# PHYSICAL REVIEW LETTERS

VOLUME 55 | 8 JULY 1985 | NUMBER 2


## Experiments to Detect Possible Weak Violations of Special Relativity


A. K. A. Maciel and J. Tiomno

*Centro Brasileiro de Pesquisas Físicas–Conselho Nacional de Desenvolvimento Científico e Technológico, 22290 Rio de Janeiro, Rio de Janeiro, Brazil*



(Received 14 January 1985)



Effects that could distinguish the Lorentz ether theory from Einstein's special relativity, and their measurability, are analyzed.



PACS numbers: 03.30.+p


In 1980 one of us (J.T.) argued[1] that almost all of the very precise experiments which supposedly confirm Einstein's special theory of relativity (SR) are also in agreement with a version of the Lorentz ether theory (LET).[1-3] In this formulation, which does not consider the propagation of light in dispersive media, almost all of the physical phenomena are assumed to be Lorentz invariant, such as, electromagnetism and the propagation of light in vacuum, dynamics of point particles and field equations, and properties of materials in uniform translation relative to some privileged inertial frame ($S_a$) to be possibly identified with that in which the Universe's background radiation is isotropic.[4] Leaving other considerations for the future, it was assumed that only for accelerated solid bodies do violations of SR exist. They originate from the basic assumption that, for rotating-translating "rigid" bodies, viewed in the comoving inertial frame $S$ (where the axis of rotation is at rest), the rigidity may not be defined relative to Einstein-Lorentz coordinates $(\mathbf{x},t)$ which are related to those in $S_a(\mathbf{x}_a,t_a)$ by Lorentz transformations as required by SR. Instead, we considered the possibility that, in $S$, rigidity is associated to the Ives coordinates[5] $(\mathbf{X},T)$: $X=\gamma(x_a-Vt_a)$; $Y=y_a$; $Z=z_a$; $t_a=\gamma T$; $\gamma=(1-V^2)^{-1/2}$; $c=1$. Such coordinates conform to the principle of isotropy of the propagation of light in $S_a$ (but not in $S$), the Lorentz-Fitzgerald contraction relative to the global translation velocity $\mathbf{V}=V\hat{\mathbf{x}}_a$, and the Lorentz time dilation. They differ from the Einstein-Lorentz coordinates in that they do not contain the Einstein synchronization phase differences in time. Thus $T$ is an absolute time as well as $t_a$, and relates to the Einstein time by $T=t+\mathbf{V}\cdot\mathbf{x}$. Rigidity in LET is therefore such that if $i$ and $j$ are any two points in a rotating solid body, then $|\mathbf{X}_i(T)-\mathbf{X}_j(T)|=\text{const}$ (we are neglecting possible local Lorentz contractions of the rotating body[6] which are effects of higher order than those considered here). Notice that this definition necessarily implies nonrigidity either in the Einstein coordinates, because of the mentioned differences in synchronization, or in absolute coordinates $(\mathbf{x}_a,t_a)$, because of a global Lorentz contraction associated with $\mathbf{V}$. This theory was called strict LET (SLET) in Ref. 2.

A straightforward consequence of the above-defined rigidity is that any Ives-described point attached to a uniformly rotating body will have its angular equation of motion $\phi(T)$ given by $d\phi/dT=\omega_0$, a constant. As we shall see, in the Einstein and absolute descriptions, respectively, $d\phi/dt=\omega(t)$ and $d\phi_a/dt_a=\omega_a(t_a)$ are both functions of time. Thus, our formulation of SLET[1-3] is characterized by the Ives-rigidity assumption together with its consequence $d\phi/dT=\omega_0$. These are the sources of the possible violations of SR that we consider in experiments involving rotating bodies (or the Earth itself). We note that the results of the Marinov experiment,[7] which lead us to a value of $\mathbf{V}$ compatible with that of Ref. 4, do agree with LET but not with SR.

