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The Equation of State and Phase Structure in A Model with Dynamical Spontaneous Symmetry Breaking at Finite Temperature and Density

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Based on the Lurie model, a convenient scheme is constructed for calculating the equation of state approximately. The parametric equation of state is given in the Lurie model. The phase diagram of the model shows the existence of a critical point separating first order from second order chiral phase transition. A careful analysis of the isotherms of pressure versus net baryon number density suggests the existence of overheat and overcool metastable state and the coexistence of broken phase and normal phase.

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1. INTRODUCTION

The Monte Carlo calculation in lattice QCD theory has predicted [1,2] that the phase transition of deconfinement and restoration of spontaneous-breaking-chiral symmetry will take place at high temperature and density. Unfortunately, the Monte Carlo calculation can only give the eventual numerical results. There is therefore a need for seeking analytical method to inquire into the real physical reason of the phase transition with the help of the strong interaction model theory. Our previous works [3,4] were just some preliminary attempt in this direction.

It is believed that the chiral symmetry breaking in QCD theory is caused by the fermionic condensate, so the research on chiral phase transition in the model with dynamical spontaneous symmetry breaking (i.e., fermionic condensate is nonzero) is helpful to understanding chiral phase transition in QCD theory. In recent years, some authors [5] have devoted efforts to the investigation

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of the behavior of the order parameter describing phase transition and the determination of the critical temperature and the order of the phase transition by calculating the effective potential in the models with Nambu type Lagrangian [6] at finite temperature. As is well known, the study of the behavior of the thermodynamical quantities near the critical point is an important method. In particular, the investigation of the equation of state will be helpful to the careful analysis of the phase transition feature. In addition, the equation of state is a fundamental relation among thermodynamical quantities; it plays an important role in analyzing the thermodynamical properties. In addition, the theoretical analysis of phase transition signal from a lot of experimental data obtained in relativistic heavy ion collisions has become an important research topic recently. The analysis of the signal, such as the investigation of the space-time evolution [7] in heavy ion collisions, depends heavily on the equation of state to a certain extent. So seeking for the suitable equation of state at high temperature and density in strong interaction system becomes more and more urgent.

In this paper, we attempt to give a method for calculating the equation of state approximately with the help of Lurie model. Combining our previous works [4], the chiral phase diagram of the Lurie model indicates that a critical point c exists separating first order from second order phase transition. The careful analysis of the isotherms of pressure versus the baryon number density suggests the existence of overheat and overcool metastable state and the coexistence of broken phase with dynamical spontaneous symmetry breaking and normal phase without the breaking when first order chiral phase transition takes place.

2. MODEL AND THE EQUATION OF STATE AT ZERO TEMPERATURE AND FINITE DENSITY

Consider the model with the following Lagrangian [8] proposed by Lurie:

$$\mathscr{L} = \mathscr{L}_0 + \mathscr{L}_I, \tag{2.1a}$$

$$\mathscr{L}_0 = -\bar{\psi}\gamma_\mu\partial_\mu\psi - \frac{1}{2}\partial_\mu\phi_s\partial_\mu\phi_s - \frac{\mu^2}{2}\phi_s^2 - \frac{1}{2}\partial_\mu\phi_p\partial_\mu\phi_p - \frac{\mu^2}{2}\phi_p^2, \tag{2.1b}$$

$$\mathscr{L}_I = g\bar{\psi}\psi\phi_s + ig\bar{\psi}\gamma_5\psi\phi_p, \tag{2.1c}$$

where ψ is the nucleon field, ϕ_s the scalar field, and ϕ_p the pseudoscalar field.

Set

$$\sigma_s = \langle 0|\phi_s|0\rangle, \quad \sigma_p = \langle 0|\phi_p|0\rangle \tag{2.2}$$

as the vacuum expectation values of the scalar and pseudoscalar field, respectively. As pointed out by Lurie [8], the conservation of the parity in the model demands

$$\sigma_p = \langle 0|\phi_p|0\rangle \equiv 0. \tag{2.3}$$

and the dynamical spontaneous symmetry breaking demands $\sigma_s = \langle 0|\phi_s|0\rangle \neq 0$. We have established the self-consistency equation satisfied by σ_s [4],

