Lorentz Invariance and the Cosmological Constant

O. Bertolami

Instituto Superior Técnico, Departamento de Física,
Av. Rovisco Pais 1, 1096 Lisboa Codex, Portugal

Abstract

Non-trivial solutions in string field theory may lead to the spontaneous breaking of Lorentz invariance and to new tensor-matter interactions. It is argued that requiring the contribution of the vacuum expectation values of Lorentz tensors to account for the vacuum energy up to the level that $\Omega^\Lambda_0 = 0.5$ implies the new interactions range is $\lambda \sim 10^{-4} m$. These conjectured violations of the Lorentz symmetry are consistent with the most stringent experimental limits.

\footnote{This essay was selected for an Honorable Mention by the Gravity Research Foundation, 1997}
It is a well known fact that there is no version of the Higgs mechanism in gravity. Indeed, the breaking of Lorentz invariance via non-vanishing vacuum expectation values of Lorentz tensors does not give origin to mass terms to the graviton as this field couples only through derivative interactions. This feature creates a difficulty in multidimensional gravity theories as the extra dimensions components of the graviton will, in 4 dimensions, give origin to long-range interactions, which are severely constrained by observation. This problem may be circumvented for instance, assuming the compactification process respects certain requirements, such as for instance, the condition the dimensional reduction procedure involves compact manifolds that are coset spaces and accordingly $K$—symmetric metric and matter fields [1, 2] (see [3, 4] for thorough discussions and a complete set of references). However, this of course cannot be regarded as a dynamical explanation. In the context of string theories, in particular, the spontaneous breaking of the Lorentz symmetry can be envisaged as an interesting way out [5, 6] as string field theory contains interactions that are not present in Kaluza-Klein type theories and their generalizations. As pointed out in Refs. [1, 3], this breaking is rather natural in some string theories, such as in the bosonic string where the tachyon is present. This breaking may also occur in the superstring if the dilaton acquires a non-vanishing expectation value and its interactions give origin to negative quadratic couplings for tensors, possibly non-perturbatively. Notice however, that arguments based in the effective dilation potential suggesting the need of strong coupling [4], and of the implied presence of those interactions in the superstring, do not hold once $S$—duality symmetry is imposed in the effective theory through demanding modular invariance of the $N = 1$ supergravity superpotential [8].

It is worth mentioning that the idea of dropping the Lorentz invariance has been previously considered. Indeed, a background or constant cosmological vector field throughout space has been suggested as a way to introduce into the physical description our velocity with respect to a preferred reference frame [4]. It has also been argued, based on the behaviour of the renormalization group $\beta$—function of non-abelian gauge theories, that Lorentz invariance may be actually just a low-energy phenomenon [10]. Finally, closer to our discussion, theories of gravity in more than 4 dimensions that are not locally Lorentz invariant have been considered in order to
obtain light fermions in chiral representations [11] as an alternative to introducing extra gauge fields in topologically non-trivial vacuum configurations [12].

The breaking of the Lorentz symmetry due to non-trivial solutions of string field theory is of course related with the breaking of the CPT symmetry [13]. Interestingly, this possibility can, in principle, be verified experimentally in the $K^0 - \bar{K}^0$ [14], B and D [15] systems. Moreover, this violation of the CPT symmetry also allows for an explanation of the baryon asymmetry of the Universe as the tensor-fermion-fermion interactions (see below) give origin, after the breaking of the Lorentz and CPT symmetries, to a chemical potential that creates in equilibrium a baryon-antibaryon asymmetry in the presence of baryon number violating interactions [17].

The main argument in favour of the breaking of the Lorentz invariance arises in the bosonic open string field theory where interactions are trilinear type [18]. The static potential in this string field theory proposal has the following form [5]:

$$V(S^i, T^j_M) = \frac{1}{2} \sum_{i,j} m^2_{ij} S^i S^j + \frac{1}{3!} \sum_{i,j,k} g_{SSS}^{ijk} S^i S^j S^k + \frac{1}{2} \sum_{i,j} M^2_{ij} T^i_M T^j_M + \frac{1}{3!} \sum_{i,j,k} g_{T T T}^{ijk} T^i_M T^j_M T^k_N ,$$

(1)

where $S$ and $T$ represent generic scalar and tensor fields, the indices $M, N$ denote the set of Lorentz tensor indices, $m^2_{ij}$ and $M^2_{ij}$ are the scalar and tensor mass-squared matrices and $g_{SSS}^{ijk}, g_{STT}^{ijk}$ and $g_{T T T}^{ijk}$ the relevant coupling constants.

