# Does a possible laboratory observation of a frequency anisotropy of light result from a non-zero photon mass $m$?

J.V. Narlikar [1]
*Tata Institute of Fundamental Research, Bombay, India*

J.C. Pecker
*Collège de France, Paris, France*

and

J.P. Vigier
*Institut Henri Poincaré, Paris, France*

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Assuming a priori the existence of a non-zero photon rest-mass $m_\gamma > 0$ and justifying this assumption, we can predict the existence of an anisotropy in velocity and frequency of light in the direction of the apex of the 3 K background cosmic radiation field. Since this frequency shift can now be tested in the laboratory, it is important to improve the precision of these measurements in order to check our predictions. Its possible confirmation implies indeed the definition of an absolute evolution parameter in the rest frame $\Sigma_0$ of this 3 K background microwave radiation.

## 1. Introduction. General relativity, isotropy of light velocity, and the rest-mass of photons

The isotropy of our universe and its homogeneity are the two components of the "cosmological principle". This principle has found a strong argument in the negative result of the Michelson–Morley experiment, which, according to the general opinion, is a proof of the *isotropy* of the velocity of light with respect to all possible inertial frames of reference, i.e. a straightforward consequence of the theory of special relativity.

But this is not so. An additional assumption is *necessary*, but indeed almost always *implicit*, i.e. that of the zero rest-mass of photons. We shall come back on it in the next section.

That very hypothesis was however, even for Einstein himself [1], contradictory with general relativity (GR). For him, the existence of a positive non-zero rest-mass for all particles (including photons and neutrinos) is indeed a consequence of GR. If we denote the Laplace–Beltrami operator by $(1/\sqrt{-g})\partial_\mu g^{\mu\nu}\partial_\nu$, one finds for the electromagnetic potential $A_\mu$ the relation $A_\mu + R_\mu{}^\nu A_\nu = 0$ which can be approximated by $A_\mu + R\delta_\mu{}^\nu A_\nu = 0$ and yields a lower limit $m^2c^2/h^2 \sim R > 0$ for all possible masses [1,2].

Bass and Schrödinger [3] and de Broglie [4] have adopted the same point of view. They have stressed that if the photon has a non-zero rest-mass $m_\gamma > 0$, its velocity $v_\gamma$ becomes frequency-dependent, according to the relation

$$E = h\nu = m_\gamma c^2 (1 - v_\gamma^2/c^2)^{-1/2} . \quad (1)$$

The value $c$ represents therefore only an upper limit (just like the zero "absolute" temperature), which can only be reached for infinite frequencies (or in-

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[1] Present address: International University Centre for Astronomy and Astrophysics, Post. Bag 4, Ganeshkhind, Pune 411007, India.

finite energies), but never effectively realized in nature.

The non-zero rest-mass of the photon is a property which leads to interesting consequences as noted in a set of slightly noticed papers. Deser [5] (but see also ref. [4]) has shown that one can construct a non-zero-mass quantum electrodynamics where one splits the corresponding e.m. waves of spin 1 into transverse ($J_3 = \pm 1$) and longitudinal ($J_3 = 0$) parts; the latter corresponds practically to a decoupled action-at-a-distance scalar Yukawa potential, replacing the Coulomb field: it would vanish for a zero rest-mass of the photon. Moreover, Molès and Vigier [6] have shown that for $m_\gamma$ small enough (observational constraints, according to Barnes and Seargle [7], limit it to $m_\gamma < 10^{-56}$ g) there is no observable contradiction with known quantum mechanical predictions, including Planck's spectral distribution. Theoretical attempts to relate $m_\gamma$ with the vacuum's dissipation processes, to interpret Hubble's constant (taken equal to $H \sim 100$ km s$^{-1}$ Mpc$^{-1}$) led some authors [8,9] to the relation $m_\gamma = hH/2c^2 \sim 10^{-65}$ g, quite compatible with the constraints mentioned here above.

