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Ether drift experiments and electromagnetic momentum

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Abstract. Propagation of Aharonov-Bohm matter waves and light waves in moving media is characterized by the interaction electromagnetic momentum. Thus, recent models of light propagation in moving rarefied media justify and call for an optical experiment of the Mascart-Jamin type, capable of testing the modern interpretations of ether drift experiments.

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1 Introduction

In recent years a growing number of articles questioning the standard interpretation of special relativity has appeared [1–5]. Some of the authors adhere to a point of view close to the historical works of Lorentz and Poincaré, who maintained the existence of a preferred frame. For example, Selleri [2] has developed Bell's idea [1] and obtained a true Lorentzian theory, fully compatible with Einstein's special relativity in what concerns the description of physical phenomena, but very different in their interpretation and in philosophical terms. Another Lorentzian theory, very close to Selleri's formulation, was derived independently in reference [3].

The possibility of maintaining the existence of a preferred frame, and parallel interests in the Michelson-Morley, Trouton-Noble and related effects, arise because the coordinate transformation used, the Tangherlini transformations [6] (denoted by *inertial transformation* in [2] and by *synchronized transformation* in [3,4]), foresee the same length contraction and time dilation as the Lorentz transformations. For a primed frame moving with velocity $\mathbf{v}$ with respect to a non-primed frame, we have

$$\begin{array}{ll} \text{Tangherlini} & \text{Lorentz} \\ x' = \gamma(x - vt) & x' = \gamma(x - vt) \\ y' = y;\ z' = z & y' = y;\ z' = z \\ t' = t/\gamma & t' = \gamma(t - vx/c^2). \end{array} \tag{1}$$

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However, since the time synchronization parameter is arbitrary, there are quantities which eventually cannot be measured, such as the one-way speed of light [7], since its measured value depends on the synchronization procedure adopted [7].

The theory is thus undetermined, unless somehow the value of the one-way speed of light is indeed unambiguously determined. Using the internal, or round-trip, synchronization procedure Einstein solves the problem in an extremely simple and elegant way, providing a straightforward and effective operational procedure for studying physics. Nonetheless, other solutions based on different synchronization procedures are possible [1–5], fully compatible with Einstein's relativity in practice, but with very different assertions in fundamental and philosophical terms [2–4].

If these different views are indeed truly compatible, it can be argued that the discussion is mostly just an academic and philosophical one, because these contrasting formulations can be seen just as merely different aspects of the same theory. However, even if different formulations lead to the same mathematical results, their different underlying assumptions might either stimulate or obstruct further research.

Some have argued that these different formulations of special relativity are truly compatible only in vacuum, as differences may appear when light propagates in transparent media. Thus, physicists have recently proposed experiments for predictions of the theory that have not been fully tested. Moreover, some have formulated untested assumptions that differ from the standard interpretation of special relativity [3,5,8,9].

Consoli and Costanzo [5], Cahill and Kitto [10], and Guerra and de Abreu [3,4], point out that for experiments of the Michelson–Morley type, which are often said to have given a null result, it has been stressed that this was not the case, and cite the famous work by Miller [11]. These authors thus claim that the available data point towards a consistency of non-null results when the interferometer is operated in the "gas-mode", corresponding to light propagating through a gas [5] (for example, air or helium). Furthermore, as shown by Consoli and Costanzo [5], the conclusion that the Michelson-Morley experiment may be a non-null result applies also to all of its more recent versions that include refined maser tests. The original important assumption (which to now still lacks a truly solid justification) that was made by the authors that seek to corroborate their claims of a non-null result, can be stated as:

– light in a moving rarefied gas of refractive index n very close to 1 propagates with speed very close to c/n in the preferred frame, as if the medium were practically isotropic and at rest.

In the following we refer to the above light propagation property as the Consoli and Costanzo assumption or model. In order to clarify how the Consoli model differs from special relativity, we consider in this paper light propagation in a slowly moving medium ($v/c \ll 1$) and recall that according to special relativity, the speed of light for propagation in the direction of v is

$$c(n) = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right) v, \tag{2}$$

as predicted also by Fresnel [12] and corroborated by the Fizeau [13] type of experiments. The point is that in the experiments that support (2), a compact refractive medium (water, glass, etc.) was used so that up to the present there are no direct or dedicated tests of the validity of (2) for light in a moving rarefied medium.

The Consoli assumption about light propagation in rarefied moving media can be conveniently expressed, instead, as

$$c_R(n) = \frac{c}{n} + e_f \left(1 - \frac{1}{n^2}\right) v \tag{3}$$

where $c_R(n)$ is the speed of light in the preferred frame, v the speed of the moving medium, and the coefficient e_f is $\ll 1$. Actually, $e_f \simeq 0$ in Consoli's original assumption, so that $c_R(n) \simeq c/n$.

