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# Axion mass in a hot QCD plasma

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We estimate axion mass in a QCD medium. To take into consideration the non-perturbative nature of the QCD we model the QCD medium using three (2+1) flavor Polyakov loop extended Nambu Jona Lasinio (PNJL) model. Axion is incorporated within the framework of the PNJL model through the Kobayashi-Maskawa-t'hooft determinant interaction. We argue that chiral transition and confinement-deconfinement transition affect the mass of axion in a QCD medium. Our results suggest that the in-medium mass of axion is correlated with the chiral and confinement-deconfinement transition. We compare our results with the Nambu Jona Lasinio (NJL) model results and Lattice QCD calculations.

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## 1. Introduction

Due to the non-abelian nature of gluons ($\mathcal{A}^{\mu}_{c}$), effective action of QCD ($S_{\rm eff}$) can contain a topologically non-trivial, and CP (charge conjugation and parity) violating term [1–3],

$$S_{\rm eff}[\mathcal{A}^{\mu}] = S_{\rm QCD}[\mathcal{A}^{\mu}] + \theta\frac{g_s^2}{32\pi^2}\int d^4x \mathcal{G}^{c\mu\nu}\tilde{\mathcal{G}}^{c}_{\mu\nu}. \tag{1}$$

Here $g_s$ is the strong coupling constant, $\mathcal{G}^{c\mu\nu}$ is the gluon field strength tensor and $\tilde{\mathcal{G}}^{c}_{\mu\nu}$ is its dual. The Chern-Simons term that contains the parameter $\theta$ respects $SU(3)$ color symmetry, and does not affect the Euler Lagrange equation for the QCD gauge fields. The Chern-Simons term can be expressed in terms of color electric and magnetic field, $\propto \theta\vec{E}^c\cdot\vec{B}^c$ [4]. Such a term in the action breaks the CP symmetry explicitly unless $\theta = 0 \mod \pi$. Moreover, CP violation can also appear from the weak interaction processes. If we consider the diagonalization of the quark mass matrix ($\mathcal{M}$) one effectively obtains, $\bar{\theta} = \theta + \arg\det\mathcal{M}$. The intrinsic electric dipole moment of neutrons put a strong constraint on $CP$ violating $\theta$ term, $\bar{\theta} < 0.7\times 10^{-11}$ [5, 6]. Peccei-Quinn (PQ) symmetry breaking dynamics gives an elegant and dynamical way to explain the smallness of $\bar{\theta}$ term [1]. An unavoidable consequence of the Peccei-Quinn (PQ) symmetry breaking dynamics is the prediction of a new Goldstone boson, known as axion. The flat axion effective potential at the PQ symmetry breaking scale gets correction at the QCD transition scale which gives a nonvanishing mass to axion. Therefore axion dynamics is governed by the Peccei-Quinn (PQ) symmetry breaking scale ($f_a$), and QCD phase transition dynamics. It can be argued that axion mass, its self-coupling, and coupling with other standard model particles are inversely proportional to the Peccei-Quinn (PQ) symmetry breaking scale ($f_a$) which can be as high as the grand unified symmetry (GUT) breaking scale[7, 8]. Therefore axions have a small mass and are weakly interacting. Such interesting properties make axions phenomenologically very appealing [9]. Since the QCD phase transition dynamics affect the axion's effective potential, in the present article we calculate and study the effect of QCD phase transition on the mass of the axion. Axion mass plays a crucial role to determine its abundance in early universe cosmology, stellar cooling, etc. Due to the nonperturbative physics associated with the QCD transition scale, we estimate the axion mass using QCD-inspired effective models, e.g. Polyakov loop extended Nambu Jona Lasinio (PNJL) model, Nambu Jona Lasinio (NJL) model, etc. Axion mass can also be obtained using the dilute instanton gas model [10], chiral perturbation theory, etc. But such models do not incorporate the QCD phase transition dynamics across the transition scale. The NJL model describes the chiral transition in a QCD medium very successfully. However the NJL model does not include any QCD gauge field. Therefore the phenomenology of the confinement-deconfinement transition is missing in the NJL model. Moreover, the PNJL model can describe the chiral transition, as well as the confinement-deconfinement transition in a QCD medium, in a unified way. Therefore in the present article, we give an estimation of axion mass within the framework of the PNJL model. We also compare our results with the NJL model result and the lattice QCD result.



