Constraints on pseudoscalar-photon interaction from CMB polarization observation

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Effective pseudoscalar-photon interactions would induce a rotation of linear polarization of electromagnetic wave propagating with cosmological distance in various cosmological models. Pseudoscalar-photon interactions are proportional to the gradient of the pseudoscalar field. From the phenomenological point of view, this gradient could be neutrino number asymmetry, any density current, or a constant vector. In these situations, Lorentz invariance or CPT may effectively be violated. CMB polarization observations are superb tests of these models and have the potential to discover new fundamental physics. In this paper, we review the constraints on pseudoscalar-photon interactions from CMB polarization observations.

1 Introduction

In 1973, we studied the relationship of Galilio Equivalence Principe (WEP I) and Einstein Equivalence Principle in a framework (the χ-g framework) of electromagnetism and charged particles, we found the following theory with (gravitational) interaction Lagrangian density

$$L_{\rm int} = -(\frac{1}{16\pi})(-g)^{1/2}[\frac{1}{2}g^{ik}g^{jl} - \frac{1}{2}g^{il}g^{kj} + \phi\varepsilon^{ijkl}]F_{ij}F_{kl} - A_k j^k(-g)^{1/2} - \Sigma_I \frac{ds_I}{dt}\delta(x - x_I), \quad (1)$$

as an example which obeys WEP I, but not EEP [1, 2, 3]. The nonmetric part of this theory is

$$L^{(NM)}{}_{\rm int} = -(\frac{1}{16\pi})(-g)^{1/2}\phi\varepsilon^{ijkl}F_{ij}F_{kl} = -(\frac{1}{4\pi})(-g)^{1/2}\phi_{,i}\varepsilon^{ijkl}A_jA_{k,l} \text{ (mod div)}, \quad (2)$$

where 'mod div' means that the two Lagrangian densities are related by partial integration in the action integral. The Maxwell equations [1, 3] are

$$F^{ik}{}_{|k} + \varepsilon^{ikml}F_{km}\varphi_{,l} = -4\pi j^i, \quad (3)$$

where the derivation | is with respect to the Christoffel connection. The Lorentz force law is the same as in metric theories of gravity or general relativity. Gauge invariance and charge conservation are guaranteed. The Maxwell equations are also conformally invariant.

The last term in equation (2) is reminiscent of Chern-Simons [4] term $e^{\alpha\beta\gamma}A_\alpha F_\beta\gamma$. There are two differences: (i) Chern-Simons term is in 3 dimensional space; (ii) Chern-Simons term is a total divergence.

A term similar to the one in equation (2) (axion-gluon interaction) occurs in QCD in an effort to solve the strong CP problem (Peccei and Quinn [5], Weinberg [6], Wilczek [7]). Carroll, Field and Jackiw [8] proposed a modification of electrodynamics with an additional $e^{ijkl}V_iA_jF_{kl}$ term with V_i a constant vector. This term is a special case of the term $e^{ijkl}\varphi F_{ij}F_{kl}$ (mod div) with $\varphi_{,i} = -\frac{1}{2}V_i$.

Various terms in the Lagrangians discussed in this section are listed in Table 1. Empirical tests of the pseudoscalar-photon interaction (2) from CMB polarization observation will be discussed in section 2. Section 3 will present an outlook.

Term	Dimension	Reference	Meaning
$e^{\alpha\beta\gamma}A_\alpha F_{\beta\gamma}$	3	Chern-Simons (1974[4])	Integrand for topological invariant
$e^{ijkl}\varphi F_{ij}F_{kl}$	4	Ni (1973[1], 1974[2],1977[3])	Pseudoscalar-photon coupling
$e^{ijkl}\varphi F^{QCD}{}_{ij}F^{QCD}{}_{kl}$	4	Peccei-Quinn (1977[5]) Weinberg (1978[6]) Wilczek (1978[7])	Pseudoscalar-gluon coupling
$e^{ijkl}V_iA_jF_{kl}$	4	Carroll-Field-Jackiw (1990[8])	External constant vector coupling

Table 1: Various terms in the Lagrangian and their meaning.

2 Constraints from CMB polarization observation

Pseudoscalar-photon interactions induce polarization rotation in electromagnetic propagation. From (3), for the right circularly polarized electromagnetic wave, the propagation from a point P_1 to another point P_2 adds a phase of $\alpha = \varphi(P_2) - \varphi(P_1)$ to the wave; for left circularly polarized light, the added phase will be opposite in sign [1]. Linearly polarized electromagnetic wave is a superposition of circularly polarized waves. Its polarization vector will then rotate by an angle α. When the propagation distance is over a large part of our observed universe, we call this phenomenon cosmic polarization rotation [9, 10].

Since the first successful polarization observation of the cosmological microwave background (CMB) in 2002 by DASI [11] (Degree Angular Scale Interferometer), there have been a number of observations [12-16] with better precision. These observations set limits on the electromagnetic polarization rotation due to effective pseudoscalar-photon interaction.

In the CMB polarization observations, there are variations and fluctuations. The variations and fluctuations due to scalar-modified propagation can be expressed as $\delta\varphi(2) - \delta\varphi(1)$, where 1 denotes a point at the last scattering surface in the decoupling epoch and 2 the observation point. $\delta\varphi(2)$ is the variation/fluctuation at the last scattering surface. $\delta\varphi(1)$ at the present observation point is fixed. Therefore the covariance of fluctuation $< [\delta\varphi(2) - \delta\varphi(1)]^2 >$ gives the covariance of $\delta\varphi^2(2)$ at the last scattering surface. Since our Universe is isotropic to $\sim 10^{-5}$, this covariance is $\sim (\xi \times 10^{-5})^2$ where the parameter ξ depends on various cosmological models [10, 17].

