguments amply justify the need and call for much further work and discussion on STR and related issues.

We consider in Sec. 2 a generalization of the law of Faraday. The concept of locality (or nonlocality) is introduced together with the em momentum of interaction fields **Q**. It turns out that **Q** appears in a wide class of phenomena such as in quantum effects of the Aharonov-Bohm (AB) type [18], [21], [14], the nonconservation of the mechanical angular momentum of an isolated charged system [9], and the propagation of em waves in moving media [13].

Several experiments that test the locality of Faraday's law are proposed in Sec.3. We consider only experiments that are realizable with present technology. Among the various experiments, we consider in Sec. 4 a test of the nonconservation of the mechanical angular momentum and one [8] that has the aim of testing the correct force on the magnetic dipole. In Sec. 5 we consider tests related directly to investigations of Rowland's effect [26]-[37], viz., that electrified bodies in motion produce magnetic effects. Polemical aspects of Rowland's experiment, related to the locality of em interactions, are revised. The role of the em momentum **Q** in each of these tests is discussed, as it turns out that the test of Faraday's law for open currents is also indirectly a test of the "reality" of the em momentum **Q** [9].

The majority of optical experiments such as Michelson-Morley's and tests of the Sagnac effect are well understood, even though according to some physicists [38], [12], their physical interpretation may still contain some controversial facets. In the present context, in Secs. 6-10, we present a revised design of the Fizeau experiment of 1851 as a test for the speed of light in a moving medium. The original Fizeau's experiment is based on an interferometric technique, analogous to the one used in testing effects of the AB type. As mentioned above, the analogy between effects of the AB type and light wave propagation in moving media is formally represented in the so-called magnetic model of light propagation. It turns out that even for the case of light wave propagation in moving media the em interaction is represented by the em momentum $\mathbf{Q}$, which provides a surprisingly unified view of all these effects [14].

However, with an interferometric technique one can measure only phase variations of waves. Thus, contrary to what has been believed for more than a century, Fizeau's experiment provides corroboration of the phase speed of the light wave but not of the speed of the light particle (i.e., the photon), so that it cannot be used to corroborate the addition of velocity foreseen by STR. This result is quite important because Fizeau's experiment seems to be the only one dedicated to a test of the relativistic addition of velocities. A new experiment of the Fizeau type [13], capable of measuring the speed of photons in moving media with present technology, is described in Sec. 10.

2 Nonlocality and electromagnetic interaction

In the context of em interactions, in this Section we discuss the concept of nonlocality, Faraday's law of induction, and its relation to nonconservation of the action and reaction principle in STR (violation of Newton's third law). Taken separately, these concepts have been discussed in detail in the literature. However, what is probably not well known is that an important link between them is represented by the em momentum, the linear and angular momentum of the em interaction fields. In usual ordinary em interactions, the em momentum vanishes so that it does not play an important role. Nevertheless, in several of the proposed tests discussed in this paper the em momentum does not vanish and can be related to the locality (or nonlocality) of the em interactions or to a violation of Newton's third law. The latter are important aspects of the theory not yet supported or corroborated by experimental evidence.

2.1 Faraday's law and the em momentum

Faraday's law of induction is an integral law that relates the potential difference (the electromotive force or emf) induced in a closed loop or circuit to the time variation of the linked magnetic flux and is expressed as

$$emf = \oint \mathbf{E}_{eff} \cdot d\mathbf{l} = -c^{-1}\frac{d}{dt}\oint \mathbf{B}\cdot d\mathbf{S}. \tag{1}$$

For circuits (or part of them) in motion, the field $\mathbf{E}_{eff}$ appearing in (1) is actually the effective field experienced by an observer at rest with the loop, i.e., $\mathbf{E}_{eff} = \mathbf{E} + c^{-1}\mathbf{u} \times \mathbf{B}$ to first order in v/c and where $\mathbf{E}$ and $\mathbf{B}$ are the fields as measured in the laboratory frame. The quantity $\Phi_m = \oint \mathbf{B} \cdot d\mathbf{S}$ is the linked magnetic flux, $\mathbf{B}$ being the magnetic (induction) field. The differential form of Faraday's law is nothing more than Maxwell's equation

$$\nabla \times \mathbf{E} = -c^{-1} \frac{\partial \mathbf{B}}{\partial t}. \tag{2}$$

Since $\mathbf{B} = \nabla \times \mathbf{A}$, where $\mathbf{A}$ is the vector potential, in the present context Eq.(2) implies that $\mathbf{E} = -c^{-1}\partial \mathbf{A}/\partial t$, which yields a force on a test charge q given by

$$\mathbf{f} = q\mathbf{E} = -\frac{\partial}{\partial t}(\frac{q}{c}\mathbf{A}). \tag{3}$$

Expression (3) has been derived only to highlight here a fact that is not well known, i.e., that the quantity $q\mathbf{A}/c$ in Eq.(3) is actually the em momentum of the interaction fields $\mathbf{Q}$, i.e.

$$\mathbf{Q} = \frac{1}{4\pi c} \int (\mathbf{E} \times \mathbf{B})\, d\mathbf{x}^3 = \frac{1}{c} \int \rho\, \mathbf{A}\, d\mathbf{x}^3 = \frac{q}{c}\mathbf{A} \tag{4}$$

where in the volume integral, $\mathbf{E}$ is the electrostatic field produced by the charge q and $\mathbf{B}$ the external magnetic field. The em momentum is *per se* a nonlocal quantity, while the equality (4) is valid in the *natural* Coulomb gauge and has been derived by several authors [39] in the context of discussions on the nonlocality of the AB effect. We see from the above relations that Faraday's law is related to the em momentum which, in turn, plays an important role in the nonlocality of effects of the AB type. Faraday's law in integral form (1) is *per se* a nonlocal law in the sense that it does not specify in which part of the circuit the emf is induced. The differential form of Faraday's law (2) is local in the sense that it links the fields $\mathbf{E}$ and $\mathbf{B}$ in space and time while these fields themselves are local in that they could act locally on a test charge q via the Lorentz force $q\mathbf{E} + c^{-1}q\mathbf{u} \times \mathbf{B}$.

2.2 Nonlocal em interactions and effects of the Aharonov-Bohm type

As an example of nonlocal em interaction we consider the one appearing in the context of the quantum effects of the AB type. In the magnetic AB effect, matter waves (electrons) encircle a thin solenoid and are made to interfere to form an observable interference pattern visible on a screen. Since the electrons travel outside the solenoid, where $\mathbf{E} = \mathbf{B} = 0$ but $\mathbf{A} \neq 0$, there is no force acting on the electrons. Thus, there is an em interaction momentum given by $(q/c)\mathbf{A}$ as in (4) but the Lorentz force on the particles is zero. The em interaction has the effect of modifying the phase of the matter wave function, i.e., the solution of the Schrödinger equation, by the amount $\int (q/c)\mathbf{A} \cdot d\mathbf{l}$, in units of $\hbar$. Classically, one would expect the interference pattern not to be displaced when the solenoid is placed in the path of the particles. However, this is not the case: the pattern is displaced by an amount related to the path integral $\oint (q/c)\mathbf{A} \cdot d\mathbf{l}$, where $(q/c)\mathbf{A} = \mathbf{Q}$ is the em momentum of the interaction fields. Indeed, it has been shown that in all the effects of the AB type [18] the interaction momentum is given by the em momentum. This fact provides a unitary view of all these effects, which besides electrons involve particles with magnetic and electric dipole moments. Generally speaking and according to classical electrodynamics there are no forces acting *locally* on the interfering particles in these effects. Because of this, they are considered to be quantum *nonlocal* effects. However, a polemic on nonlocality related to effects of the AB type surges after the discussion on what is the correct expression of the force on particles possessing em properties and specifically what is the correct force on a magnetic dipole [8], [10], [11].

Recently it has been pointed out that the observable quantity in effects of the AB type is related to the *variation* $\Delta\mathbf{Q}$ of the em momentum [21]. Although the fields and potentials are constant in time when the interference pattern is formed and observed, the quantum observable is measured by comparing the interference pattern for a value of $\mathbf{Q}$ with the interference pattern for a different value of $\mathbf{Q}$. The variation $\Delta\mathbf{Q}$ implies a change in the fields and potentials which gives rise to a force and this, in turn, suggests a hypothetical local action of the nonvanishing force on particles. This aspect of the AB class of effects enriches the discussion and adds to the related polemic on nonlocality.

2.3 Generalization of Faraday's law for electric and magnetic dipoles

Faraday's law in differential form (2) may be obtained from the force relation (3) which, through (4) links the force to the variation of the em momentum.

From (2), dividing this expression by q, one can then derive by integration Faraday's law in integral form (1). As mentioned above, the em interaction momentum appears in the AB effect for particles with charge q and for effects involving particles possessing electric ($\mathbf{d}$) and magnetic ($\mathbf{m}$) dipole moments.

Starting from the expression of the force on q, it is possible to build Faraday's law in integral form where the effective field acts on a charge q in a closed loop. Can one then build analogous laws for electric ($\mathbf{d}$) and magnetic ($\mathbf{m}$) dipoles? For this purpose we consider the Lagrangian for a particle possessing em properties (q, $\mathbf{d}$, $\mathbf{m}$, etc.) expressed in the general form $\mathfrak{L} = K - V + \mathbf{v}\cdot\mathbf{Q}$, where V is the scalar potential and $\mathbf{Q}$ is the em interaction momentum. In AB effects the quantum phase of the particle for the corresponding Hamiltonian H reads $\phi = \hbar^{-1}\int \mathbf{Q}\cdot d\vec{\ell}$.

The equations of motion for $\mathfrak{L}$ yields

$$\mathbf{f} = \frac{d}{dt}(m\mathbf{v}) = -\frac{d}{dt}\mathbf{Q} + \boldsymbol{\nabla}\mathfrak{L} = -\,\boldsymbol{\nabla}V - \partial_t\mathbf{Q} + \mathbf{v}\times(\boldsymbol{\nabla}\times\mathbf{Q}). \qquad (5)$$

For a flux or beam of particles along a path C of length l_p, let us consider the force density $\overline{\mathbf{f}} = \mathbf{f}/l_p$. In the absence of scalar potentials ($V=0$) and taking for simplicity $l_p = 1$, evaluation of the closed path integral $\oint_C \mathbf{f}\cdot d\vec{\ell}$, yields

$$\oint_C \mathbf{f}\cdot d\vec{\ell} = -\frac{d}{dt}\oint_C \mathbf{Q}\cdot d\vec{\ell} = -\frac{d}{dt}\oint_S \boldsymbol{\nabla}\times\mathbf{Q}\cdot d\mathbf{S} = -\frac{d}{dt}\Phi_{em}, \qquad (6)$$

where $\delta\boldsymbol{\Phi}_{em} = \boldsymbol{\nabla}\times\mathbf{Q}$ is the flux tube density and Φ_{em} the em flux through the surface S.

Before deriving from (6) a law for em dipoles analogous to Faraday's, we show how (6) can be used to establish a relation between the quantum phase shift of effects of the AB type and the hypothetical forces that would be acting on the particles if the em momentum is varied.

The initial phase $\phi = \hbar^{-1}(\mathbf{p}\cdot\mathbf{x} - E\,t)$ of a free non-interacting beam of particles is shifted by the amount

$$\delta\phi = \hbar^{-1}\oint_C \delta\,\mathbf{p}\cdot d\mathbf{x} = \hbar^{-1}\oint_C \delta\,(m\mathbf{v})\cdot d\vec{\ell} = \hbar^{-1}\int dt \oint_C \mathbf{f}\cdot d\vec{\ell}$$

by the action of the force $\mathbf{f}$ producing the momentum change $\delta\,\mathbf{p}$. Integration of (6) over dt, from $t=0$ to t with $\mathbf{Q} = \mathbf{Q}(t)$ and $\mathbf{Q}^0 = \mathbf{Q}(t=0)$, yields

$$-\int_0^t dt \oint_C \mathbf{f}\cdot d\vec{\ell} = \oint_C (\mathbf{Q}-\mathbf{Q}^0)\cdot d\vec{\ell} = \oint_S \boldsymbol{\nabla}\times\mathbf{Q}\cdot d\mathbf{S} = \Phi_{em}. \qquad (7)$$

For simplicity in Eq. (7) we have assumed that $\mathbf{Q}^0 = 0$ ($\Delta\phi = \delta\phi$ and $\Delta\Phi_{em} = \Phi_{em}$) as usual. Expression (7) establishes the relation between the phase shift variation of effects of the AB type and the hypothetical action of the em forces on the particles corresponding to the variation $\Delta\mathbf{Q}$.