Thus, the physical models of light propagation that we wish to test are:

– special relativity, or equivalent theories based on the Tangherlini transformations that make the same basic assumptions of special relativity in the preferred frame. The standard expression (2), valid in general for a rarefied or compact moving medium, is assumed by these theories;
– Consoli's model or assumption $c_R(n) \simeq c/n$, based on expression (3) and valid for a rarefied moving medium only.

Obviously, expression $c_R(n)$ in (3) differs from $c(n)$ in (2). Therefore, an optical experiment capable of testing $c_R(n)$ versus $c(n)$, can discriminate Consoli's model (3) with $e_f \simeq 0$, from special relativity's prediction (2).

Before discussing our novel optical experiment, we deem it convenient to consider recent discussions on the electromagnetic momentum and its role in the equations for propagation of matter and light waves. In fact, wave propagation in moving media has attracted the attention of several physicists in recent years for purposes not necessarily related to the ether-frame hypothesis. The analogy between the wave equation for light in moving media and that for charged matter waves has been pointed out by Hannay [14] and later addressed by Cook et al. [14] who have suggested that light propagation at a fluid vortex is analogous to the Aharonov-Bohm (AB) effect, where charged matter waves (electrons) encircle a localized magnetic flux [15]. These other models of wave propagation are not to be considered in the present scenario as alternative additional models to be tested. However, they are not incompatible with Consoli's assumption and are introduced here because they are useful for providing a rough estimate of the coefficient e_f appearing in expression (3). Indeed, for equation (3) to be meaningful and agree with the results of the Fizeau type of experiments, e_f must tend to 1 for compact media, as in (2).

The main contribution of this paper consists in proposing a new optical experiment that is particularly suitable for testing the speed of light in rarefied media. The experiment is analogous to the historical test of Mascart and Jamin [16], that yields observable variations in the first order in v/c for the test of the speed v of the preferred frame. Before describing the experiment and in order to justify the need for this or other optical tests, it is worth revisiting the above-mentioned aspects of the controversy of the preferred-frame hypothesis versus special relativity that are related to light propagation in moving media.

2 Wave equations for matter and light waves

According to Fresnel [12], light waves propagating in a transparent, incompressible moving medium with uniform refractive index n, are dragged by the medium and develop an interference structure that depends on the velocity $\mathbf{v}$ of the fluid. The speed achieved in the ether frame is (2) as later corroborated by Fizeau [13]. We recall that there is a formal analogy between the non-relativistic expression of the wave equation for light in slowly moving media and the Schrödinger equation for charged matter waves in the presence of the external vector potential $\mathbf{A}$, i.e. the magnetic AB effect. Generally, in quantum effects of the AB type [15,17,18] matter waves undergo an electromagnetic (em) interaction as if they were propagating in a flow of em origin that acts as a moving medium [18] and modifies the wave velocity. This analogy has led to the formulation of the so-called magnetic model of light propagation [9,14]. In both cases the waves interact with the medium so that the wave equations contain a term that is generically referred to as the interaction momentum $\mathbf{Q}$. In seeking an analogy between the equations for matter waves and light waves, the Schrödinger equation for quantum effects of the AB type (with $\hbar = 1$) [18] and the wave equation for light in moving media can be written [9,14] as

$$(-i\boldsymbol{\nabla} - \mathbf{Q})^2 \Psi = p^2 \Psi. \tag{4}$$

Equation (4) describes matter waves if the momentum p is that of a material particle, while, if p is taken to be the momentum $\hbar k$ of light (in units of $\hbar = 1$), equation (4) describes light waves.

(a) In quantum effects of the AB type [15–18] there are no external forces acting locally on the particles so that the particle momentum $\mathbf{p} = m\mathbf{v}$ and energy $E = (1/2)mv^2$ are conserved. For these quantum effects, the solution to equation (4) is given by the matter wave function

$$\Psi = e^{i\phi}\Psi_0 = e^{i\int \mathbf{Q}\cdot d\mathbf{x}}\Psi_0 = e^{i\int \mathbf{Q}\cdot d\mathbf{x}}\, e^{i(\mathbf{p}\cdot\mathbf{x}-Et)}\,\mathcal{A} \tag{5}$$

where Ψ_0 solves the Schrödinger equation with $\mathbf{Q} = 0$.

