Precision tests with a new class of dedicated ether-drift experiments

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Abstract

In principle, by accepting the idea of a non-zero vacuum energy, the physical vacuum of present particle physics might represent a preferred reference frame. By treating this quantum vacuum as a relativistic medium, the non-zero energy-momentum flow expected in a moving frame should effectively behave as a small thermal gradient and could, in principle, induce a measurable anisotropy of the speed of light in a loosely bound system as a gas. We explore the phenomenological implications of this scenario by considering a new class of dedicated ether-drift experiments where arbitrary gaseous media fill the resonating optical cavities. Our predictions cover most experimental set up and should motivate precise experimental tests of these fundamental issues.

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1. Introduction

The idea of a 'condensed vacuum' is generally accepted in modern elementary particle physics. Indeed, in many different contexts one introduces a set of elementary quanta whose perturbative empty vacuum state $|o\rangle$ is not the true ground state of the theory. For instance, in the physically relevant case of the Standard Model of electroweak interactions, the situation can be summarized by saying that "What we experience as empty space is nothing but the configuration of the Higgs field that has the lowest possible energy. If we move from field jargon to particle jargon, this means that empty space is actually filled with Higgs particles. They have Bose condensed" [1]. The translation from field jargon to particle jargon can be obtained, for instance, along the lines of Ref.[2] where the substantial equivalence between the effective potential of quantum field theory and the energy density of a dilute particle system was established.

For this reason, it becomes natural to ask [3] if Bose condensation, i.e. the spontaneous creation from the empty vacuum of elementary spinless quanta and their macroscopic occupation of the same quantum state, say $\mathbf{k} = 0$ in some reference frame Σ, might represent the operative construction of a "quantum ether". This would characterize the *physically realized* form of relativity and could play the role of preferred frame in a modern Lorentzian approach.

Usually this possibility is not considered with the motivation, perhaps, that the average properties of the condensed phase are summarized into a single quantity that transforms as a world scalar under the Lorentz group. For instance, in the Standard Model, the vacuum expectation value $\langle\Phi\rangle$ of the Higgs field.

However, this does not imply that the vacuum state itself has to be *Lorentz invariant*. Namely, Lorentz transformation operators $\hat{U}'$, $\hat{U}''$,..might transform non trivially the reference vacuum state $|\Psi^{(0)}\rangle$ (appropriate to an observer at rest in Σ) into $|\Psi'\rangle$, $|\Psi''\rangle$,.. (appropriate to moving observers S', S",..) and still, for any Lorentz-invariant operator $\hat{G}$, one would find

$$\langle\hat{G}\rangle_{\Psi^{(0)}} = \langle\hat{G}\rangle_{\Psi'} = \langle\hat{G}\rangle_{\Psi''} = .. \quad (1)$$

The possibility of a non-Lorentz-invariant vacuum state was addressed in Ref.[4] by considering two basically different approaches. In a first description, by following the axiomatic approach to quantum field theory [5], the vacuum is described as an eigenstate of the energy-momentum vector. Therefore, by observing that (with the exception of unbroken supersymmetries) there are no known interacting theories with a vanishing vacuum energy, and using the Poincaré algebra of the boost and energy-momentum operators, one deduces that the physical vacuum cannot be a Lorentz-invariant state and that, in any moving frame, there should be a non-zero vacuum spatial momentum $\langle \hat{P}_i \rangle_{\Psi'} \neq 0$ along the direction of motion. In this way, for a moving observer S' the physical vacuum would look like some kind of ethereal medium for which, in general, one can introduce a momentum density $\langle \hat{W}_{0i} \rangle_{\Psi'}$ through the relation (i=1,2,3)

$$\langle \hat{P}_i \rangle_{\Psi'} \equiv \int d^3x \ \langle \hat{W}_{0i} \rangle_{\Psi'} \neq 0 \tag{2}$$

On the other hand, in an alternative picture where one assumes the following form of the vacuum energy-momentum tensor [6, 7]

$$\langle \hat{W}_{\mu\nu} \rangle_{\Psi^{(0)}} = \rho_v \ \eta_{\mu\nu} \tag{3}$$

(ρ_v being a space-time independent constant and $\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$), one is driven to completely different conclusions. In fact, by introducing the Lorentz transformation matrices Λ^μ_ν to any moving frame S', defining $\langle \hat{W}_{\mu\nu} \rangle_{\Psi'}$ through the relation

$$\langle \hat{W}_{\mu\nu} \rangle_{\Psi'} = \Lambda^\sigma{}_\mu \Lambda^\rho{}_\nu \ \langle \hat{W}_{\sigma\rho} \rangle_{\Psi^{(0)}} \tag{4}$$

and using Eq.(3), it follows that the expectation value of $\hat{W}_{0i}$ in any boosted vacuum state $|\Psi'\rangle$ vanishes, just as it vanishes in $|\Psi^{(0)}\rangle$, i.e.

$$\int d^3x \ \langle \hat{W}_{0i} \rangle_{\Psi'} \equiv \langle \hat{P}_i \rangle_{\Psi'} = 0 \tag{5}$$

As discussed in Ref.[4], both approaches have their own good motivations and it is not so obvious to decide between Eq.(2) and Eq.(5) on pure theoretical grounds.