Returning now to the discussion of Faraday's law, let us consider explicitly Eq. (6). If $\mathbf{Q}$ is given by (4) as in the magnetic AB effect, then $\mathbf{f}$ is given by (3) and (6) reads

$$\oint_C -\frac{\partial}{\partial t}(\frac{q}{c}\mathbf{A})\cdot d\vec{\ell} = -\frac{d}{dt}\Phi_{em}.$$

Dividing this equation by q, considering that the em flux becomes the magnetic flux, $\Phi_{em} \to \Phi_m$, and with the help of $\mathbf{E} = -c^{-1}\partial\mathbf{A}/\partial t$, it yields Faraday's law in integral form (1). It follows that expression (6), which contains (1) as a special case, represents a generalization of Faraday's law. In fact, the same procedure used for q can be applied to particles possessing electric and magnetic dipoles, as shown in Ref. [19]. Therefore, with the introduction of the em momentum and associated em flux Φ_{em}, Eq.(6) contains the usual Faraday's law in integral form and analogous or corresponding laws for electric and magnetic dipoles, and in general for any particle with em properties. These analogous "Faraday's laws" and the related tests for electric and magnetic dipoles will be discussed elsewhere (in preparation).

In closing, we simply mention here that the force expression (5) has been used to determine the correct, although controversial, expression for the force on a magnetic dipole [8], [10], [11].

2.4 Faraday's law and the violation of the action and reaction principle

Our purpose is to discuss and propose experiments that verify the locality of the standard Faraday's law, i.e. that verify directly the validity of the differential form (2) and the locality of the em interactions involved. There are several aspects that will be considered:

a) the case when the magnetic field $\mathbf{B}$ is produced by closed currents (either conduction currents or charges moving in closed paths) while the effective field $\mathbf{E}_{eff}$ associated with the emf is measured with test charges (open currents or circuits).

b) the case when the magnetic field $\mathbf{B}$ is produced by open currents (convection currents) and the emf is measured through induction in a closed circuit.

c) the case analogous to a) but involving an isolated system where the mechanical angular momentum is not conserved and can be detected.

In the last of the mentioned tests, Faraday's law in differential form plays an important role in conceptualizing violations of Newtons third law. The conservation law of electrodynamics tells us that what is conserved in an isolated system is the sum of the mechanical momentum plus the em momentum. If we find a system where the em angular momentum is not conserved, then also the mechanical momentum cannot be conserved.

A well known example of violation of Newton's third law is the system composed of two interacting charged particles in relative motion. In general, the em forces between the two charges are not equal and opposite. The mechanical momentum is not conserved in this case, but the total momentum, sum of the em momentum + mechanical momentum, is conserved.

In the next sections we exploit this property to test the locality of Faraday's law of induction. Curiously, in our proposed experiment, the em momentum is given by Eq.(4), which represents the nonlocal interaction of the AB effect and now is responsible for the violation of Newton's third law in this test.

3 Test of Faraday's law with an open circuit

3.1 Testing Faraday's law with a Trouton-Noble type of capacitor

With the same spirit that motivated the papers mentioned above [7]-[9], we believe that it is worth reconsidering here one of the tests of classical electrodynamics, the Trouton-Noble (TN) experiment, that has been recently discussed in the literature. In providing a short review of this experiment, we relate a proposed new experiment of the TN type to the test of the locality of Faraday's law. Historically, the outcome of the TN experiment has been considered to indicate a null result only. A charge moving with respect to the ether frame where the Maxwell equations were valid, would create a magnetic field. To check this hypothesis, TN suspended a charged capacitor from a thin thread. According to Maxwell, the Earth (and the capacitor) was supposed to be moving with respect to the frame of the ether.

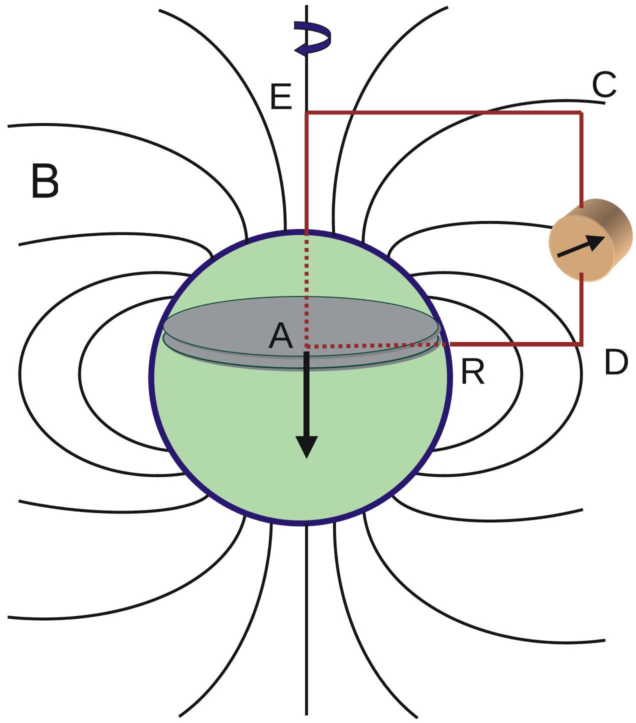

Figure 1. A section of the Earth, perpendicular to its rotation axis, mimics a Faraday's disk. A simplified scheme of the lines of the magnetic field $\mathbf{B}$ of the Earth are drawn, assuming cylindrical symmetry and neglecting the asymmetric components of $\mathbf{B}$. According to the standard interpretation of special relativity, the field lines of a rotating magnet do not rotate and the emf is induced on the rotating portion AR of the closed circuit ADCE. 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.

The magnetic field produced by one of the charges of the capacitor in motion would act, via the Lorentz force, on the other charge producing a torque and an observable rotation of the apparatus. The experiment was first performed by TN [40] and later by Chase [41] and others, and more recently and with a high sensitivity by Hayden [42]. The result of all these experiments indicate so far that the effect sought by Trouton and Noble does not exist: a null result.

Recently Cornille [6] has described the outcome of a TN experiment in which a positive result is claimed and he discusses a number of reasons why the previous experiments did not arrive at the same finding. This outcome is surprising because it seems to stand in contrast to the generally accepted interpretation of the TN experiment and of the standard, relativistic interpretation of classical electrodynamics.

We wish to show that a test of the Faraday law in differential form can be related to an experiment of the TN type such as the one performed by Cornille. Cornille's experimental set up differs from the others because he did not shield the suspended condenser from external electric fields. He also mentions that the magnetic field of the Earth cannot produce a torque because the charges of the capacitor are at rest in the laboratory frame of the Earth. However, according to the standard interpretation of Faraday's law of induction, a positive result may be theoretically possible if the effect of the magnetic field of the Earth on the capacitor is taken into account.

The Faraday disk, as shown in Fig. 1, consists of a conducting disk rotating about its symmetry axis and connected to an electric circuit ARDCE with one end (A) on the axis at the center of the disk and the other end (R) in the form of a sliding contact touching the external circumference. When a magnet is placed near the rotating disk with its magnetic pole aligned along the disk axis, an induction current flows in the circuit.

If the magnetic field $\mathbf{B}$ is uniform near the disk of radius R rotating with angular frequency ω, the electromotive force is given by

$$emf = \oint \mathbf{E}_{eff} \cdot d\mathbf{l} = \oint (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{l} = \frac{1}{2}\omega R^2 B. \tag{8}$$

In many textbooks, result (8) is deduced from the integral form of Faraday's law taking into account the change of the magnetic flux as the material segment AR rotates in the presence of the field $\mathbf{B}$. The integral form of Faraday's law cannot tell where, along ARDCE, the emf is induced.

However, the term $\mathbf{v} \times \mathbf{B}$ represents the induced effective field $\mathbf{E}_{eff}$ seen by the charges co-moving with the disk along the segment AR. It is a consequence of the validity of the Lorentz force $\mathbf{F} = \mathbf{E} + q\mathbf{v} \times \mathbf{B}$, written in a reference frame S, that indicates that the charge moving with velocity $\mathbf{v}$ in the presence of $\mathbf{B}$ and with $\mathbf{E} = 0$, experiences the field $\mathbf{E}_{eff} = \mathbf{F}/q = \mathbf{v} \times \mathbf{B}$. According to the transformations of the electromagnetic fields of special relativity, an observer in a reference frame S$'$ instantaneously co-moving with a point on the disk experiences the fields $\mathbf{B}' \simeq \mathbf{B}$ and $\mathbf{E}' \simeq \mathbf{v} \times \mathbf{B}$.

The observers of both frames S and S$'$ agree that the emf is induced in the radial path of the disk and the description of the effect is essentially the same for S and S$'$. The same result is obtained if the magnet is rotating with the disk or if a rotating conducting magnet alone is used as a Faraday disk. In fact, according to the standard relativistic interpretation of electrodynamics a cylindrical magnet can be thought of as made of a cylindrical current distribution, and the current and field produced by the current is the same even if the current loops rotate about the symmetry axis.

Historically, the field lines of $\mathbf{B}$ were considered to have a precise physical reality. The potential difference generated across the radius AR was interpreted as due to the cutting of the magnetic field lines by the rotating metal. In the term $q\mathbf{v} \times \mathbf{B}$, the velocity was interpreted as that of the charge with respect to the field lines, and not as the velocity of the charge relative to the reference frame.

In the case of a Faraday disk formed by a rotating magnet, in the pre-relativistic interpretation, Faraday's hypothesis of 1851 – in which he visualized the magnetic lines as fixed to the magnet and rotating with it – was assumed. In this case, the lines will be cut by the external branch RDCE and the emf is not induced in the disk but instead in the stationary part RDCE of the electric circuit. In this interpretation $\mathbf{v}$ represents the velocity of the "cutting" field lines at the position of the RDCE.

Measurements of the induced voltage and/or current cannot discriminate between one theory or the other since in both cases the generated intensities are the same. In 1917 Kennard [43] achieved a breakthrough when he suppressed the RDCE branch and was capable of measuring an induced potential difference along AR when the whole system rotated as a unit. Kennard's experiment consisted of a cylindrical capacitor and a coaxial solenoid. The induced electrostatic charge separation was measured by inserting an electrometer by means of two leads located along the axis. One of the leads was connected to the inner part of the capacitor, the other was connected to a radial wire reaching the outer part of the capacitor. When Tate [44] in 1922 reviewed the whole problem, he acknowledged Kennard's result and the implied disproof of the theory of rotating lines of force.

Without negating the validity of Kennard's experiment, we point out some of its limitations. First of all the apparatus consisted, as in the case of the Faraday disk, of two parts in relative motion: the measuring device, or electrometer, at rest; and the rotating capacitor in motion. What is being measured is always a potential difference between the two parts and not the local field. The inner part of the capacitor had finite dimensions and, if the flux lines are rotating, one cannot exclude that they may induce a potential difference in the stationary part of the electrometer. Furthermore, the results are necessarily qualitative because of the difficulties of calibrating and reading the electrometer and eliminating additional electrostatic effects, e.g. due to the air drag produced by the rotating parts.

In an ideal experiment the measuring device should be co-moving with the rotating apparatus and measure the local electric field intensity, so that these objections no longer apply. This ideal situation is achieved with the set up of an experiment of the TN type that exploits the Earth's rotation, as described below.

What we look for in the present experiment is the effect of the external magnetic field of the Earth on the moving charges. The magnetic field of the Earth is usually approximated by the equivalent field due to a magnetic dipole placed at the center of the Earth of intensity $\mathbf{m}_o \simeq 8 \times 10^{22} A \cdot m^2$ ($= 8 \times 10^{25} gauss \cdot cm^3$). Correspondingly, the magnetic field on the surface of the Earth varies from 0.3 to 0.6 *gauss* depending on the latitude. Neglecting the small deviation of the axis of the Earth's magnetic dipole $\mathbf{m}_o$ with respect to the geographic North-South direction, the Earth can be considered equivalent to a rotating magnet so that the results valid for the Faraday disk, can be applied here. In analogy with the interpretation of the Faraday disk, a charge fixed on the Earth and rotating with it in the presence of the field $\mathbf{B}$ due to $\mathbf{m}_o$ will feel an effective electric field $\mathbf{E}_{eff} = \mathbf{F}/q = \mathbf{v} \times \mathbf{B}$, where the components of $\mathbf{B}$ are known.