$$\mu^2\sigma_s = g\langle 0|\bar{\psi}\psi|0\rangle. \tag{2.4}$$

Based on the background-field theory [9], assuming that the nonperturbative effects of the fermion field are described by the interaction among the classical field (background field) $\psi_c(x)$, and that perturbative effects are described by the quantum fluctuation field $\eta(x)$ around background field, we performed a fermion field shift

$$\psi(x) = \psi_c(x) + \eta(x), \tag{2.5}$$

and using Walecka's mean-field approximation [10], we can read the fermionic mass from the equation of motion,

$$m = g\sigma_s. \tag{2.6}$$

Notice that the net baryon number density and scalar density of the system can be expressed as

$$\rho_b = \frac{1}{V}\langle 0 | \int d^3x : \eta^+\eta : | 0 \rangle = \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k = \frac{\gamma k_F^3}{2\pi^2}, \tag{2.7a}$$

$$\rho_s = \frac{1}{V}\langle 0 | \int d^3x : \bar{\eta}\eta : | 0 \rangle = \frac{\gamma}{(2\pi)^3}\int_0^{k_F} \frac{m d^3k}{\sqrt{k^2 + m^2}}, \tag{2.7b}$$

where $\gamma = 2$ is spin degeneracy factor and k_F is fermion momentum, and using the method given in Ref. [4], we reduce Eq.(2.4) into

$$\hat{m}F(\hat{m}) = 0, \tag{2.8a}$$

$$F(\hat{m}) = \hat{\mu}^2 - \frac{g^2}{2\pi^2}\left[\sqrt{1+\hat{m}^2} - \hat{m}^2 \ln \frac{1+\sqrt{1+\hat{m}^2}}{\hat{m}}\right]$$

$$+ \frac{2g^2}{(2\pi)^3}\int_0^{\hat{k}_F} \frac{d^3\hat{k}}{\sqrt{\hat{k}^2 + \hat{m}^2}}. \tag{2.8b}$$

For convenience, throughout this paper, we use Λ to rescale any physical quantity A with mass dimension and define a dimensionless quantity $\hat{A} = A/\Lambda$, where Λ is a three-momentum cutoff [11] introduced when calculating the divergence integral $<0|\bar{\psi}_c\psi_c|0>$. $\Lambda \approx 860$ MeV has been given in Ref. [11].

It is very difficult to solve the equation of state of the system exactly. Following the technique proposed by Linde [12], we can obtain it approximately. First we perform a shift for boson field with respect to its vacuum average. Because of the restriction of Eq.(2.3), it needs only to shift scalar field, i.e.,

$$\phi_s \rightarrow \phi_s + \sigma_s. \tag{2.9}$$

According to Eq.(2.5), the effective lagrangian can be written as

$$\mathcal{L}_{eff} = \mathcal{L}_c + \mathcal{L}^0 + \mathcal{L}^I, \tag{2.10a}$$

$$\mathcal{L}_c = -\bar{\psi}_c(\gamma_\mu\partial_\mu - m)\psi_c, \tag{2.10b}$$

$$\mathcal{L}^0 = -\bar{\eta}(\gamma_\mu\partial_\mu - m)\eta - \frac{1}{2}\partial_\mu\phi_s\partial_\mu\phi_s - \frac{\mu^2}{2}\phi^2$$

$$- \frac{1}{2}\partial_\mu\phi_p\partial_\mu\phi_p - \frac{\mu^2}{2}\phi_p^2, \tag{2.10c}$$

$$\mathscr{L}^I = g\bar{\psi}_c\psi_c\phi_s + ig\bar{\psi}_c\gamma_5\psi_c\phi_p - \frac{\mu^2}{2}\sigma_s^2 - \mu^2\phi_s\sigma_s$$

$$+ g\bar{\eta}\eta\phi_s + ig\bar{\eta}\gamma_5\eta\phi_p. \tag{2.10d}$$

and corresponding energy-momentum tensor can be deduced as

$$T_{\mu\nu} = \bar{\psi}_c\gamma_\mu\partial_\nu\psi_c + \bar{\eta}\gamma_\mu\partial_\nu\eta + \partial_\mu\phi_s\partial_\nu\phi_s + \partial_\mu\phi_p\partial_\nu\phi_p$$