(b) For light in moving media, the interaction term is the Fresnel-Fizeau momentum [9]

$$\mathbf{Q} = -\frac{\omega}{c^2}(n^2-1)\mathbf{v}, \tag{6}$$

and a solution of the type of (5) may assume the forms

$$\Psi = e^{i\phi}\Psi_0 = e^{i\phi}e^{i\int(\mathbf{k}\cdot d\mathbf{x}-\omega\, dt)}\mathcal{A};$$
$$\Psi = e^{i\int(\mathbf{K}(\mathbf{x})\cdot d\mathbf{x}-\omega\, dt)}\mathcal{A} \tag{7}$$

where $\mathbf{k}$ and $\mathbf{K}(\mathbf{x})$ are wave vectors, $\omega = k\,c/n$ the angular frequency, and n the index of refraction, while Ψ_0 solves equation (4) with $\mathbf{Q} = \mathbf{v} = 0$. Actually, the same wave equation (4) can be derived without reference to special relativity by taking into account the polarization of the moving medium [19].

Although electrons and photons do not necessarily exhibit the same behavior, the fact that the corresponding waves share the same wave equation (4) implies a close analogy for the behavior of matter and light waves. Moreover, it has been shown [18,20] that for both matter waves of effects of the AB type [18] and light waves in moving media [20] , the interaction momentum $\mathbf{Q}$ is related to the linear momentum of the em fields $\mathbf{P}_e$. Thus, the existing analogy between the two wave equations is corroborated by the fact that they share a physically meaningful term that involves an interaction of the same physical nature. Two theoretical possibilities arise [9]:

– by incorporating the phase ϕ in the term $\int \mathbf{K}(\mathbf{x})\cdot d\mathbf{x}$, the last expression on the rhs of equation (7) keeps the usual invariant form of the solution as required by special relativity and one finds [20] for the speed of light the result $\mathbf{c}(n) = (c/n)\widehat{\mathbf{c}} + (1-1/n^2)\mathbf{v} = (c/n)\widehat{\mathbf{c}} - \mathbf{Q}(c^2/n^2\omega)$ in agreement with equation (2) and special relativity;
– maintaining instead the analogy with the AB effect, the solution can be chosen to be represented by the first term of equation (7), $\Psi = e^{i\phi}\Psi_0$. In this case, the phase velocity changes but the speed of light (the particle, or photon) may not change [9]. This result is in total agreement with the analogous result for the AB effect where $\mathbf{Q} = (e/c)\mathbf{A}$ and the particle speed is left unchanged by the interaction with the vector potential $\mathbf{A}$.

3 Interaction momentum for matter and light

The magnetic model has been applied to light propagating in liquids or solids in motion. It is not in conflict with the hypothesis of Consoli and Costanzo on light propagation in rarefied moving media. In fact, it may lend support to this hypothesis as we show below. To demonstrate this, we first recall the existing relation between the interaction momentum $\mathbf{Q}$ and the linear momentum of the em fields $\mathbf{P}_e$ [20]. In general, with T^M_{ik} as the Maxwell stress-tensor, the covariant description of the em momentum leads to the four-vector em momentum P^α_e expressed as

$$P^i_e\, c = \gamma\int (c\,\mathbf{g} + T^M_{ik}\beta^i)d^3\sigma \quad cP^0_e = \gamma\int (u_{em} - \mathbf{v}\cdot\mathbf{g})d^3\sigma \tag{8}$$

where $\beta = v/c$. The em energy and momentum are evaluated in a special frame $K^{(0)}$ moving with velocity $\mathbf{v}$ with respect to the laboratory frame. Here, u_{em} is the energy density of em waves and the energy flow is $\mathbf{S} = \mathbf{g}c$.

All the effects of the AB type discussed in the literature [15–18] can be described by equation (4), provided that the interaction momentum $\mathbf{Q}$ is related [18,20] to $\mathbf{P}_e$, the momentum of the em fields. If $\mathbf{Q}$ is thought of as describing a moving fluid or a flow $\mathbf{v}$, the particles or matter waves propagate through this moving em fluid. The AB term $\mathbf{Q} = (e/c)\mathbf{A}$ of the magnetic AB effect is obtained by taking $\mathbf{Q} = \mathbf{P}_e = \frac{1}{4\pi c}\int(\mathbf{E}\times\mathbf{B})d^3\mathbf{x}'$ where $\mathbf{E}$ is the electric field of the charge and $\mathbf{B}$ the magnetic field of the solenoid. A general proof that this result holds in the *natural* Coulomb gauge, has been given by several authors [21]. Actually, the observable quantity is not the phase but the phase shift variation $\Delta\Phi$ [18] so that what is physically meaningful is the variation of $\mathbf{P}_e$ as related to $\Delta\Phi$.