With respect to frame S, the velocity $\mathbf{v}$ of the charges is in the West to East direction. With $\mathbf{B}$ the magnetic field of the Earth, in the frame S the sought for effect is due to the Lorentz force $q\mathbf{v} \times \mathbf{B}$, while in the frame co-moving with the charge the effect is due to the existence of the electric field $\mathbf{v} \times \mathbf{B}$. In order to detect this electric field, shielding screens around the capacitor must be avoided, as in the case of Cornille's experimental set up. A resulting torque τ will act on a capacitor with parallel plates separated by the distance $\mathbf{r} = \mathbf{d}$. This torque generates a rotation of the capacitor that tends to set $\mathbf{d}$ perpendicular to $\mathbf{v}$. At the position of equilibrium the capacitor has rotated by an angle δ such that $\tau = k\delta$. In order to verify that this angle is detectable with an apparatus of the Trouton-Noble type, we express the charge on the capacitor, for a parallel-plate capacitor, as $q = CV$

and $C = \varepsilon_o S/d$. The result is that, in optimal conditions,

$$\delta = \frac{\varepsilon_o SV(vB)}{k}. \tag{9}$$

In order to estimate δ, we consider a location near the equator where the tangential velocity is greater, for example in Venezuela at 8^o above the equator and this corresponds to an angle $\theta = 82^o$ between $\mathbf{r}$ and the rotation axis. In this case, with the radius of the Earth given by $r = 6.37 \times 10^6 m$ and a velocity of $v = \omega r \sin\theta = 445 m/\sec$ near the Equator, the useful perpendicular field component turns out to be $B \simeq 0.17 gauss$ directed toward the centre of the Earth and $E_{eff} = v \times B \simeq 7.5 \times 10^{-3} V/m$. With a potential difference of $V = 2 \times 10^4 V$, a plate surface $S = 1m^2$ and a torsion constant $k = 10^{-8} kg \cdot m^2/\sec^2$, the torsion angle turns out to be of the order of $\delta \simeq 0.13 radians \simeq 7.5^o$, which is easily observable. Actually, the charge on the plates of the capacitor can be increased by filling it with a dielectric. For a relative dielectric constant $\varepsilon \simeq 100$ the torsion angle should be observable even with a smaller potential difference.

3.2 Testing Faraday's law with a capacitor rotating in the magnetic field of the Earth

The force $\mathbf{f} = qc^{-1}\mathbf{v} \times \mathbf{B}$ (or the corresponding field $\mathbf{f}/q = \mathbf{E} = c^{-1}\mathbf{v} \times \mathbf{B}$) has been tested and confirmed in many experiments performed in the laboratory frame of reference where the test charge moves with velocity $\mathbf{v}$ with respect to an external magnetic field $\mathbf{B}$ (for example, charged particles moving in a cyclotron). However, there are no tests of $\mathbf{f}$ or $\mathbf{E}$ performed, for example, in the rest frame of a charged particle. Such an experiment is described below. Referring to the test of $\mathbf{E}_{eff} = c^{-1}\mathbf{v} \times \mathbf{B}$ described above, in an ideal experiment the measuring device should be co-moving with the rotating apparatus (magnet or solenoid) and measure the local electric field intensity. This ideal situation is achieved conceptually with the proposal, described and discussed above, for an experiment of the TN type that exploits the Earth's rotation. For the experiment under consideration, the TN apparatus works as a detector of a static electric field. However, one of the limitations of this apparatus is that it needs a generator to charge the capacitor and then to keep its charge constant.

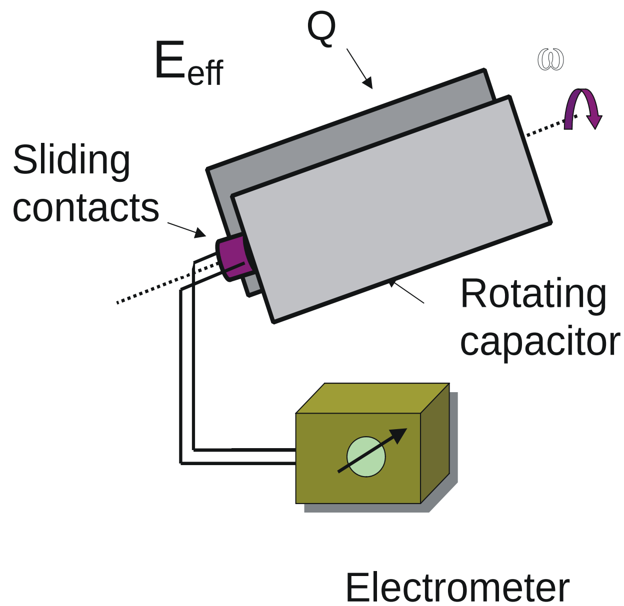

Figure 2. A capacitor placed in the effective local electric field $\mathbf{E}_{eff} = \mathbf{v} \times \mathbf{B}$, where $\mathbf{B}$ is the magnetic field of the Earth, $\mathbf{v}$ is the tangential velocity of the Earth's surface at the location of the laboratory. If the capacitor is placed with its plates perpendicular to $\mathbf{E}_{eff}$ and the plates are connected electrically, a charge Q flows from one plate to the other. If the capacitor is rotated by 180 degrees while the plates are connected to an electrometer, the flowing charge Q is detected by the instrument. Knowing the electrical parameters, the charge Q may be related to the value of $\mathbf{E}_{eff}$ that can thus be measured.

This experiment was performed by one of us (GS) in Mérida, Venezuela where, although the TN apparatus had good sensitivity, the external conditions did not permit the attainment of meaningful results. In fact one of the problems was that the capacitor was influenced by the electrostatic field produced by the generator, even when the latter was placed far away. Also, the charged capacitor was found to induce electrostatic charges in nearby objects that in turn influenced the orientation of the capacitor. Moreover, the potential difference V could not be set too high because, when it reached $10 - 15\ kV$, the capacitor was observed to get out of balance suddenly, due to the emission of charges at the edges that had the effect of setting the TN apparatus in continuous rotational motion. Even though these difficulties can be alleviated with a better experimental arrangement and generator system in particular, and with a larger working space in the laboratory, and by avoiding sharp edges in the design of the capacitor, they indicate that successful realization of the experiment is still not an easy task. Thus, in order to perform the proposed test and retain the possibility of double-checking the results, we believe that alternative arrangements should be considered.

Let us introduce a parallel-plate capacitor that can be set in rotational motion about a central axis parallel to the plane of the plates and passing through the center of the capacitor as shown in Fig. 2. The capacitor possesses a capacitance $C = k\varepsilon_0 S/d = Q/V$ and rotates in the presence of the external electric field $E_{eff} = v \times B \simeq 10^{-2} V/m$ that we wish to measure. When the field is perpendicular to the plates that are electrically connected, these will be charged by the potential difference $V = E_{eff}d$. During the course of a measurement sequence, the capacitor would be charged to a level of $Q = E_{eff}k\varepsilon_0 S \simeq 10^{-12}C$, the entire assembly would be set into constant-speed rotational motion, and the time varying charge states of the pairs would then be monitored via electrometry (the sensitivity of a modern commercial electrometer is $\simeq 10^{-13}C$). There could be several advantages to such an arrangement. For instance, the surface area of the plates, S, that need not be suspended as in the case of the TN apparatus, could be as large as required, e.g., $2 - 3\ m^2$. By rotating at a constant angular speed, one could use synchronous detection techniques to demodulate the signal from the rotational carrier frequency, and thus gain factors of approximately 1000:1 in improved signal-to-noise ratio for long integration times [45], while averaging over any direction-dependent background couplings that could otherwise mask the effect being sought (See [46] for citations to the various such experiments where mercury bearings of this type have been used and also [47]).

4 Conservation laws and forces on charges and magnets

For our physical system we consider a small cylindrical magnet of radius R height H and magnetic moment $\mathbf{m}$, placed at the center of a charged conducting spherical shell of radius a, and suspended by a thin fiber, as shown in Fig. 3.

4.1 Faraday's law and nonconservation of mechanical angular momentum

The system magnet + charged shell represents an isolated system. In the SI system the em momentum is given by Eq.4 where $\rho(\mathbf{x}) = \sigma\,\delta(r) = Q\,\delta(r-a)/4\pi a^2$ is the charge density and Q is the total charge distributed uniformly on the sphere.

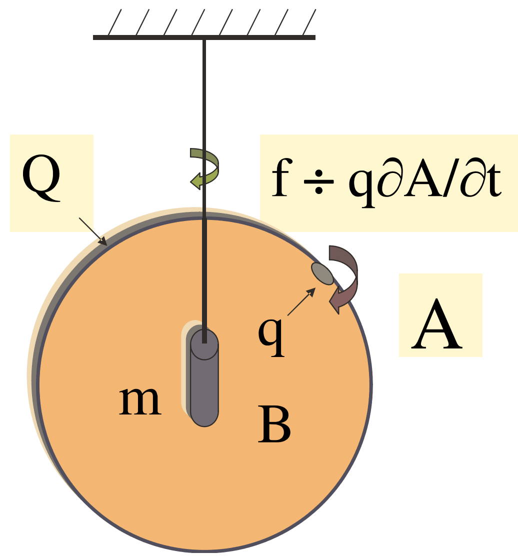

Figure 3. Faraday's law and the nonconservation of the mechanical angular momentum of an isolated system. A magnetic dipole $\mathbf{m}$ (a small rod magnet) is placed at the centre of a charged spherical shell. The whole system is suspended by a thin vertical torsion fiber. If $\mathbf{m}$ varies with 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.

Let us suppose that the spherical shell, initially grounded, is charged with the charge Q through the conducting fiber or wire, or that, since the shell is already charged, the magnetic moment $\mathbf{m}$ is switched on (or off). In correspondence to the force $\mathbf{f} = q\mathbf{E}$ of Eq.(3), there is a torque τ acting on the total charge Q that will produce the variation of the mechanical angular momentum $\vec{\Gamma}_{mech}$. If $\mathbf{m}$ is constant and the charge Q varies, the same torque and corresponding mechanical angular momentum variation is applied because of the force $\mathbf{f} = q\mathbf{v} \times \mathbf{B}$ acting on the elementary charges q while these transfer with velocity $\mathbf{v}$ from the wire to the sphere that is being charged. However, there is no hidden angular momentum [11] for our system, i.e., there is no reaction torque on the magnet. In fact, the electric field inside the shell is zero and there are no stresses or charges induced on the magnet. Thus, there is action on the charge Q when the dipole moment $\mathbf{m}$ of the magnet varies with time, but no reaction due to the charge Q on the magnet.

In the absence of a hidden angular momentum, the em angular momentum of the system is

$$\vec{\Gamma}_{em} = \int \mathbf{r}\times(\rho(\mathbf{x})\mathbf{A}(\mathbf{x}))\, d^3x, \tag{10}$$

and the law of conservation of the total angular momentum of the isolated system reads

$$\vec{\Gamma}_{em} + \vec{\Gamma}_{mech} = const. \tag{11}$$

Thus, if $\vec{\Gamma}_{em}$varies with time, then $\vec{\Gamma}_{mech}$ must also vary.

The component of $\vec{\Gamma}_{em}$ about the symmetry or suspension axis is easily calculated using the dipole approximation $\mathbf{A}(\mathbf{x}) = (\mu_0/4\pi)(\mathbf{m} \times \mathbf{r})\, r^{-3}$ and yields

$$\Gamma_{em} = \int \rho(\mathbf{x})\, m\, \frac{x^2+y^2}{r^3}\, d^3x = \frac{\mu_0}{6\pi}\, \frac{m}{4\pi}\, \frac{Q}{a} = \frac{\varepsilon_0\mu_0}{6\pi}\, V_a\, m, \tag{12}$$

where $V_a = Q/4\pi\varepsilon_0 a$ is the electric potential of the charged shell. The magnetic moment m of the small cylindrical magnet may be expressed as

$$m = \frac{B_0 \pi R^2 H}{\mu_0 \sin\alpha_m} \tag{13}$$

where B_0 is the value of the magnetic induction at the center of the magnet and $\tan\alpha_m = H/2R$.

The torsional impulse transmitted to the system is $\int \tau\, dt = I\,\omega_0$ where I is the moment of inertia and ω_0 the initial angular velocity. If k is the torsion constant of the fiber, when the angular kinetic energy is transformed into elastic torsional potential energy, we have $(1/2)k\,\theta^2 = (1/2)I\,\omega_0^2$. It follows that

$$\theta = \frac{\Gamma_{em}}{\sqrt{I\,k}} = \frac{\varepsilon_0\mu_0}{6\pi}\frac{V_a\,m}{\sqrt{I\,k}}, \tag{14}$$

where θ is the observable maximum angle of rotation of the system that can be considered as a sort of torsion pendulum.

