AXION DARK MATTER, CP VIOLATION PROBLEM IN QCD

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Abstract

Attempts are made to give a brief description of axion dark matter and its possible root from CP problem in strong interaction. First of all, the theoretical background of symmetry and symmetry breaking in particle physics have been reviewed in detail . Then, the role of Goldstone's theorem, Goldstone's bosons in Gauge theories are investigated. It has been shown that spontaneous symmetry breaking of gauge symmetry can be described by Higgs mechanism. The most popular solution to the CP problem in strong interaction : the addition of an additional $U(1)_{PQ}$ symmetric field and its quanta- axion is presented. A rough estimate of the axion mass is also conducted using currently available constraints on QCD and quantum cosmology.

Keywords: symmentry braking, Goldstone's theorem, Higgs mechanism, axion dark matter ,$U(1)_{PQ}$ symmetric field

Introduction

The axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD). If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter. As shown by Gerard 't Hooft, strong interactions of the standard model, QCD, possess a non-trivial vacuum structure that in principle permits violation of the combined symmetries of charge conjugation and parity, collectively known as CP. Together with effects generated by weak interactions, the effective periodic strong CP-violating term, Θ, appears as a Standard Model input – its value is not predicted by the theory, but must be measured. However, large CP-violating interactions originating from QCD would induce a large electric dipole moment (EDM) for the neutron. Experimental constraints on the currently unobserved EDM implies CP violation from QCD must be extremely tiny and thus Θ must itself be extremely small. Since a priori Θ could have any value between 0 and 2π, this presents a "naturalness" problem for the standard model. Why should this parameter find itself so close to 0? (Or, why should QCD find itself CP-preserving?) This question constitutes what is known as the strong CP problem.

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In 1977, Roberto Peccei and Helen Quinn postulated a more elegant solution to the strong CP problem, the Peccei–Quinn mechanism. The idea is to effectively promote Θ to a field. This is accomplished by adding a new global symmetry (called a Peccei–Quinn symmetry) that becomes spontaneously broken. This results in a new particle, as shown by Frank Wilczek and Steven Weinberg, that fills the role of Θ, naturally relaxing the CP-violation parameter to zero. This hypothesized new particle is called the axion. The original Weinberg–Wilczek axion was ruled out. Current literature discusses the mechanism as the "invisible axion", which has two forms: KSVZ (Kim–Shifman–Vainshtein–Zakharov) and DFSZ (Dine–Fischler–Srednicki–Zhitnitsky).

It had been thought that the invisible axion solves the strong CP problem without being amenable to verification by experiment. Axion models choose coupling that does not appear in any of the prior experiments. The very weakly coupled axion is also very light because axion couplings and mass are proportional. The situation changed when it was shown that a very light axion is overproduced in the early universe and therefore excluded. The critical mass is of order 10^{-11} times the electron mass, where axions may account for the dark matter. The axion is thus a dark-matter candidate, as well as a solution to the strong CP problem. Furthermore, in 1983, Pierre Sikivie wrote down the modification of Maxwell's equations from a light stable axion and showed that axions can be detected on Earth by converting them to photons, using a strong magnetic field, the principle of the ADMX. Solar axions may be converted to x-rays, as in CAST. Many experiments are searching laser light for signs of axions.

Maxwell's equations with axion modifications

If magnetic monopoles exist then there is a symmetry in Maxwell's equations where the electric and magnetic fields can be rotated into each other with the new fields still satisfying Maxwell's equations. Luca Visinelli showed that the duality symmetry can be carried over to the axion-electromagnetic theory as well. Assuming the existence of magnetic charges and axions, Maxwell's equations read

Name	Equations
Gauss's Law	$\nabla.(E - c\kappa\theta B) = \dfrac{\rho_e}{\varepsilon_0}$
Gauss's Law for magnetism	$\nabla.\left(B + \dfrac{\kappa}{c}\theta E\right) = \mu_0\rho_m$
Faraday's Law	$\nabla \times (E - c\kappa\theta B) = -\partial_t\left(B + \dfrac{\kappa}{c}\theta E\right) - \mu_0 J_m$
Ampere-Maxwell Law	$\nabla \times \left(B + \dfrac{\kappa}{c}\theta E\right) = \dfrac{1}{c^2}\partial_t(E - c\kappa\theta B) + \mu_0 J_e$
Axion Law	$(\square + m_a^2)\theta = -\kappa E.B$