This hypothesis of a non-zero rest-mass of the photon thus leads to the violation of the anisotropy of light properties. The purpose of this paper is first to predict how, and how much, second, to relate it with recent experiments by Riis et al. [10].

## 2. Observable consequences of a non-zero photon rest-mass

### *2.1. Anisotropy properties in the velocity propagation of light*

As already noted shortly, the important fact is that $m_\gamma > 0$ destroys, within the reference frame of the theory of relativity, the isotropy of light itself.

Let us denote by $v_\gamma$ the velocity of light in a given inertial reference frame $\Sigma$. The velocity $v_\gamma < c$ is frequency-dependent, since one has, from relation (1),

$$v_\gamma = c\left(1 - \frac{m_\gamma^2 c^4}{h^2 \nu^2}\right)^{1/2} . \tag{2}$$

This can be expressed by saying that the vacuum behaves like a dispersive medium with a refraction index $n = c/v_\gamma$.

This velocity $v_\gamma$ corresponds of course to the group velocity of any electromagnetic wave packet. It is associated, in the inertial reference frame $\Sigma$, with a frequency $\nu$ and a wavelength $\lambda$ which satisfy the relation

$$\lambda\nu = v_\gamma . \tag{3}$$

There is no reason why it should be isotropic in general. To show this, let us consider a reference frame $\Sigma_0$ where all these frequency-velocities are *assumed* to be isotropic. Incidentally, it is the same reference frame with respect to which the background radiation field is also assumed to be isotropic. Let us denote by the symbol $w$ the velocity of a reference frame $\Sigma$ moving in a given direction with respect to $\Sigma_0$. One sees that photons moving in opposite directions in $\Sigma_0$, i.e. with velocities $+v_{\gamma 0}$ and $-v_{\gamma 0}$, associated with a given isotropic frequency $\nu_0$ and wavelength $\lambda_0$, are observed, in the reference frame, to move with different velocities. According to Einstein's theory itself, one should write

$$v_{+\gamma} = \frac{+v_{\gamma 0} + w}{1 + v_{\gamma 0} w/c^2} \quad \text{and} \quad v_{-\gamma} = \frac{-v_{\gamma 0} + w}{1 - v_{\gamma 0} w/c^2} \tag{4}$$

associated, respectively, with frequencies $\nu_+$ and $\nu_-$ and wavelengths $\lambda_+$ and $\lambda_-$.

Of course $w \ll v_\gamma \sim c$, and the effect is therefore very small. Nevertheless, the difference $\delta v_\gamma = |v_{+\gamma}| - |v_{-\gamma}|$ is easy to compute. One has

$$\frac{\delta v_\gamma}{v_{\gamma 0}} = \frac{v_{+\gamma} + v_{-\gamma}}{v_{\gamma 0}} = 2\frac{w}{v_{\gamma 0}} \frac{1 - w_{\gamma 0}^2/c^2}{1 - v_{\gamma 0}^2 w^2/c^4} , \tag{5}$$

which can be approximated easily:

$$\frac{\delta v_\gamma}{v_{\gamma 0}} \sim \frac{\delta v_\gamma}{c} \sim \frac{2w}{c}\left(1 - \frac{v_{\gamma 0}^2}{c^2}\right) . \tag{6}$$

The quantity $v_{\gamma 0}^2/c^2$ can be computed assuming $m_\gamma \ll 10^{-56}$ g, and using relation (2). One finds $1 - v_{\gamma 0}^2/c^2 \ll 2.5 \times 10^{-14} \nu^{-2}$; if $\nu = c/\lambda$ is larger than unity (i.e. $\lambda < 3 \times 10^8$ cm), then $1 - v_{\gamma 0}^2/c^2 \ll 2.5 \times 10^{-14}$ and $\delta v_\gamma/c \ll 5 \times 10^{-17}$. Therefore, the quantity (6) is therefore much beyond the present capability of detection, even on a very large distance, for example the assumed distance of distant quasars.

The important point, as we shall now show, is that such a differential anisotropic effect, how small as it may be, can be detectable through its influence upon frequency or wavelength differences, i.e. through frequency anisotropies.