The test can be performed having the spherical shell and the magnet mechanically connected or not. If they are connected the whole system (shell + magnet) rotates. In this case, as a first approximation, we neglect the moment of inertia of the thin spherical shell and assume that I is essentially the moment of inertia of the magnet. Using in Eqs. (12), (13) and (14) the values $B_0 = 4\,T$, $R = 1\,cm$, $H = 4R$, $k = 10^{-9}kg\ m^2/s^2$, and $V_a = 10^6V$, the resulting maximum angle is $\theta \simeq 10^{-3}rad$. With this value of θ, a standard optical lever method of detecting the system angular displacement would yield a motion of $\theta D \simeq 1\ mm$ for a lever arm of $D = 1\ m$, which in principle is observable.

The non-conservation of mechanical angular momentum is a well known theoretical aspect of classical electrodynamics discussed in many textbooks. However, there are no experimental tests performed related to the Shockley-James paradox or to the force on the magnetic dipole, a controversy that goes beyond classical physics and ushers in a discussion [11] of the nonlocality of the quantum effects of the AB type. The interesting feature of the experiment described above is that, as far as we know, it is the only feasible and viable test of the non-conservation of mechanical angular momentum of an isolated system.

4.2 the force on a magnetic dipole

For the test of the effective electric field $\mathbf{E}_{eff} = -c^{-1}\partial_t\mathbf{A}$ of Faraday's law in differential form, we consider the interaction between a short solenoid (or magnet) and a charge q, forming an isolated system as in the Shockley-James paradox [48]. The conservation of the total linear momentum $\vec{\Gamma}_t = \vec{\Gamma}_{em} + \vec{\Gamma}_{mech}$is given by Eq.(11). Here, $\vec{\Gamma}_{em} = \mathbf{Q}_{em} + \mathbf{Q}_h$ is the total linear momentum the em fields that includes the hidden momentum $\mathbf{Q}_h$. In the case of a conducting magnet, $\mathbf{Q}_h$ is due to the electric field of the charges induced on the magnet, and , in the case of a nonconducting magnet, $\mathbf{Q}_h$ is due to the internal stresses. For this stationary system there is no mechanical momentum and, even though there is em momentum, it has been shown [10] that the total momentum is zero

$$\mathbf{Q}_{em} + \mathbf{Q}_h = 0 \tag{15}$$

where in (15) $\mathbf{Q}_h = \mathbf{m} \times \mathbf{E}$ is the hidden momentum [10] of the magnet of dipole moment $\mathbf{m}$ in the presence of external field $\mathbf{E}$.

Let us suppose that the magnetic moment $\mathbf{m}$ is switched on (or off). The em momentum will vary from zero to the value $\mathbf{Q}_{em}$ and there is a force $\mathbf{f}_q = -(d/dt)\mathbf{Q}_{em} = -q\partial_t\mathbf{A}$ acting on the elementary charges q (the test of the force on the charge q has been described in the previous section). As required by the solution of the Shockley-James paradox [48], [10] the reaction force

$$\mathbf{f}_m = -\frac{d}{dt}\mathbf{Q}_h = -\frac{d}{dt}\mathbf{m} \times \mathbf{E} = -\mathbf{f}_q \tag{16}$$

acts on the magnet. Since action and reaction are equal and opposite ($\mathbf{f}_m + \mathbf{f}_q = 0$), the total linear mechanical momentum of the isolated system is conserved. In the usual induction experiments where the Faraday law is tested by inducing an *emf* in a coil, there is no Shockley-James paradox because the coil is neutral. The total force on the coil is zero and, thus, no reaction force on the magnet is expected. Therefore, it would be interesting to perform a test of the force (16).

In the controversy about nonlocality of the Aharonov-Casher effect and the correct force on a magnetic dipole [10], [11], the standard force on a magnetic dipole in its rest frame is $\mathbf{f}_{mst} = \boldsymbol{\nabla}(\mathbf{m} \cdot \mathbf{B})$. Taking into account the hidden momentum variation (16), when $\mathbf{E}$ and $\mathbf{B} \neq 0$ the force is given by $\mathbf{f}_m = \boldsymbol{\nabla}(\mathbf{m} \cdot \mathbf{B}) - \frac{d}{dt}(\mathbf{m} \times \mathbf{E})$. In order to check which of the two expressions (16) and $\mathbf{f}_{mst}$ is the correct one, we have to find a convenient distribution of the sources of the em fields such that $\boldsymbol{\nabla}(\mathbf{m} \cdot \mathbf{B}) = 0$ and the two expressions predict different values. It is suitable, for this purpose, a parallel plate capacitor with plates of rectangular shape where one of the sides, L, is much larger than the other, H, and is also much larger than the plate separation d (see Fig. 4).

In order to test the force on the dipole, it is convenient to use a torsion pendulum composed, as in Fig. 4, of a vertical suspension fiber, which has a small torsion constant k, and that carries a horizontally oriented, thin rigid bar. The dipole may be suspended at one end of the bar of this pendulum. To measure the supposedly correct expression of the force let us place the magnetic dipole (e.g.., a small permanent magnet) inside the capacitor with $\mathbf{m}$ oriented in the z direction. With this configuration, the dipole may move horizontally in the y direction and the component of the standard force is then $\mathbf{f}_{mst} = \boldsymbol{\nabla}(\mathbf{m} \cdot \mathbf{B}) = 0$, while the expression (16) predicts that a force of the order of

$$f_m = (\mathbf{f}_m)_y = (\mathbf{m} \cdot \boldsymbol{\nabla})\mathbf{B}_y = m\partial_z B_y = \frac{m}{c^2}\frac{\partial E}{\partial t}. \tag{17}$$

will act on the dipole. The impulse $\int f_m dt$ transmitted to the dipole during the discharge of the capacitor sets the dipole in motion with an initial momentum Mv and the corresponding kinetic energy $(1/2)Mv^2$ is transformed into the torsional potential energy $(1/2)k\varepsilon^2$, where the small rotation angle ε reached by the torsion pendulum can be measured.

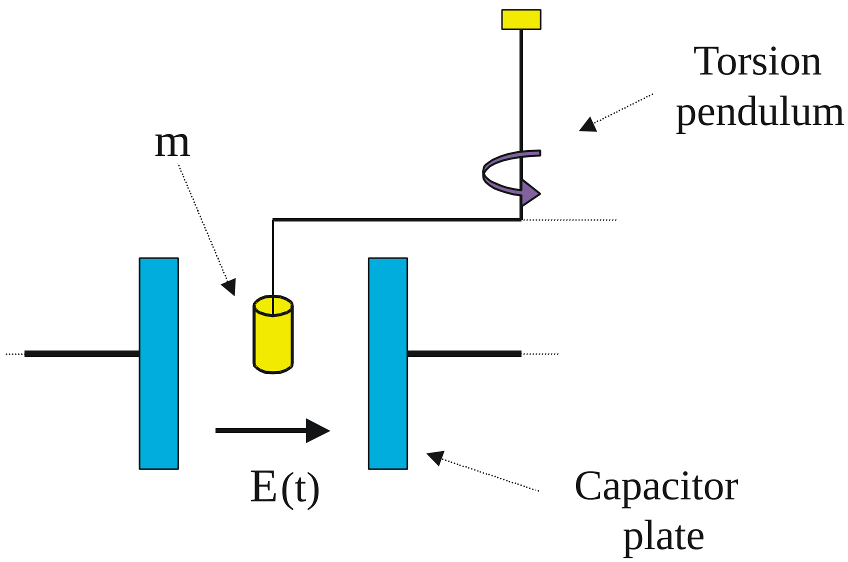

Figure 4. Testing the force on a magnetic dipole. A magnetic dipole $\mathbf{m}$ is suspended to a torsion pendulum and placed between the plates of a capacitor. While the capacitor is being charged (or discharged), a net force is being applied to $\mathbf{m}$. This force transmits an impulse to the magnetic dipole producing the rotation of the torsion pendulum by a small angle that can be measured providing an estimate of the force. If $\mathbf{E}$ is constant and $\mathbf{m}$ varies with time, by Faraday's law of induction an equal and opposite reaction force must act on the charges q of the capacitor. The action and reaction principle for the forces holds in this case.

The magnetic field intensity inside a small bar magnet, that can be used to simulate the magnetic dipole is given by $B = \mu_0(N/L)I \sin\theta_m$, where N is the number of turns, L the length of the bar magnet of radius R, I the current and $\sin\theta_m \simeq R/(L/2)$ (for $R \ll L$) characterizes the geometry of the bar. Correspondingly, the magnetic dipole moment expressed in terms of B, reads $m = \pi R^2 NI = \pi R^2 BL/(\mu_0 \sin\theta_m)$. Introducing the density $\rho = M/(\pi R^2 L)$ of the bar magnet, we obtain

$$\varepsilon = \sqrt{\frac{\pi L}{k\rho}} \frac{E\ B\ L}{2\ c^2 \mu_0} \simeq 10^{-3} rad. \tag{18}$$

The estimated value of $\varepsilon \simeq 10^{-3}\ rad$ for (18), has been obtained with $L = 10^{-1}m$, $k = 10^{-9}kg\ m^2/s^2$, $\rho = 7.6 \times 10^3 kg/m^3$, $E = 10^6 V/cm$, and $B = 10^{-1}T$. With this value of ε, a standard optical lever method of detecting the pendulum's angular displacement would yield a motion of $\varepsilon D \simeq 1\ mm$ for a lever arm of $D = 1\ m$, which is easily observable.

To obtain high potential differences to charge the capacitors and produce a large maximum value for the field E, it might be possible to use pulse modulation transformers of the type employed to charge flashlamp-pumped lasers and Klystron tubes. Such devices are commercially available, but expensive. Alternatives include "home made" devices such as "Marx generators", but no matter what one uses, obtaining high fields will call for very special design considerations to prevent arcing and spurious discharges. The electromagnetic stress in the dielectrics will be huge, and the experimental design will have to accommodate those forces.

In case of need, one can amplify the swing of the torsion pendulum using the usual resonance technique. If the electric field E is a periodic function of time, the corresponding successive impulses at the resonance frequency may increase ε by at least one order of magnitude.

5 Rowland's experiment and its reciprocal

5.1 A short survey of tests of Rowland's effect

Rowland's experiment consisted in detecting the magnetic field produced by moving charges. It is generally claimed that the outcome of Rowland's experiment of 1876 indicates that isolated moving charges produce a magnetic field. In collaboration with von Helmholtz, Rowland performed the experiment using a circular parallel plate capacitor that was charged and set spinning about its axis of symmetry. The charges moving in circular motion represent a convection current that, according to Maxwell, produces a magnetic field. This field was found to affect a delicately suspended pair of astatic magnetic needles hung in proximity to the disk just as would, by Oersted's rule, a circular electric current coincident with the periphery of the disk. Hence the statically charged but rotating disk becomes in effect a circular electric current.

The experiments were repeated and confirmed by Röntgen [27] and by Himstedt [28]. Later Crémieu again repeated them and obtained negative results [29]. Although Crémieu's null results were confirmed by Korda, they were again reconducted by Pender [30] and by Adams [31]. Pender's work showed beyond any doubt that electric convection does produce a magnetic effect. Adams employed charged copper spheres rotating at a high speed in place of a disk, and was able to prove that the rotation of such spheres produced a magnetic field similar to that due to a circular current and agreeing numerically with the theoretical value. It has been shown earlier by Thomson [32] and Heaviside [33] that an electrified sphere, moving with velocity v and carrying a quantity of electricity q, should produce a magnetic force H related to q and v. Adams found the field produced by a known electric charge rotating at a known speed had a strength not very different from that predetermined by Heaviside. An observation recorded by Wood [34] provides a confirmatory fact.

The publication of Crémieu's experiments raised a controversy that involved leading French and British physicists. The importance of the null result of Crémieu's tests was stressed by Poincaré in some of his publications. Poincaré's role in the Crémieu-Pender controversy over electric convection, was pointed out in a review paper by Indorato and Masotto [35]. Poincaré was supporting young scientist Crémieu and apparently was the one who suggested what kind of experiment to perform. Pender was instead Rowland's student and was supported by him until his death in 1901. Participating in the controversy were several well-known scientists, such as Wilson, Larmor, Schuster, Gray, Hicks, Thomson, Righi, Levi-Civita, and Lord Kelvin.

