New Tests of Lorentz Invariance Following from Observations of the Highest Energy Cosmic Gamma Rays

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Abstract

We use the recent reanalysis of multi-TeV γ-ray observations of Mrk 501 to constrain the Lorentz invariance breaking parameter involving the maximum electron velocity. Our limit is two orders of magnitude better than that obtained from the maximum observed cosmic ray electron energy.

Key words: Lorentz invariance; gamma-rays

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1 Introduction

It is occasionally suggested that Lorentz invariance (LI) may be only an approximate symmetry of nature [1][2]. A simple and self-consistent framework for analyzing possible departures from exact LI was suggested by Coleman and Glashow[3], who assume LI to be broken perturbatively in the context of conventional quantum field theory. Small Lorentz noninvariant terms are introduced that are both renormalizable (*i.e.,* of dimension no greater than four) and gauge invariant under $SU(3) \times SU(2) \times U(1)$. It is further assumed that the Lagrangian is rotationally invariant in a preferred frame which is presumed to be the rest frame of the cosmic microwave background.

Consequent observable manifestations of LI breaking are either CPT even or odd, but the former effects are dominant at high energies. These can be described quite simply in terms of different maximal attainable velocities of different particle species as measured in the preferred frame. Indeed, this type

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of LI breaking within the hadron sector is one way to circumvent the predicted but unseen 'GZK cutoff' in the ultrahigh energy cosmic-ray spectrum owing to photomeson interactions with 2.7K cosmic background photons[4] which is expected to produce an effective absorption mean-free-path for ultrahigh energy cosmic rays in intergalactic space of < 100 Mpc [5] in the absence of LI breaking.

In this paper, we focus on possible departures from LI in the context of quantum electrodynamics, whose effects conceivably could make the universe transparent to ultra-high energy γ-rays[6].

2 The LI Breaking Parameter

We follow the well-defined formalism for LI breaking discussed in reference[3]. Within this scenario, the maximum attainable velocity of an electron need not equal the *in vacua* velocity of light, *i.e.,* $c_e \neq c_\gamma$. The physical consequences of this violation of LI depend on the sign of the difference. We define

$$c_e \equiv c_\gamma(1+\delta) \ , \qquad 0 < |\delta| \ll 1 \ , \tag{1}$$

and consider the two cases of positive and negative values of δ separately.

Case I: If $c_e < c_\gamma$ ($\delta \leq 0$), the decay of a photon into an electron-positron pair is kinematically allowed for photons with energies exceeding

$$E_{\rm max} = m_e \sqrt{2/|\delta|} \ . \tag{2}$$

The decay would take place rapidly, so that photons with energies exceeding $E_{\rm max}$ could not be observed either in the laboratory or as cosmic rays. From the fact that photons have been observed with energies $E_\gamma \geq 50$ TeV from the Crab nebula[7], we deduce for this case that $E_{\rm max} \geq 50$ TeV, or that $-\delta < 2 \times 10^{-16}$.

Case II: Here we are concerned with the remaining possibility, where $c_e > c_\gamma$ ($\delta \geq 0$) and electrons become superluminal if their energies exceed $E_{\rm max}/2$. Electrons traveling faster than light will emit light at all frequencies by a process of 'vacuum Čerenkov radiation.' This process occurs rapidly, so that superluminal electron energies quickly approach $E_{\rm max}/2$. However, because electrons have been seen in the cosmic radiation with energies up to ~ 1 TeV[8], it follows that $E_{\rm max} \geq 2$ TeV, which leads to an upper limit on δ for this case of 1.3×10^{-13}. We note that this limit is three orders of magnitude weaker than the limit obtained for Case I.

In this note, we show how stronger bounds on δ can be set through searches for energetic cosmic ray photons. For case I, the discussion is trivial: The mere detection of cosmic γ-rays with energies greater that 50 TeV from sources within our galaxy would improve the bound on δ. The situation for case II is more interesting.

If LI is broken so that $c_e > c_\gamma$, the threshold energy for the pair production process $\gamma + \gamma \rightarrow e^+ + e^-$ is altered because the square of the four-momentum becomes

$$2\epsilon E_\gamma(1-\cos\theta) - 2E_\gamma^2\delta = 4\gamma^2 m_e^2 > 4m_e^2 \tag{3}$$

where ϵ is the energy of the low energy (infrared) photon and θ is the angle between the two photons. The second term on the left-hand-side comes from the fact that $c_\gamma = \partial E_\gamma/\partial p_\gamma$.

For head-on collisions ($\cos\theta = -1$) the minimum low energy photon energy for pair production becomes

$$\epsilon_{min} = m_e^2/E_\gamma + (E_\gamma\,\delta)/2 \tag{4}$$

It follows that the condition for a significant increase in the energy threshold for pair production is $E_\gamma \geq E_{\rm max}$, or equivalently,

$$\delta \geq 2m_e^2/E_\gamma^2\,. \tag{5}$$

3 Recent Observations of the Blazar Mrk 501

The highest energy extragalactic γ-ray sources in the known universe are the active galaxies called ‘blazars,’ objects that emit jets of relativistic plasma aimed directly at us with typical bulk Lorentz factors $\sim$10. Those blazars known as X-ray selected BL Lac objects (XBLs), or alternatively as high frequency BL Lac objects (HBLs), are expected to emit photons in the multi-TeV energy range[9], but only the nearest ones are expected to be observable, the others being hidden by intergalactic absorption[10].