### *2.2. The anisotropy of light properties: the frequency*

Starting from the relation $\lambda\nu = v_\gamma$ and its differentiation, namely $\lambda\,\delta\nu + \nu\,\delta\lambda = \delta v_\gamma \sim 0$, one sees that $\delta\lambda/\lambda \sim -\delta\nu/\nu$, so that the relative variation in frequency is of the same order as the relative variation in wavelength, when passing from system $\Sigma_0$ to system $\Sigma$. The relative variation of frequency $\nu$ can be immediately calculated from the standard relativistic formula which connects the frequencies of the frames $\Sigma$ and $\Sigma_0$ (relativistic Doppler effect):

$$\nu = \nu_0(1 - w^2/c^2)^{1/2}\,. \tag{7}$$

This expression does not explicitly depend upon the mass value $m_\gamma$. It is in fact "hidden" in the frequency values $\nu$ and $\nu_0$ as a consequence of de Broglie's relation $E = h\nu$. This yields, *whatever the actual value of* $m_\gamma$, a frequency shift, in the laboratory, $\delta\nu/\nu \sim -2w^2/c^2$, of the order of $4\times10^{-6}$ between light beams moving in opposite directions with respect to the background radiation field apex, if the values of $w$ are determined from astronomical determinations.

We should note that this effect would be equal to zero, would the proper photon mass be equal to zero. Of course, as stated above, the value of $m_\gamma$ does not *explicitly* enter eq. (7) since, in the laboratory case, there is no motion of the source with respect to the observer, i.e. no "ordinary" Doppler effect. The theory of relativity implies, whatever the accuracy of the measurements, that in such laboratory experiment no motion should be detected with respect to the reference frame $\Sigma_0$ (either through the velocity shift, or through the frequency shift) if the proper mass of the photon is strictly equal to zero.

However, such frequency shifts should be observable in principle in the laboratory, whenever, in a similar type of geometry, the velocity shift is undetectable (as exemplified by the Michelson–Morley experiments). We shall later come back on the present astronomical and laboratory evidence.

### *2.3. Tired-light mechanisms of redshift*

This consequence of the non-zero rest-mass of the photon has been largely described in many papers, following different mechanisms of interaction of photons and the media crossed by them. We shall only refer to our more recent papers on the subject [11–13], since this aspect of the photon rest-mass is not linked with the main subject of our paper, the anisotropy of light frequency.

## 3. The observational evidence

### *3.1. Astronomical anisotropy of the background radiation*

The anisotropy of the so-called cosmological 3 K background radiation has been discovered by Smoot et al. [14] (see also ref. [15], and more recently, two American teams at Berkeley (Lubin et al. [16]) and at Princeton (Fixsen et al. [7]) have refined the data with small error bars (well put in evidence by their detection of the motion of the Earth around the Sun, i.e. ± 30 km s$^{-1}$ at six months intervals). They found that the Earth's motion with respect to the apex of the background radiation (which defines our $\Sigma_0$ reference frame), once the Sun's motion with respect to its local apex is corrected, is characterized by the values

$$v_{3\,\mathrm{K}} = 586\ \mathrm{km\,s^{-1}}\ \text{towards apex}\,,$$
$$\alpha = 10\,\mathrm{h}\,26\,\mathrm{m}\,,\ \delta = -27°30'\ [16]\,;$$
$$v_{3\,\mathrm{K}} = 614\ \mathrm{km\,s^{-1}}\ \text{towards apex}\,,$$
$$\alpha = 10\,\mathrm{h}\,35\,\mathrm{m}\,,\ \delta = -24°\,42'\ [17]\,.$$

They do not find a quadrupolar component. The value of the solar velocity towards its local apex was taken as 300 km s$^{-1}$ (apex: $l = 90°$, $b = 0°$); this estimation may have introduced only a minor error.