$$+ \Big[-\frac{1}{2}\partial_\mu\phi_s\partial_\mu\phi_s - \frac{\mu^2}{2}\phi_s^2 - \frac{1}{2}\partial_\mu\phi_p\partial_\mu\phi_p - \frac{\mu^2}{2}\phi_p^2$$

$$- \frac{\mu^2}{2}\sigma_s^2 - \mu^2\phi_s\sigma_s + g\bar{\psi}_c\psi_c\phi_s + ig\bar{\psi}_c\gamma_5\psi_c\phi_p$$

$$+ g\bar{\eta}\eta\phi_s + ig\bar{\eta}\gamma_5\eta\phi_p \Big] \delta_{\mu\nu}. \tag{2.11}$$

On the other hand, for a uniform fluid in a local rest frame, the energy-momentum tensor has the general form

$$T_{\mu\nu} = P\delta_{\mu\nu} + (\varepsilon + P)u_u u_\nu, \tag{2.12}$$

with

$$u_u = (0, i). \tag{2.13}$$

So the operators corresponding to energy and pressure may be identified as

$$\varepsilon = -T_{44}, \tag{2.14a}$$

$$P = \frac{1}{3}T_{ii}. \tag{2.14b}$$

The energy density and pressure can be determined approximately with the help of Linde's technique [12], i.e., the shifted boson fields can be regarded as fluctuation field and may be expanded as free fields approximately,

$$\phi_s(x) = \frac{1}{(2\pi)^{3/2}}\int d^3\boldsymbol{k}\,\frac{1}{\sqrt{2\omega_k}}(a_k e^{i\boldsymbol{k}\cdot x} + a_k^+ e^{-i\boldsymbol{k}\cdot x}), \tag{2.15a}$$

$$\phi_p(x) = \frac{1}{(2\pi)^{3/2}}\int d^3\boldsymbol{k}\,\frac{1}{\sqrt{2\omega_k}}(b_k e^{i\boldsymbol{k}\cdot x} + b_k^+ e^{-i\boldsymbol{k}\cdot x}), \tag{2.15b}$$

where $\omega_k = \sqrt{k^2 + \mu^2}$, a_k, a_k^+ and b_k, b_k^+ are annihilation and creation operator of the scalar and pseudoscalar particle, respectively. As an approximate result, the correlation of the different fluctuation fields can be ignored, i.e.,

$$\langle 0|\bar{\eta}\eta\phi_s|0\rangle = \langle 0|\bar{\eta}\eta|0\rangle\langle 0|\phi_s|0\rangle = 0, \tag{2.16a}$$

$$\langle 0|\bar{\eta}\gamma_5\eta\phi_p|0\rangle = \langle 0|\bar{\eta}\gamma_5\eta|0\rangle\langle 0|\phi_p|0\rangle = 0. \tag{2.16b}$$

Using the above approximation, we can deduce the energy density of the system

$$\varepsilon = \frac{1}{V}\langle 0|\int d^3x:(-T_{44}):|0\rangle = \varepsilon_c + \frac{2\Lambda^4}{(2\pi)^3}\int_0^{\hat{k}_F} d^3\hat{\boldsymbol{k}}\,\sqrt{\hat{\boldsymbol{k}}^2 + \hat{m}^2} + \frac{\Lambda^4\hat{\mu}^2\hat{m}^2}{2g^2}, \tag{2.17}$$

where

$$\varepsilon_c = \frac{\Lambda^4}{4\pi^2}\left[\frac{\hat{m}^2}{2}\left(\sqrt{1+\hat{m}^2} + \hat{m}^2 \ln\frac{1+\sqrt{1+\hat{m}^2}}{\hat{m}}\right) - (\sqrt{1+\hat{m}^2})^3\right]. \tag{2.18}$$

and the pressure

$$P = \frac{1}{V}\langle 0|\int d^3x : \frac{1}{3}T_{ii} : |0\rangle$$
$$= P_c + \frac{2\Lambda^4}{3(2\pi)^3}\int_0^{\hat{k}_F}\frac{\hat{k}^2 d^3\hat{k}}{\sqrt{\hat{k}^2 + \hat{m}^2}} - \frac{\Lambda^4 \hat{\mu}^2 \hat{m}^2}{2g^2}, \tag{2.19}$$

where

$$P_c = \frac{\Lambda^4}{12\pi^2}\left[\frac{3\hat{m}^2}{2}\left(\sqrt{1+\hat{m}^2} - \hat{m}^2\ln\frac{1+\sqrt{1+\hat{m}^2}}{\hat{m}}\right) - \sqrt{1+\hat{m}^2}\right]. \tag{2.20}$$