At the same time, checking the Lorentz invariance of the physical vacuum by an explicit microscopic calculation, in the realistic case of the Standard Model, seems to go beyond the present possibilities. To this end, in fact, one should construct the transformed vacuum state $|\Psi'\rangle$ by acting with the appropriate boost generator on the reference condensed vacuum state $|\Psi^{(0)}\rangle$. Even disposing, at least in the simplified case of spontaneous symmetry breaking in a pure scalar theory [8], of a non-perturbative ansatz for $|\Psi^{(0)}\rangle$, as a coherent state expressed in terms of the creation and annihilations operators $a^\dagger_{\mathbf{p}}$ and $a_{\mathbf{p}}$ of the trivial empty vacuum state $|o\rangle$, one is faced with a serious problem: the standard second-quantized form of the boost generators

$$\hat{M}_{0i} = i \int \frac{d^3\mathbf{p}}{(2\pi)^3} \ a^\dagger_{\mathbf{p}} \ \omega(\mathbf{p}) \frac{\partial}{\partial p_i} \ a_{\mathbf{p}} \tag{6}$$

is only valid for a free-field theory. For an interacting theory, the explicit construction of the boost generators is only known in perturbation theory (see e.g. [9, 10] and references quoted therein) and thus this type of approximation could hardly be trusted in the presence of non-perturbative phenomena such as vacuum condensation. In addition, even in perturbation theory, the elimination of ultraviolet divergences in global operators represents a delicate task so that only very simple theories or low-dimensionality cases have been worked out so far. For these reasons, deciding on the Lorentz-invariance of the condensed vacuum of present particle physics represents a highly non-trivial problem.

Alternatively, one might argue that a satisfactory solution of the vacuum-energy problem lies definitely beyond flat space. A non-zero ρ_v, in fact, will induce a cosmological term in Einstein's field equations and a non-vanishing space-time curvature which anyhow dynamically breaks global Lorentz symmetry.

Nevertheless, in our opinion, in the absence of a consistent quantum theory of gravity, physical models of the vacuum in flat space can be useful to clarify a crucial point that, so far, remains obscure: the huge renormalization effect that is seen when comparing the typical vacuum-energy scales of modern particle physics with the experimental value of the cosmological term needed in Einstein's equations to fit the observations. For instance, the picture of the vacuum as a superfluid explains in a natural way why there might be no non-trivial macroscopic curvature in the equilibrium state where any liquid is self-sustaining [11]. In this framework, the condensation energy of the medium plays no observable role so that the relevant curvature effects may be orders of magnitude smaller than those expected by solving Einstein's equations with the full $\langle \hat{W}_{\mu\nu} \rangle_{\Psi(0)}$ as a source term. In this perspective, "induced-gravity" [12] approaches, where gravity somehow arises from the excitations of the quantum vacuum itself, may become natural and, to find the appropriate form of the energy-momentum tensor in Einstein's equations, we are lead to sharpen our understanding of the vacuum structure and of its excitation mechanisms by starting from the physical picture of a superfluid medium.

By following this approach, in Ref.[4], to explore the possible effects of the energy-momentum flow expected in a moving frame according to Eq.(2), it was adopted a phenomenological two-fluid model in which the quantum vacuum, in addition to the main zero-entropy superfluid component, contains a small fraction of "normal" fluid. This is responsible for a non-zero $\langle \hat{W}_{0i} \rangle_{\Psi'}$ and gives rise to a small heat flow and to an effective thermal gradient

$$\frac{\partial T}{\partial x^i} \equiv -\frac{\langle W_{0i} \rangle_{\Psi'}}{\kappa_0} \tag{7}$$

Here κ_0 is an unknown parameter, introduced for dimensional reasons, that plays the role of thermal conductivity of the vacuum. Since its value is unknown, the effective thermal gradient is left as an entirely free quantity whose magnitude should be constrained by experiments.