To derive the result of (6) for light propagation in moving media, the standard classical-quantum correspondence $\int u_{em}\, d^3\mathbf{x}' \to n^2\omega$ and $c^{-1}\int \mathbf{g}\, d^3\mathbf{x}' \to \mathbf{k}$, that holds ($\hbar = 1$) for the energy ω and the momentum $\mathbf{k}$, has been used [20]. It turns out that the relevant variation of the momentum $\mathbf{P}_e$ is the one that is due to the interaction polarization em momentum [20], which we denote as $\mathbf{P}_{ei}$. The sought-for variation of the interaction polarization em momentum yields the result [20]

$$\mathbf{Q} = \Delta\mathbf{P}_{ei}(\mathbf{v}) \simeq -\frac{\omega}{c^2}(n^2-1)\mathbf{v}, \tag{9}$$

which is the Fresnel-Fizeau momentum of equation (6). Thus, the Fresnel-Fizeau momentum $\mathbf{Q}$ is given by the variation of the interaction polarization em momentum $\mathbf{P}_{ei}$ due the flow $\mathbf{v}$, i.e., $\mathbf{Q}$ is the dragged interaction em momentum. This interpretation in terms of the drag of the interaction polarization momentum agrees with the one given by Panofsky and Phillips [19].

4 Consequences of the magnetic model of light

The following properties: (i) in AB effects the velocity of particles differs from that of the waves; (ii) the matter-wave equation for AB effects is analogous to that of light in slowly moving media; and (iii) the interaction momentum $\mathbf{Q}$ has the same physical origin for both matter and light waves, leave open the possibility that the speed of photons in moving media may differ from the wave (or phase) speed. This possibility has been discussed elsewhere [9] in relation to the interpretation of the Fizeau experiment. A clear-cut way to clarify this important point is to perform measurements of the time of flight of photons in moving media to assure the correspondence foreseen by special relativity between phase velocity and photon velocity.

If we suppose in the following that the phase and particle velocities of light coincide in moving media, we can then explore possible modifications of the present Fresnel-Fizeau momentum when the moving medium is composed of rarefied gas. In effects of the AB type the flow $\mathbf{v}$ has an em origin and is determined by the interaction em momentum $\mathbf{Q}$. It is the em interaction that characterizes the flow $\mathbf{Q} \div \mathbf{v}$ and the corresponding "ether dragging". Depending on the properties of the interaction fields, the velocity of the particles through the medium may or may not be affected. For example, in the magnetic AB effect the speed of particles is not affected by the em flow. Analogously, also in the case of light propagation it is the interaction fields that characterize the flow $\mathbf{Q} \div \mathbf{v}$ and the corresponding ether dragging, so that the velocity of photons through a moving medium will be affected to a degree that depends on the various properties of the interaction fields, such as the intensity and relative spatial extension over the total volume, both of which are measures of the effective local interaction em energy and momentum. The speed of light c/n in a medium is proportionally related to the total em momentum [20] which is the volume integral (8) of the momentum density. The fields $\mathbf{E}$, $\mathbf{B}$, $\mathbf{D}$, and $\mathbf{H}$ that appear in the em momentum extend over the total volume V of the medium where light propagates. Instead, the Fresnel-Fizeau term $\mathbf{Q}(\mathbf{v})$ is related to the integral of the interaction em momentum density over the volume V_i which stands for the region of space where the interaction fields, such as the polarization fields of the molecules, extend.

It is worth emphasizing that the mechanism proposed here is far more general than Fresnel's drag and it may be misleading to use the expression "ether drag". Therefore, one should perhaps use the expression "drag-like" or "light delay" to refer to this phenomenon.

It is not completely unconceivable to suppose that the effectiveness of the light delay mechanism in a compact moving medium differs, and perhaps even substantially so, from that of a non-compact moving medium, such as a rarefied gas, even if they have the same index n. In a compact medium the polarizable molecules interact and form bonds, and the velocity-dependent em fields induced on a moving molecule influence the nearby molecules. It is likely that the effectiveness of the drag-like phenomenon may in part be due to a collective effect of the fields of the interacting, polarized moving molecules. If one visualizes these fields, in a compact medium the field lines form a thick net comoving with the polarized molecules. Light propagates through and within this net and its motion affects the light velocity. For a moving compact medium, the interaction fields that depend on the flow $\mathbf{v}$ and contribute to the Fresnel-Fizeau momentum $\mathbf{Q}(\mathbf{v})$, occupy the whole available volume and we have $V_i \simeq V$. However, in a rarefied gas the molecules do not interact much and the em fields of the light wave act locally on the molecule whose polarization and the $\mathbf{v}$-dependent interaction fields do not overlap significantly. The effectiveness of the drag-like effect due to the moving net of polarization field lines could be reduced in this case.

It may be objected that the value of the speed of light in different moving media is already factored in by the value of the refractive index n so that the dragging, or light delay, would be the same for a compact solid/fluid or a rarefied gas. This could be true for a medium at rest, where n represents its average refractive properties and where the total em momentum determining the speed c/n spans the total volume V, which is the same for both compact and rarefied media. However, as shown in (2) and (9), the functional dependence on n of $\mathbf{Q}(\mathbf{v})$ (proportional to $n^2 - 1$) differs from that of the total em momentum (proportional to $1/n$). In a moving medium, even if n were the same for both compact and rarefied media, the $\mathbf{v}$-dependent polarization fields responsible for the light delay differ from those of a medium at rest and, moreover, extend over the volume $V_i \simeq V$ for a compact medium, but only over the volume $V_i < V$ for a rarefied medium. Since the Fresnel-Fizeau interaction momentum $\mathbf{Q}(\mathbf{v})$ is effective over the volume V_i only, the drag-like effect could be different for the two different media.