As we are looking now only at the orders of magnitude, we have used in our estimations

$$v_{3\,\mathrm{K}} = 600\ \mathrm{km\,s^{-1}}\ \text{towards apex}\,,$$
$$\alpha = 10\,\mathrm{h}\,30\,\mathrm{m} \pm 15\,\mathrm{m}\,,\ \delta = -26°30'\,.$$

This apex corresponds to $l = 268°$, $b = 27°$, in galactic coordinates. One has $v_{3\,\mathrm{K}} \sim 0.002c$.

### *3.2. Laboratory anisotropy of the 3 K radiation*

Riis et al. [10] have precisely tried to measure whether the radiation, *within the reference frame of the laboratory*, displays some velocity or some frequency anisotropy, or not.

In these experiments, the authors have first attempted to measure the possible anisotropy of the speed of light. They measure to that effect the Doppler shift of a two-photon transition, in a fast beam of $^{20}$Ne atoms, resonantly excited by a collinear laser beam; the transition in question ($3s[3/2]^0_2$–$4d'[5/2]^0_3$ in Ne I) is compared to a $I_2$ reference transition in a molecular iodine cell, at rest in the laboratory. The direction of the beam is modified by the Earth's rotation with respect to the fixed stars. The observed frequency is analysed. The authors found that it indicates essentially an upper limit for $\delta c/c$ of the order of $3\times10^{-9}$. However, their results are slightly suggestive of another effect, concerning the *frequency* of the photons.

Actually, the authors fit the data by a constant and a 24 sidereal-hour-cosine, with adjustable amplitude and phase. But, before doing so, they have to correct the data for slow drifts in the emittance of the ion source, which includes a dominating spurious periodic variation, which they find to be of a 11.8 sidereal-hour period, and of a 7.1 kHz amplitude. The residual 24 sidereal-hour period is of an amplitude of $0.81\pm1.0$ kHz, not significative of course, but at least suggestive. The maximum occurs at the right ascension $\alpha = 12.6\pm1.3$ h, *only slightly different from the apex of the* 3 *K radiation.*

We interpret this data as suggestive of a *frequency* shift of photons, of the order $\delta\nu/\nu \sim 2(v_{3\,\mathrm{K}}/c)^2$ ($\delta\nu \sim 0.8$ kHz; $\nu \sim 2.6\times10^5$ kHz; hence $\delta\nu/\nu \sim 3\times10^{-6}$, conform to our eq. (7)).

Actually, a light-speed anisotropy, of the type $v'_\gamma = v_\gamma(1+\epsilon\cos\theta)$, discussed by Riis et al. [10] and by Mansouri and Sexl [18], with respect to a certain direction $\theta$ relative to a reference direction would produce, in the laser frequency $\nu_0$, a change of $\delta\nu/\nu_0 = \epsilon\cos\theta\, u/c$, where $u$ is the beam velocity, as seen from the isotropic reference frame $\Sigma_0$. This relation is derived [19] from a heuristic modification of the special relativity formulation. The passage from $\Sigma_0$ to $\Sigma$ induces a suggested Doppler-induced frequency shift $\delta\nu < 2$ kHz corresponding to $\epsilon = (1+2a)u/c < 2.8\times10^{-9}$ corresponding to $a = -\frac{1}{2}\pm1.4\pm10^{-6}$ (whenever, in the special theory of relativity, $a = -\frac{1}{2}$ and $\epsilon = \delta\nu/\nu_0 = 0$).

## 4. Physical discussion

An astonishing result of these laboratory experiments, if confirmed, is that it implies that external (radiotelescope in millimeter range) and internal (laboratory at about 40 nm wavelength) observations yield the same type of motion with respect to the background distant sky. This closed room observation (if confirmed by subsequent experiments) tells us, in other words, how the laboratory is moving with respect to the background sky.