Incorporating *the* axion has the effect of rotating the electric and magnetic fields into each other.

$$\begin{pmatrix} \boldsymbol{E}^{\square} \\ \boldsymbol{B}^{\square} \end{pmatrix} = \frac{\boldsymbol{1}}{\boldsymbol{cos\xi}} \begin{pmatrix} \boldsymbol{cos\xi} & \boldsymbol{csin\xi} \\ -\dfrac{\boldsymbol{1}}{\boldsymbol{c}}\boldsymbol{sin\xi} & \boldsymbol{cos\xi} \end{pmatrix} \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{B} \end{pmatrix}$$

where the mixing angle □ depends on the coupling constant □ and the axion field strength$\boldsymbol{\theta}$

$$\boldsymbol{tan\xi = -\kappa\theta}$$

By plugging the new values for electromagnetic field and into Maxwell's equations we obtain the axion-modified Maxwell equations above. Incorporating the axion into the electromagnetic theory also gives a new differential equation – **the axion law** – which is simply the Klein-Gordon Equation (the quantum field theory equation for massive spin-zero particles) with an source term.

A term analogous to the one that would be added to Maxwell's equations to account for axions also appears in recent (2008) theoretical models for topological insulators. giving an effective axion description of the electrodynamics of these materials. This term leads to several interesting predicted properties including a quantized magnetoelectric effect. Evidence for this effect has recently been given in THz spectroscopy experiments performed at The Johns Hopkins University.

Gauge Transformation

Let G be a lie group , g is lie algebra and T^a the generators of the lie algebra where the index ‘a’ takes values from 1 to dim G.

$$[T^a, T^b] = i f^{abc} T^c$$

$$Tr(T^a T^b) = \frac{1}{2}\delta^{ab}$$

The lie group is called abelian, if all structure constants f^{abc} vanish, it can be called non-abelian.

An example for abelian case in particle physics is given by QED with abelian group U(1) and, non-abelian case is given by QCD corresponding group SU(3). This non-abelian gauge group was first suggested by Yang and Mills in 1954 and the name called “Tang-Mills theory” which is another name of “Gauge theory”.

The Search for QCD Axion

Dark matter remains the most compelling evidence of physics beyond the Standard Model (SM). Since we have only observed it through its gravitational effects, there is a wide range of possible dark matter candidates. A very interesting possibility is that dark matter is made of light bosonic fields which only interact extremely weakly with the SM. The QCD axion is a particularly well-motivated example of such weakly-coupled light fields.

Further, the axion makes the CP-violating QCD θ angle dynamical, with a minimum at $\theta = 0$. Thus, the axion can naturally explain the severe constraints on CP violation in the strong sector, $\theta \lesssim 10^{-10}$, from null measurements of the neutron/Hg electric dipole moments.

The mass of the QCD axion is set by its decay constant f_a. Its couplings to other SM fields are model-dependent, but are expected to be given by higher-dimension operators suppressed by f_a. Astrophysical observations impose a lower bound on the decay constant, $f_a \gtrsim 10^9$GeV for generic couplings. On the other hand, axion decay constants of $f_a > 10^{12}$GeV predict a dark matter abundance in excess of observations for generic initial conditions. These two considerations determine the axion window, $10^9\text{GeV} < f_a < 10^{12}\text{GeV}$.