After criticisms were made of Crémieu's works and Pender's experiments obtained favorable support, Poincaré realized that the latter were to be taken seriously. It was in the interest of science and of everybody involved that the controversy be settled with definitive, clear-cut experimental results. At the end, Poincaré obtained Kelvin's support to organize Crémieu and Pender's joint experiments. In order to understand the difficulties involved in this type of experiments, it should be pointed out that in the firsts attempts made by Rowland to observe the magnetization produced by moving electrified bodies, the magnetic field to be detected was about 1/50000 times the horizontal component the Earth's magnetic field, a very small value unlikely to be observable. Nevertheless, it seems that Rowland succeeded in observing it. The magnetic field to be observed in Crémieu and Pender's joint experiments was a little greater but close to that order of magnitude. After many trials, the results seemed to favor the existence of Rowland's effect. However, the authors were cautious in their final comments:

"*It is not for us to say if these effects are really due to electric convection in the sense in which Faraday and Maxwell understood this expression, nor to decide if they are in accord with the fundamental hypotheses of present theories.*"[36]

The controversy faded out after Poincaré accepted the results of the experiment by Vasilesco-Karpen [37], who confirmed in 1904 the existence of the Rowland effect.

Some objections on the conclusions drawn from Rowland's type experiments are the following. In Stokes-Planck ether theories the Earth is a local privileged frame where the ether is at rest. In this case the charges of the capacitor are moving with respect to the ether and according to Maxwell's theory they produce a magnetic field (direct Rowland's experiment). Moreover, the charges on the plates 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. But there is no experimental evidence that a charge in *uniform* motion produces a magnetic field. Moreover, the Rowland experiment does not prove 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 (reciprocal of Rowland's experiment). Therefore, Rowland's experiment furnishes only a partial proof of Maxwell and Lorentz's theories.

Most of the weak points of these experiments are pointed out in the Crémieu-Pender controversy. However, in revising for example the experiment by Pender, which is considered the most reliable, we found that he did not take into account the effect of induction produced by the current in the circuit used to charge the capacitor. Crémieu and Pender used a coil as the sensor of the magnetic field, instead of the magnetic needle used by Rowland. By charging or discharging the rotating capacitor, the magnetic field to be detected, $\mathbf{v} \times \mathbf{E}/c^2$, changes and it induces an emf in the coil. However, while charging or discharging the capacitor a current I must flow in the electrical circuit connecting the capacitor to the potential difference ΔV of the generator. Unfortunately, these authors do not provide details of the electric circuit. However, for the capacitor used by Crémieu and Pender, where $\Delta V = 10^4 V$, supposing charging times of the order of $10^{-6} s$, the corresponding current can reach high values, depending on the parameters of the electric circuit. In this case the magnetic field produced by I may overcome the value $\mathbf{v} \times \mathbf{E}/c^2$ that one is supposed to measure.

In conclusion, although it has been accepted that the above-mentioned experiments prove the existence of magnetic effects due to moving charges, a quantitative corroboration, showing the dependence with $\mathbf{v}$ and $\mathbf{E}$, is desirable. In view of all these arguments, we believe that the direct Rowland experiment on the magnetic field produced by moving charges should be repeated for a quantitative corroboration, while a reciprocal Rowland experiment, as the one described below, also needs to be performed.

5.2 A modern approach to the direct Rowland experiment

The set up for a modern version of Rowland's experiment is shown in Fig. 5. The rotating plates of the circular capacitor used by Crémieu and Pender are substituted by a parallel plate capacitor fixed to a rotating arm R. The capacitor is kept at the fixed potential difference ΔV by means of wires which, through sliding contacts on the axis of rotation, are connected to the high voltage electrostatic generator. By keeping ΔV fixed, there is no conduction current I in the electrical circuit that might produce undesired time-varying magnetic fields. The only time-varying $\mathbf{B}$ field produced is the one due to the moving charges of the capacitor. If $\mathbf{E}$ is the electric field intensity between the plates of the capacitor at rest, the magnetic field produced by the moving capacitor is $\mathbf{v} \times \mathbf{E}/c^2$, where $v = \omega R$ is the tangential speed.

In its motion, the plates of the capacitor sandwich a coil, fixed in the laboratory system. Faraday's induction law (1) implies that an emf force is induced in the coil while the capacitor moves by and the magnetic field $\mathbf{B}$ varies from zero to its maximum value. The coil acts as a sensor that detects the time varying magnetic field. The maximum variation of the flux induced in the coil is

$$\Delta\Phi = \int_S \mathbf{B}\cdot d\mathbf{a} = \frac{\mathbf{v}}{c^2}\mathbf{E}_o S = \frac{\mathbf{v}}{c^2}\frac{V}{d}S \tag{19}$$

while the time it takes for the capacitor of linear dimension l to enclose the coil and move past it, is $\Delta t \simeq l/2v$.

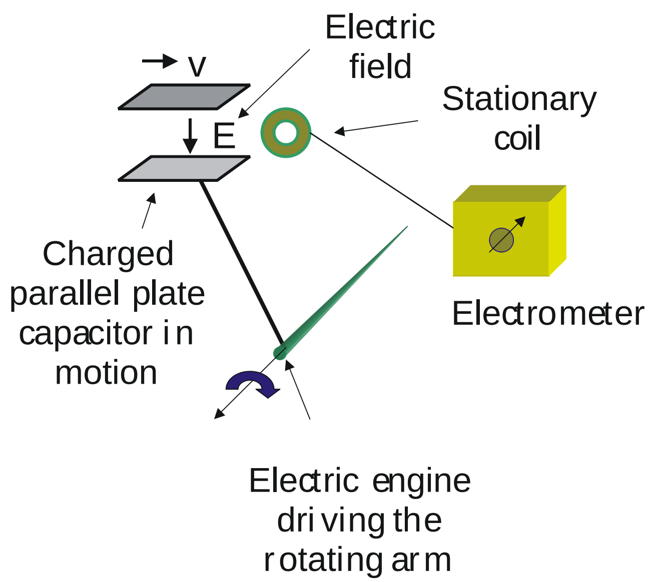

Figure 5. The direct Rowland experiment as a test of "open" currents and Faraday's law in differential form. A parallel plate capacitor, fixed at the extremity of a rotating arm, moves with velocity $\mathbf{v}$ in the laboratory frame. A stationary coil is placed in such a way that, when the arm passes by, the coil is located between the parallel plates. If the capacitor is charged and the electric field between the plates is $\mathbf{E}'$, the coil experiences a time-varying magnetic induction field $\mathbf{B} = -\mathbf{v} \times \mathbf{E}'/c^2$. This induction, produced by the charges of the plates comoving with the capacitor, is evidence of the existence of convection or "open" currents. The induced emf, which would corroborate the validity of Faraday's law for open currents, may be detected by a sensitive electrometer. The use of a superconducting coil or an analogous superconducting device that senses the magnetic induction, can increase by a factor of 10^4 the sensitivity of the historical Rowland experiment.

We suggest $R = 50cm$ and $\omega = 50rev/s$ for this experiment. The area of the coil linking the $\mathbf{B}$ 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 $V = 10^5 V$ and $d = 1cm$, the maximum emf induced in the coil is

$$emf = \frac{\Delta\Phi}{\Delta t} = 2\frac{v^2}{c^2}\frac{V\,S}{d\,l} \simeq 1 \times 10^{-9} V. \qquad (20)$$

Modern electrometers have sensibility of as much as $10^{-12}V$. Therefore, the emf (20) should be measurable with a sensitive electrometer.

It might also be possible to consider a much different alternative arrangement, which exploits technological advances. We propose a set up where the experimental apparatus is at low temperature and the signal is coupled out of it by superconducting transformer. The principal advantages of such an approach would arise from the very low levels of noise intrinsic to that type of superconducting device, and thus, the relatively higher overall signal-to-noise ratios. The essence of the technique would be similar to that applied in the Weber-bar types of gravitational wave detectors, in which the entire antenna mass is at liquid helium temperatures and the motions of it in response to the quadrupole oscillations induced by the gravitational wave are sensed by sophisticated superconducting quantum interference device (SQUID) magnetometry. The principal disadvantages of this approach lie in the considerable cost of the technologies involved, such as the superconducting dewar system, high-vacuum pumplines and chamber, etc. [and the unavoidable difficulties associated with a design calling for complex moving parts to function dependably at temperatures of 4 K]. Because of the great expense associated with doing anything with superconducting hardware, we just mention it as a technological possibility and do not elaborate further on it.

The best signal detection system would be one that monitors the voltage as a function of time, but does so synchronously with some reference signal (e.g., a marker voltage tied to the rotation rate of the wheel to which the capacitor is fixed). In that way, the change in current in the coil takes place at precisely the time that the detector is "looking" for a change in voltage to occur. This is a way of discriminating against background noise. In such cases, one can further help the system by increasing L through an increase in the number of turns. It is true that this increases the resistance, but that is partly the reason why we suggest a superconducting coil. With no resistance due to the superconductivity, we can use lots of turns, say 10^4. In this case the emf to be measured is much greater: $emf \simeq 1 \times 10^{-5} V$ and, since the resistance is very low (ideally, it should be zero), we have a relatively high output current. This approach increases the sensibility of our experiment by a factor that we estimate to be about 10^4 times that of Pender's. Thus, with this technique, we should be able to perform quantitative measurements of the field $\mathbf{v} \times \mathbf{E}/c^2$ as a function of both $\mathbf{v}$ and $\mathbf{E}$.

Of course, as already mentioned, that would be an impracticably expensive approach. So, instead we think the way to do this in a less expensive way, is to carry out simple empirical experiments with sensor coils at room temperature, but with ones having different numbers of turns. As one goes up in turns, it goes up in voltage, but down in the size of the current. There will likely be some optimum in the curve of voltage vs. current that will dictate the best "operating point" at which to work. The use of a lock-in amplifier as the voltage sensing instrument for this experiment would provide the demodulation capabilities needed to complete the synchronous detection approach. Due to advances in electronics, and the availability of modern electrometers with high sensitivity, we estimate that, even without superconducting sensors, this approach might allow the detection of signals 10^2 times smaller those of Crémieu and Pender.

5.3 Reciprocal of the Rowland experiment: The magnetic field induced on a moving coil by an electric charge at rest.

This experiment constitutes the reciprocal of the Rowland experiment. The positive result of Rowland's experiment indicates that convection currents, or "open" currents, have the effect foreseen by Maxwell and Lorentz, i.e., that moving electrified bodies produce magnetic effects in the same way as conduction currents do. A more complete scenario of the transformation properties of em fields can be achieved by means of the reciprocal of Rowland's experiment where the charge or electrified body is at rest in the laboratory frame, while the sensor consists of a coil in motion.

Why should one doubt that an emf is induced in the coil?

Objections to the conclusions that are generally drawn from Rowland's experiment are mentioned above and we reconsider some of them here. In Stokes-Planck ether theories, the Earth is a local privileged frame where the ether is at rest. In this case the charges of the capacitor of Rowland's experiment are moving with respect to the ether, i.e. possess absolute velocity and according to Maxwell they produce a magnetic field. But Rowland's experiment does not prove that, for a charge 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. As mentioned above, independently of the specific ether theory considered, a privileged frame for this motion is established, similarly to the case of charges moving in the closed circuit of a conductor. On the contrary, there are no experiments showing that a uniformly moving isolated charge is equivalent to a current that produces a magnetic field. Thus, the law (1) has not been tested for the case of a an isolated charge distribution moving with respect to the coil.

In view of all these arguments, we believe that the magnetization produced by moving charges, foreseen by the STR, should be tested by means of a reciprocal Rowland experiment that tests the magnetic field induced on a moving coil by an electric charge at rest. This charge produces an electric field in the laboratory frame and possesses no absolute velocity. However, in the rest frame of the coil the charge is moving and, according to STR, it produces a current and corresponding magnetic field. In this case we are dealing with the relative, and not absolute, motion of the charge. If this relative motion produces the sought-for magnetic induction to be tested with the reciprocal Rowland experiment, Lorentz's theory and STR are finally confirmed both in the laboratory frame and in the rest frame of the coil. Actually, the reciprocal of Rowland's experiment that is being proposed here, also represents a test of Faraday's law of induction in its differential form.

Let us consider a static charge distribution, which produces an electric field $\mathbf{E}$. 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 6. 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 moving charge distribution produces a magnetic field $\mathbf{B}' \simeq \mathbf{v} \times \mathbf{E}/c^2$ (SI system).

