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PROTECTING INVISIBLE AXION from PLANCK SCALE PHYSICS

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November 1992

Abstract

It is pointed out, contrary to what is commonly believed, size of the intrinsic Peccei-Quinn symmetry breaking due to nonperturbative quantum gravity may be small. I exemplify this and explicitly estimate the breaking size arising from a certain class of gravitational instantons, wormholes and virtual black holes. Decoupling of pure gravity dynamics from the Peccei-Quinn mechanism and large hierarchies put into the standard model are seen to underlie in suppressing the forementioned gravitational effects. Conditions to the standard model matter representations for a 'gravitationally natural' axion model are also given.

*Talk given at APS Division of Particle and Fields '92 Meeting at Fermilab, November 10-14, 1992. E-mail: soo@puhep1.princeton.edu

Short distance physics near the Planck scale is said to induce an intrinsic breaking to the otherwise conserved global symmetries. Based on this, it was pointed out recently that quantum gravity effects might invalidate Peccei-Quinn (PQ) symmetry and associated axion solutions to the 'strong-CP' problem [1]. However, serving only as a plausible *existence* argument, the above works were not able to estimate *size* of the induced PQ symmetry breaking operators. Thus, the very issue whether and how big the PQ mechanism and axion physics are to be modified by Planck scale physics has remained unsettled.

In this talk, under certain assumptions on semiclassical gravity, I present a *quantitative* estimate of the forementioned effects. Since gravitational interaction is CP conserving perturbatively, the only conceivable source of CP violation is nonperturbative quantum gravity dynamics. Known sources include gravitational instantons, Euclidean wormholes and virtual black holes of near-Planck scale size. Assuming these nonperturbative effects to be included in physical S-matrix calculations, I estimate how big their effects are and point out that the effects appear so small that axion solution to the strong CP problem remains hardly affected.

The standard model including gravity contains three CP-odd θ terms:

$$S_\theta = \int_M [\frac{\theta_{\rm QCD}}{16\pi^2}{\rm Tr}\mathbf{G}_{\mu\nu}\tilde{\mathbf{G}}_{\mu\nu} + \frac{\theta_{\rm em}}{32\pi^2}F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{\theta_{\rm grav}}{384\pi^2}Tr\mathbf{R}_{\mu\nu}\tilde{\mathbf{R}}_{\mu\nu}] \qquad (1)$$

In the semiclassical gravity, the CP violating effects associated with $\theta_{\rm em}$ and $\theta_{\rm grav}$ arise through gravitational vacuum tunnelling configuration M (with a nontrivial $H_2(M;\mathbf{Z})$). The simplest gravitational instanton is known to be Eguchi-Hanson (EH) instanton [2] of size $a > M_{\rm pl}^{-1}$ with self-dual curvature and Maxwell fields:

$$g_{\mu\nu} = \delta_{\mu\nu} - \frac{a^4}{x^4}\frac{x^\mu x^\nu}{x^2} + \frac{a^4}{x^4 - a^4}\frac{\tilde{x}^\mu\tilde{x}^\nu}{x^2}; \quad A_\mu = \frac{2Pa^2\tilde{x}^\mu}{x^4} \quad (\tilde{x}^\mu \equiv (y, -x, t, -z)). \quad (2)$$

On the EH instanton background, fermion chiral charge $Q_5 \equiv \int d^3\mathbf{x}J_5^0$ becomes anomalous because of the self-dual $U_{\rm em}(1)$ gauge field:

$$\Delta Q_5 = \int_M [{\rm Tr}\mathbf{R}\tilde{\mathbf{R}} - F\tilde{F}] = 2P^2Q_{\rm em}^2. \qquad (3)$$

Neutral EH instanton has a vanishing action. Fortunately, Eq.(3) implies it does not affect the PQ symmetry. Pure semiclassical gravity dynamics does

not affect the axion physics. On the other hand, charged EH instanton does break PQ symetry, but the size is suppressed by e^{-S_E} where $S_E = P^2\pi/\alpha$. Therefore, semiclassical gravity is seen to affect the axion physics only indirectly through nontrivial $U_{\rm em}(1)$ gauge field supported by the topologically nontrivial EH metric. Scale invariance of $U_{\rm em}(1)$ gauge field then implies $M_{\rm pl}$ *independence* of the instanton action. Operator induced by a minimally charged, $P = 3$ EH instanton is calculated as [3]:

$$\begin{aligned}\mathcal{O}_{\rm EH}[a] =& \frac{1}{a^4}\exp[-\frac{9\pi}{\alpha(a)} + i\frac{Na}{f_{\rm pq}} + i\theta_{\rm em}] \\ & Det[\{(\bar{E}_R E_L)^9 \prod_{\rm color}(\bar{U}_R U_L)^4(\bar{D}_R D_L)\}^{N_g} \prod_{\rm heavy}(\bar{Q}_R Q_L)^{9Q^2_{\rm em}}].\end{aligned} \tag{4}$$

in which $N \equiv Tr[Q_{\rm pq}Q^2_{\rm em}]$, N_g denotes number of the standard model generations, and $Q_{\rm L,R}$'s possible extra heavy fermions.