It is our intent here to propose some crucial experiments which could either discard this formulation of SLET or prove the existence of other instances of violation of SR. Such experiments, all within present technological possibilities, have not yet been performed because experimental physicists were looking for different effects and frequently their choice of experimental arrangement induced a cancellation of the SR-violating effects that we predict (see below). The simplest example is that of the Michelson-Morley experiment for which an effect $\Delta L/L \sim \boldsymbol{\omega}\times\mathbf{R}\cdot\mathbf{V}$ is predicted for the length variation of one of the optical arms $\mathbf{L}$ if it is placed along its tangential rotation velocity $\mathbf{v}=\boldsymbol{\omega}\times\mathbf{R}$ (Einstein description), and a vanishing effect if $\mathbf{L}\cdot\mathbf{v}=0$. Thus, if $\mathbf{L}$ is in the East-West direction and fixed to the ground, $\Delta L/L \sim 10^{-9}\cos(\omega t)$ which could have been detected by Michelson and Morley themselves. However, not only were they looking for a $\cos(2\omega t)$ effect, but also they soon made the spectrometer rotate as was done in all following such experiments. This brings the effect down to $10^{-12}\cos(\omega t)$, as now $\boldsymbol{\omega}$ and $\mathbf{R}$ are no longer those of the rotating Earth but of the table. Besides, since the light rays travel approximately along diameters of the rotating table, there is a nearly total cancellation of the effect [see the $\cos\psi_0$ factor in Eq. (3)]. Nevertheless some effect might survive if, given that the rotation of the equipment is not completely free, an existing friction torque would transmit to the rotating table some fraction $\alpha$ (presumably small) of the Earth's deformation due to its own rotation, thus leading to $\Delta L/L \sim 10^{-9}\alpha\cos(\omega t)$. Therefore we shall consider only experiments with equipment firmly anchored to the rotating Earth ($\alpha=1$), or in fast free rotation ($\alpha \ll 1$).

Let us first derive our predictions for a few SR-violating effects. We use, even in LET, Einstein coordinates in the comoving frame (where now light propagates isotropically), and the definitions $v_0=\omega_0 R$ and $c=1$. Consider a freely rotating disk that travels with a translational velocity $\mathbf{V}=V\hat{\mathbf{x}}$ with respect to the absolute frame $S_a$. For simplicity we assume $\mathbf{V}$ to be in the plane of the disk. In the comoving inertial frame $S$, in Ives coordinates, some point in that disk is described by the polar vector relative to the center of rotation $\mathbf{R}(T)=(R,\phi(T))$ such that $d\phi/dT=\omega_0$, $R$ and $\omega_0$ being constants of the motion. In Einstein coordinates, $\mathbf{R}(t)=(R_\epsilon,\phi_\epsilon(t))$, where $R_\epsilon\equiv R$, $\phi_\epsilon(t)\equiv\phi(T)$, and (an overdot means $d/dt$)

$$\dot{\phi}_\epsilon(t)=[d\phi(T)/dT]\dot{T}=\omega_0[1+\mathbf{V}\cdot\dot{\mathbf{R}}(t)],$$

which may be integrated to (we now drop the index $\epsilon$)

$$\phi(t)=\phi(0)+\omega_0 t+Vv_0\cos[\phi(0)+\omega_0 t]+O(v_0^2V^2). \quad (1)$$

The optical distance between any two points in the disk is $L(t)=|\mathbf{R}_2(t+\delta t)-\mathbf{R}_1(t)|$, where $L(t)=\delta t(t)$ is the light transit time from 1 to 2. If $|R_1(t)|=|R_2(t)|=R$, then $L(t)=2R\sin(\Delta\phi/2)$, where $\Delta\phi=\phi_2(t+\delta t)-\phi_1(t)$ is readily obtained from Eq. (1). With the convention $\phi_2(0)=2\psi_0$ and $\phi_1(0)=0$ we find

$$L(t)=L_0-Rv_0V\sin2\psi_0\sin(\omega_0 t+\psi_0)+O(v_0^2V^2), \quad (2)$$

where (we consider $v_0\lesssim V^2$, $V\sim 10^{-3}$)

$$L_0=2R\sin\psi_0[1+v_0\cos\psi_0-(v_0^2/2)\sin^3\psi_0+O(v_0^3)].$$

If $\mathbf{V}$ is in the direction of the axis of rotation no time-dependent distortion of the body is produced. Thus only the component of $\mathbf{V}$ orthogonal to the axis is effective.

We shall concentrate here on two different methods of search for SR violations in the dynamics of rotating bodies. One deals with the detection of length shifts $\Delta L$ in the optical path (or equivalently shifts in the photon time of flight) between two points, generally two reflecting mirrors, solidly anchored to a rotating disk. The other method uses Doppler-shift technology with an emitter and an absorber as end points of the rotating optical path.

In Eq. (2), $L(t)$ corresponds to the observed length of a chord with central angle $2\psi_0$ as measured before rotation. Therefore, our prediction for experiments which are sensitive to length shifts $\Delta L$ is

$$\Delta L/L_0=-v_0V\cos\psi_0\sin(\omega_0 t+\psi_0)+O(v_0^2V). \quad (3)$$

As for Doppler detection, let $\nu$, $\nu_0$, and $\nu_a$ be the light frequency (Einstein time) as measured, respectively, in $S$, in the instantaneous rest frame of the emitter, and in that of the absorber. Then, according to SR (or SLET in Einstein coordinates), whatever the position and motion of the emitter and absorber,

$$\nu=\nu_0[\gamma_e(1-\hat{\mathbf{k}}\cdot\dot{\mathbf{R}}_e)]^{-1}=\nu_a[\gamma_a(1-\hat{\mathbf{k}}\cdot\dot{\mathbf{R}}_a)]^{-1},$$

where $\gamma(1-\dot{\mathbf{R}}^2)^{-1/2}$ with subscripts referring to emitter and absorber, and $\hat{\mathbf{k}}$ is the unit vector in the direction of propagation as observed in $S$. In Doppler-type experiments, the observed quantity is the frequency shift

$$\Delta\nu/\nu_0=(\nu_a-\nu_0)/\nu_0=\hat{\mathbf{k}}\cdot[\dot{\mathbf{R}}_e(t)-\dot{\mathbf{R}}_a(t+\delta t)]+O(v_0^3). \quad (4)$$