Considering this problem from a theoretical point of view, is there a way to predict in frame S the result implied by Eq.(1) 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 uniform, static electric field [49]. 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. For the problem discussed in the literature, one wished to justify, as seen from frame S, the existence of the torque on the loop moving in a static electric field. This task was accomplished [49] 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 and its variation gives 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 [50].

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 with even a qualitative justification of the result implied by Eq.(1). 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 (1) applied in frame S.

We find it convenient to point out the difference between the test of Faraday's law related to the Trouton-Noble experiment (described in Sec. 3) and the test for open currents by means of (1). In the first case what is involved is the localization of the emf on a part or segment of the closed circuit which includes Faraday's disk. Usually, the law of induction for a Faraday's disk is verified measuring the emf induced in the closed loop of which the disk is a part. The TN capacitor acts as a device that measures locally the effective field, without the necessity of the complete closed circuit. In this case, although the magnetic field of the Earth is produced by closed currents, the effective induction is measured on an open segment, the TN capacitor.

Instead, in the present experiment, we are testing Faraday's law of induction in its differential form in the sense that in the rest frame of the coil the magnetic field is produced (supposedly, according to STR) by an open current (the moving charge distribution) while the induction is measured in a closed loop (the coil).

We are left now with the evaluation of the emf (1) to check that this test is realizable with present technology. The argument is similar to that used for the direct Rowland experiment but with some minor changes. The maximum variation of the flux induced in the coil is again given by (19) while the time it takes for the coil to enter and reach the centre of a capacitor with linear dimension l is again $\Delta t = l/2v$.

To detect the emf we propose an arrangement of the type described in Fig. 6. The parallel plates of the capacitor sandwich the extremity or circumference of a spinning wheel or arm where a thin coil is fixed. The coil will move trough the capacitor at the speed $v = \omega R$, which is the tangential speed of the wheel. The coil is connected electrically to the fixed axis of rotation by some sliding contacts near to it and the electric contacts close on an electrometer.

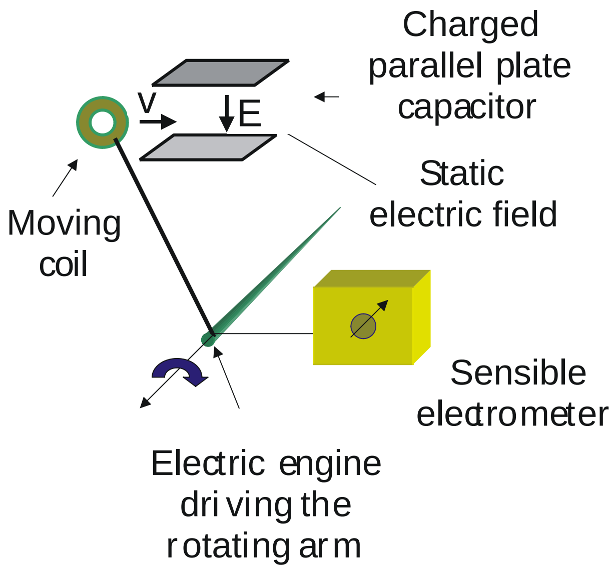

Figure 6. The reciprocal Rowland experiment as a complementary test of "open" currents and Faraday's law in differential form. A coil, fixed at the extremity of a rotating arm, moves with velocity $\mathbf{v}$ in the laboratory frame. A stationary parallel plate capacitor is placed in such a way that, when the arm passes by, the coil passes between the parallel plates. If the capacitor is charged and the electric field between the plates is $\mathbf{E}$, the coil experiences a time-varying magnetic induction field $\mathbf{B}' = -\mathbf{v} \times \mathbf{E}/c^2$. In the rest frame of the coil, the magnetization eventually experienced is produced by the charges of the plates comoving with the capacitor, and is evidence of the existence of convection or "open" currents. The induced emf, which would corroborate the validity of Faraday's law for open currents, can be transmitted by means of sliding contacts to a stationary circuit and may be detected by a sensitive electrometer.

In order to decrease the resistance of the sliding contacts, the speed at the center should be minimized with respect to the tangential speed by choosing R to be as large as possible. We suggest $R = 50cm$ and $\omega = 50rev/s$ for this experiment. The area of the coil linking the **B** 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 $V = 10^5 V$ and $d = 1cm$, the maximum emf induced in the coil is, as in (20),

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

As mentioned in the previous Section, application of superconducting devices requiring liquid helium temperatures is possible but quite expensive and in this case impractical because the sensor is rotating at high speed. Another problem is that the output from the moving coil has to be transmitted to the measuring device or electrometer by means of sliding contacts near the center of the rotation axis. Sliding contacts introduce electronic noise so that the sensibility of this reciprocal Rowland's experiment is potentially lower than that of the direct Rowland's experiment described above.

In order to avoid the problems raised by the sliding contacts, we suggest the possible use of a secondary coil at rest that will face the primary coil when this, in its circular motion, passes through the charged capacitor. The magnetic flux variation experienced by the primary coil induces an emf which results in a current in the coil. This induced current produces a magnetic field that is linked to the secondary coil at rest so that, at the end, an emf is induced also in the secondary coil. Since the secondary coil is at rest, we can measure this secondary emf with the same techniques applied to the direct Rowland experiment. Thus, similar conclusions can be drawn as far as the feasibility of the reciprocal Rowland experiment.

6 Phase and photon velocities in the Fizeau experiment

In this and in the following Sections we consider the magnetic model of light propagation in moving media and show how it can be used for a crucial test of the addition of velocities 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. We begin with placing Fizeau's experiment in the context of early ether theories.

6.1 Fizeau's experiment and early ether theories

As a theoretical support of the experiments related to the measurement of the velocity of the Earth relative to the ether, such as the Michelson-Morley experiment, theories were developed [51] to account for the actual mechanism of the propagation of light waves in the hypothetical ether in terms of its mechanical and elastic properties. It was assumed originally that the wave motion constituting light was a longitudinal wave motion. Longitudinal waves can be propagated in liquids and gases, so that an early model the ether could be pictured as a gas.

About 1820 Young and Fresnel found that, in order to account for the phenomenon of the polarization of light with the wave theory, light had to be pictured as a transverse wave motion. The existence of transverse surface waves, such as water waves, had been known for some time, but there had been no experimental or theoretical investigations of the transmission of transverse waves through the volume of a solid. Fresnel pointed out that if the ether possessed rigidity it would be possible for the ether to transmit transverse waves.

The theory of luminiferous ether, i.e. the propagation of light waves in a transparent elastic solid, was developed later 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. Gases and liquids have no rigidity and transverse waves cannot normally be transmitted through the volume of a fluid. On the other hand, solids have a rigidity, so that the ether had to be pictured as having some of the properties of an elastic solid.

Another difficulty facing the elastic solid model of the ether at that time was how to account for the absence of the longitudinal waves which should accompany transverse waves in a solid. Ether theories that dealt with this problem were developed. In 1839 Cauchy suggested that the ether had a negative compressibility so that the velocity of the longitudinal waves would then be zero. This theory became known as the 'contractile' or 'labile' theory. It was developed extensively by Lord Kelvin. Green pointed out that such an ether would be unstable, tending to contract all the time. To overcome this difficulty Kelvin suggested that the ether was like homogeneous foam free from air, and was prevented from collapsing due to its adhesion to solid bodies. In 1839 MacCullagh suggested that the ether was a new type of elastic substance unlike known elastic substances. MacCullagh suggested that the elements of the ether could resist rotatory twisting stresses, but could not resist longitudinal stresses. On this basis MacCullagh was able to interpret a wide range of optical phenomena and developed 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 [52]. Later, 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 planets, much in the same way as the Earth does it with its own atmosphere [25]. The Fresnel dragging coefficient

$$f = 1 - \frac{1}{n^2}$$

was used in interpreting Fizeau's experiment on the velocity of light in moving water. When the medium, through which the light was passing, was moving relative to the laboratory, fringe shifts were observed. Thus, relative motion between the observer and the water produced observable effects to first order of v/c. Fizeau's result was positive in contrast with the null result of the Michelson-Morley experiment and was supportive of the existence of an ether partially dragged by the moving fluid.

According to Fresnel [52] the speed achieved by light in a medium moving with velocity $\mathbf{u}$ is given by the Galilean composition of velocities provided that the dragging by the flow $\mathbf{u}$ is partial, i.e. reduced accordingly by a factor of f. The velocity of light in the direction of the flow should then be $c/n + fu$, i.e.,

$$v_\phi = \frac{c}{n} + (1 - \frac{1}{n^2})\, u \tag{21}$$

as later corroborated by Fizeau [15]. Thus, this result could be interpreted in terms of the ether theory and was considered to confirm the existence of the ether, but the interpretation was not without its difficulties. The dragging coefficient depends on the refractive index n. Since the refractive index of a medium varies with the frequency of the light used, the dragging coefficient had to vary depending on the color of the light used. White light is composed of light of all frequencies and it was difficult to account for the transmission of white light in moving water, unless of course one was prepared to postulate a different ether dragged along by a different amount for every frequency present in the light used.

Because of all these difficulties with ether theories, the simpler interpretation of the Fizeau effect offered by STR appears to be superior. In fact, the speed (21) is nothing but the speed resulting from the relativistic composition of velocities to first order of v/c. However, on revising the observable quantities measured in the Fizeau experiment, we noticed that in the usual, 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.

6.2 magnetic model of matter and light waves

The relationship between light in moving media and charged matter waves has been addressed by Cook, Fearn, and Milonni [22] 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 [16]. Analogous effects for water and sound waves have been considered. More recently, a magnetic model of light propagation has been developed by Leonhardt and Piwnicki [23]. In quantum effects of the AB type [17], [20], [18], matter waves propagate in a flow of em origin that, according to Spavieri [18], acts as a moving medium and modifies the wave velocity.

Although in effects of the AB type the propagating matter waves are dragged by the em flow, the material particles move nevertheless in a field- or force-free classical path and their initial speed is not modified by the em flow. As mentioned above, according to Fresnel [52] light waves propagating in a transparent, incompressible moving medium with uniform refraction index n, are dragged by the medium and develop an interference structure that depends on the velocity $\mathbf{u}$ of the fluid. The speed achieved, corroborated experimentally by Fizeau [15], is given by Eq. (21).

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 for the momentum of both particle and wave, suggesting that the natures of matter and light waves are closely related. Recently, it has shown [14] that the interaction momentum in both AB type effects and the magnetic model of light has the same physical origin and is related to the momentum of the em interaction fields.

The relevant point is that, if the analogy between matter wave and light wave 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. An important consequence is that, 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 velocity of photons does not, a point which has not been discussed previously in the literature.

7 Wave equations for matter and light waves

In quantum effects of the AB type[16] - [18], 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

$$\frac{1}{2m}(-i\hbar\boldsymbol{\nabla} - \mathbf{Q})^2\Psi = E\Psi \tag{22}$$

and its solution is given by the matter wave function

$$\Psi = e^{i\phi}\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,e^{i\frac{1}{\hbar}(\mathbf{p}\cdot\mathbf{x}-Et)}\,\mathcal{A} \tag{23}$$

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 [18] to the linear momentum of the interaction em fields in the form $\mathbf{Q} \propto \int \mathbf{E}\times\mathbf{B}\,d^3\mathbf{x}$, which has dimensions proportional to a velocity $\mathbf{u}(\mathbf{x})$ and permeates the whole space. If $\mathbf{Q}$ 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. (22) is the Schrödinger equation for a charged matter wave in a magnetic field [53], 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 $\mathbf{Q} = \mathbf{m}\times\mathbf{E}/c$ [17], while for an electric dipole $\mathbf{d}$ in a magnetic field $\mathbf{B}$, we have $\mathbf{Q} = (\mathbf{d}\cdot\boldsymbol{\nabla})\mathbf{A}/c$ [18].