### *4.1. Does this not contradict an essential principle of the special relativity theory?*

No, it does not. Actually one has to be very careful in extending this special principle to the GR (remember also the discussion by Ernst Mach of the Newton torqued water pendulum). If indeed photons have a non-zero rest-mass, their motion, in any frame, is supposed to be influenced by the distribution of gravitational sources in the external universe, since it is another general principle that there exists no screen against gravitational forces acting between distant massive sources. In other terms, and this has been known for some time [10,21], given a curved space–time with a metric tensor $g_{\mu\nu}$, Maxwell's equations, with $m_\gamma > 0$, may be written as if they were valid in a flat space–time in which there is an optical medium with a constitutive equation, a pseudo-refractive index. As far as optical phenomena are considered, this medium turns out to be equivalent to the gravitational field. Along the same line, one can also interpret the gravitational redshift within the frame of the electrodynamics of continuous media; the introduction of the proper time of the emitting and of the absorbing atoms at rest in the gravitational field being shown to define a medium interacting with the electromagnetic field through a drag force giving place to a velocity which increases linearly with time [12].

This equivalence between the optical properties of the medium and a gravitational field have been exemplified, as follows, by de Felice [20]. According to his paper, let us consider a source-free electromagnetic field in an optical medium located in a flat space–time with the special relativity metric tensor $\eta_{\mu\nu}$. The electromagnetic field is described by the skew-symmetric tensors $F_{\mu\nu}$ and $G_{\mu\nu}$ which satisfy the covariant Maxwell equations

$$\partial[_{\mu}F^{\mu\nu}]=0\,,\quad \partial[_{\mu}G_{\mu\nu}]=0\,, \tag{8}$$

and the constitutive equations

$$G^{\mu\nu}=\tfrac{1}{2}\chi^{\mu\nu\alpha\beta}F_{\alpha\beta}\,. \tag{9}$$

The tensor $\chi^{\mu\nu\alpha\beta}$, called the "constitutive tensor", describes the properties of the optical medium, and satisfies the following relations: Let $\chi^{\alpha\beta\gamma\delta}$ be equal to $(1/4!)\delta_{i_1i_2i_3i_4}\chi^{\alpha_{i_1}\alpha_{i_2}\alpha_{i_3}\alpha_{i_4}}$, then one has

$$\chi^{\alpha\beta\gamma\delta}=\chi^{\gamma\delta\alpha\beta}=-\chi^{\alpha\beta\delta\gamma}=-\chi^{\beta\alpha\gamma\delta}\,,$$

$$\chi^{[\alpha\beta\gamma\delta]}=0\,,\quad \partial_{s}\chi^{[\alpha\beta\gamma\delta]}=0\,, \tag{10}$$

according to the classical notation. Eqs. (8) and (9) are valid in the case of instantaneous and local interactions between the fields. The constitutive tensor for a general medium at rest with respect to a given observer has the form

$$\chi^{\mu\nu\alpha\beta}=\begin{array}{c|cccccc} & 01 & 02 & 03 & 23 & 31 & 32 \\ 01 & & & & & & \\ 02 & & \{\epsilon^{\alpha\beta}\} & & & \{\gamma^{\alpha\beta}\} & \\ 03 & & & & & & \\ 23 & & & & & & \\ 31 & & \{\bar{\gamma}^{\alpha\beta}\} & & & \{\chi^{\alpha\beta}\} & \\ 32 & & & & & & \end{array} \tag{11}$$

There, $\epsilon^{\alpha\beta}$ and $\chi^{\alpha\beta}$ are symmetric three-dimensional tensors describing the dielectric constant and the inverse of the magnetic permeability; $\gamma^{\alpha\beta}$ and $\bar{\gamma}^{\alpha\beta}$ are antisymmetric quantities describing "peculiar" properties of the medium. The "equivalent medium" is described as follows,

$$\mu^{\alpha\beta}=\epsilon^{\alpha\beta}=-\sqrt{-g}\begin{pmatrix}g^{\alpha\beta}\\ g_{00}\end{pmatrix},$$

$$\gamma^{\alpha\beta}=\bar{\gamma}^{\alpha\beta}=-\delta^{\alpha\beta\gamma}\begin{pmatrix}g_{\epsilon\gamma}\\ g_{00}\end{pmatrix}. \tag{12}$$