Naively, size of the axion potential induced by the EH instanton is of order $\sim \frac{1}{a^4} \sim M^4_{\rm pl}$. However, fermion 'quasi' zero modes in Eq.(4) is needed to be contracted using Yukawa interaction and Higgs self-coupling vertices. This gives

$$\int_{M_{\rm pl}^{-1}} \frac{da}{a} \mid <\mathcal{O}_{\rm EH}[a]> \mid \leq 10^{-10}\Lambda^4_{\rm qcd}. \tag{5}$$

In this estimate, I have taken $\alpha_e(f_{\rm pq}) = 0.1$, top quark mass $\sim 150\,GeV$ and added four color triplet heavy quarks of charge $Q_{\rm em} = 2/3$ and mass $10^{10}\,GeV$ to exemplify possible enhancement of the effect. I refer to Ref. 1 for details of the calculation. The result Eq.(5) turned out rather insensitive to variations such as a different choice of instanton size integration measure, but is generically dominated by $a \sim f^{-1}_{\rm pq}$. Therefore, the effect is seen sensitive to the heavy matter content near the PQ scale but *not* to details of the Planck scale physics! Hence, under certain variations of the standard model, Eq.(5) implies that the gravitational instantons does not affect axion solution to the strong CP problem.

What are responsible for the suppression of near-Planck scale physics? Eq. (4) indicates this due to (1) *decoupling* of pure gravity sector CP violation from the PQ mechanism and axions, (2) *light* charged fermion masses compared to $M_{\rm pl}$ and $f_{\rm pq}$, and (3) presence of *large hierarchies* among various scales: $\Lambda_{\rm QCD} < < M_W \ll f_{\rm pq} \ll M_{\rm pl}$. The latter two points strongly suggest an intimate connection between the very issue of intrinsic global symmetry breaking by

Planck scale physics and solutions to *naturalness and hierarchy problems* within the standard model.

Generalizing the above observations, the most 'efficient' decoupling of Planck scale effect to the axion physics is found achieved if the matter content satisfy

$$\mathrm{Tr}[Q_{\mathrm{pq}}\mathbf{T}_a^2] \neq 0; \quad \mathrm{Tr}[Q_{\mathrm{pq}}Q_{\mathrm{em}}^2] = \mathrm{Tr}[Q_{\mathrm{pq}}] = 0. \tag{6}$$

This implies, in particular, quarks of at least two different color and $U_{\mathrm{em}}(1)$ representations should appear. Quite amusingly, Eq.(6) are found satisfied by several automatic axion models arising in superstring theory with either discrete gauge symmetries or anomalous $U(1)$ symmetry and hidden sector gaugino condensates.

What about wormholes and virtual black holes? Self consistent, semiclassical gravity implies that the wormholes supported by global symmetries are exponentially suppressed [4]. After all, it is rather artificial that wormhole requires a continuous global symmetry near Planck scale for its existence, which then breaks the symmetry intrinsically. From this point of view, a particularly natural class of wormholes are those supported by nontrivial Yang-Mills (YM) gauge fields [5]:

$$g_{\mu\nu} = \delta_{\mu\nu}(1+\frac{R^2}{x^2}); \quad A_\mu^a = \eta_{\mu\nu}^a \partial^\nu \ln(x^2+R^2)^{1/2} \qquad (0 < R^2 < (g^2 M_{\mathrm{pl}}^2)^{-1}). \tag{7}$$

They represent *nonsingular* gravitating merons with a *finite action.* However, a detailed calculation shows that YM wormholes do not induce fermion chiral charge asymmetry, hence, neither wormhole induced axion potentials (as does the neutral EH instantons).

'Micro-black holes' in a rapidly decaying state is expected to have a strong CPT symmetric antipodal correlations of Hawking radiation. The antipodal correlation suggests [2] that such a state may be approximated by Minkowski spacetime rotated EH instantons. Problem associated with complex metric is get around if the metric is interpreted to represent an off-diagonal matrix element. If the above interpretation of EH instanton were correct, the calculation presented above shows little influence of such black holes to the invisible axion physics.

In conclusion, through concrete semiclassical gravity calculations, I pointed out near-Planck scale physics may not be so dangerous to the fate of Peccei-Quinn mechanism and axion physics as it is commonly said.

References

[1] R. Holman et.al., *Phys. Lett.* **282B** (1992) 132; M. Kamionkowski and J. March-Russell, *ibid.* 137; S. Barr and D. Seckel, *Phys. Rev.* **D64** (1992) 333.

[2] T. Eguchi and A. Hanson, *Ann. Phys.* **120** (1979) 82; G. 't Hooft, *Nucl. Phys.* **B315** (1989) 517.

[3] R. Holman, T. Kephart and S.-J. Rey, *Semiclassical Gravity and Invisible Axion,* NSF-ITP-92-85 preprint, to appear in *Phys. Rev. Lett.* (1992).

[4] S.-J. Rey, *Phys. Rev.* **D25** (1989) 2015.

[5] S.-J. Rey, *Nucl. Phys.* **B336** (1990) 146.