Fresnel derived the historical dragging coefficient, $f = 1 - 1/n^2$, assuming that the speed of light in a refractive medium is related to the density of the ether in that medium. It has been shown that the coefficient f is accounted for by the expression (9) of $\mathbf{Q}(\mathbf{v})$. As an ad hoc hypothesis or tentative model of the light delay mechanism, we suppose now that its effectiveness e_f arises from the relative spatial extension V_i of the interaction em momentum $\mathbf{Q}(\mathbf{v})$ with respect to the extension V of the total em momentum. We then introduce the ratio $e_f = V_i/V$, where the volume V_i can be calculated by determining the region of space over which the interaction fields due to polarization extend, that is, the region of space wherein there is a non-zero energy density due to polarization, while the total volume V corresponds to the whole region of space over which the effective fields of the propagating light wave extend. The effective em interaction momentum, to be used in determining the speed of light in moving media, will be assumed to be given by the effective Fresnel-Fizeau term

$$e_f\,\mathbf{Q} = (V_i/V)\,\mathbf{Q}.$$

These arguments, which might partly justify the assumption of Consoli et al. on the speed of light in moving

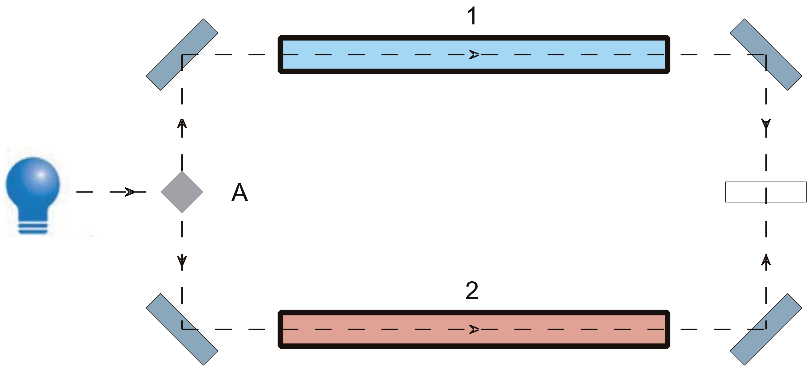

Fig. 1. Scheme of the optical experiment.

rarefied gases, are based mainly on the established relation between the Fresnel-Fizeau term $\mathbf{Q}$ and the em momentum of interaction fields and are being proposed in the context of standard electromagnetism. However, it is worth recalling that other arguments and approaches outside of classical electrodynamics also suggest the validity of this assumption [22]. As mentioned by Consoli and Costanzo one argument is based on the presence of ingredients that are often found in present-day elementary particle physics, namely: (a) vacuum condensation, as with the Higgs field in the electroweak theory, and (b) an approximate form of locality, as with cutoff-dependent, effective quantum field theories [23]. The resulting picture is closer to a medium with a non-trivial refractive index [22] than to the empty space-time of special relativity.

The tentative and untested model based on the em interaction momentum here proposed foresees that the velocity of light in moving rarefied media is

$$\mathbf{c}_R(n, \mathbf{v}) = \frac{c}{n}\widehat{\mathbf{c}} - \frac{c^2}{n^2\omega} e_f \, \mathbf{Q} = \frac{c}{n}\widehat{\mathbf{c}} + e_f \left(1 - \frac{1}{n^2}\right) \mathbf{v}, \quad (10)$$

that coincides with equation (3). The hypothesis of Consoli of the speed $\mathbf{c}_R(n) \simeq c/n$ in the preferred frame for moving rarefied gases, will be justified for our model if $e_f = V_i/V$ turns out to be very small and negligible in this case. Let us provide a rough estimate of V_i/V for air at room temperature. Supposing that an average air molecule has spherical shape and possesses a radius a, and that the external effective fields of the light wave are uniform and extend over the volume V, the interaction momentum is given by terms such as $\int_{Vi} E_{i\,pol}\, d^3x$ (i.e., proportional to the volume integral) where $E_{i\,pol}$ is the interaction field of the polarized molecule localized in the volume V_i of the molecule. Assuming uniform polarization we have $\int_{Vi} E_{i\,pol}\, d^3x = E_{i\,pol}\, V_i = E_{i\,pol}(4\pi/3)a^3$ so that $V_i/V = (a/R)^3$ where R is the size of the medium where light propagates. However, the polarization field is not limited to the size a of the molecule. The field of a polarized molecule possessing dipole moment $\mathbf{p}$ is $\mathbf{E}_{i\,pol} = [3\mathbf{n}(\mathbf{p}\cdot\mathbf{n}) - \mathbf{p}]/x^3$. The volume integral of all the components of $\mathbf{E}_{i\,pol}$ vanishes except for the term $\mathbf{p}/x^3$. Writing $E_{i\,pol} = p/r^3 = E_i a^3/r^3$ we see that the $1/r^3$ dependence increases the effectiveness of the interaction momentum because the interaction does not vanish completely outside the volume of the molecule. The extra contribution is $\int E_{i\,pol}\, d^3x = \int_a^R E_i\,(a^3/r^3)r^2\, dr = E_i\, a^3 \ln(R/a)$ which, with N_a the air concentration of molecules, implies