In principle, this effective gradient could induce small convective currents in a loosely bound system as a gaseous medium (placed in a container at rest in the laboratory frame) and produce a slight anisotropy of the speed of light in the gas. On the other hand, for a strongly bound system, such as a solid or liquid transparent medium, the small energy flow generated by the motion with respect to the vacuum condensate should dissipate mainly by heat conduction with no particle flow and no light anisotropy in the rest frame of the medium, in agreement with the classical experiments in glass and water.

For this reason, one should design a new class of ether-drift experiments where two optical cavities are filled with a gas and study the frequency shift $\Delta\nu$ between the two resonators that gives a measure of the possible anisotropy of the two-way speed of light. Such a type of "non-vacuum" experiment would be along the lines of Ref.[13] where just the use of optical cavities filled with different materials was considered as a useful tool to study possible deviations from Lorentz invariance.

The aim of this paper is to give a set of precise predictions for this new class of ether-drift experiments. In Sect.2 we shall provide a definite model for the two-way speed of light. In Sect.3, we shall discuss various experimental set up and the expected form of the signal. Finally, in Sect.4 we shall present our summary and conclusions.

2. The two-way speed of light in a gaseous medium

Rigorous treatments of light propagation in dielectric media are based on the extinction theory [14]. This was originally formulated for continuous media where the interparticle distance is smaller than the light wavelength. In the opposite case of an isotropic, dilute random medium [15], it is relatively easy to compute the scattered wave in the forward direction and obtain the refractive index. However, if there are convective currents, taking into account the motion of the molecules that make up the gas is a non-trivial problem. If solved, one expects an angular dependence of the refractive index and an anisotropy of the phase speed of the refracted light.

This expectation derives from a much simpler, semi-quantitative approach where one introduces from scratch the refractive index $\mathcal{N}$ of the gas and the time t spent by refracted light to cover some given distance L within the medium. By assuming isotropy, one would find $t = \mathcal{N}L/c$. This can be expressed as the sum of $t_0 = L/c$ and $t_1 = (\mathcal{N} - 1)L/c$ where t_0 is the same time as in the vacuum and t_1 represents the additional, average time by which the refracted light is "slowed" down by the presence of matter. If there are convective currents, so that t_1 is different in different directions, one can deduce an anisotropy of the speed of light proportional to $(\mathcal{N} - 1)$. To see this, let us consider light propagating in a 2-dimensional plane and express t_1 as

$$t_1 = \frac{L}{c} f(\mathcal{N}, \theta, \beta) \tag{8}$$

with $\beta = V/c$, V being the velocity of the laboratory with respect to the preferred frame Σ where the isotropic form

$$f(\mathcal{N}, \theta, 0) = \mathcal{N} - 1 \tag{9}$$

is assumed. By expanding around $\mathcal{N} = 1$ where, whatever β, f vanishes by definition, one finds for gaseous systems (where $\mathcal{N} - 1 \ll 1$) the universal trend

$$f(\mathcal{N}, \theta, \beta) \sim (\mathcal{N} - 1) F(\theta, \beta) \tag{10}$$

with

$$F(\theta, \beta) \equiv (\partial f / \partial \mathcal{N})|_{\mathcal{N}=1} \tag{11}$$

and $F(\theta, 0) = 1$. Therefore, from

$$t(\mathcal{N}, \theta, \beta) = \frac{L}{c(\mathcal{N}, \theta, \beta)} \sim \frac{L}{c} + \frac{L}{c}(\mathcal{N} - 1)\ F(\theta, \beta) \tag{12}$$

one gets

$$c(\mathcal{N}, \theta, \beta) \sim \frac{c}{\mathcal{N}}\ [1 - (\mathcal{N} - 1)\ (F(\theta, \beta) - 1)] \tag{13}$$

Analogous relations hold for the two-way speed of light $\bar{c}(\mathcal{N}, \theta, \beta)$

$$\bar{c}(\mathcal{N}, \theta, \beta) = \frac{2\ c(\mathcal{N}, \theta, \beta) c(\mathcal{N}, \pi + \theta, \beta)}{c(\mathcal{N}, \theta, \beta) + c(\mathcal{N}, \pi + \theta, \beta)} \sim \frac{c}{\mathcal{N}} \left[1 - (\mathcal{N} - 1)\ \left(\frac{F(\theta, \beta) + F(\pi + \theta, \beta)}{2} - 1\right)\right] \tag{14}$$

that is commonly measured in optical resonators. In this case, one predicts a non-zero anisotropy

$$\frac{\Delta \bar{c}_\theta}{c} \equiv \frac{\bar{c}(\mathcal{N}, \pi/2, \beta) - \bar{c}(\mathcal{N}, 0, \beta)}{c} \sim (\mathcal{N} - 1)\ \frac{\Delta F}{2} \tag{15}$$

with $\Delta F = F(0, \beta) + F(\pi, \beta) - F(\pi/2, \beta) - F(3\pi/2, \beta)$ and the characteristic scaling law

$$\frac{\Delta \bar{c}_\theta(\mathcal{N})}{\Delta \bar{c}_\theta(\mathcal{N}')} \sim \frac{\mathcal{N} - 1}{\mathcal{N}' - 1} \tag{16}$$