At a given baryon number density ρ_b, k_F and the fermionic mass m can be determined from Eqs.(2.7a) and (2.8), respectively. Substituting these values into Eqs.(2.17) and (2.19), we can obtain the parametric equation of state $\varepsilon(\rho_b)$ and $P(\rho_b)$. The baryon number density ρ_b can be eliminated to give the equation of state $P(\varepsilon)$.

3. THE EQUATION OF STATE AT FINITE TEMPERATURE AND DENSITY

With regards to thermodynamical equilibrium system with temperature T and chemical potential α, the physical observable quantities are described by Gibbs average

$$\langle\cdots\rangle^{\alpha\beta} = \frac{\mathrm{Tr}\{\exp[-\beta(H-\alpha N)]\cdots\}}{\mathrm{Tr}\{\exp[-\beta(H-\alpha N)]\}} \tag{3.1}$$

where $\beta = 1/T$. In the following, we use superscripts $\alpha\beta$ to indicate physical quantities at finite temperature and density. Notice the correspondent relation between temperature field theory and quantum field theory [13], i.e., if the vacuum expectation value in quantum field theory is replaced with corresponding Gibbs average, then the physical results at finite temperature and density in temperature field theory can be obtained in the form of the expression. It follows that the equation of state at finite temperature and density can be deduced.

In Ref. [4] we established the self-consistency equation at finite temperature and density,

$$\hat{m}^{\alpha\beta}F(\hat{m}^{\alpha\beta}) = 0, \tag{3.2a}$$

$$F(\hat{m}^{\alpha\beta}) = \hat{\mu}^2 - \frac{g^2}{2\pi^2}\left[\sqrt{1+(\hat{m}^{\alpha\beta})^2} - (\hat{m}^{\alpha\beta})^2\ln\frac{1+\sqrt{1+(\hat{m}^{\alpha\beta})^2}}{\hat{m}^{\alpha\beta}}\right]$$
$$+ \frac{g^2}{\pi^2}\int_0^\infty \frac{\hat{k}^2 d\hat{k}}{\sqrt{\hat{k}^2 + (\hat{m}^{\alpha\beta})^2}}(\langle c^+_{k\sigma}c_{k\sigma}\rangle^{\alpha\beta} + \langle d^+_{k\sigma}d_{k\sigma}\rangle^{\alpha\beta}), \tag{3.2b}$$

where $\hat{m}^{\alpha\beta}$ is the effective fermionic mass depending on temperature and density

$$\hat{m}^{\alpha\beta} = g\sigma_s^{\alpha\beta}, \tag{3.3a}$$

$$\sigma_s^{\alpha\beta} = \langle\phi_s\rangle^{\alpha\beta}. \tag{3.3b}$$

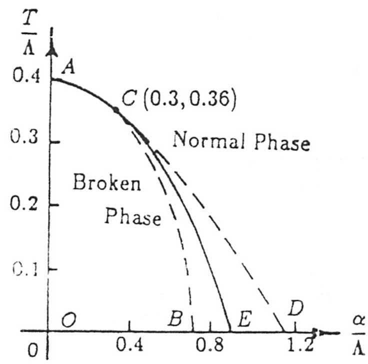

Fig. 1
Chiral Phase diagram of the model.

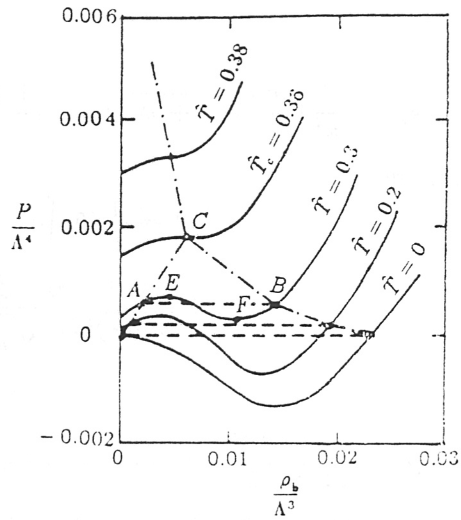

Fig. 2
Isotherms of pressure vs. net baryon number density. In this diagram we have taken the pressure at zero temperature and zero chemical potential to be zero.