In 2002, the DASI microwave interferometer observed the polarization of the cosmic background [11]. E-mode polarization is detected with 4.9 σ. The TE correlation of the temperature and E-mode polarization is detected at 95% confidence. This correlation is expected from the Raleigh scattering of radiation. However, with the (pseudo)scalar-photon interaction (2), the polarization anisotropy is shifted differently in different directions relative to the temperature anisotropy due to propagation; the correlation will then be downgraded. In 2003, from the first-year data (WMAP1), WMAP found that the polarization and temperature are correlated to more than 10 σ [12]. This gives a constraint of about 10^{-1} for $\Delta\varphi$ [9, 18].

Further results [13-16] and analyses [15, 19-27] of CMB polarization observations came out after 2006. In Table 1, we update our previous compilations of [10, 17]. Although these results look different at 1 σ level, they are all consistent with null detection and with one another at 2 σ level. For the interpretation of cosmic polarization rotation in various cosmologic models, please see [10, 17].

The Faraday rotation due to a magnetic field is wavelength-dependent while the cosmic polarization rotation due to effective pseudoscalar-photon interaction is wavelength-independent. This property can be used to separate the two effects in more precise observations.

Reference	Constraint [mrad]	Source data
Ni [9, 18]	± 100	WMAP1 [12]
Feng, Li, Xia, Chen, and Zhang [19]	-105 ± 70	B03 [14]
Liu, Lee, Ng [20]	± 24	B03 [14]
Kostelecky and Mews [21]	209 ± 122	B03 [14]
Cabella, Natoli and Silk [22]	-43 ± 52	WMAP3 [13]
Xia, Li, Wang, and Zhang [23]	-108 ± 67	WMAP3 [13] & B03 [14]
Komatsu, *et al.* [15]	-30 ± 37	WMAP5 [15]
Xia, Li, Zhao, and Zhang [24]	-45 ± 33	WMAP5 [15] & B03 [14]
Kostelecky and Mews [25]	40 ± 94	WMAP5 [15]
Kahniashvili, Durrer, and Maravin	± 44	WMAP5 [15]
Wu, *et al.* [27]	$9.6 \pm 14.3 \pm 8.7$	QuaD [16]

Table 2: Constraints on cosmic polarization rotation from CMB (cosmic microwave background).

3 Discussion and Outlook

Better accuracy in CMB polarization observation is expected from PLANCK mission launched on May 14, 2009. Dedicated CMB polarization observers like B-Pol mission, CMBpol mission and LiteBIRD mission would improve the sensitivity further. These development would probe the fundamental issues of effective pseudoscalar-photon interactions discussed in this paper more deeply in the future.

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References

[1] W.-T. Ni, A Nonmetric Theory of Gravity, preprint, Montana State University, Bozeman, Montana, USA (1973), http://cgc.pmo.ac.cn

[2] W.-T. Ni, Bull. Am. Phys. Soc. **19** 655 (1974).

[3] W.-T. Ni, Phys. Rev. Lett. **38** 301 (1977).

[4] S.-S. Chern and J. Simons, Characteristic forms and geometric invariants *The Annals of Mathematics*, 2nd Ser. **99** 48 (1974).

[5] R. D. Peccei and H. Quinn, Phys. Rev. Lett. **38** 1440 (1977).

[6] S. Weinberg, Phys. Rev. Lett. **40** 233 (1978).

[7] F. Wilczek, Phys. Rev. Lett. **40** 279 (1978).

[8] S. M. Carroll, G. B. Field and R. Jackiw, Phys. Rev. **D41** 1231 (1990).

[9] W.-T. Ni, Chin. Phys. Lett. **22** 33 (2005) [arXiv:gr-qc/0407113].

[10] W.-T. Ni, Prog. Theor. Phys. Suppl. **172** 49 (2008) [arXiv:0712.4082] .

[11] J. M. Kovac *et al.*, Nature **420** 722 (2002).

[12] C. L. Bennett *et al.*, Astrophys. J. Suppl. **148** 1 (2003); and references therein.

[13] D. N. Spergel *et al.*, Astrophys. J. Suppl. **170** 377 (2007); and references therein.

[14] T. E. Montroy *et al.*, Astrophys. J. **647** 813 (2006); and references therein.

[15] E. Komatsu *et al.*, Astrophys. J. Suppl. **180** 330 (2009) [arXiv:0803.0547].

[16] C. Pryke *et al.*, Astrophys. J. **692** 1247 (2009).

[17] W.-T. Ni, Int. J. Mod. Phys. **A18 & 19** 3493 (2009) [arXiv:0903.0756].

[18] W.-T. Ni, Int. J. Mod. Phys. **D14** 901 (2005) [arXiv:gr-qc/0504116].

[19] B. Feng *et al.*, Phys. Rev. Lett. **96** 221302 (2006).

[20] G. C. Liu, S. Lee and K. W. Ng, Phys. Rev. Lett. **97** 161303 (2006); private communication.

[21] A. Kostelecky and M. Mewes, Phys. Rev. Lett. **99** 011601 (2007).

[22] P. Cabella, P. Natoli and J. Silk, Phys. Rev. **D76** 123014 (2007).

[23] J.-Q. Xia *et al.*, Astron. Astrophys. **483** 715 (2008).

[24] J.-Q. Xia *et al.*, Astrophys. J. **679** L61 (2008).

[25] V. A. Kostelecky and M. Mewes, Astrophys. J. **689** L1 (2008).

[26] T. Kahniashvili, R. Durrer and Y. Maravin, Phys. Rev. **D78** 123009 (2008).

[27] E.-Y.-S. Wu *et al.*, Phys.Rev. Lett. **102** 161302 (2009).