$$e_f = \frac{V_i}{V} = N_a \frac{a^3}{R^3}\left[1 + (3/4\pi)\ln(R/a)\right] \quad (11)$$

to be used in (10).

To compute e_f in the case of air, we take $N_a \simeq 10^{25}$ m^{-3} for the number density or concentration of air molecules at sea level and at $T_a \simeq 300$ K. Air is composed mainly by nitrogen and oxygen molecules. From Chemistry WebElements Periodic Table we find: N: covalent radius 75 pm, Van der Waals radius 152 pm; O: covalent radius 70 pm, Van der Waals radius 149 pm. For light propagating in a unit volume of air, assuming an average molecular size $a = 300$ pm $= 300 \times 10^{-12}$ m we have $a/R = 300 \times 10^{-12}$ and from (11), $e_f = N_a(a^3/R^3)\,22.9 = 6.1 \times 10^{-3}$, which can be neglected.

Thus, our model foresees that the speed of light $\mathbf{c}_R(n, \mathbf{v})$ in rarefied moving media depends on $\mathbf{v}$ and is actually not c/n but, quantitatively, the changes found do not alter significantly the basic hypothesis $c_R(n) \simeq c/n$ and the resulting analysis by Consoli and Costanzo [5,10] and de Abreu and Guerra [3,4].

5 Optical test in the first order in v/c

At the time it was formulated, Fresnel's theory was able to explain the null result of ether drift experiments that were attempting to detect the ether wind to first order in v/c. With the present hypothesis of a negligible drag-like effect for moving rarefied gases, ether drift experiments of the order v/c become meaningful again. Let us consider for example the following experiment which is a variant of the Mascart and Jamin experiment of 1874 [16].

A ray of light is split into two rays at A, which then propagate separately through the arms 1 and 2 of the interferometer which is moving with velocity $\mathbf{v}$ with respect to the preferred frame. The rays recombine at B where the interference pattern is observed. The arms 1 and 2 are made of a transparent rarefied gas or material with indices of refraction n_1 and n_2 (see Fig. 1).

(a) First we recover the null-result prediction of special relativity (or equivalent preferred frame theories based on the Tangherlini transformations). One could use the expressions for the speed in moving frames resulting from the Tangherlini transformation (1), which can be found also in [3,6]. Alternatively, the calculation can be done using the standard velocity addition from the Lorentz transformation, i.e., using the definition of *Einstein speed* as detailed in [3]. In the preferred frame, the light speeds in the arms are $\mathbf{c}(n_1)$ and $\mathbf{c}(n_2)$, as given by (2). The speed of light in arm 1 in the frame of the interferometer, moving with speed v with respect to the preferred frame, is for Tangherlini and Lorentz, respectively,

$$w_{1T} = \frac{c(n_1) - v}{1 - v^2/c^2} \simeq \frac{c}{n_1} - \frac{v}{n_1^2}, \quad \text{or} \quad w_{1L} = \frac{c(n_1) - v}{1 - v/(c\,n_1)} \simeq \frac{c}{n_1}, \tag{12}$$

where for $c(n_1)$ we have used (2), and analogously for w_2. The speeds w_{1T} and w_{1L} differ because the one-way speed is undetermined. However, the final observable result is the same for both transformations. Choosing either w_{1T} or w_{1L}, if L is the length of the arms, the time delay, or optical path difference, for the two rays yields, to first order in v/c,

$$\Delta t(0^o) = L\left(\frac{1}{w_1} - \frac{1}{w_2}\right) \simeq \frac{L}{c}(n_1 - n_2)$$

that does not depend on v. To observe a fringe shift, the interferometer needs to be rotated, typically by 90 or 180 degrees. The time delay for 180 degrees, $\Delta t(180°)$, is the same as $\Delta t(0°)$ with v replaced by $-v$. Since the time delay does not depend on v, the final observable result $\Delta t(0°) - \Delta t(180°)$ is a null result, and this is what special relativity (or equivalent preferred frame theories based on the Tangherlini transformations) foresees.