As discussed in Ref. [5], after expanding the string field in terms of the tachyon $\phi$, vector $A_\mu$ and tensor fields in the Siegel-Feynman gauge, one obtains the following static potential:

$$V(\phi, A_\mu, ...) = -\frac{\phi^2}{2\alpha'} + a g \phi^3 + b g \phi A_\mu A^\mu + ... ,$$

(2)

$a$ and $b$ being order one constants and $g$ the on-shell three-tachyon coupling. The vacuum is then clearly unstable and neglecting loop contributions and other scalars, this instability gives origin to a mass-square term to $A_\mu$ which is proportional to $\langle \phi \rangle$. If $\langle \phi \rangle$ is negative, then the Lorentz symmetry itself is spontaneously broken. The

---

2The CPT violating effects discussed here are unrelated with the ones due to the presence of non-linearities in quantum mechanics, presumably induced by quantum gravity, that were recently searched by the CPLEAR Collaboration [16].
vacuum expectation values of any scalars in the static potential are all of order \( M \equiv (\alpha'g)^{-1} \), a mass scale which is presumably close to the Planck mass, and the resulting contribution to the vacuum energy is of order \( M^4 \) [5]. Hence, string interactions involving the tachyon give origin to large violations of the Lorentz invariance, which are not observed (see below) as well as to large contributions to the cosmological constant, a fact that is bluntly contradicted by large scale observations.

Supposedly, the solution for the above embarrassment must be found in the field theory of closed strings, where the graviton is present. Unfortunately, little is known about that theory and its relation to the yet even more fundamental M-Theory. Nevertheless, as far as the Lorentz symmetry is concerned, it seems reasonable to assume that scalar-tensor-tensor interactions will also be present in closed string field theory and, if these have the appropriate sign, Lorentz-symmetry breaking ensues in this theory as well. In any case, no mechanism is known on how to explain the way contributions to the vacuum energy from large vacuum expectation values are cancelled such that compatibility with observations are achieved (for a discussion of the most salient (failed) attempts see [19] and [20] for an update). String theory has however, some features as well as symmetries that put this difficulty in a somewhat different standing. Strings are non-local objects and that gives origin, as depicted in (1), to interactions that are not present in renormalizable field theories. It is conceivable that non-localities and duality symmetries present in string theories may provide the underlying “awareness” [21, 22] the high-energy theory seems to have in order to account for the vanishing or almost perfect cancelling of contributions to the cosmological term at low energies. In this respect, it has been recently suggested by Witten [23] the possibility of relating, via a duality transformation, a 4-dimensional field theory to a 3-dimensional one with the advantage that in the latter the breaking of supersymmetry, a condition imposed upon by phenomenology, does not imply that \( \Lambda \neq 0 \). Furthermore, at least at one-loop in string perturbation theory, the so-called Atkin-Lehner symmetry ensures the vanishing of the cosmological constant up to that level [24]. These features seem however, insufficient to guarantee, to our present knowledge of string theory, the complete vanishing of contributions to the potential at the vacuum, and for all purposes what is required is a quite radical mechanism to
reduce the vacuum energy by about 120 orders of magnitude.

Another distinct feature of string theory is the presence of scalar fields, the moduli, which like fields lying in the hidden sector of supergravity theories interact only gravitationally and, in case of being light, may live long enough to dominate the energy density of the Universe. This is the well-known Polonyi problem which is closely related with the issues of supersymmetry breaking and inflation [22, 25-33]. In what follows we shall assume that the mechanism accounting for the vanishing or nearly vanishing of the vacuum energy does cancel the contributions of all scalar fields to the vacuum energy.