More quantitative estimates can be obtained by exploring some general properties of the function $F(\theta, \beta)$. By expanding in powers of β

$$F(\theta, \beta) - 1 = \beta F_1(\theta) + \beta^2 F_2(\theta) + ... \tag{17}$$

and taking into account that, by the very definition of two-way speed, $\bar{c}(\mathcal{N}, \theta, \beta) = \bar{c}(\mathcal{N}, \theta, -\beta)$, it follows that $F_1(\theta) = -F_1(\pi + \theta)$. Therefore, we get the general structure of the two-way speed of light to $\mathcal{O}(\beta^2)$

$$\bar{c}(\mathcal{N}, \theta, \beta) \sim \frac{c}{\mathcal{N}} \left[1 - (\mathcal{N} - 1)\ \beta^2 \sum_{n=1}^{\infty} \zeta_{2n} P_{2n}(\cos\theta)\right] \tag{18}$$

in which we have expressed the combination $F_2(\theta) + F_2(\pi + \theta)$ as an infinite expansion of even-order Legendre polynomials with unknown coefficients $\zeta_{2n} = \mathcal{O}(1)$.

This general structure can be compared with the corresponding result [16] obtained by using Lorentz transformations to connect S' to the preferred frame

$$\bar{c}(\mathcal{N}, \theta, \beta) \sim \frac{c}{\mathcal{N}} \left[1 - \beta^2 \left(A + B \sin^2 \theta\right)\right] \tag{19}$$

with

$$A \sim 2(\mathcal{N} - 1) \qquad\qquad B \sim -3(\mathcal{N} - 1) \tag{20}$$

that corresponds to set in Eq.(18) $\zeta_2 = 2$ and all $\zeta_{2n} = 0$ for $n > 1$. Eqs.(19)-(20), that represent a definite realization of the general structure in (18), provide a partial answer to the problems posed by our limited knowledge of the electromagnetic properties of gaseous systems and will be adopted in the following as our basic model for the two-way speed of light.

Notice that Eqs.(19)-(20) lead to

$$\frac{\Delta \bar{c}_\theta(\mathcal{N})}{c} \sim 3(\mathcal{N} - 1)\, \frac{V^2}{c^2} \tag{21}$$

and thus Eq.(16) is identically satisfied. At the same time, one gets agreement with the pattern observed in the classical and modern ether-drift experiments, as illustrated in Refs.[16], that suggests (for gaseous media *only*) a relation of the type in Eq.(21). In fact, in the classical experiments performed in air at atmospheric pressure, where $\mathcal{N} \sim 1.000293$, the observed anisotropy was $\frac{\Delta \bar{c}_\theta}{c} \lesssim 10^{-9}$ thus providing a typical value $V/c \sim 10^{-3}$, as that associated with most cosmic motions. Analogously, in the classical experiments performed in helium at atmospheric pressure, where $\mathcal{N} \sim 1.000035$ (and in a modern experiment with He-Ne lasers where $\mathcal{N} \sim 1.00004$), the observed effect was $\frac{\Delta \bar{c}_\theta}{c} \lesssim 10^{-10}$ so that again $V/c \sim 10^{-3}$.

Notice also that, although originating from a different theoretical framework, Eq.(19) is formally analogous to the expression of the two-way speed of light in the RMS formalism [17, 18] where A and B are taken as free parameters.

One conceptual detail concerns the gas refractive index whose reported values are experimentally measured on the earth by two-way measurements. For instance for the air, the most precise determinations are at the level 10^{-7}, say $\mathcal{N}_{\rm air} = 1.0002926..$ for yellow light at STP (Standard Temperature and Pressure). By assuming a non-zero anisotropy in the earth's frame, one should interpret the isotropical value $c/\mathcal{N}_{\rm air}$ as an angular average of Eq.(19), i.e.

$$\frac{c}{\mathcal{N}_{\rm air}} \equiv \langle \bar{c}(\bar{\mathcal{N}}_{\rm air}, \theta, \beta) \rangle = \frac{c}{\bar{\mathcal{N}}_{\rm air}} \left[1 - \frac{1}{2}(\bar{\mathcal{N}}_{\rm air} - 1)\frac{V^2}{c^2}\right] \tag{22}$$

