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SCREENING OF THE ELECTRIC CHARGE DEGREE OF FREEDOM OF AN ABELIAN DYON BY AN AXION CLOUD

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By assuming the presence of an axion cloud surrounding an Abelian dyon we demonstrate that the electric charge degree of freedom of the dyon can be completely screened by a specific choice of the boundary conditions for the axion field. Such a semiclassical analysis demonstrates that strong CP violations can give rise to the apparent violation of electric charge conservation.

I. INTRODUCTION

One of the outstanding questions in particle theory is why CP does not seem to be a broken symmetry for the strong interactions in an appreciable way when the topological vacuum structure of Q.C.D. demands the presence of the term $\Theta F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$ which breaks CP [1]. The conventional solution to the problem is to introduce a Peccei Quinn U(1) global symmetry that allows for the rotation away of the angle Θ through the argument of the quark mass matrix [2]. When this U(1) symmetry is broken, the theory is that the angle produced is small, and a pseudo-Goldstone boson, the axion, is left. The axion gains a small dynamical mass through Q.C.D. instanton effects after the electroweak phase transition [3]. The axion interacts with the electromagnetic field through quark loops and an effective lagrangian of the axion interacting with photons results at low energy. In a quite different approach E. Witten has discussed the effect that CP violating interactions would have on the electric charge degree of freedom of a dyon and has demonstrated that such CP violating interactions give rise to a non-integral electric charge for the electric charge degree of freedom of the dyon [4]. The purpose of this note is to demonstrate that because of the anomolous axion — electromagnetic interaction an Abelian dyon can be totally screened by an axion cloud with specific boundary conditions on the axion field. Such a result suggests that the electric charge can in a sense be hidden or is not

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conserved in the presence of this interaction. The actual mechanism of this charge screening is carried by the interaction between the magnetic charge of the dyon and the axion field with the result that to a probe outside the axion cloud no electric charge of the dyon will be noticed if the probe is a test charge.

II. CHARGE SCREENING OF A DYON BY AN AXION CLOUD

To motivate the charge screening effect, we first point out that the existence of monopoles was first suggested by Dirac [5] in order to understand the quantization of the electric charge. In a more modern context, t'Hooft [6] and Polyakov [7] pointed out that monopoles are a consequence of any G.U.T. theory whose symmetry is broken to leave a residual U(1) factor. Whenever monopoles are permitted by a theory, dyons also exist as solutions to the field equations with the addition of the electric charge degree of freedom to the monopole. As mentioned above, the axion was introduced to solve the strong CP problem by introducing a global U(1) symmetry to adjust the CP violating parameter in the CP violating term of Q.C.D. $\Theta F^{a}_{\mu\nu} F^{a\mu\nu}$. The axion is the pseudo-Goldstone boson that remains after breaking the global U(1) symmetry, this in turn leaves a small CP violating term $\Theta F^{a}_{\mu\nu} F^{a\mu\nu}$. Axions can be produced in the core of stars through the coupling to photons and electrons as discussed by Pantziris and Kang [8] and Raffelt [9], if they escape from the stellar interior they could be found in clouds that might attach themselves to other astrophysical objects. Of course, in the early universe, axions would be produced copiously through the same interaction that produced them in stellar interiors. If a surviving dyon produced after the G.U.T. phase transition captured an axion cloud, we have the possibbility of the cloud forming a shell about the dyon wherein the space close to the dyon is free of axions. Such a dyon axion shell might also be found in the vicinity of axion domain walls in the early universe as discussed by Sikivie (Ref. [1]). Assuming that such a dyon axion cloud has formed, we write for the effective lagrangian of electromagnetism and the axion field,

$$L = \left[\frac{-1}{16\pi} F_{\mu\nu} F^{\mu\nu} + \frac{\partial^{\mu}\Phi\partial_{\mu}\Phi}{2} = -\frac{m_a^2 V^2 C^2}{N^2 \hbar^2}\left(1 - \cos\frac{N\Phi}{V}\right) \right.\sqrt{-g} \\ \left. + \frac{e^2}{\hbar c}\left(\Theta_\delta + \frac{T_\Theta}{2\pi}\right)\frac{N\Phi}{V}\frac{\varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}F_{\mu\nu}}{64\pi^2 \sin^2\Theta_W \sqrt{-g}} \right] . \tag{2.1}$$

This lagrangian results from integrating the quark loops that convert the axion

field into two photons as pointed out in Ref. [3]. We define

$$\bar{K} = \frac{e^2}{\hbar C}\left(\Theta_\delta + \frac{T_\Theta}{2\pi}\right)\frac{N}{V}\frac{1}{64\pi^2 \sin^2\Theta_W},$$

where Φ = axion field, N = number of axion vacuum, m_a = axion mass, V = vacuum expectation value that breaks the P.Q. symmetry, Θ_W^0 = electro-weak angle at the G.U.M. scale, $e^2 = e_s^2 \sin^2\Theta_W^0$, e_s = gauge coupling of Q.C.D., $\Theta_\delta = \Theta$(Q.C.D.) at the G.U.M., $T_\Theta = 2\pi$ for Q.C.D. and SU(5) as the G.U.T. group, $\sin\Theta_W$ = the Weinberg angle at an electro-weak scale. (G.U.M. signifies the grand unified mass scale). Also, $F_{\mu\nu}$ = electromagnetic field strength.