One can easily see that, if $E_{\alpha}$ and $H_{\alpha}$ are the usual electric and magnetic vector fields in the medium (12), one recovers Maxwell's equation in the medium (11). It is important to notice that when $\gamma_{\mu\nu}$ reduces to $\eta_{\mu\nu}$ their $\epsilon^{\alpha\beta}$ becomes $\delta^{\alpha\beta}$; and $\gamma^{\alpha\beta}$ and $\bar{\gamma}^{\alpha\beta}$ both vanish. Furthermore conformal transformations, on the metric $\gamma_{\mu\nu}$, leave $\chi^{\alpha\beta\gamma\delta}$ unchanged.

Evidently, the space isotropy of light in a given reference frame $\Sigma_0$ implies the local isotropy of the $g_{ij}$ in that frame ($i=1, 2, 3$), but in any other frame, they are anisotropic, this anisotropy being tied to the fact that $m_{\gamma}>0$. At the cosmological scales, one could associate this anisotropy with a slowly variable cosmological constant $\Lambda(\chi_{\mu})$ in Einstein's equations $R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=\chi T_{\mu\nu}-\Lambda g_{\mu\nu}$, where the last term (according to Sakharov [22], Sinha et al. [23], and Peebles [24]) describes a variable Dirac-type aether (another word to designate a real vacuum) of which the scalar density is so expressed [21]. This vacuum density can be endowed of course with dissipative properties which might explain the so-called "anomalous" redshifts observed in the universe (see for example ref. [25]). *Since this is not the subject of the present paper*, we shall only indicate here two possible cosmological consequences which result from the introduction of variable $\Lambda$ values and $m_{\gamma}>0$.

The first consequence is that the introduction of an average vacuum density implies in Einstein's equations new, still undiscussed, possible physical consequences on the behaviour of cosmological models. It destroys for example the well known instability of Einstein's static world model. Indeed, if one recalls the well known fact that the introduction of $\Lambda$ (i.e. $R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+\Lambda g_{\mu\nu}=\chi T_{\mu\nu}$) in Einstein's equation implies that attractive gravitational forces become repulsive beyond a certain distance one sees that a variation of $\Lambda$'s average value $\langle\Lambda\rangle$ evidently grows if the universe's radius decreases (and vice versa). If the universe has reached a stable equilibrium state any increase of its radius will decrease $\langle\Lambda\rangle$, i.e. increase the range of the gravitational attractive forces and decreases the said radius. Alternatively a decrease of $R$ increases $\langle\Lambda\rangle$, i.e. decreases the range of gravitational forces, i.e. increases the action of gravitational repulsions: which leads to an increase of $R$. If $\Lambda$ can vary, Einstein's static universe model becomes stable.

The second consequence is that, curiously enough, one has never seriously discussed in the literature the possible action of gravitational waves (if as believed by the authors their existence will be confirmed by future experiments within the next few years) on the behaviour of $\Lambda$ and the consequences of their existence on the propagation of light in the universe. Indeed if, as has recently been suggested [26], intergalactic space contains a large amount of intergalactic neutral plasma and if one remarks that all massive matter is in fact a superposition of real gravitational multipoles, then what we call vacuum is necessarily filled with a background chaos of superposed gravitational waves. Taking into account the interaction between gravitation and Maxwellian waves this implies of course (1) that the vacuum should be filled with the gravitational analogue of the 2.7 K microwave background, (2) that this gravitational black body should/could be in equilibrium with its 2.7 K e.m. counterpart, and (3) that one should construct the gravitational stochastic counterpart of Dirac's aether model [22]. Since this will also be discussed in a subsequent publication we only want here to stress the importance of James and Wolf's result [27] that one can generate Doppler-like frequency shifts by dynamical scattering in random media. A background of $g_{\mu\nu}$ fluctuations which induce fluctuating geodetics (i.e. zero-length geodetics for $m_\gamma=0$) behave precisely like such media since they modify in a random way the geodetics followed by $m_\gamma=0$ or $m_\gamma>0$ photons. Since other similar vacuum induced mechanisms have also been presented in the literature [12] it is now possible to assume that the modern theory of light provides various possible redshift mechanisms.

