INDUCED COLOR CHARGES IN MAGNETIZED QUARK-GLUON PLASMA AT LHC EXPERIMENT ENERGIES

V. Skalozub*, I. Hamolskyi

Oles Honchar Dnipro National University, Dnipro, Ukraine
e-mail: Skalozub@ffeks.dnu.edu.ua

In quark-gluon plasma (QGP), at high temperature the spontaneous generation of colormagnetic fields, $H^3(T), H^8(T) \neq 0$, and usual magnetic field $H(T) \neq 0$ is realized. Also, the classical field $-A_0(T)$ condensate directly related to the Polyakov loop – is spontaneously created. The common generation of both within the two loop effective potential was investigated recently for $SU(2)$ gluodynamics. The values of the field strengths and the mechanism of the magnetic fields stabilization due to $A_0(T)$ have been discovered.

In the present paper, we continue these investigations to detect new effects of QGP. We generalize the $SU(2)$ consideration to the case of full quantum chromodynamics. Then we calculate the induced color charge Q^3_{ind} at the background magnetic field generated at LHC experiment energies and the condensate $A^3_0(T)$. The field $A^8_0(T)$ and the charge Q^8_{ind} are zero in the used approximation.

We conclude that magnetic fields essentially influence the Q^3_{ind} compared to the zero field case. The extension to other type magnetic fields is given and a number of possible effects of this charge are briefly discussed.

Keywords: spontaneous magnetization, high temperature, asymptotic freedom, effective potential, A_0 condensate, effective charge, effective vertexes.

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1. Introduction

Quark-gluon plasma (QGP) is the state of matter consisting of quarks and gluons liberated from nuclei at high temperature due to asymptotic freedom of non-Abelian gauge fields. A classical background of QGP is formed out of two type condensates – the $A_0(T)$ (Polyakov loops (PL)) and the spontaneously generated temperature dependent chromomagnetic $H^3(T), H^8(T)$, where 3 and 8 are color indexes of $SU(3)$ group, and usual magnetic $H(T)$ fields [1]. The first kind condensate results in the color $Z(3)$ symmetry breaking and the Furry's theorem violation. The second ones considerably change the spectra of quarks and gluons as well. So, new phenomena have to be realized. In particular, the induced color charges Q^3_{ind}, Q^8_{ind} are expected. The PL and $A_0(T)$ are the order parameters for the phase transition. At low temperature, PL and A_0 equal zero. At high temperature they become nonzero. The same concerns the magnetic fields. Recently, on the principles of the Nielsen's identity method and new type integral and sum representations we derived the gauge invariant expression for the A_0 condensate in the magnetic fields in the two-loop approximation [2, 3]. This opens (in particular) a possibility for calculating the induced color charges for this case.

To implement such idea, we have to calculate the contribution of the diagram depicted in Fig. 1. Here, the solid line presents the quark propagator in the A_0 and magnetic fields and the wavy line presents the zero component of gluon fields G^3_0or G^8_0. At finite temperature, in the Matsubara formalism one has to calculate the temperature sum over discrete momenta $p_4 = 2\pi T\left(l + \frac{1}{2}\right),\ l = 0, \pm 1, \ldots$, integrate over momentum component p_3 oriented along the space field direction, calculate the sum over spin variable $\sigma = \pm 1$, and sum up over $n = 0, 1, 2, \ldots$, in correspondence to the fermion spectrum in magnetic field H: $(p_4 + gA_0)^2 = m^2 + p_3^2 + (2n+1)gH - \sigma gH$. Here we write gH as a general expression corresponding to each of the fields. For instance, this is eH for usual magnetic field, gH^3, gH^8– for color fields.

In what follows, we apply the low-level approximation, $n = 0$, $\sigma = +1$ giving a leading contribution for strong external fields. We obtain that the induced color charge Q^3_{ind} is nonzero. The presence of the magnetic fields changes the values of it compared to the zero field case so that the QGP has to be magnetized and color charged.

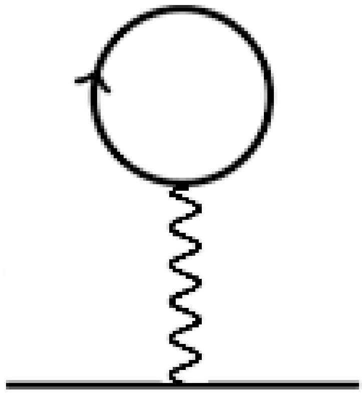

Fig.1. Tadpole diagram.

2. Induced color charge

In this section, we calculate the induced color charge generated by the tadpole diagram of Fig. 1. In charged basis, we have two components of the induced charge for the shifts A^3_0 and A^8_0. But accounting for the result [4] $A^8_0 = 0$, we have to calculate the contribution for the case $(A_0)^a_\mu = A_0\delta_{\mu 4}\delta^{a3}$. The explicit form in the Euclid space-time is $Q^3_4 Q^3_{ind}$, and we have

$$Q^3_{ind} = \frac{g}{\beta}\sum_{p_4}\int\frac{d^3p}{(2\pi)^3}\mathrm{Tr}\left[\frac{\lambda^3}{2}\gamma_4\frac{\hat{p}_\sigma\gamma_\sigma + m}{\hat{p}^2 + m^2}\right], \tag{1}$$

where $p = (p_4 = p_4 \pm A_0, \boldsymbol{p})$, $p_4 = 2\pi T\left(l + \frac{1}{2}\right), l = 0, \pm 1, \ldots,$ The trace is calculated over either space-time or color variables. λ^3 is Gell-Mann matrix. Here also we denoted as A_0 the value $A_0 = \frac{gA_0}{2}$.