Nevertheless, if from the theoretical point of view on one hand it does seem that a symmetry is missing in order to explain the cancellation of the cosmological constant by many orders of magnitude at quite different scales, from the observational side on the other, there is mounting evidence of a residual non-vanishing vacuum energy, that may be even substantial, although not dominating, when compared to the contribution of matter in the Universe. Indeed, a non-vanishing cosmological constant contributing to the density parameter, by $\Omega_0^\Lambda = 0.8$ (together with $\Omega_0^{CDM} = 0.15$ and $\Omega_0^{Baryons} = 0.05$) allows for the power spectrum of the Cold Dark Matter (CDM) model to be consistent with both COBE and IRAS observations [34] and also to make the age of the Universe compatible with the age of the oldest globular clusters $t_0 = (15.8 \pm 2.1) \ Gyr$ [35] for $0.58 < h_0 < 0.76$. Furthermore, a non-vanishing upper bound for the cosmological constant also arises from gravitational lensing studies, $\Omega_0^\Lambda < 0.75$ [38, 39], and is consistent with the Cosmic Background Radiation (CBR) power spectrum for $\Omega_0^\Lambda = 0.65$ [40] as well as with recent results of the Supernova Cosmology Project suggesting that $\Omega_0^\Lambda < 0.51$ [41]. Actually, strategies to determine $\Lambda$ from the anisotropies of the CBR, thanks to the Rees-Sciama effect, have also been proposed [42]. Finally, it has been argued that observations from various quarters, such as for instance, from nucleosynthesis and X-ray studies of the amount of baryons in rich clusters of galaxies to the age of Universe crisis, suggest that $\Omega_0^\Lambda = 0.6 - 0.7$

$^3$Values in this range are consistent with the ones arising from studies using the Type I supernovae as standard candles that indicate $h_0 = 0.67 \pm 0.07$, but are somewhat lower than the values emerging from studies using classical Cepheid variables observed by the Hubble Space Telescope, $h_0 = 0.82 \pm 0.17$ [37].
(and $\Omega_0^{Matter} = 0.3 - 0.4$ with $h_0 = 0.7 - 0.8$)\[43].

In order to relate the theoretical possibility of spontaneous breaking of the Lorentz symmetry with the observational contraints and also with the nearly complete cancellation of the vacuum energy we parametrize the vacuum expectation values of the Lorentz tensors as suggested in Ref. \[14] when studying the limits on the violation of the CPT symmetry:

$$\langle T \rangle = c \left( \frac{m_l}{M} \right)^l M,$$  \(3\)

where $c$ is an order one constant, $l$ is a non-negative integer and $m_l$ a light energy scale when compared to $M$.

We now assume that the yet unknown mechanism to solve the cosmological constant problem cancels out all contributions from scalars to the vacuum energy of order $M^4$, (and actually contributions of order $M^4_{GUT}$, $M^4_{SUSY}$, $G_F^{-2}$, etc ...) while leaving uncancelled contributions of order $m_V^4$, possibly through some soft symmetry breaking effect, where we assume consistently with the previous discussion that $\Omega_0^A = 0.50$ or in terms of energy density $\rho_V = (2.39 \times 10^{-3} \sqrt{h_0} \, eV)^4 \equiv m_V^4$. Hence the surviving contributions to the vacuum energy from (1) are: $m_T^2 M^2 (m_l/M)^2$, $M^4 (m_l/M)^2$ and $M^4 (m_l/M)^3$, where $m_T^2$ is the mass-squared (a positive eigenvalue of $M^2_{ij}$ in (1) after the Lorentz symmetry breaking) of a tensor field arising from the extra dimensional components of $T$, the coupling constants $g^{STT}_{ijk}$ and $g^{TTT}_{ijk}$ are all order one in $M$ units and $<S> \sim M$. A quite interesting possibility then follows supposing the relevant light scale is the one given by the mass, $m_T$, of the tensor field and that the contribution to the vacuum energy due to the non-vanishing expectation values of Lorentz tensors saturates $m_V^4$, that is:

$$m_l \equiv m_T = m_V,$$  \(4\)

for $l = 1$ when taking the third term in eq. (1) or $l = 2$ when considering the last two terms in (1). As we shall see below, the case $l = 1$ is compatible with experiments designed to detect deviations from the Lorentz invariance. This implies that the contributions from the vacuum expectation of Lorentz tensors can account for the observed vacuum energy if $m_T \sim m_V$ for $l = 1$. In this context, the cosmological constant puzzle consists in explaining the conditions under which the cancellation of
zeroth order terms and of scalar fields do occur. The preceeding assumptions lead
to a fairly interesting possibility from the phenomenological point of view as from
these new intermediate range interactions with $\lambda = m_T^{-1} = 8.26 \ h^{-1/2} \times 10^{-5} \ m$ are
expected. This range is essentially untested, for practically any coupling strength, by
experiments designed to test putative new finite range interactions \cite{44} and is not, so
far, ruled out.