In seeking an analogy between the equations for matter waves and light waves, we conveniently write Eq. (22) as ($\hbar = 1$)

$$(-i\boldsymbol{\nabla} - \mathbf{Q})^2\Psi = p^2\Psi. \tag{24}$$

After specifying the physical meaning and the value of the interaction momentum $\mathbf{Q}$ for light waves, we can show that, with $p = k$ the wave vector, this equation represents also the equation for light waves . 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 $[\nabla'^2 - \frac{n^2}{c^2}\partial^2_{t'}]\Psi = 0$ which is written in the comoving frame of the medium, will read as follows in the laboratory frame

$$(\nabla^2 - 2\frac{n^2-1}{c^2}\mathbf{u}\cdot\boldsymbol{\nabla}\,\partial_t - \frac{n^2}{c^2}\partial^2_t)\Psi = 0, \tag{25}$$

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

$$\begin{aligned}\Psi &= e^{i\phi}\Psi_0 = e^{i\frac{1}{\hbar}\int \mathbf{Q}\cdot d\mathbf{x}}\,\Psi_0 = e^{i\int -\frac{n^2-1}{c^2}\omega\mathbf{u}\cdot d\mathbf{x}}\,\Psi_0 \\ &= e^{i\int -\frac{n^2-1}{c^2}\omega\mathbf{u}\cdot d\mathbf{x}} e^{i\int \mathbf{k}\cdot d\mathbf{x} - \omega\, dt)}\,\mathcal{A}\end{aligned} \tag{26}$$

where Ψ_0 solves Eq. (25) with $\mathbf{u} = 0$.

On account of the solution (26), for a magnetic model of light propagation in moving media [22], [23], we set in Eq. (24)

$$\mathbf{Q} = -\frac{\omega}{c^2}(n^2-1)\mathbf{u} \tag{27}$$

in agreement with Fresnel's predictions [52] and Fizeau's experiment [15], while the quantity p in Eq. (24) is the one corresponding to light, $p = k = n\omega/c$, where n is the index of refraction, $\mathbf{k}$ the wave vector, and ω the angular frequency. In units of $\hbar = 1$, $\mathbf{k}$ represents the momentum and ω the energy. The wave equation (24) reads now

$$(-i\boldsymbol{\nabla} + \frac{n^2-1}{c^2}\omega\mathbf{u})^2\Psi = n^2\frac{\omega^2}{c^2}\Psi \tag{28}$$

which, in lowest order in u/c, is identical to (25), as can be seen by performing the derivatives $\boldsymbol{\nabla}\,\partial_t$ and ∂^2_t. Actually, the same wave equation (25) can be derived without reference to special relativity by taking into account the polarization produced by the effective field in the moving media [54].

7.1 the interaction em momentum

As discussed above, we wish to show that the wave equation (24), which in the form (22) is used for matter waves, can be used also for description of light waves. This general property of Eq. (24) would be corroborated by showing that, for both matter and light waves, $\mathbf{Q}$ is the variation of the interaction em momentum. If this is so, $\mathbf{Q}$ has the same physical origin in both cases, i.e., is given by the interaction em momentum. That this is the case for all the effects of the AB type, as mentioned above, has been shown already by one of us in Ref.[18]. More recently [14], it has been shown 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, calculations yield $\mathbf{Q} = (e/c)\mathbf{A}$ for the Aharonov-Bohm effect, while it yields the Fresnel-Fizeau momentum $\mathbf{Q} = -\,\omega(n^2-1)\mathbf{u}/c^2$ of Eq. (27) for light waves propagating in a moving medium with flow $\mathbf{u}$.

These findings may be summarized as follows: In general, with T^M_{ik} the Maxwell stress-tensor, the covariant description of the em momentum leads to the four-vector em momentum P_e^α expressed as $(c=1)$

$$P_e^i = \gamma \int (\mathbf{g} + T^M_{ik}\beta^i) dV, \;\; P_e^0 = \gamma \int (u_{em} - \mathbf{v}\cdot\mathbf{g}) dV \tag{29}$$

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. The standard classical-quantum correspondence $(\hbar = 1)$,

$$\int u_{em}\, d^3\mathbf{x}' = \frac{1}{4\pi}\int \varepsilon\,(\mathbf{E}^2)\, d^3\mathbf{x}' \rightarrow n^2\omega, \;\; c^{-1}\int \mathbf{g}\, d^3\mathbf{x}' = \frac{\sqrt{\varepsilon}\mathbf{e}_o}{4\pi c}\int (\mathbf{E}^2)\, d^3\mathbf{x}' \rightarrow \mathbf{k}$$

holds for the em energy and momentum. The natural choice for $K^{(0)}$ is the rest frame in which the momentum $\int(\mathbf{g})d^3\sigma$ vanishes, i.e., the frame comoving with the light ray, as if the em mass of the fields were nonvanishing.

The meaningful quantities for light propagation in moving polarizable media is the *interaction* em momentum, i.e., the em momentum due to polarization, which is proportional to (n^2-1) and is found [14] to be

$$\mathbf{P}_e = (n^2-1)\frac{\gamma_v}{\gamma_{c/n}}\frac{\omega_o}{c^2}\mathbf{v}. \tag{30}$$

On calculating the variation of $\mathbf{P}_e$ due to the flow $\mathbf{u}$, with $\gamma_v = \gamma_{c/n}\gamma(1 + \mathbf{u}\cdot\mathbf{e}_o/cn)$ equation (30) yields

$$\mathbf{Q} = \mathbf{P}_{oe} - \mathbf{P}_e(\mathbf{u}) \simeq -\frac{\omega}{c^2}(n^2-1)\mathbf{u}. \tag{31}$$

The last term of Eq.(31), the variation $\mathbf{P}_e(\mathbf{u}) - \mathbf{P}_{oe}$ in first order in u/c, is the Fresnel-Fizeau momentum $\mathbf{Q}$ of Eq.(27), i.e., the dragged interaction em momentum.

8 Energy and momentum flow of matter and light in a moving medium

So far we have considered the main properties of the equivalent wave equations (22), (24), and (28), (25) describing matter and light waves. The Hamiltonian $H_{AB} = (\mathbf{P} - \mathbf{Q})^2/2m$ of Eq. (22) can be derived from the classical Lagrangian

$$L = \frac{\mathbf{p}^2}{2m} + \mathbf{v} \cdot \mathbf{Q} \tag{32}$$

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

$$\frac{d\mathbf{p}}{dt} = -\frac{\partial}{\partial t}\mathbf{Q} + \mathbf{v}\times(\boldsymbol{\nabla} \times \mathbf{Q}), \tag{33}$$

while (with $-i\hbar\boldsymbol{\nabla} \longleftrightarrow \mathbf{P}$) $\mathbf{P} = \partial L/\partial \mathbf{v} = \mathbf{mv} + \mathbf{Q}$ is the canonical momentum. In the case of field-free or force-free effects, the rhs of Eq. (33) 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. The wave function of Eq.(23) represents a matter wave associated with a particle of speed v and energy E which is simply out of phase by ϕ with respect to the original wave function.

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

a) Instead of taking (26) as solution of the wave equation, one may follow the approach of Leonhardt and Piwnicki [23] and consider, as a solution Ψ of Eq. (28), the ansatz

$$\Psi = e^{i\int \mathbf{k}_\phi \cdot d\mathbf{x} - \omega\, dt)}\, \mathcal{A} \tag{34}$$

in order to obtain from Eq. (28) the relation

$$k_\phi^2 - \frac{n^2}{c^2}\omega^2 + 2\omega\frac{n^2-1}{c^2}\mathbf{u} \cdot \mathbf{k}_\phi = 0. \tag{35}$$

Eq.(35) represents now a dispersion relation which yields the Hamiltonian

$$H_\phi = \omega = \frac{c}{n} k_\phi + (1 - \frac{1}{n^2}) \mathbf{u} \cdot \mathbf{k}_\phi \tag{36}$$

In this case, the Hamilton equations

$$\frac{d\mathbf{x}}{dt} = \frac{\partial H_\phi}{\partial \mathbf{k}_\phi}, \qquad \frac{d\mathbf{k}_\phi}{dt} = -\frac{\partial H_\phi}{\partial \mathbf{x}} \tag{37}$$

imply that the velocity of the wave (or its phase velocity) coincides with the velocity of the photon and is given by

$$\mathbf{v}_\phi = \frac{d\mathbf{x}}{dt} = \frac{c}{n} \widehat{\mathbf{k}}_\phi + (1 - \frac{1}{n^2}) \mathbf{u}, \tag{38}$$

which agrees with STR.

b) In close analogy with the effects of the AB type we seek a solution of the type $\Psi = \exp[i\phi + i(\int \mathbf{k} \cdot d\mathbf{x} - \omega\, dt)]\, \mathcal{A}$ as in (26), for the wave equation Eq. (28). Substitution of Ψ into (28) yields the dispersion relation

$$k^2 - \frac{n^2}{c^2} \omega^2 = 0, \tag{39}$$

while the Hamiltonian for light rays is

$$H = H_\phi = \omega = \frac{c}{n} k. \tag{40}$$

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 frequency of the wave does not change, $\omega_\phi = \omega$. However, since the phase of the wave function changes, the phase velocity may be thought of as having changed. In this case, the phase change does not influence the energy, frequency and momentum of the photon although it results in a change of the phase or wave velocity.

The Hamilton equations yield

$$\mathbf{v} = \frac{d\mathbf{x}}{dt} = \frac{c}{n} \widehat{\mathbf{k}}, \quad \frac{d\mathbf{k}}{dt} = -\boldsymbol{\nabla}(H), \tag{41}$$

for the group velocity and for the light momentum. In this case, 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.

9 Consequences of the magnetic model

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

1) An interpretation of the results established by Eqs.(35), (36) and (38) 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 $\mathbf{Q} = \mathbf{P}_e$ 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. Thus, $\mathbf{P}_e$ is not carried by the particle and does not modify the mechanical momentum $\mathbf{p}$ of the particle. 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 $\mathbf{k} = -i\boldsymbol{\nabla}$ in Eq. (28) is carried by the moving medium or by the light particle (photon). If this additional momentum 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 (33), and their momentum $\mathbf{p}$ is not modified because, for this field-free effect, we have $(\partial/\partial t)\mathbf{A}+\mathbf{v}\times(\boldsymbol{\nabla}\times\mathbf{A}) = 0$. 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. Thus, there would be forces acting locally on the photon and the analogy with the force- and field-free AB effect breaks down.

2) The magnetic model of light propagation in moving media [22], [23] is supported by the equivalence of the Eqs. (22), (24), and (28), (25) 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. (23) and (26) 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. In tests of Aharanov-Bohm effects and in the Fizeau type of experiments [15], [**?**], 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. (23) and (26), 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.(39) and (40) and the group velocity is given by $d\omega/d\mathbf{k} = \mathbf{c}/n$ as implied by Eq.(41).

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. 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 photons in moving media proposed below, possesses a physical relevance not contained in the traditional Fizeau approach.

10 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 interested in showing that such an experiment is feasible and can be realized with present technology. Technical aspects and details of a proposed experiment of this type are given elsewhere.

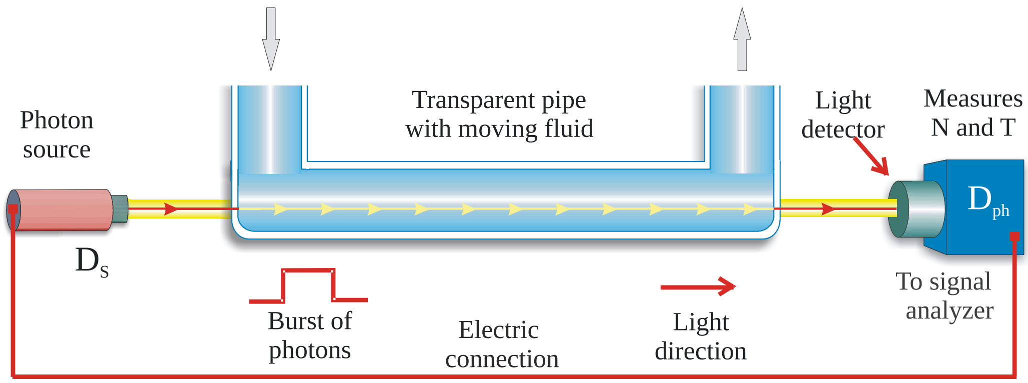

Figure 7. A short burst of light emitted by the source D_S propagates through a transparent fluid moving with velocity $\mathbf{u}$ in a pipe of length L and then hits a photodetector D_{ph}. At this time, the device D_{ph}, which is electrically connected to the source D_S, triggers it so that another 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 sensitive enough to allow for checking the functional dependence of the photon speed as a function of the refractive index n and the flow $\mathbf{u}$.