$<c^+_{k\sigma}c_{k\sigma}>^{\alpha\beta}$ and $<d^+_{k\sigma}d_{k\sigma}>^{\alpha\beta}$ are decided by Fermi-Dirac distribution function, i.e.,

$$\langle c^+_{k\sigma}c_{k\sigma}\rangle = \frac{1}{\exp[\hat{\beta}(\sqrt{\hat{k}^2+(\hat{m}^{\alpha\beta})^2}-\hat{\alpha}]+1}, \tag{3.4a}$$

$$\langle d^+_{k\sigma}d_{k\sigma}\rangle = \frac{1}{\exp[\hat{\beta}(\sqrt{\hat{k}^2+(\hat{m}^{\alpha\beta})^2}+\hat{\alpha}]+1}. \tag{3.4b}$$

It is completely analogous to the derivation at zero temperature and finite density. Introducing the background-field $\psi_c(x)$ and thermal-fluctuation-field $\eta(x)$ and using the Linde technique, i.e., performing a shift for boson field with respect to its Gibbs average,

$$\phi_s \rightarrow \phi_s + \sigma_s^{\alpha\beta}. \tag{3.5}$$

and substituting Gibbs average for vacuum expectation value at zero temperature and finite density, we can deduce the energy density of the system:

$$\varepsilon = \frac{1}{V}\left\langle\int d^3x:(-T_{44}):\right\rangle^{\alpha\beta}$$

$$= \varepsilon_c^{\alpha\beta} + \frac{\Lambda^4}{(2\pi)^3}\int_0^\infty d^3\hat{k}\sqrt{\hat{k}^2+\hat{\mu}^2}\,(\langle a^+_k a_k\rangle^\beta + \langle b^+_k b_k\rangle^\beta)$$

$$+ \frac{2\Lambda^4}{(2\pi)^3}\int_0^\infty d^3\hat{k}\sqrt{\hat{k}^2+(\hat{m}^{\alpha\beta})^2}\,(\langle c^+_{k\sigma}c_{k\sigma}\rangle^{\alpha\beta} + \langle d^+_{k\sigma}d_{k\sigma}\rangle^{\alpha\beta})$$

$$+ \frac{\Lambda^4\hat{\mu}^2(\hat{m}^{\alpha\beta})^2}{2g^2}, \tag{3.6a}$$

$$\varepsilon_c^{\alpha\beta} = \frac{\Lambda^4}{4\pi^2}\left[\frac{(\hat{m}^{\alpha\beta})^2}{2}\left(\sqrt{1+(\hat{m}^{\alpha\beta})^2} + (\hat{m}^{\alpha\beta})^2 \ln\frac{1+\sqrt{1+(\hat{m}^{\alpha\beta})^2}}{\hat{m}^{\alpha\beta}}\right)\right.$$
$$\left. - (\sqrt{1+(\hat{m}^{\alpha\beta})^2})^3\right]. \tag{3.6b}$$

where $<a_k^+ a_k>^\beta$ and $<b_k^+ b_k>^\beta$ are number density of scalar particle. If we assume that the chemical potential of the boson is zero, then

$$\langle a_k^+ a_k \rangle^\beta = \langle b_k^+ b_k \rangle^\beta = \frac{1}{\exp(\hat{\beta}\sqrt{\hat{k}^2+\hat{\mu}^2}) - 1}. \tag{3.7}$$

The pressure of the system can be expressed as

$$P = \frac{1}{V}\left\langle \int d^3x : \frac{1}{3} T_{ii} : \right\rangle^{\alpha\beta}$$
$$= P_c^{\alpha\beta} + \frac{\Lambda^4}{3(2\pi)^3}\int_0^\infty \frac{d^3\hat{k}\hat{k}^2}{\sqrt{\hat{k}^2+\hat{\mu}^2}}(\langle a_k^+ a_k\rangle^\beta + \langle b_k^+ b_k\rangle^\beta)$$
$$+ \frac{2\Lambda^4}{3(2\pi)^3}\int_0^\infty \frac{d^3\hat{k}\hat{k}^2}{\sqrt{\hat{k}^2+(\hat{m}^{\alpha\beta})^2}}(\langle c_{k\sigma}^+ c_{k\sigma}\rangle^{\alpha\beta} + \langle d_{k\sigma}^+ d_{k\sigma}\rangle^{\alpha\beta})$$
$$- \frac{\Lambda^4 \hat{\mu}^2 (\hat{m}^{\alpha\beta})^2}{2g^2}, \tag{3.8a}$$