From this relation, one can determine the unknown value $\bar{\mathcal{N}}_{\rm air} \equiv \mathcal{N}(\Sigma)$ (as if the gas were at rest in Σ), in terms of the experimentally known quantity $\mathcal{N}_{\rm air} \equiv \mathcal{N}(earth)$ and of V. In practice, for the standard velocity values involved in most cosmic motions, say 200 km/s $\leq V \leq$ 400 km/s, the difference between $\mathcal{N}(\Sigma)$ and $\mathcal{N}(earth)$ is well below 10^{-9} and thus completely negligible. The same holds true for the other gaseous systems at STP (say nitrogen, carbon dioxide, helium,..) for which the present experimental accuracy in the refractive index is, at best, at the level 10^{-6}. Finally, the isotropic two-way speed of light is better determined in the low-pressure limit where $(\mathcal{N} - 1) \to 0$. In the same limit, for any given value of V, the approximation $\mathcal{N}(\Sigma) = \mathcal{N}(earth)$ becomes better and better.

3. Ether-drift experiments in gaseous media

From the point of view of ether-drift experiments, the crucial ingredient, that might indicate the existence of a preferred frame, consists in detecting the characteristic modulations of the signal due to the earth's rotation. Descriptions of this important effect are already available in the literature. For instance, within the SME model [19] the relevant formulas are given in the appendix of Ref.[20] and for the RMS test theory [17, 18] one can look at Ref.[21]. However, either due to the great number of free parameters (19 in the SME model) and/or to the restriction to a definite experimental set up, it is not always easy to adapt these papers to the actual conditions needed for our experimental test. For this reason, in the following, we will present a set of compact formulas that can be immediately used by the reader to evaluate the signal when two arbitrary gaseous media fill the resonating cavities. The formalism covers most experimental set up including the very recent type of experiment proposed in Ref.[22] to perform tests of the Standard Model.

The main point is that the earth's rotation enters only through two quantities, $v = v(t)$ and $\theta_0 = \theta_0(t)$, respectively the magnitude and the angle associated with the projection of the unknown cosmic earth's velocity $\mathbf{V}$ in the plane of the interferometer.

Once the angle θ_0 is conventionally defined when one of the arms of the interferometer is oriented to the North point in the laboratory (counting θ_0 from North through East so that North is $\theta_0 = 0$ and East is $\theta_0 = \pi/2$), we can immediately use the formulas given by Nassau and Morse [23]. These are valid for short-term observations, say 3-4 days, where there are no appreciable changes in the cosmic velocity due to changes in the earth's orbital velocity around the Sun and the only time dependence is due to the earth's rotation.

In this approximation, introducing the magnitude V of the full earth's velocity with respect to a hypothetic preferred frame Σ, its right ascension α and angular declination γ, we get

$$\cos z(t) = \sin\gamma \sin\phi + \cos\gamma \cos\phi \cos(\tau - \alpha) \tag{23}$$

$$\sin z(t) \cos\theta_0(t) = \sin\gamma \cos\phi - \cos\gamma \sin\phi \cos(\tau - \alpha) \tag{24}$$

$$\sin z(t) \sin\theta_0(t) = \cos\gamma \sin(\tau - \alpha) \tag{25}$$

$$v(t) = V \sin z(t), \tag{26}$$

Here $z = z(t)$ is the zenithal distance of $\mathbf{V}$. Namely, $z = 0$ corresponds to a $\mathbf{V}$ which is perpendicular to the plane of the interferometer and $z = \pi/2$ to a $\mathbf{V}$ that lies entirely in that plane. Further, ϕ is the latitude of the laboratory and $\tau = \omega_{\mathrm{sid}} t$ is the sidereal time of the observation in degrees ($\omega_{\mathrm{sid}} \sim \frac{2\pi}{23^h 56'}$).

Let us now consider two orthogonal cavities oriented for simplicity North-South (cavity 1) and East-West (cavity 2) in the laboratory frame. They are filled with two different gaseous media with refractive indices $\mathcal{N}_i$ (i=1,2) such that $\mathcal{N}_i = 1 + \epsilon_i$, and $0 \leq \epsilon_i \ll 1$. The frequency in each cavity is

$$\nu_i(\theta_i) = \bar{c}_i(\mathcal{N}_i, \theta_i, \beta) k_i \tag{27}$$

and the frequency shift is

$$\Delta\nu = \nu_1(\theta_1) - \nu_2(\theta_2) \tag{28}$$

In the above relations we have introduced the parameters k_i

$$k_i = \frac{m_i}{2L_i} \tag{29}$$

where m_i are integers fixing the cavity modes and L_i are the cavity lengths. Finally, θ_i is the angle between $\mathbf{V}$ and the axis of the i-th cavity and $\bar{c}_i(\mathcal{N}_i, \theta_i, \beta)$ denote the two-way speeds of light in (19).