(b) Let us now check the result of this experiment assuming the light speed (3), according to Consoli's model. In the preferred frame, the light speeds in the arms are $\mathbf{c}_R(n_1) \simeq c/n_1$ and $\mathbf{c}_R(n_2) \simeq c/n_2$, respectively. The speed of light in arm 1 in the frame of the interferometer is now

$$w_{1T} = \frac{c_R(n_1) - v}{1 - v^2/c^2} \quad \text{or} \quad w_{1L} = \frac{c_R(n_1) - v}{1 - v/(c\,n_1)}, \tag{13}$$

where we may take $c_R(n_1) \simeq c/n_1$. In this case, the time delay yields, to first order in v/c,

$$\Delta t(0°) = L\left(\frac{1}{w_1} - \frac{1}{w_2}\right) \simeq \frac{L}{c}(n_1 - n_2)\left[1 + \frac{v}{c}(n_1 + n_2)\right]. \tag{14}$$

The time delay for 180 degrees is the same as that of equation (14) with v replaced by $-v$. The observable fringe shift upon rotation of the interferometer does not vanish to first order in v/c and it is related to the time delay variation

$$\delta t = \Delta t(0°) - \Delta t(180°) \simeq 2\frac{v}{c}(n_1^2 - n_2^2)\frac{L}{c}. \tag{15}$$

Therefore, for our experiment of the Mascart-Jamin type Consoli's model for light propagation in moving rarefied media leads to a nonnull result, that obviously differs from the prediction of special relativity because of the respective different propagation assumptions (3) and (2).

Choosing two media with different refractive index such that $n_1^2 - n_2^2$ is not too small ($>10^{-3}$), the resulting fringe shift should be easily observable if the preferred frame exists and its speed v is not too small. Knowing the sensitivity of the apparatus, one could set the lower limit of the observable preferred speed v. Standard interferometers, used in the Michelson-Morley type of experiments, could detect a speed v as small as 1 km/s. Thus, this optical experiment, in passing from second order (v^2/c^2) to first order tests, should be able to improve the range of detectability of v by a factor $(c/v)(n_1^2 - n_2^2) \simeq 3 \times 10^5 \times 10^{-3} = 3 \times 10^2$, i.e., detect with the same interferometer speeds as small as $(3 \times 10^2)^{-1}$ km/s $= 3.3$ m/s. The same improvement applies to a more sensitive interferometer or apparatus, such as the one used in maser tests.

The advantage of the modified Fizeau experiment proposed by Guerra and de Abreu [4] over experiments of the Michelson-Morley type as considered by Consoli and Costanzo [5], is that it is an experiment of the order v/c. Nevertheless, the feasibility and sensitivity of both experiments can be relatively similar [22], as the former one has to *reject* detection in order to prove a null result. The advantage of the present experiment over that proposed by de Abreu and Guerra is that one does not require a moving fluid, and it is thus easier to perform.

6 Conclusions

The outcome of historical optical tests have been discussed and interpreted in a great variety of contexts and models, mostly within classical ether theories that range, for example, from the preferred frame where Maxwell's equation are valid, to the Stokes-Planck ether dragged locally by massive bodies [24]. In the present paper we have considered light propagation in slowly moving rarefied media within a more limited scenario that essentially entails two different basic models:

(a) special relativity (or equivalent preferred frame theories based on Tangherlini's transformations) with the corresponding expression for the light speed $c(n)$ (2), valid for any type of media, compact or rarefied;

b) Consoli's assumption $c_R(n) \simeq c/n$, supported by the modified light speed expression $c_R(n)$ (3) that contains the coefficient e_f. Consoli's hypothesis is valid for rarefied media only.

In recalling the properties of matter and light wave propagation, we have pointed out that the interaction momentum $\mathbf{Q}$ appearing in the effects of the AB type and in the description of light propagation in moving media, possesses the same physical origin, i.e., is given by the variation of the momentum of the interaction em fields $\mathbf{P}_e$. Furthermore, we have emphasized that, even assuming that the particle and wave velocities coincide, it is conceivable to expect that the effectiveness e_f of the light delay mechanism in a rarefied gas differs from that of a compact transparent fluid or solid. On the basis that the Fresnel-Fizeau term $\mathbf{Q}(\mathbf{v})$ is given by the polarization interaction em momentum evaluated over the volume V_i spanned by the polarization fields, and under the assumption of an ether with non-trivial refractive index, we have introduced the tentative hypothesis that the effective interaction em momentum is $e_f\,\mathbf{Q} = (V_i/V)\,\mathbf{Q}$ where the volume V corresponds to the case of a compact medium. Thus, e_f is nearly zero for rarefied media, and $e_f = 1$ for compact media.