$$P_c^{\alpha\beta} = \frac{\Lambda^4}{12\pi^2}\left[\frac{3(\hat{m}^{\alpha\beta})^2}{2}\left(\sqrt{1+(\hat{m}^{\alpha\beta})^2} - (\hat{m}^{\alpha\beta})^2 \ln\frac{1+\sqrt{1+(\hat{m}^{\alpha\beta})^2}}{\hat{m}^{\alpha\beta}}\right)\right.$$
$$\left. - \sqrt{1+(\hat{m}^{\alpha\beta})^2}\right]. \tag{3.8b}$$

When temperature T and chemical potential α are given, Eq.(3.2) can be solved self-consistently to determine the effective mass $\hat{m}^{\alpha\beta}$ of the fermion. With Eqs.(3.6) and (3.8), we can obtain the energy density and pressure of the system, i.e., the parametric equation of state.

4. PHASE STRUCTURE OF THE MODEL

By solving the self-consistency equation (3.2) for the order parameter $\hat{m}^{\alpha\beta}$ and Eq.(3.6) for the energy density as a function of the temperature, the chiral phase diagram of the model is illustrated in Fig. 1. There is a critical point $c(\hat{\alpha} = 0.3, \hat{T} = 0.36)$ in the diagram, which distinguishes first order from second order chiral phase transition. If we cross line AC starting from the broken phase, the chiral phase transition is second order. Beyond this line it becomes first order. The region $OABO$ is the broken phase. Beyond the region $OADO$ is the normal phase without spontaneous chiral symmetry breaking. The area surrounded by $CDBC$ corresponds to the coexistence of the broken phase and the normal phase, and the true chiral phase transition occurs on the line CE, but the overheat and overcool metastable state may appear.

In order to analyze the feature of the phase structure carefully, we notice that the net baryon number density of the fermions can be expressed as

$$\rho_b = \frac{1}{V}\left\langle \int d^3x : \eta^+\eta : \right\rangle^{\alpha\beta}$$

$$= \frac{2\Lambda^3}{(2\pi)^3}\int_0^\infty d^3\hat{k}(\langle c^+_{k\sigma}c_{k\sigma}\rangle^{\alpha\beta} - \langle d^+_{k\sigma}d_{k\sigma}\rangle^{\alpha\beta}), \tag{4.1}$$

and the pressure of the system is given in Eq.(3.8). We obtain some isotherms of pressure versus net baryon number density, as illustrated in Fig. 2. As an example, consider the $\hat{T} = 0.3$ isotherm, we can fix the points A and B by the condition that they have the same transition chemical potential and pressure when phase transition takes place, i.e.,

$$\alpha_A = \alpha_B, \tag{4.2a}$$

$$P_A = P_B \tag{4.2b}$$

The straight line AB is the Maxwell isotherm. When $\rho_b < \rho_b^A$ (ρ_b^A is the net baryon number density corresponding to point A), only broken phase exists. When $\rho_b > \rho_b^B$, only normal phase is present. When $\rho_b^A < \rho_b < \rho_b^B$, we have a mixture, i.e., the coexistence, of the broken phase and the normal phase. The lines AE and FB correspond to the metastable state, which indicates the occurrence of the overcool and overheat phenomena. The state corresponding to the line EF is unstable because $\partial P/\partial\rho_b < 0$. When $\hat{T} = \hat{T}_c = 0.36$, the points A, E, F, B merge into an inflection point corresponding to critical point c in Fig. 1, and the chiral phase transition changes its character to second order. When $\hat{T} > \hat{T}_c$, the inflection point still exists, the phase transition therefore remains as second order. So we can see clearly that point c separates first order from second order chiral phase transition. Compared with liquid-gas phase transition, the above chiral phase transition features are similar below the critical point c but different above it.

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