We observe that, in the presence of an effective vacuum thermal gradient, one might also consider pure thermal conduction effects in the solid parts of the apparatus. Even by using cavities with an ultra-low thermal expansion coefficient, these conduction effects could induce tiny differences of the cavity lengths (and thus of the cavity frequencies) upon active rotations of the apparatus or under the earth's rotation. However, this effect does not depend on the gas that fills the cavity and therefore can be preliminarily evaluated and subtracted out by first running the experiment in the vacuum mode, i.e. at the same room temperature but when no gas is present inside the cavities. The precise experimental limits of Ref.[24] (obtained with vacuum cavities at room temperature) show that any such effect can be reduced to the level $10^{-15} - 10^{-16}$ and thus would be irrelevant for our purpose. In fact, as we shall show in a moment, the typical magnitudes of the signal, expected by running the experiments in the gaseous mode, should be larger by 4-5 orders of magnitude.

By introducing the unit vectors $\hat{\mathbf{n}}_i$ that fix the direction of the two cavities and the projection $\mathbf{v}$ of the full $\mathbf{V}$ in the interferometer's plane, one finds

$$V^2 \sin^2\theta_i = V^2(1-\cos^2\theta_i) = V^2 - (\hat{\mathbf{n}}_i \cdot \mathbf{v})^2 \tag{30}$$

so that ($v = |\mathbf{v}|$)

$$V^2 \sin^2\theta_1 = V^2 - v^2\cos^2\theta_0 \tag{31}$$

and

$$V^2 \sin^2\theta_2 = V^2 - v^2\sin^2\theta_0 \tag{32}$$

Therefore, by defining the reference frequency $\nu_0 = \frac{ck_1}{\mathcal{N}_1}$ and introducing the parameter ξ through

$$\xi = \frac{\mathcal{N}_1 k_2}{\mathcal{N}_2 k_1} \tag{33}$$

one finds the relative frequency shift

$$\frac{\Delta\nu(t)}{\nu_0} = 1 - \xi + \frac{V^2}{c^2}[\xi(A_2+B_2) - (A_1+B_1)] + \frac{v^2(t)}{c^2}[B_1\cos^2\theta_0(t) - \xi B_2 \sin^2\theta_0(t)] \tag{34}$$

For a symmetric apparatus where $\mathcal{N}_1 = \mathcal{N}_2$, $A_1 = A_2$, $B_1 = B_2 = B$ and $\xi = 1$, one finds

$$\frac{\Delta\nu(t)_{\rm symm}}{\nu_0} = B\frac{v^2(t)}{c^2}\cos 2\theta_0(t) \tag{35}$$

On the other hand for a non-symmetric apparatus of the type considered in Ref.[22] with $L_1 = L_2 = L$, but where one can conveniently arrange $\mathcal{N}_1 = 1$ (up to negligible terms) so that $A_1 \sim B_1 \sim 0$, denoting $\mathcal{N}_2 = \mathcal{N}$, $A_2 = A$, $B_2 = B$, $\frac{m_2}{m_1} = \mathcal{P}$, we find

$$\frac{\Delta\nu(t)}{\nu_0} = 1 - \frac{\mathcal{P}}{\mathcal{N}} + \frac{\mathcal{P}}{\mathcal{N}}\frac{V^2}{c^2}(A+B) - B\frac{\mathcal{P}}{\mathcal{N}}\frac{v^2(t)}{c^2}\sin^2\theta_0(t) \tag{36}$$

To consider experiments where one or both resonators are placed in a state of active rotation (at a frequency $\omega_{\rm rot} \gg \omega_{\rm sid}$), it is convenient to modify Eq.(34) by rotating the resonator 1 by an angle δ_1 and the resonator 2 by an angle δ_2 so that the last term in Eq.(34) becomes

$$\frac{v^2(t)}{c^2}[B_1\cos^2(\delta_1 - \theta_0(t)) - \xi B_2 \sin^2(\delta_2 - \theta_0(t))] \tag{37}$$