Before we discuss the strength of the tensor-matter interactions arising from the
breaking of the Lorentz symmetry and the related issue of quantifying the resulting
violating effects in order to confront with observation, we mention that the possibility
of saturating the vacuum energy with the contribution of a (scalar) field associated to
some new symmetry has been previously discussed in Ref. \cite{45}. It was also pointed
out in that reference that cryogenic mechanical oscillator techniques \cite{46} may allow
for an improvement of existing limits on Yukawa type interactions by a factor up to
$10^{10}$ in the range about 100 $\mu m$. This range seems also to be favoured for scalar field
interactions in certain classes of supersymmetric theories \cite{47}.

Of course, parametrization (3) gives already an estimate of the Lorentz symme-
try violating effects, through the ratio $<T>/M$, which can be compared with
experimental limits. However, in order to better quantify this we have actually to
consider the coupling of Lorentz tensor fields to fermions via the trilinear string field
interactions. These are actually, the relevant couplings when studying CPT violation
\cite{14,15} and baryogenesis \cite{17}. The most general form for these interactions is the
following:

$$L_I = \frac{T}{M^k} \psi (\Gamma)^{k+1} (i \partial)^k \chi + h.c. ,$$

(5)

where $\lambda$ is a dimensionless coupling constant, $\chi$ and $\psi$ denote generic fermionic fields,
$\Gamma$ denotes a gamma-matrix structure, $(i \partial)^k$ represents the action of a four-derivative
at order $k \geq 0$ and the Lorentz indices were suppressed for simplicity. As before,
Lorentz and now CPT symmetries are violated as $T$ acquires non-vanishing vacuum
expectation values $\langle T \rangle$. From (3) one sees that factors of $i \partial_0$ also introduce a sup-
pression at low-energies.

An estimate of the violation of the Lorentz symmetry can be obtained from the
effect of the interactions \((3)\) between tensor field fluctuations around \((3)\), generically denoted by \(h\), to for instance a nucleon field, \(N\), with momentum \(p\):

\[
\lambda < T > \left( \frac{p}{M} \right)^k \frac{h}{M} \tilde{N}N, \quad (6)
\]

where we have scaled \(h\) by \(< T >\) and assumed that the appropriate contraction of indices is implied. Since in most experiments \(p \ll M\), hence for \(m_l \sim p\), the condition \(k + l \geq 1\) has to be respected in order to avoid obvious contradictions with existing experimental tests (see below). We can now study the set of values consistent with the measured deviations from the Lorentz symmetry. Notice, however that these considerations imply that a direct detection of the interaction \((6)\) is experimentally ruled out as its coupling strength \(\alpha = \lambda (m_1/M)^{k+1}\) is well within the region that, due to Newtonian and electrostatic background effects, is at present inaccessible for \(\alpha \leq 10^{-2}\) when \(\lambda \sim 10^{-4}m [43]\).

Limits on the violations of the Lorentz symmetry have been searched via laser-interferometric versions of the Michelson-Morley experiment that allow a comparison between the velocity of light, \(c\), and the maximum attainable velocity of massive particles, \(c_0\), up to \(\delta \equiv |c^2/c_0^2 - 1| < 10^{-9} [48]\), and through the measurement of the quadrupole splitting time dependence of nuclear Zeeman levels along Earth’s orbit. Experiments of the latter nature, known as Hughes-Drever tests \([49, 50]\), have been performed over the years \([51, 52]\), the most recent one \([53]\) revealing that \(\delta < 3 \times 10^{-21}\) \([\text{4}]\). Limits on the violation of the momentum conservation and existence of a preferred reference frame can be also inferred from the limits on the parametrized post-Newtonian parameter \(\alpha_3\) obtained from the pulse period of pulsars \([54]\) and millisecond pulsars \([55]\). This parameter vanishes identically in general relativity and the recent bound \(|\alpha_3| < 2.2 \times 10^{-20}\) obtained from binary pulsar systems \([56]\) implies the Lorentz symmetry holds up to the level established by that limit.