Cosmic photons with the highest energies yet observed originated in a powerful flare coming from the object known as Markarian (Mrk) 501[11]. Its spectrum was interpreted by Konopelko *et al.*[12] as most naturally showing the absorption effect predicted using the calculations of Stecker and De Jager[13], based on the infrared spectra predicted by Malkan and Stecker[14]. This absorption is the result of electron-positron pair production by interactions of the multi-TeV γ-rays from Mrk 501 with intergalactic infrared photons.

An analysis of direct far infrared data from the *COBE-DIRBE* satellite[15] was alleged to imply that there should be more absorbtion than evidenced in the Mrk 501 spectrum. Indeed, LI breaking was invoked[16] as one of various remedies for this supposed conflict. However, newer work on the infrared background[17] and a reanalysis of the Mrk 501 data with better energy resolution[18] indicate that the Mrk 501 spectrum is consistent with what one would expect from intergalactic absorption[19].

Intrinsic absorption within Mrk 501 is apt to be negligible because it is a giant elliptical galaxy with little dust to emit infrared radiation and because BL Lac objects have little gas (and therefore most likely little dust) in their nuclear regions. It also appears that γ-ray emission in blazars takes place at superluminal knots in the jet downstream of the core and at any putative accretion disks[20]. Thus, it appears that the Mrk 501 γ-ray spectrum above $\sim$ 10 TeV can be understood as a result of intergalactic absorption. We therefore interpret the Mrk 501 data as evidence for intergalactic absorption with no indication of LI breaking up to a photon energy of ~ 20 TeV.

4 Conclusion

If, as we argue above, there is no significant decrease in the optical depth to Mrk 501 for $E_\gamma \leq 20$ TeV, then it follows from eq. (5) that $\delta \leq 2(m_e/E_\gamma)^2 = 1.3 \times 10^{-15}$. This constraint is two orders of magnitude stronger than that obtained from cosmic-ray electron data as discussed in section II for the case when $\delta \geq 0$ (Case II). Our result for Case I ($\delta \leq 0$) is $|\delta| \leq 2 \times 10^{-16}$.

Further tests of LI could emerge from future observations. We mentioned earlier that the detection of galactic γ-rays with energies greater than 50 TeV would strengthen the bound on δ for Case I. As for Case II, the detection of cosmic γ-rays above $100(1+z_s)^{-2}$ TeV from an extragalactic source at a redshift z_s, would be strong evidence for LI breaking with $\delta \geq 0$. This is because the very large density (~ 400 cm^{-3}) of 3K cosmic microwave photons would otherwise absorb γ-rays of energy ≥ 100 TeV within a distance of ~ 10 kpc, with this critical energy reduced by a factor of $\sim (1+z_s)^2$ for sources at redshift z_s[21].

References

[1] H. Sato and T. Tati, Prog. Theor. Phys. **47**, 1788 (1972).

[2] G. Amelino-Camilia *et al.*, Nature **393**, 763 (1998).

[3] S. Coleman and S.L. Glashow, Phys. Rev. **D59**, 116008 (1999); see also D. Colladay and V.A. Kostelecky, Phys. Rev. **D58**, 116002 (1998).

[4] K. Greisen, Phys. Rev. Lettrs **16**, 148 (1966); G.T. Zatsepin and V.A. Kuz'min, JETP Letters **4**, 78 (1966).

[5] F.W. Stecker, Phys. Rev. Letters **21**, 1016 (1968).

[6] T. Kifune, Astrophys. J. **518**, L21 (1999).

[7] T. Tanimori *et al.*, Astrophys.J. **492**, L33 (1998).

[8] J. Nishimura *et al.*, Astrophys. J. **238**, 394 (1980).

[9] F.W. Stecker, O.C. De Jager and M.H. Salamon, Astrophys. J. **473**, L75 (1996).

[10] F.W. Stecker, O.C. De Jager and M.H. Salamon, Astrophys. J. **390**, L49 (1992).

[11] F.A. Aharonian *et al.*, Astron. and Astrophys., **349**, 11 (1999).

[12] A.K. Konopelko, J.G¿ Kirk, F.W. Stecker and A. Mastichiadas, Astrophys. J. **518**, L13 (1999).

[13] F.W. Stecker and O.C. De Jager, Astron. and Astrophys. **334**, L85 (1998).

[14] M.A. Malkan and F.W. Stecker, Astrophys. J. **496**, 13 (1998).

[15] M.G. Hauser *et al.*, Astrophys. J. **508**, 25 (1998).

[16] R.J. Protheroe and H. Meyer, Phys. Letters B **493**, 1 (2000).

[17] M.A. Malkan and F.W. Stecker, Astrophys. J., in press (2001), e-print astro-ph/0009500.

[18] F. A. Aharonian *et al.*, Astron. and Astrophys., in press (2001), e-print astro-ph/0011483.

[19] F.W. Stecker and O.C. De Jager, in prep.

[20] S.G. Jorstad *et al.*, submitted to the Astrophys. J., astro-ph/0102012.

[21] F.W. Stecker, Astrophys. J. **157**, 507 (1969); G.G. Fazio and F.W. Stecker, Nature **226**, 135 (1970).