Therefore, in a fully symmetric apparatus where $\mathcal{N}_1 = \mathcal{N}_2$, $A_1 = A_2$, $B_1 = B_2 = B$ and $\xi = 1$ and both resonators rotate, as in Ref.[25], setting

$$\delta_1 = \delta_2 = \omega_{\rm rot} t \tag{38}$$

one obtains

$$\frac{\Delta\nu(t)_{\rm symm}}{\nu_0} = B\frac{v^2(t)}{c^2}\cos 2(\omega_{\rm rot}t - \theta_0(t)) \tag{39}$$

On the other hand, if only one resonator rotates, as in Ref.[24], setting $\delta_1 = 0$ and $\delta_2 = \omega_{\rm rot}t$ one obtains the alternative result

$$\frac{\Delta\nu(t)}{\nu_0} = B\frac{v^2(t)}{2c^2}[\cos 2\theta_0(t) + \cos 2(\omega_{\rm rot}t - \theta_0(t))] \tag{40}$$

By first filtering the signal at the frequency $\omega = \omega_{\rm rot} \gg \omega_{\rm sid}$, the main difference between the two expressions is an overall factor of two.

Let us now return to the general case of a non-rotating set up Eq.(34). Using Eqs.(23)-(26) we obtain the simple Fourier expansion

$$\frac{\Delta\nu(t)}{\nu_0} = 1 - \xi + (g_0 + g_1\sin\tau + g_2\cos\tau + g_3\sin 2\tau + g_4\cos 2\tau) \tag{41}$$

where

$$g_0 = \frac{V^2}{c^2}[\xi(A_2 + B_2) - (A_1 + B_1) + B_1(\sin^2\gamma\cos^2\phi + \frac{1}{2}\cos^2\gamma\sin^2\phi) - \frac{1}{2}\xi B_2\cos^2\gamma] \tag{42}$$

$$g_1 = -\frac{1}{2}\frac{V^2}{c^2}B_1\sin 2\gamma\sin 2\phi\sin\alpha \qquad g_2 = -\frac{1}{2}\frac{V^2}{c^2}B_1\sin 2\gamma\sin 2\phi\cos\alpha \tag{43}$$

$$g_3 = \frac{1}{2}\frac{V^2}{c^2}(B_1\sin^2\phi + \xi B_2)\cos^2\gamma\sin 2\alpha \qquad g_4 = \frac{1}{2}\frac{V^2}{c^2}(B_1\sin^2\phi + \xi B_2)\cos^2\gamma\cos 2\alpha \tag{44}$$

Since the mean signal is most likely affected by systematic effects, one usually concentrates on the daily modulation. In this case, assuming that g_1, g_2, g_3 and g_4 can be extracted to good accuracy from the experimental data, one can try to obtain a pair of angular variables through the two independent determinations of α

$$\tan\alpha = \frac{g_1}{g_2} \qquad \tan 2\alpha = \frac{g_3}{g_4} \tag{45}$$

and the relation

$$\tan|\gamma| = \frac{|B_1\sin^2\phi + \xi B_2|}{|2B_1\sin 2\phi|}\sqrt{\frac{g_1^2 + g_2^2}{g_3^2 + g_4^2}} \tag{46}$$

Notice that Eqs.(42)-(44) remain unchanged under the replacement $(\alpha, \gamma) \to (\alpha + \pi, -\gamma)$. Also, two dynamical models that predict the same anisotropy parameters up to an overall re-scaling $B_i \to \lambda B_i$ would produce the same $|\gamma|$ from the experimental data.

Finally for a symmetric apparatus, where $B_1 = B_2 = B$ and $\xi = 1$, one obtains the simpler relation

$$\tan|\gamma| = \frac{1 + \sin^2\phi}{|2\sin 2\phi|}\sqrt{\frac{g_1^2 + g_2^2}{g_3^2 + g_4^2}} \tag{47}$$

where any reference to the anisotropy parameters drops out.

To obtain some order of magnitude estimate, let us consider the amplitude of the modulation of the signal at the sidereal frequency for a typical latitude of the laboratory $|\phi| \sim 45^o$. This is given by

$$g_{\omega_{\rm sid}} = \sqrt{g_1^2 + g_2^2} = \frac{1}{2}\frac{V^2}{c^2}\ |B_1 \sin 2\gamma| \tag{48}$$

By assuming the cavity 1 to be filled with carbon dioxide (whose refractive index at atmospheric pressure is $\mathcal{N}_1 \sim 1.00045$) and the typical value $\frac{V^2}{c^2} \sim 10^{-6}$ (associated with most cosmic motions) one expects a typical modulation of the relative frequency shift $g_{\omega_{\rm sid}} \sim 10^{-10}$. Analogously, for helium at atmospheric pressure (where $\mathcal{N}_1 \sim 1.000035$) one expects $g_{\omega_{\rm sid}} \sim 10^{-11}$. As anticipated, these values would be $4-5$ orders of magnitude larger than the limit $10^{-15} - 10^{-16}$ placed by the present ether-drift experiments in vacuum.