If we vary equation 2.1 with respect to $\lesseqgtr$, $F_{\mu\nu}$, we have after approximating

$$\left(1 - \cos\frac{N_\Phi}{V}\right) \approx \frac{N^2\Phi^2}{2V^2}$$

$$-\Box\Phi - \frac{m_a^2 C^2 \Phi}{\hbar^2} + \bar{K}\left(\frac{\varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}F_{\mu\nu}}{\sqrt{-g}}\right) = 0 \tag{2.2}$$

$$\frac{\partial}{\partial x^{\upsilon}}\left(\frac{1}{4\pi}\sqrt{-g}F^{\mu\upsilon}\right) - \frac{\partial}{\partial x^{\upsilon}}(4\bar{K}\Phi\varepsilon^{\mu\upsilon\alpha\beta}F_{\alpha\beta}) = 0. \tag{2.3}$$

We now consider an Abelian dyon with $F_{14} = E(r)$, $F_{23} = r^2 \sin\Theta B_r$, at $r = 0$. The electric charge and magnetic charge are e_0, q_0. In choosing the axion configuration we assume that an axion free region exists about the dyon and a cloud of axions forms between an inner and an outer radius. We assume that the dyon is originally in matter free space and this lends justification to the axion configuration to have an inner radius. We also assume that the axion configuration is not too large so as to prevent a collapse due to self-gravitational effects. The dyon can be viewed as Abelian far from the core of the dyon since even the G.U.T. dyons appear as Abelian dyons in the far field regions. The axion field in the separate regions around the dyon is

$$(0 < r < r_1, (\Phi = 0))$$

having no axion field, $r_1 \le r \le r_2$ with $\Phi = \Phi(r)$, $\Phi(r_1) = \Phi_1$, $\Phi(r_2) = \Phi_2$ and $\Phi(r) = 0$ for $r > r_2$. For $r < r_1$, equation 2.3 gives

$$\frac{\partial}{\partial r}(r^2 E(r)) = 0, \quad E = \frac{e_0}{r^2}. \tag{2.4}$$

For the magnetic field we use the condition

$$\frac{\partial}{\partial x^{\upsilon}}(\varepsilon^{\mu\upsilon\alpha\beta}F_{\alpha\beta}) = 0,$$

which is a statement of the anti-symmetry of $F_{\mu\nu}$. This gives

$$\frac{\partial}{\partial r}(\varepsilon^{4123}F_{23}) = 0, \quad \frac{\partial}{\partial r}(r^2 \sin\Theta B_r) = 0 \tag{2.5}$$

or

$$B_r = \frac{q_0}{r^2} \tag{2.6}$$

for $r < r_1$.

For $r_1 \leq r \leq r_2$ equation 2.3 integrates to give where we still have $F_{14} = E(r)$, $F_{23} = r^2 \sin\Theta B_r$;

$$\frac{1}{4\pi} r^2 E(r) - 8\bar{K}\Phi(r) r^2 B_r = C \tag{2.7}$$

At $r = r_1$ we have $E = \frac{e_0}{r_1^2}$, $B = \frac{q_0}{r_1^2}$ giving $C = \frac{e_0}{4\pi} - 8\bar{K}\Phi(r_1)q_0$. (2.8)

Here we match the electric and the magnetic field at the boundaries r_1 and r_2. We note from equation 2.5 that the solution $B = \frac{q_0}{r^2}$ holds also for $r_1 \leq r_2$ and $r > r_2$ since $B(r)$ must match axross each boundary and always has the form $B = \frac{q}{r^2}$ from Equation 2.5 in all regions. Thus equation 2.7 gives

$$\frac{r^2 E(r)}{4\pi} - 8\bar{K}\Phi(r) r^2 B_r = \frac{e_0}{4\pi} - 8\bar{K}\Phi_1 q_0 \quad \text{for } r_1 \leqslant r \leqslant r_2. \tag{2.9}$$

Now at

$$r = r_2, \quad \frac{r_2^2 E(r_2)}{4\pi} = \frac{e_0}{4\pi} + 8\bar{K}(\Phi_2 - \Phi_1)q_0 \tag{2.10}$$

if

$$\frac{e_0}{4\pi} + 8\bar{K}(\Phi_2 - \Phi_1)q_0 = 0; \tag{2.11}$$

this implies $E(r_2) = 0$ at $r = r_2$ and thus $E(r) = 0$ for $r > r_2$ since the solution for $r > r_2$ from equation 2.3 is $E(r) = \frac{e}{r^2}$ and must match the value of $E(r)$ found in the inner-region at $r = r_2$. Thus $e = 0$ for $r > r_2$ since $E = 0$ and the dyon has an effective electric charge of zero for the region $r > r_2$.