### *4.2. An absolute space–time?*

The preceding allusions to the anisotropy of our *local* laboratory with respect to the distant galaxies, and to Mach's reasoning, might lead us to think that, as there seems to be a reference frame $\Sigma_0$ within which the Planck distribution and the light velocity is isotropic, one should perhaps return to the concept of *absolute* space–time.

Again, this is not so.

Actually the 3 K background radiation is, by nature, not invariant, and it always fluctuates in time and space, so that the reference frame $\Sigma_0$ is itself never stable but always fluctuating at each space–time point, be it only because of the finite time of propagation of both gravity and radiation. It is not connected with any stable material configuration. It is actually determined only by averaging over time, space, and locally random variables such as frequency intensities of the Planck distribution. In this sense, $\Sigma_0$ is not identical with either an aether, in Dirac's terminology, or with an absolute space–time, in Mach's description; the concept of a covariant (but random) aether should be strictly reserved to Dirac's model recently revisited [24].

The meaning of the frame $\Sigma_0$ has therefore to be taken with caution. Some consequences of its introduction have been discussed by Mansouri and Sexl [18]. Assuming the two known methods of clock synchronization (i.e. Einstein's procedure, $S_E$, by light signals, and the classical synchronization, $S_T$, by slow clock transport) one first introduces three straightforward hypotheses: (a) the velocity of light is independent of the velocity of the source at all frequencies; (b) $S_E$ and $S_T$ are done in $\Sigma^0$, so that the velocity of light as measured by $S_T$ (synchronized clocks) is isotropic in $\Sigma_0$; and, (c) one can detect at each space–time point the apex of the 3 K and our velocity $w$ with respect to it. Assuming (a), (b), (c) to be true, we can define the time and space transformations which transform the coordinates $X$, $T$ of $\Sigma_0$ into the coordinates $x$, $t$ of any frame $\Sigma$ moving with a velocity $w$ with respect to $\Sigma_0$ by the usual relativistic transformations

$$\begin{aligned} t &= (1-w^2/c^2)^{1/2} T , \\ x &= (1-w^2/c^2)^{-1/2} (X-wT) , \end{aligned} \tag{13}$$

where we have of course $X=wT$.

Following the conventions of relativity theory, we can then synchronize all clocks in all frames S simply by synchronizing all clocks by $S_E$ in $\Sigma_0$ and then synchronizing clocks in all other systems moving past $\Sigma_0$ by adjusting these clocks to $t=0$ whenever they fly past a clock in $\Sigma_0$ which shows $T=0$. This particular choice of synchronization procedure (in which clocks in any system S are synchronized by comparing them with clocks in $\Sigma_0$) has been called "absolute synchronization $S_A$" (A stands for "absolute" simultaneity) by Mansouri and Sexl [18]. It is of course compatible with relativity, but it destroys (only apparently) the beautiful formal equivalence of all inertial systems by choosing a different synchronization procedure for each system. It implies however a striking analogy with Lorentz's aether model, since the relations (13) imply that, in a system S moving with velocity $w$, rods shrink by a factor $(1-w^2c^2)^{1/2}$, clocks are slow by a factor $1-w^2/c^2$ when moving with respect to $\Sigma_0$, and $\Delta T=0$ implies $\Delta t=0$, so that with our chosen synchronization procedure, a theory which *maintains absolute simultaneity is still equivalent to special relativity* provided one preserves the time dilatation and length contraction proposed by Lorentz. Of course there is no preferred direction in $\Sigma_0$ and each light frequency propagates with an identical (but specific) velocity in all directions. One sees immediately that the use of formulae (4) implies an anisotropy of the wavelength of light in any frame S if the photon's rest-mass is different from zero. Whether this very phenomenon has been established (definitely or not) by Riis et al.'s experiments mentioned above [10] is now open to discussion by experimentalists and theoreticians, but (in the authors' opinion) this would not weaken, but in fact strengthen Einstein's discovery of relativity theory.