Calculating the traces over the space and the internal indices, we get

$$Q^3_{ind} = \frac{4g}{\beta}\int\frac{d^3p}{(2\pi)^3}\sum_{p_4}\frac{(p_4 + A_0)}{(p_4 + A_0)^2 + \epsilon_p^2}, \tag{2}$$

where $\epsilon_p^2 = \vec{p}^2 + m^2$. In the case of nonzero field, $\epsilon_p^2 = p_3^2 + m^2 + (2n+1)gH - gH\sigma$.

To calculate the temperature sum, we use the following representation

$$Q^3_{ind} = 4g\int\frac{d^3p}{(2\pi)^3}\frac{\beta}{\pi}\oint_C \tan\frac{\beta\omega}{2}\frac{(\omega + A_0)}{(\omega + A_0)^2 + \epsilon_p^2}d\omega\,. \tag{3}$$

This is in the case of zero field. If the field is nonzero, we have to replace $\frac{d^3p}{(2\pi)^3} \to \frac{dp_3}{2\pi}\frac{gH}{(2\pi)^2}$ in correspondence to the particle spectrum. The integrand function has two imaginary poles of the first order. We use the residues to find the charge value.

The result, after transformation into spherical coordinates and angular integration, is

$$Q_{ind}^3 = \frac{g\sin(A_0\beta)}{\pi^2}\int_0^\infty p^2 dp \frac{1}{\cos(\beta A_0) + \cosh(\beta\epsilon_p)}. \tag{4}$$

In what follows, we calculate the integral in the high-temperature limit $T \to \infty$. In this case we use

$$\epsilon_p\sqrt{\boldsymbol{p}^2 + m^2} \approx |\boldsymbol{p}| + \frac{1}{2}\frac{m^2}{|\boldsymbol{p}|} \tag{5}$$

because large values of momentum give dominant contribution.

After integration over the momentum, we obtain at zero field [4]

$$Q_{ind}^3 = gA_0^3\left[\frac{T^2}{3} - \frac{m^2}{2\pi^2}\right]. \tag{6}$$

As we see, the first term depends on temperature as $\sim T^2$. The second one depends on mass, only. At high temperature, the first term is dominant and the plasma acquires the spontaneous induced charge in the case $m = 0$, also.

Now, we turn to nonzero H. Using the low Landau level approximation, $\sigma = +1, n = 0$, we get after integration over momentum p_3

$$Q_{ind}^3(H,T) = g\frac{gH}{2\pi^3}\frac{\sin(A_0^3\beta)}{\beta}\left(1 + 7\beta^2m^2\zeta(-2)\right). \tag{7}$$

At high temperature, this expression is read

$$Q_{ind}^3(H,T) = g\frac{gH}{2\pi^3}(gA_0^3)\left(1 + 7\beta^2m^2\zeta(-2)\right). \tag{8}$$

Note that numerically $\zeta(-2) = -0.03044485$. Thus, one of the consequences of the A_0 condensate presence is the $Z(3)$ symmetry and the C-parity violation, which leads to the induction of color charge in the plasma.

As we noted in Introduction, the factor gH presents different kinds of magnetic fields – usual magnetic field eH, color magnetic fields gH^3, gH^8 or even some combination of them. For instance, in [1] it was shown that in QGP at LHC energies the combinations of fields $H_f^1 = q_fH + g\left(\frac{H^3}{2} + \frac{H^8}{2\sqrt{3}}\right)$, $H_f^2 = q_fH + g\left(-\frac{H^3}{2} + \frac{H^8}{2\sqrt{3}}\right)$, $H_f^3 = q_fH - g\frac{H^8}{2\sqrt{3}}$ have to be produced, where q_f is electric charge of quark. The strengths of the fields at various temperatures have been estimated. In particular, it was shown that the strength of color fields is two order bigger compared to the usual magnetic one. The spectra of all charged particles become discrete, which influences all the manifestations of QGP. It is also important to stress that all the fields, independently of the kind, are directed collinearly in space-time. The reason is that for such type orientation of fields the free energy is lower and they are spontaneously generated.

Also remind that in the above formulas A_0^3 has to be substituted by $\frac{gA_0^3}{2}$.

3. Discussion

Let us compare the values of induced color charges given by formulas (6) and (8). Now the first leading in temperature terms are of interest. Both expressions have the factor gA_0^3 but a different temperature dependence. In the first case, the factor $\sim T^2$ stands and determines high temperature behavior. In the latter case, it is determined by the temperature dependence of the magnetic field $H(T)$. This behavior has been investigated recently in two-loop approximation [5]

$$gH = \frac{1}{16}\frac{(2a_2\alpha_s)^{\frac{2}{3}}}{\pi^{\frac{2}{3}}}T^2. \tag{9}$$

Here, $a_2 = 1.856$ is a number, $\alpha_s = g^2/(1 + \frac{11}{12}\frac{g^2}{\pi^2}\log\left(\frac{T}{\mu}\right))$ is a running coupling constant, μ is a normalization point for temperature. So, at reference temperature $\alpha_s = g^2$. Because of this factor, the value of the field strength is always smaller compared to T^2. As a result, the induced color charge (8) in the magnetic field is also smaller compared to Eq.(6).

On the other hand, during carried out calculations we have taken the field strength as a given number which is arbitrary. Thus, it can be the field produced by some external current. In this case the induced color charge will be completely determined by the external field. Such a situation is expected and discussed for heavy ion collision experiments.

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