Among the implications of such a result we have the possibility that such an axion screened dyon well could live in the early universe or even in the late universe without decaying since the magnetic field whose source is the magnetic charge would not attract charged particles to cause a decaying of the system through charge neutralization. Such configurations might serve as nucleating centres to trigger galaxy formation if the dyons were of astrophysical size. Though the configuration might be quite small it could at least trigger an inhomogeneity to start the process of galaxy formation in the early universe.

III. CONCLUSION

We have seen from the above analysis that by a proper choice of boundary conditions on the axion field at r_1 and r_2 such that Equation 2.11 is satisfied, the electric charge in the region $r \geqslant r_2$ is effectively zero. The dyon has effectively become converted into a monopole with magnetic charge q_0. In early universe studies this would provide an efficient screening mechanism to prevent the electrical attraction or repulsion of dyons. The boundary conditions on the axion fields at $r = r_1$, $r = r_2$ seem rather unrealistic, however our model at this point was created to illustrate the charge screening mechanism. We also note that if e_0 is an integer charge, then by choosing Φ_2, Φ_1 arbitrarily in Equation 2.10 we have for the external electric charge

$$\frac{e}{4\pi} = \frac{e_0}{4\pi} + 8\bar{K}(\Phi_2 - \Phi_1)q_0,$$

which could very well generate a non-integral e. Just recently T. Wada et al [10] have reported charge (4/3e) leptons which, if confirmed in other experiments, would suggest that fractional charges do exist and are either fractional charged partners of ordinary leptons in the G.U.T. theory with exotic multiplets, or have an internal structure that is generated through a microscopic analogue of the above mechanism that gives rise to a fractional charge to the external world. We thus have an analogue of the Witten effect in this simplified model. It is also abvious that by choosing $\Phi_2 - \Phi_1 < 0$, $e = -e_0$,

$$\text{for } \Phi_2 - \Phi_1 = \frac{-2e_0}{(4\pi)(8\bar{K}q_0)}.$$

Thus we may invert the sign of the electric charge by proper choice of Φ_2 and Φ_1. With the anomalous term in Equation 2.1 on a microscopic level, we have the possibility of transforming repulsive forces into attractive forces which might be useful in preon binding models that use an electric and a magnetic charge as basic elements (11). The last interesting possibility is that of having alternate layers of axion configurations to give rise to an alternating sign to the effective charge seen by a test particle. Before concluding we note that the discontinuous change of Φ from one side of the boundary to the other would be hard to simulate in a real physical situation but might in a more realistic model be replaced by a transition layer across which E and B are constant but Φ rapidly changes.

REFERENCES

[1] Sikivie, P., Phys. Rev. Lett. *48* (1982), 1156.
[2] Peccei, R. D., Quinn, H. R., Phys. Rev. Lett. *38* (1977), 1440.
[3] Sikivie, P., Phys. Rev. Lett. *137B* (1984), 355.
[4] Witten, E., Phys. Lett. *86B* (1979), 287.
[5] Dirac, P. A. M., Proc. Roy, Soc. London, Sec. A. *133* (1931), 60.
[6] t'Hooft, G., Nucl. Phys. B *79* (1978), 276.
[7] Polyakov, A., Pis'ma Zh. Eksp. Theor. Fiz. *20* (1974), 430; (J.E.T.P. Lett. *20* (1974) 194.).
[8] Pantziris, A., Kang. K., Phys. Rev. D. *33* (1986), 3509.
[9] Raffelt, G. G., Phys. Rev. D. *33* (1986), 897.
[10] Wada, T., Tamashita, Y., Yamamoto, I., Tomiyama, T., Il Nuovo Cimento, *11C* (1988), 229.
[11] Patti, J. C., Phys. Lett. *98B* (1981), 40.

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ЭКРАНИРОВАНИЕ СТЕПЕНЕЙ СВОБОДЫ ЭЛЕКТРИЧЕСКОГО ЗАРЯДА АБЕЛОВСКОГО ДИОНА ОБЛАКОМ АКСИОНА

Б предположении ирисутствия облака аксиона окружающего Абеловский дион показано, что степени свободы заряда диона будут полностью экранированы специфическим вбором граничных условий поля аксиона. Полуклассический анализ показывает, что сильное CP несохранение будет очевидной причиной увеличения несохранения электрического заряда.