### *4.3. Conclusion*

It seems now possible to get rid technically of the uncertain character of the frequency shift suspected by Riis et al. [10]. As noted by these authors, the use of heavy ion storage rings, presently under construction, will make available cold and high velocity particle beams. When these are combined with the recent development of ultrastable and ultranarrowband cw dye lasers and Rydberg atom spectroscopy, one can gain at least one order of magnitude in the precision of fast beam experiments. Our analysis shows that such a confirmation could be interpreted as a confirmation of the existence of a non-zero photon mass: a fact which does not contradict general relativity, but would imply far-reaching consequences in quantum electrodynamics and certainly modify presently known cosmological models. However, the direct experimental detection *in the laboratory* of a non-zero photon rest-mass which would induce a very small $\delta v_\gamma/c$ velocity difference is still far from reach of experimental physicists.

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## References

[1] A. Einstein, Ann. Phys. (Leipzig) 18 (1917) 121.
[2] A. Einstein, Ann. Phys. (Leipzig) 7 (1905) 132.
[3] L. Bass and E. Schrödinger, Proc. R. Soc. A 232 (1955) 1.
[4] L. de Broglie, La mécanique ondulatoire du photon, tome 1. Une nouvelle théorie de la lumière (Hermann, Paris, 1940) pp. 121–145.
[5] S. Deser, Ann. Inst. H. Poincaré 16 (1972) 79.
[6] M. Moles and J.P. Vigier, C.R. Acad. Sci. 276 (1974) 697.
[7] A. Barnes and J. Sergle, Phys. Rev. Lett. 35 (1975) 1117.
[8] L. Fuli, Nuovo Cimento Lett. 31 (1981) 289.
[9] T.L. Chow, Nuovo Cimento Lett. 33 (1982) 565.
[10] E. Riis, L. Andersen, N. Bjerre, O. Poulsen, S.A. Lee and J.L. Hall, Phys. Rev. Lett. 60 (1988) 81.
[11] J.C. Pecker and J.P. Vigier, IAU Symp. no. 124 (1987) 507.
[12] J.P. Vigier, IEEE Trans. Plasma Sci. 18 (1990) 64.
[13] P. Kaloyerou and J.P. Vigier, Phys. Lett. A 130 (1988) 260.
[14] G.F. Smoot, N. Gorenstein and R.A. Muller, Phys. Rev. Lett. 39 (1977) 1898.
[15] N. Kaiser and J. Silk, Nature 324 (1986) 529.
[16] P.M. Lubin, G.L. Epstein and G.F. Smoot, Phys. Rev. Lett. 50 (1983) 616.
[17] O.J. Fixen, E. Cheng and D.T. Wilkinson, Phys. Rev. Lett. 50 (1983) 620.
[18] R. Mansouri and R.V. Sexl, Gen. Rel. Grav. 8 (1977) 497.
[19] F.C. Vessot, M.W. Levine, Gen. Rel. Grav. 10 (1979) 181.
[20] F. de Felice, Gen. Rel. Grav. 2 (1971) 347.
[21] F. Pegoraro, Gen. Rel. Grav. 14 (1982) 831.
[22] A.P. Sakharov, Sov. Phys. Dokl 12 (1968) 1040.
[23] K.P. Sinha, E.C.G. Sudarshan and J.P. Vigier, Phys. Lett. A 114 (1980) 298.
[24] P.J.E. Peebles, Astrophys. J. Lett. 332 (1988) 1058;
P.J.E. Peebles and B. Ratra, Astrophys. J. Lett. 235 (1988) 31.
[25] H.C. Arp, Quasars redshifts and controversies (Interstellar Media, Berkeley, 1987) pp. 173–185.
[26] Proc. Palo-Alto Conf. 1988, IEEE Trans. Plasma Sci. 18 (1990).
[27] F.V. James and E. Wolf, Phys. Lett. A 146 (1990) 167.