This tentative model of light propagation lends quantitative support to the analysis made by Consoli and Costanzo [5] and Guerra and de Abreu [4]. With Consoli's $c_R(n) \simeq c/n$ hypothesis for rarefied moving media, optical experiments of first order in v/c now yield non-null results. Thus, as a test of Consoli's assumption for the speed of light and the preferred frame velocity, we propose a first order optical test that is a variant of the historical Mascart-Jamin experiment.

Regardless of the polemical aspects involved, our considerations of wave propagation and the simple optical test proposed could be useful for future studies of light propagation in moving rarefied media.

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References

1. J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Univ. Press, Cambridge, 1988); C. Leubner, K. Aufinger, P. Krumm, Eur. J. Phys. **13**, 170 (1992)
2. F. Selleri, Found. Phys. **26**, 641 (1996); F. Selleri, Found. Phys. Lett. **18**, 325 (2005)
3. R. de Abreu, V. Guerra, *Relativity–Einstein's Lost Frame*, 1st edn. (Extramuros, Lisboa, 2005); V. Guerra, R. de Abreu, Found. Phys. **36**, 1826 (2006)
4. V. Guerra and R. de Abreu, Phys. Lett. A **361**, 509 (2007)
5. M. Consoli, E. Costanzo, Phys. Lett. A **333**, 355 (2004)
6. F.R. Tangherlini, Supp. Nuovo Cim. **20**, 1 (1961)
7. T. Sjodin, Nuovo Cim. B **51**, 299 (1979); T. Sjodin, M.F. Podlaha, Lett. Nuovo Cim. **31**, 433 (1982); R. Mansouri, R.V. Sexl, Gen. Rel. Grav. **8**, 497, Gen. Rel. Grav. **8**, 515, Gen. Rel. Grav. **8**, 809 (1977)
8. G. Spavieri, G.T. Gillies, Nuovo Cim. B **118**, 205 (2003); G. Spavieri, L. Nieves, M. Rodriguez, G.T. Gillies, *Has the last word been said on Classical Electrodynamics?-New Horizons* (Rinton Press, USA, 2004), p. 255
9. G. Spavieri, G.T. Gillies, Chin. J. Phys. **45**, 12 (2007); G. Spavieri et al., in *Ether, Spacetime and Cosmology* (2008), in press
10. R.T. Cahill, K. Kitto, Apeiron **10**, 104 (2003); R.T. Cahill, Apeiron **11**, 53 (2004)
11. D.C. Miller, Rev. Mod. Phys. **5**, 203 (1933)
12. A.J. Fresnel, Ann. Chim. Phys. **9**, 57 (1818)
13. H. Fizeau, C. R. Acad. Sci. Paris **33**, 349 (1851)
14. J.H. Hannay, unpubl., Cambridge Univ. Hamilton prize essay (1976); R.J. Cook, H. Fearn, P.W. Milonni, Am. J. Phys. **63**, 705 (1995)
15. Y. Aharonov, D. Bohm, Phys. Rev. **115**, 485 (1959)
16. E. Mascart, J. Jamin, Ann. Éc. Norm. **3**, 336 (1874)
17. Y. Aharonov, A. Casher, Phys. Rev. Lett. **53**, 319 (1984); G. Spavieri, Phys. Rev. Lett. **81**, 1533 (1998); G. Spavieri, Phys. Rev. A **59**, 3194 (1999); M. Wilkens, Phys. Rev. Lett. **72**, 5 (1994); V.M. Tkachuk, Phys. Rev. A **62**, 052112-1 (2000)
18. G. Spavieri, Phys. Rev. Lett. **82**, 3932 (1999); G. Spavieri, Phys. Lett. A **310**, 13 (2003); G. Spavieri, Eur. Phys. J. D **37**, 327 (2006)
19. W.K.H. Panofsky, M. Phillips, *Classical Electricity and Magnetism*, 2nd edn. (Addison-Wesley, Reading, 1962), Sect. II-5
20. G. Spavieri, Eur. Phys. J. D **39**, 157 (2006)
21. T.H. Boyer, Phys. Rev. D **8**, 1667 (1973); X. Zhu, W.C. Henneberger, J. Phys. A **23**, 3983 (1990); G. Spavieri, in Refs. [18]
22. M. Consoli, A. Pagano, L. Pappalardo, Phys. Lett. A **318**, 292 (2003); M. Consoli, Phys. Rev. D **65**, 105017 (2002); M. Consoli, Phys. Lett. B **541**, 307 (2002); M. Consoli, E. Costanzo, Phys. Lett. A **361**, 513 (2007)
23. G.E. Volovik, JETP Lett. **73**, 162 (2001)
24. G. Cavalleri, L. Galgani, G. Spavieri, G. Spinelli, Scientia. III **9-12**, 675 (1976)