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## 2. QCD effective model, axion effective potential, and axion mass

The Lagrangian density of three (2+1) flavour PNJL model can be expressed as [11–14],

$$\begin{aligned}\mathcal{L} =&\bar{q}(i\gamma^{\mu}D_{\mu}-\hat{m})q+G_{s}\sum_{A=0}^{8}\left[(\bar{q}\lambda^{A}q)^{2}+(\bar{q}i\gamma_{5}\lambda^{A}q)^{2}\right]\\ &-K\left[e^{i\theta}\det\{\bar{q}(1+\gamma^{5})q\}+e^{-i\theta}\det\{\bar{q}(1-\gamma^{5})q\}\right]+\mathcal{U}(\Phi,\bar{\Phi},T),\end{aligned} \tag{2}$$

here the quark field is $q = (q_u, q_d, q_s)^T$, current quark matrix $\hat{m} \equiv \mathrm{diag}(m_u, m_d, m_s)$. $\lambda^0 = \sqrt{2/3}\ I_{3\times3}$, here $I_{3\times3}$ is the $3\times3$ identity matrix in flavor space, $\lambda^A$ with $A = 1, 2, ..., 8$ are the Gell Mann matrices in flavor space. $D^{\nu} = \partial^{\nu} - iA^{\nu}$ is the QCD gauge covariant derivative, and $A^{\nu} = \delta^{\nu}_{0}A^0$. $A^{\nu}$ contains the QCD gauge fields [14]. Four quark interaction is represented by terms proportional to $G_s$. $K$ is the coupling of the Kobayashi-Maskawa -'t Hooft (KMT) determinant interaction term which breaks the $U(1)_A$ symmetry of the QCD Lagrangian. Four fermion interaction term and KMT determinant interaction term give rise to the phenomenology of the chiral transition. $\theta = a/f_a$, $a$ is the axion field and $f_a$ is the PQ symmetry breaking scale. The Polyakov loop potential $\mathcal{U}(\Phi, \bar{\Phi}, T)$, is the effective potential of the traced Polyakov loop and its Hermitian conjugate [11],

$$\Phi=\frac{1}{N_c}\mathrm{Tr}L,\quad \bar{\Phi}=\frac{1}{N_c}\mathrm{Tr}L^{\dagger},\quad L(\vec{x})=\mathcal{P}\exp\left[i\int_0^{\beta}d\tau A_0(\vec{x},\tau)\right],\quad \beta=1/T. \tag{3}$$

Here $N_c = 3$ is the number of colors, $\beta$ is the inverse temperature $(T)$. The Polyakov loop potential term give rise to the phenomenology of the confinement-deconfinement transition in QCD. We consider the values of different parameters in the above Lagrangian, and the Polyakov loop potential as given in Ref. [15–17]. The thermodynamic potential $(\Omega)$ for the system can be obtained in the mean field approximation in terms of various condensates, scalar $(\sigma)$, pseudo-scalar $(\eta)$, $\Phi$, $\bar{\Phi}$. Values of various condensates, e.g., $\sigma$, $\eta$, $\Phi$, $\bar{\Phi}$ can be obtained as a function of $\theta = a/f_a$, temperature $(T)$, and chemical potential $(\mu)$ by minimizing the effective potential. Resultant axion effective potential can be expressed as [14, 18, 19],

$$\tilde{\Omega}(\theta,T,\mu)=\Omega\left[\sigma^{i}(\theta,T,\mu),\eta^{i}(\theta,T,\mu),\Phi(\theta,T,\mu),\bar{\Phi}(\theta,T,\mu),\theta,T,\mu\right].$$

Here $\sigma_i = -\langle\bar{q}_i q_i\rangle$ represents the scalar condensates for different flavors $i(i = u, d, s)$, and $\eta_i = -\langle\bar{q}_i i\gamma_5 q_i\rangle$ are pseudoscalar condensates for flavor $i(i = u, d, s)$. Using the axion effective potential $(\tilde{\Omega})$ axion mass $(m_a)$ can be obtained, and it can be expressed in terms of the topological susceptibility $(\chi)$, $m_a^2 = (d^2\tilde{\Omega}/da^2)|_{a=0} \equiv \chi/f_a^2$.