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. 7. The pulse travels through the pipe, propagates in the moving fluid and, as it exits, hits a photodetector D_{ph} that is electrically connected to the source D_S. When photodetector 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, this apparatus 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

$$T(u) = NL/[c/n(u)] + NL'/c + Nt_D. \tag{42}$$

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

$$T(u) - T = \frac{NL}{c}[n(u) - n]. \tag{43}$$

With $n(u) = n[1 + (c/nNL)(T(u) - T)]$ from (43), the resulting measured speed difference is

$$\frac{c}{n(u)} - \frac{c}{n} = \frac{c^2}{n^2 N\,L}(T - T(u)), \tag{44}$$

which can be determined by measuring N and $T(u)-T$. As shown elsewhere, supposing that the clock precision for the measurable time difference $T(u)-T$ is $\simeq 10^{-5}s$, with $L = 10\ m$ in Eq.(44) the number of passes or round trips necessary to detect the speed difference $(1 - 1/n^2)u$ is about $N = c^2[T(u) - T]/[L(n^2 - 1)u] \simeq 2.4 \times 10^{10}$ for $u \simeq 3\,m/s$. The time of measurement is of the order of Eq.(42) 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 $L/(c/n)$, the required minimum time of measurement turns out to be

$$T \simeq NL/(c/n) = 1.2 \times 10^3\,s = 0.33h.$$

We 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 increase the length of the photon path indefinitely by increasing the number N of passes or photon flights. Thus, regardless of the outcome of tests of the magnetic model, this approach should be able to improve upon the results of Fizeau and of the traditional interferometric approaches that test special relativity, by providing a measurement of the speed of a burst of photons with an increased sensitivity. Therefore, we conclude that a non-interferometric approach may indeed be viable and that the quantity $c/n(u)$ is measurable as a function of both n and $\mathbf{u}$ with existing experimental techniques.

11 Conclusions

We have considered and 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's surface would feel while moving with the tangential rotational velocity $\mathbf{v}$ in the presence of the field $\mathbf{B}$ of the Earth. The nonshielded TN capacitor can be used as a testing device. The field $\mathbf{B}$ is produced by real (closed) currents such as those of an ordinary magnet. However, the detecting device for the law of induction is not the usual closed circuit or loop where the emf is induced, but a charge at rest on the Earth. In the nonrotating frame, the charges in motion producing $\mathbf{B}$ form a closed current while the test charge forms an open current.

An analogous situation represents the test of Faraday's law via the non-conservation of the mechanical angular momentum of an isolated system. 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 producing $\mathbf{B}$ and $\mathbf{A}$ form a closed current while the test charges on the spherical shell form an open current, which corresponds to static charges in this case. Reciprocally, the interaction between a charge and a magnet can be exploited to perform a test of the force on a magnetic dipole. This test is related to the Shockley-James paradox and conservation of the total linear momentum of an isolated system.

The null result of the traditional TN experiment can be interpreted also as indicating that charges in motion with respect to the ether (open currents) do not produce a magnetic field. Considering that the concept of ether is elusive, is there another way to test the effect of open currents? Such a test can be realized by detecting the magnetic field produced by charges in circular motion, as in the direct Rowland experiment proposed in Sec. 5. In the reciprocal Rowland experiment one detects the magnetic field seen by a coil moving with respect to a charge distribution fixed in the laboratory frame of reference. In this case we test the assumption of Maxwell (and STR) that a moving isolated charge forms a current producing a time-varying magnetic field in the rest frame of the coil. This field is detected by the coil via Faraday's law of induction, and the analysis performed in Sec. 5 shows that these experiments are viable.

Finally, the impact and range of validity of the Fizeau experiment is 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. The outcome of the Fizeau experiment agrees with the addition of velocities of special relativity. However, as shown by Su [12], the roles of Earth's rotation and of the Sagnac effect make the results somewhat different from those based on special relativity.

In any event, even if these differences are neglected, in the case of the traditional Fizeau's experiment 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. Instead, via the principle of the method proposed here, 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. Thus, a 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. Our non-interferometric experiment is being proposed both as a test of the magnetic model and as a new test of special relativity that complements the traditional interferometric approach. In principle, a dedicated experiment that measures the speed of photons and particles (such as electrons in the AB effect) should be sensitive enough to corroborate the analogy and either confirm or refute the model. The possible experimental outcomes are:

a) the speed of photons and particles is not modified by the flow. In this case the magnetic model holds, but there is no agreement with special relativity for the photon speed.

b) the photon and particle speeds are modified by the flow. The magnetic model continues to hold and there is agreement with special relativity but, in this case, the standard interpretation of the effects of the AB type needs considerable revision.

c) the photon speed is modified by the flow but that of particles is not. In this case STR is confirmed but the magnetic model of light is refuted.

In closing, we have reviewed several recent crucial tests of STR, realizable with present technology, necessary to corroborate the locality of em interactions and the addition of velocities foreseen by STR. Although all these tests involve the em momentum of interaction fields, some of them are actually tests of Faraday's law of induction in differential form, while one explores the magnetic model of light, based on an analogy between the behavior of light and particles.

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References

[1] P. Graneau, J. Appl. Phys. **62**, 3006 (1987).

[2] P. T. Pappas, Nuovo Cimento B, 76, 189 (1983).

[3] T. E. Phipps and T. E. Phipps Jr., Phys. Lett. **146** A, 6 (1990).

[4] G. Cavalleri, G. Spavieri, and G. Spinelli, Eur. J. Phys. **17**, 205-207 (1996).

[5] G. Cavalleri, G. Bettoni, G. Spavieri and E.Tonni. Phys. Rev. E, **58**, 2505 (1998); G. Cavalleri, G. Spavieri and E. Tonni. Hadronic J. **21**, 459-478 (1998); G. Cavalleri, E. Tonni, and G. Spavieri, Phys. Rev E, **63**, 058602-1 (2001).

[6] P. Cornille, Prog. En. Comb. Science, **25**, 161-210 (1999); Galilean Electrodynamics, **9**, 33 (1998).

[7] L. Nieves, M. Rodriguez, G. Spavieri, and E. Tonni, Nuovo Cimento **116** B, 585-92 (2001).

[8] G. Spavieri and G. T. Gillies. Nuovo Cimento, **118** B, 205-222 (2003).

[9] G. Spavieri, L. Nieves, M. Rodriguez, and G. T. Gillies. *Has the last word been said on Classical Electrodynamics?-New Horizons,* 255-270, Rinton Press, USA (2004).

[10] T. H. Boyer, Am. J. Phys. **56**, 688 (1988); Y. Aharonov, P. Pearle, and P. Vaidman, Phys. Rev. A **37**, 4052 (1988); G. Spavieri, Nuovo Cimento B **109**, 45 (1994). See also Ref. [11].

[11] T. H. Boyer, Phys. Rev. D **8**, 1667, 1680 (1973); Phys Rev. A **36**, 5083 (1987); Nuovo Cimento B **100**, 685 (1987). For the force on a magnetic dipole see also Ref. [10].

[12] C. C. Su, J. Electromagn. Waves and Appl., **19**, 559-567 (2005).

[13] G. Spavieri and G. T. Gillies, Chi. J. Phys. **45**, 12 (2007).

[14] G. Spavieri, Eur. Phys. J. D, **39**, 157-166 (2006).

[15] H. Fizeau, C. R. Acad. Sci. (Paris) **33**, 349 (1851).

[16] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).

[17] Y. Aharonov and A. Casher, Phys. Rev. Lett. **53**, 319 (1984).

[18] G. Spavieri, Phys. Rev. Lett. **82**, 3932 (1999).

[19] G. Spavieri, Phys. Lett. A **310**, 13 (2003).

[20] G. Spavieri, Phys. Rev. Lett. **81**, 1533 (1998), Phys. Rev. A **59**, 3194 (1999); X.G. He and B. H. J. McKellar, Phys. Rev. A **47**, 3424 (1993); M. Wilkens, Phys. Rev. A **49**, 570 (1994), Phys. Rev. Lett. **72**, 5 (1994); J.Yi, G. S. Jeon, and M. Y. Choi, Phys. Rev. B **52**, 7838 (1995); H. Wei, R. Han, and X. Wei, Phys. Rev. Lett. **75**, 2071 (1995); J. P. Dowling, C. P. Williams, and J. D. Franson, Phys. Rev. Lett. **83**, 2486 (1999); V. M. Tkachuk, Phys. Rev. A **62**, 052112-1 (2000).

[21] G.Spavieri, Eur. Phys. J. D, **37**, 327-334 (2006).

[22] R. J. Cook, H. Fearn, and P. W. Milonni, Am. J. Phys. **63**, 705 (1955).

[23] U. Leonhardt and P. Piwnicki, Phys. Rev. A, **60**, 4301 (1999); Phys. Rev. Lett. **84**, 822 (2000).

[24] M. Duffy, private comm., Int. Conf. *Physical Interpretation of Relativity Theory* 2006.

[25] For the interpretation of optical experiments with the Stokes-Planck ether, see: G. Cavalleri, L. Galgani, G. Spavieri and G. Spinelli, Scientia. Vol. III. **9-12**- 675 (1976).

[26] H. A. Rowland, Am. J. Sci. Art., **15**, 30-38 (1878).

[27] W. C. Röntgen, Wied. Ann., **35**, 264 (1888); **40**, 93 (1890).

[28] F. Himstedt, Wied. Ann., **38**, 560 (1889).

[29] V. Crémieu, Com. Rend., **130**, 1544, and **131**, 578 and 797 (1900); **132**, 327 (1901).

[30] H. Pender, Phil. Mag., **2**, 179 (1901).

[31] E. P. Adams, Phil. Mag., **2**, 205 (1901)

[32] J. J. Thomson, Phil. Mag., **2**, 236 (1881)

[33] 0. Heaviside, Electrical Papers, vol. ii. p. 205 (1881)

[34] R. W. Wood, Phil. Mag., **2**, 659 (1902)

[35] L. Indorato and G. Masotto, Annals of Science, **46**, 117-163 (1989).

[36] V. Crémieu and H. Pender, Phys Rev, **17**, 385-409 (1903).

[37] N. Vasilesco-Karpen, Ann. Chem. Phys., **2,** 465-574 (1904).

[38] F. Selleri, Found. Phys. Lett., **10**, 73 (1997); *Open Questions in Relativistic Physics*, 69 (Apeiron Press, Montreal) 1998; G. Puccini and F. Selleri, Nuovo Cim. B, 117, 283 (2002).

[39] T. H. Boyer, Phys. Rev. D **8**, 1667 (1973); X. Zhu and W. C. Henneberger, J. Phys. A **23**, 3983 (1990); G. Spavieri et al., Hadr. J. **18**, 509 (1995).

[40] F. T. Trouton and H. R. Noble, *Proc. Royal Soc.*, **72**, 132 (1903).

[41] C. T. Chase, *Phys. Rev.*, **28**, 378 (1926).

[42] H. C. Hayden, *Rev. Sci. Instruments.*, **65**, 788 (1994).

[43] E. Kennard, *Phil. Mag.* **33**, 179 (1917).

[44] J. Tate, Bull. Nat. Res. Council, **4**, 6 (1922).

[45] G. T. Gillies and S W Allison, *Rev. Sci. Instrum.* **57**, 268 (1986).

[46] G. T. Gillies, *Rep. Prog. Phys.*, **60**, 151 (1997). See also, R. C. Ritter, L. I. Winkler, and G. T. Gillies, *Phys. Rev. Lett.*, **70**, 701 (1993).

[47] See G. T. Gillies and R. C. Ritter, *Rev. Sci. Instrum.*, **64**, 283, 1993 and also G T Gillies, *Rep. Prog. Phys.*, **60**, 151 (1997) for guides to the literature in this area.

[48] W. Shockley and R. James, *Phys. Rev. Lett.*, **18**, 876 (1967).

[49] G. Cavalleri, G. Spavieri and G. Spinelli. Nuovo Cimento. **53**B, 385 (1979); G. Spavieri, Found. Phys. Lett. **3**, 291 (1990).

[50] G. Cavalleri, O. Gron, G. Spavieri and G. Spinelli. Am. J. Phys. **46**. 108 (1978).

[51] E. Whittaker, *A History of the Theories of Aether and Electricity*, Vol. I, Thomas Nelson, Edinburgh (1951).

[52] A. J. Fresnel, C. R. Acad. Sci. (Paris) **33**, 349 (1851).

[53] L. D. Landau and E. M. Lifshitz, *Quantum Mechanics* (Pergamon, Oxford, 1977).

[54] W. K. H. Panofsky and M. Phillips, *Classical Electricity and Magnetism*, Sec. 11-5, sec. ed. (Addison-Wesley, Reading, 1962).