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Table[Plot3D[BesselJ[0, (m^2 ϕ + λ ϕ^3)], {m, 1, 10}, {λ, .5, 5}, PlotRange → {.01, .2},
  PlotLabel → Row[{"ϕ=", PaddedForm[1 * ϕ, 3]}], Axes → True, AxesLabel → {"m", "λ", "∂V/∂ϕ"},
  ColorFunction → Function[{x, y, z}, Hue[Mod[z, 1]]], ColorFunctionScaling → True,
  DisplayFunction → Identity], {ϕ, 1, 9}]
```

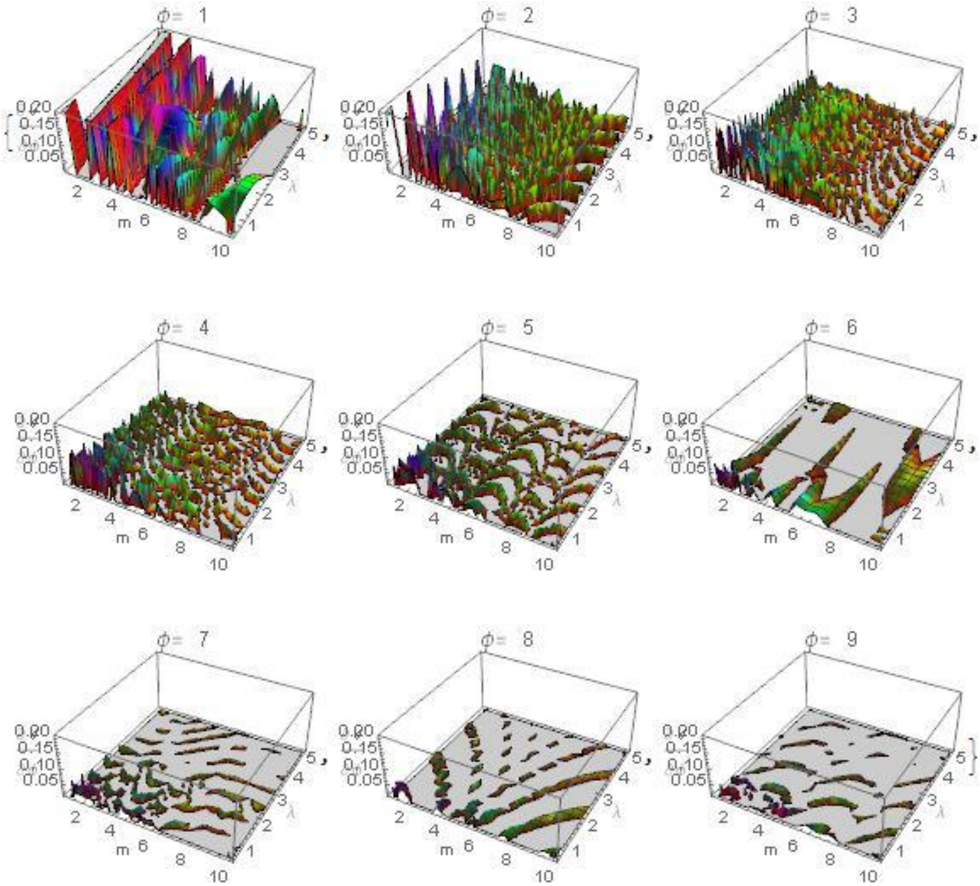

Figure: Evolution of potential energy with respect to scalar function ϕ.

Conclusions

Axion-like bosons could have a signature in astrophysical settings. In particular, several recent works have proposed axion-like particles as a solution to the apparent transparency of the Universe to TeV photons. It has also been demonstrated in a few recent works that, in the large magnetic fields threading the atmospheres of compact astrophysical objects (e.g., magnetars), photons will convert much more efficiently. This would in turn give rise to distinct absorption-like features in the spectra detectable by current telescopes. A new promising means is looking for quasi-particle refraction in systems with strong magnetic gradients. In particular, the refraction will lead to beam splitting in the radio light curves of highly magnetized pulsars and allow much greater sensitivities than currently achievable. Axions may be produced within neutron stars, by nucleon-nucleon bremsstrahlung. From the simulated work shows that the evolution of potential energy with respect to scalar function is highly turbulent and rapidly changing nature.

Acknowledgement

I would like to thank Dr Khin Khin Win, Professor and Head, Department of Physics, University of Yangon, for her kind permission and encouragements to carry out this work.

I would like to thank Dr Aye Aye Thant, Professor, Department of Physics, University of Yangon, for her kind permission and encouragements to carry out this work.

Special thanks are due to Professor, Dr Thant Zin Naing, Retired Pro-rector (Admin), International Theravā da Buddhist Missionary University, for his valuable guidance and helpful advice to carry out this work.

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