## 3. Results and conclusions

In Fig. (1) (left plot) we show the variation of scalar condensate for light quarks $(\sigma_u = \sigma_d)$, strange quark $(\sigma_s)$ quark and also the Polyakov loop variable $(\Phi)$ with temperature for $\theta = 0$. This result is for zero baryon chemical potential. Only for zero baryon chemical potential $\Phi = \bar{\Phi}$. For $\theta = 0$, all the pseudo-scalar condensates vanish (not shown here explicitly). The nonvanishing

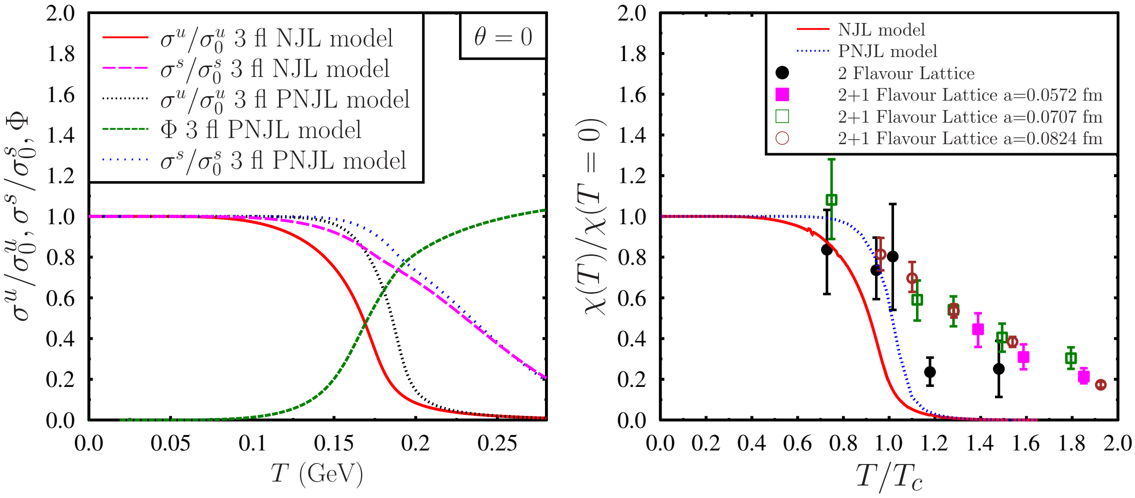


**Figure 1:** The left plot shows the variation of various scalar condensates, Polyakov loop condensate with temperature [14]. The right plot shows the variation of axion mass or topological susceptibility with temperature [14]. We compare PNJL model results with NJL model and lattice QCD results [20].

value of pseudo-scalar condensates indicates spontaneous CP violation. Therefore for $\theta = 0$ there is neither explicit symmetry breaking nor spontaneous symmetry breaking. Only for nonvanishing values of $\theta$, pseudo-scalar condensate can be non-zero (not shown here). In this figure, quark condensates are normalized with respect to their values at zero temperature. We may observe that, at low temperatures up to 100 MeV, the normalized light quark condensate is of the order unity, but the $\Phi$ has a small value. This is the confined, and chiral symmetry broken phase. In the high-temperature range, value of the scalar, condensate is small, but the value of $\Phi$ is large. This is the deconfined chiral symmetric phase. In the PNJL model, the chiral transition and deconfinement transition happens simultaneously. The nonvanishing value of $\Phi$ suppresses the medium contribution for the PNJL model as compared to the NJL model. In the right plot of Fig.(1) we show the variation of the normalized topological susceptibility $\chi(T)/\chi(T=0)$ with $T/T_c$. Note that topological susceptibility is also the measure of axion mass. In this plot, we compare the PNJL model results with the NJL model results and lattice QCD calculations [20]. From this plot, one may observe that near and below $T_c \sim 188$ MeV, PNJL model result is consistent with the lattice QCD results. However, beyond $T_c$ there is a rather large discrepancy between the PNJL model result and lattice QCD calculations. At zero temperature the PNJL model predicts axion mass to be $m_a f_a = 6.07 \times 10^{-3}$ GeV$^2$ [21]. From this figure, we also observe that in a confined, chiral symmetry broken phase the axion mass is large. But in the deconfined chiral symmetric phase axion mass is small. Hence axion mass is correlated with the chiral order parameter and Polyakov loop. The axion mass obtained here takes into account the QCD phase transition dynamics through effective interactions. This estimation of axion mass can be used in phenomenological calculations, particularly around the QCD transition scale.

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