Let us now estimate the impact at low-energy of the string interactions. For the most stringent experimental tests of the Lorentz invariance, the Hughes-Drever tests, \(m_l \sim MeV(>> p)\) and we see from \((3)\) that Lorentz invariance violating effects

\[4\text{In these tests, deviations from the Local Lorentz Invariance are inferred via possible anisotropies of the inertial mass, } m_l, \text{ and } \delta = |m_l c^2/ \sum A E^A - 1|, \text{ where the sum is over all forms of internal energy of a chosen nucleus.}\]
are consistent with the experimental limits for \(k = 0\) and \(l = 1\). We mention that these conclusions are also consistent (for \(k = 1\) in this instance) with the recently discussed bounds for \(\delta\) that can be obtained from highly energetic cosmic rays (\(E \sim 10^{20}\) eV) and from neutrino oscillations \([57]\). We also point out that as far as violation of the CPT symmetry is concerned, the relevant condition when confronting with experimental evidence is \(k + l > 1\) \([14]\). Thus, if we aim to account for both Lorentz and CPT violations, we should take \(k = 0\) and \(l = 2\). This would imply that Lorentz symmetry breaking effects are well below the existing experimental limits, although they can still saturate the vacuum energy in this case as well.

Thus, we have seen that non-trivial solutions in string field theory may lead to fairly new implications and, in particular, to the quite distinct phenomenological signatures such as the ones associated with the violations of Lorentz and CPT symmetries. The spontaneous breaking of Lorentz symmetry arising from string field theory does imply that Lorentz tensor fields acquire masses and from that follows the existence of new tensor Yukawa type interactions. Assuming that the contribution of the vacuum expectation values of Lorentz tensors to the vacuum energy are uncancelled and responsible for the observed bounds to the cosmological constant implies that the range of the new interaction is \(\lambda \sim 10^{-4}\) m.

We would like to close with two final remarks. The discussed experimental limits on preferred-frame effects affect naturally the cosmological constant itself as the absence of the exact Lorentz symmetry implies its value is not constant throughout space. This feature leads to an anti-bias factor: structure formation occurs preferably where \(\Lambda\) is smaller. Finally, in a quite recent paper, Martel, Shapiro and Weinberg \([58]\) obtained, assuming the cosmological constant takes different values at different sites (referred to as subuniverses), that \(\rho_V \leq 3\rho_{\text{Matter}}\) is under fairly reasonable assumptions the most likely value for the vacuum energy. This value for \(\rho_V\) as well as the line of reasoning of that article could, of course, very well be used in the present work.
References

[1] N.S. Manton, Nucl. Phys. B158 (1979) 141.

[2] M.J. Duff and C.N. Pope, Nucl. Phys. B255 (1985) 355.

[3] Yu.A. Kubyshin, J.M. Mourão, G. Rudolph and I.P. Volobujev, Lecture Notes in Physics 349 (Springer Verlag, 1988)

[4] D. Kapetanakis and G. Zoupanos, Phys. Rep. C219 (1992) 1.

[5] V.A. Kostelecký and S. Samuel, Phys. Rev. D39 (1989) 683.

[6] V.A. Kostelecký and S. Samuel, Phys. Rev. Lett. 63 (1989) 224.

[7] M. Dine and N. Seiberg, Phys. Lett. B162 (1986) 299.

[8] A. Font, L.E. Ibáñez, D. Lüst and F. Quevedo, Phys. Lett. B245 (1990) 401; B249 (1990) 35.

[9] P.R. Phillips, Phys. Rev. 146 (1966) 966.

[10] H.B. Nielsen and M. Ninomiya, Nucl. Phys. B141 (1978) 153.

[11] S. Weinberg, Phys. Lett. B138 (1984) 47.

[12] E. Witten, Nucl. Phys. B186 (1981) 412; B195 (1982) 481.

[13] V.A. Kostelecký and R. Potting, Nucl. Phys. B359 (1991) 545; Phys. Lett. B381 (1996) 389.

[14] V.A. Kostelecký and R. Potting, Phys. Rev. D51 (1995) 3923.

[15] D. Colladay and V.A. Kostelecký, Phys. Lett. B344 (1995) 259; Phys. Rev. D52 (1995) 6224; V.A. Kostelecký and R. Van Kooten, Phys. Rev. D54 (1996) 5585.

[16] R. Adler et al. (CLEP Collaboration), J. Ellis, J.L. Lopez, N.E. Mavromatos and D.V. Nanopoulos, Phys. Lett. B364 (1995) 239.

[17] O. Bertolami, D. Colladay, V.A. Kostelecký and R. Potting, Phys. Lett. B395 (1997) 178.
[18] E. Witten, Nucl. Phys. B268 (1986) 253.

[19] S. Weinberg, Rev. Mod. Phys. 61 (1989) 1.