Again for $|R_1(t)|=|R_2(t)|=R$ and coplanar motion, this is readily found to be $-\dot{L}(t)$ which, from Eq. (2), gives as a SLET prediction,

$$\Delta\nu/\nu_0=v_0^2V\sin2\psi_0\cos(\omega_0 t+\psi_0)+O(v_0^3,v_0^2V^2). \quad (5)$$

Next, a few words about the experimental verifications of SR. Only a few of the experiments carried out to date are potentially sensitive to the SR-violating effects that we investigate here. For instance, of all the experiments quoted in Newman *et al.*,[8] only that of Jaseja *et al.*[9] can distinguish our SLET from SR. The Champeney-Moon[10] and Turner-Hill[11] experiments, with respective results $\Delta\nu/\nu_0 \lesssim 10^{-12}$ and $10^{-14}$ with the $\cos(\omega t)$ dependence, should possibly find non-null results, if SLET is correct, only for sensitivities below $10^{-16}$ and $10^{-21}$ $[\cos(\omega t)]$, respectively. Indeed, according to SLET, both experiments should lead to exactly null results for a point absorber placed (i) radially opposite to the source in the Champeney-Moon experiment [$2\psi_0 = \pi$ in Eq. (5)]; (ii) at the axis of rotation in the Turner-Hill experiment [$\mathbf{R}_a = 0$ and $\hat{\mathbf{k}} \cdot \dot{\mathbf{R}}_e = 0$ in Eq. (4)].

Allowing for a small extension of the absorber and a small departure from $2\psi_0 = \pi$ in Eq. (5) we find the above-mentioned result of $10^{-16}\cos(\omega t)$ for the Champeney-Moon value of $\Delta\nu/\nu_0$. In the Turner-Hill experiment, the transverse Doppler effect $\Delta\nu/\nu_0 = v_a^2(t+\delta t) - v_e^2(t)]/2$ is dominant, and we find the quoted departure from the SR prediction of

$$\Delta\nu/\nu_0 + v_0^2/2 = V v_0^3 \sin(\omega t) \sim 10^{-21}\sin(\omega t),$$

where $v_0$ is the average value of $v_e$ and about 10 times larger than that of $v_a$. This is independent of the distance between the orbital planes of source and absorber, and well outside present experimental detection limits.

The Michelson-Morley–type slow-rotating experiment of Joos[12] leads to a null result of the form $\Delta L/L < 10^{-11}\cos(2\omega_E t)$ ($\omega_E$ being Earth's angular velocity), in agreement with both SLET and SR which predict no second-harmonic effects. This experiment was carried out at an angular velocity of the turntable of one rotation every ten minutes, which makes the table's $v$ far too small for detection of the SLET-predicted first-harmonic effect of Eq. (3). Besides, the fact that both optical arms meet at the center of rotation implies the vanishing of $\cos\psi_0$ in Eq. (3), rendering any detection even more remote. This illustrates well our earlier comment that frequently the choice of experimental arrangement had not been adequate for a SLET versus SR analysis since experimentalists were looking for different effects. The Turner-Hill experiment is another such example.

If an experiment similar to Joos's can be performed with (i) a much higher turntable angular velocity of one rotation per second and (ii) either one or both optical arms along $\sim 90°$ central angle chords of a circle relative to the turntable's center, then the SLET prediction from Eq. (3) is $\Delta L/L \sim 10^{-11}\sin(\omega t)$.