4. Summary and conclusions

In principle, on the basis of very general arguments related to a non-zero vacuum energy, the physical condensed vacuum of present particle physics might represent a preferred reference frame. In this case, in any moving frame there might be a non-zero vacuum energy-momentum flow along the direction of motion. By treating the quantum vacuum as a relativistic medium, this non-zero energy-momentum flow should behave as an effective thermal gradient. As such, it could induce small convective currents in a loosely bound system as a gas and an anisotropy of the speed of light.

For this reason, we have considered in this paper a new class of ether-drift experiments in which optical resonators are filled by gaseous media. The existence of convective currents leads to the general structure of the two-way speed in Eq.(18) that admits Eqs.(19)-(20) as a special case.

In this particular limit, by using the basic relations (23)-(26) to take into account the effect of the earth's rotation, we have derived a set of definite predictions that cover most experimental set up. For the typical velocities involved in most cosmic motions, the expected relative frequency shift between the two resonators should be about $4-5$ orders of magnitude larger than the limit $10^{-15} - 10^{-16}$ placed by the present ether-drift experiments in vacuum.

We want to emphasize that, due to the limited precision characterizing our knowledge of the electromagnetic properties of gaseous media, that forces us to restrict to relations (19)-(20) for the two-way speed, we cannot exclude the existence of other competing mechanisms that, while physically different from our proposed drift of the vacuum energy, may simulate the same effects. For instance, a similar direction dependence of the refractive index might also be introduced if the molecules in the gas exhibit no net motion but instead a suitable non-isotropic local interaction of the incoming radiation with the medium is introduced, for instance within the more general framework of the SME model [19]. In this case, there might be non-equivalent ways to obtain the same characteristic experimental signatures.

Still, we believe that our picture of light anisotropy, as arising from the convective currents that can be established in dilute systems, provides a simple theoretical framework to understand why Eq.(21), while being consistent with the pattern observed in gaseous systems, does *not* apply to Michelson-Morley experiments performed in solid transparent media [26] as perspex (where $\mathcal{N} \sim 1.5$).

In any case, exploring the class of scenarios consistent with Eqs.(19)-(20) leads to consider the following experimental checks:

i) for a symmetric apparatus one should try to extract from the data the product $H = B\frac{V^2}{c^2}$ and, by using Eqs.(45) and (47), two pairs of conjugate angular variables (α, γ) $(\alpha + \pi, -\gamma)$. Also, by suitably changing the gaseous medium (and its pressure) within the cavities, one should try to check the precise trend predicted in Eqs.(16) and (20), namely

$$\frac{H'}{H''} \sim \frac{\mathcal{N}' - 1}{\mathcal{N}'' - 1} \tag{49}$$

ii) for a non-symmetric apparatus of the type proposed in Ref.[22], where one can conveniently fix the cavity oriented North-South to have $\mathcal{N}_1 = 1$ (up to negligible terms), by using Eqs.(20) one predicts $B_1 \sim 0$ in Eqs.(43) and (44) so that all time dependence should be due to B_2. Thus the modulation of the signal should be a pure $\omega = 2\omega_{\rm sid}$ effect with no appreciable contribution at $\omega = \omega_{\rm sid}$

iii) for a deeper analysis, one should keep in mind that, in each single session, the direction (α, γ) cannot be distinguished from the opposite direction $(\alpha + \pi, -\gamma)$. For this reason, a whole set j=1,2..M of short-term experimental sessions should be performed in different periods along the earth's orbit to obtain an overall consistency check. Notice that, for a complete description of the observations over a one-year period, it is not necessary to modify the simple formulas Eqs.(42)-(44) and introduce explicitly the further modulations associated with the orbital frequency $\Omega_{\rm orb} \sim \frac{2\pi}{1 \text{ year}}$. Rather, by plotting on the celestial sphere all directions defined by the (α_j, γ_j) pairs obtained in the various short-term observations, one can try to reconstruct the earth's "aberration circle". If this will show up, by using the formulas of the spherical triangles, one will be able to determine the mean cosmic velocity $\langle V \rangle$ from the angular opening of the circle and the known value of the earth's orbital velocity

~ 30 km/s. In this way, given the value of $\langle H \rangle$, one will be able to disentangle $\langle V \rangle$ from B and estimate the absolute magnitude of the anisotropy parameter.

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