[20] S. Weinberg, “Theories of the Cosmological Constant” (astro-ph9610044).

[21] S. Coleman, Nucl. Phys. B307 (1988) 867.

[22] M.C. Bento and O. Bertolami, Gen. Rel. and Gravitation 28 (1996) 565.

[23] E. Witten, Int. J. Mod. Phys. 10 (1995) 1247.

[24] G. Moore, Nucl. Phys. B293 (1987) 139.

[25] G.D. Coughlan, W. Fischler, E.W. Kolb, S. Raby and G.G. Ross, Phys. Lett. B131 (1983) 59.

[26] J. Ellis, D.V. Nanopoulos and M. Quirós, Phys. Lett. B174 (1986) 176.

[27] O. Bertolami and G.G. Ross, Phys. Lett. B183 (1987) 163.

[28] O. Bertolami, Phys. Lett. B209 (1988) 277.

[29] B. de Carlos, J.A. Casas, F. Quevedo and E. Roulet, Phys. Lett. B318 (1993) 447.

[30] M.C. Bento and O. Bertolami, Phys. Lett. B336 (1994) 6.

[31] T. Banks, D.B. Kaplan and A.E. Nelson, Phys. Rev. D49 (1994) 779.

[32] T. Banks, M. Berkooz and P.J. Steinhardt, Phys. Rev. D52 (1995) 705.

[33] T. Banks, M. Berkooz, S.H. Shenker, G. Moore and P.J. Steinhardt, Phys. Rev. D52 (1995) 3548.

[34] G. Efstathiou, W.J. Sutherland and S.J. Maddox, Nature 348 (1990) 705.

[35] M. Bolte and C. Hogan, Nature 376 (1995) 399.

[36] A.G. Riess, W.H. Press and R.P. Kirshner, Ap. J. 438 (1995) L17.

[37] W.L. Freedman at al., Nature 371 (1994) 757.
[38] M. Fukugita and E.L. Turner, MNRAS 253 (1991) 99.

[39] D. Maoz and H-W. Rix, Ap. J. 416 (1993) 425.

[40] J.P. Ostriker and P.J. Steinhardt, Nature 377 (1995) 600.

[41] S. Perlmutter et al., “Measurement of the Cosmological Parameter Ω and Λ from
the First 7 Supernovae at z ≥ 0.35” (astro-ph/9608192).

[42] R.G. Crittenden and N. Turok, “Looking for Λ with the Rees-Sciama effect”
(astro-ph/9510072).

[43] L.M. Krauss and M.S. Turner, Gen. Rel. and Gravitation 27 (1995) 1137.

[44] E.Fishbach and C. Talmadge, “Ten Years of the Fifth Force” (hep-ph/9606249).

[45] S.R. Beane, “On the importance of testing gravity at distances less than 1 cm”
(hep-ph/9702419).

[46] J.C. Price, Proceedings of the International Symposium on Experimental Gravitat-ional Physics, eds. P. Michelson, H. En-Ke and G. Pizzella (D. Reidel, Dor-drecht 1987).

[47] S. Dimopoulos and G.F. Guidice, Phys. Lett. B379 (1996) 105.

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

[49] V.W. Hughes, H.G. Robinson and V. Beltran-Lopez, Phys. Rev. Lett. 4 (1960) 342.

[50] R.W.P. Drever, Philos. Mag. 6 (1961) 683.

[51] J.D. Prestage, J.J. Bollinger, W.M. Itano and D.J. Wineland, Phys. Rev. Lett. 54 (1985) 2387.

[52] S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab and E.N. Fortson, Phys.
Rev. Lett. 57 (1986) 3125.

[53] T.E. Chupp, R.J. Hoare, R.A. Loveman, E.R. Oteiza, J.M. Richardson M.E.
Wagshul and A.K. Thompson, Phys. Rev. Lett. 63 (1989) 1541.
[54] C.M. Will, “Theory and Experiment in Gravitational Physics” (Cambridge University Press, 1993).

[55] J.F. Bell, Ap. J. 462 (1996) 287.

[56] J.F. Bell and T. Damour, Class. Quantum Gravity 13 (1996) 3121.

[57] S. Coleman and S.L. Glashow, “Cosmic Ray and Neutrino Tests of Special Relativity” (hep-ph/9703240).

[58] H. Martel, P.R. Shapiro and S. Weinberg, “Likely Values of the Cosmological Constant” (astro-ph/9701099).