The Jaseja *et al.*[9] experiment is sensitive to length shifts $\Delta L$ in the optical path between the reflecting ends of two maser cavities placed orthogonally on a rotating table. By measuring the frequency shifts, which for each maser is equal to $-\Delta L/L_0$, the experiment represents an improvement over that of Michelson and Morley in that it relies on highly monochromatic maser frequency metrology rather than optical interferometry. The table oscillates horizontally between two extreme positions at angles $\theta_0$ and $\theta_0 + \pi/2$ at which it is instantly at rest relative to the Earth. From Eq. (3), assuming $\theta_0$ to be the east-west direction, we should expect

$$\Delta L/L_0 \sim v V \alpha \sin(\omega t) \quad [\sim 10^9 \alpha \sin(\omega t)],$$

$v$ and $\omega$ being Earth's rotational tangential and angular velocities. $\alpha$ is the above-mentioned friction coefficient ($\alpha = 1$ for a table anchored solidly to the Earth; $\alpha = 0$ for completely free rotation) introduced here because the table's rest position is not permanent in this experiment. Jaseja *et al.*[9] present a result $\Delta L/L_0 \lesssim 10^{-11}$ assuming a $\sin(2\omega t)$ effect. Tiomno[3] showed that fitting their results with a $\sin(\omega t)$ dependence according to Eq. (3) and using $\mathbf{V}$ as in Ref. 4 gives now $\Delta L/L_0 \sim 10^{-10}$ and thus $\alpha \sim 0.1$.

A further sensitivity improvement is the Brillet-Hall[13] readout of a stable etalon of length achieved with laser-frequency-locking techniques. They present a null result of $\Delta L/L_0 = (1.5 \pm 2.5) \times 10^{-15}$ with the $\cos(2ft)$ signature ($f$ is the angular velocity of their rotating table). This does not exclude SLET which predicts a null effect (as does SR) in $\cos(2ft)$. However, they report a spurious sine-wave signal (allegedly due to gravitational stretching of the interferometer) which gives $\Delta L/L_0 \sim 10^{-12}\sin(ft)$, about 5 times our prediction from Eq. (3) of $2 \times 10^{-13}$ which should be masked by the larger spurious effect. From the above we conclude the following:

(I) The Brillet-Hall experiment should be repeated in search of a possible separation of the contribution to the sine-wave length variation due to spurious effects from that due to the known value of $\mathbf{V}$.[4] The latter effect is linearly dependent on the rotation velocity $|\mathbf{v}|$ and also dependent on the measurable angle between $\mathbf{v}$ and $\mathbf{V}$.

(II) The Champeney-Moon[10] experiment should be repeated with absorber and source in quadrature at equal radii since Eq. (4) with $2\psi_0 = \pi/2$ gives for the conditions of this experiment, $\Delta\nu/\nu_0 \sim 10^{-15}\cos(\omega_0 t)$ which is within present measurement capabilities, being only a one order of magnitude improvement over the Turner-Hill experiment.

(III) The Jaseja *et al.*[9] experiment should be repeated with one of the optical paths aligned with the east-west direction, the whole apparatus solidly anchored to to the Earth ($\alpha = 1$). As in (I), hourly data could be recorded for several days and the experiment repeated in different times of the year. The same can be said of the traditional experiment of Michelson and Morely in anchored conditions for which Eq. (3) predicts $\Delta L/L$

$\sim 10^{-9}\sin(\omega_E t)$, $\omega_E$ being Earth's angular veloctiy.

(IV) Finally, the Marinov[7] experiment, which led one of us (J.T.) to consider such problems,[1] should be independently repeated even if to prove it wrong. Oddly enough this experiment, which apparently raises more difficult technical problems than the others mentioned here, has been carried out in a comparatively less sophisticated laboratory.

[1]J. Tiomno, in Proceedings of the Meeting of the Sociedade Brasileira de Física, Cambuquira, São Paulo, 1980 (unpublished).

[2]W. A. Rodrigues and J. Tiomno, Rev. Bras. Fís., Suppl. **14**, 450 (1984), and to be published.

[3]J. Tiomno, in Proceedings of the Symposium in Honor of the Seventieth birthday of M. Schenberg, São Paulo, August 1984 (to be published). This talk included preliminary results of the present paper and of a forthcoming publication by the present authors.

[4]G. F. Smoot, M. V. Gorenstein, and R. A. Muller, Phys. Rev. Lett. **39**, 898 (1977).

[5]H. B. Ives, J. Opt. Soc. Am. **27**, 263 (1937).

[6]H. B. Ives, J. Opt. Soc. Am. **29**, 472 (1939).

[7]S. Marinov, Czech. J. Phys. **24**, 965 (1974), and Gen. Relativ. Gravitation **12**, 57 (1980).

[8]D. Newman, G. W. Ford, A. Rich, and E. Sweetman, Phys. Rev. Lett. **40**, 1355 (1978).

[9]T. S. Jaseja, A. Javan, J. Murray, and C. H. Townes, Phys. Rev. **133**, A1221 (1964).

[10]D. C. Champeney and P. B. Moon, Proc. Phys. Soc., London **77**, 350 (1961).

[11]K. C. Turner and H. A. Hill, Phys. Rev. **134**, B252 (1964).

[12]G. Joos, Ann. Phys. (Leipzig) **7**, 385 (1930).

[13]A. Brillet and J. L. Hall, Phys. Rev. Lett. **42**, 549 (1979).