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NICA: the critical end point

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Abstract

The critical phenomena of strongly interacting matter are presented in the frame of an effective theory at finite temperatures. The phase transitions are considered in systems where the critical end point (CEP) is a distinct singular feature existence of which is dictated by the chiral dynamics. The physical approach to the effective CEP is studied via the influence fluctuations of Bose-Einstein correlations for observed particles to which the critical end mode couples. The results are the subject of the physical program at NICA accelerator to search the hadronic matter produced at extreme conditions.

Keywords: Critical end point, dilatons, deconfinement, chiral dynamics, Bose-Einstein correlations

1. Introduction

The search of strong interacting matter at high temperatures T and high baryon densities corresponding to the freezeout point is one of the issues proposed for heavy ion colliders, in particular, for **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) which is assumed to start in operation in Dubna since 2019. The freezeout point in particle physics is often referred to as critical end point (CEP) of quantum chromodynamics (QCD). The phase transitions in the proximity of CEP are associated with breaking of symmetry. At high T and at finite baryon densities, where non-vanishing baryon chemical potentials μ are assumed, the matter becomes weakly coupled and at the vicinity of CEP the color is no more confined, the chiral symmetry is restored. The CEP itself may be clarified through the search of its location on the $(\mu - T)$ plane, i.e. through the exploration of $(\mu - T)$ phase diagram (see, e.g., [1] and the refs. therein), where each point on the diagram corresponds to a (metha)stable thermodynamic state characterized by T-dependent gauge-invariant functions. The properties of these states are derived from the partition function

$$Z(T,\mu) = \sum_i \exp\left[-(E_i - \mu\, B_i)\beta\right],$$

where i labels states with energy E_i and baryon number B_i, $\beta = 1/T$. Thus, to realize the program of study the critical phenomena (e.g., to predict the CEP location) the high luminosity and high baryon density are required. The collider NICA would be one of the best tools for such a search with the c.m. energy of 4 -11 GeV/u.

A few questions arise:
- what does it mean - CEP?
- what the main observables would be measured to indicate that CEP is achieved?
- what new knowledges can be accumulated ones CEP is approached?

At large distances, QCD itself exhibits nonperturbative phenomena such as chiral symmetry breaking and confinement of color charges. The relation between these phenomena is not yet clarified in the frame of QCD, therefore the correlation or no one-to-one correspondence between phase transitions of chiral symmetry restoration and deconfinement in QCD at finite temperatures is an important issue. An intrinsic approach to analytical calculations is through the scheme with topological defects which emerge in some effective models.

The minimal model where the topological defects (strings) arise is the Abelian Higgs-like model [2].

The key point is reducing of $SU(N_c)$ gluodynamics to $[U(1)]^{N_c-1}$ dual Abelian scalar theory for N_c color numbers. The breaking of the gauge symmetry is realized through the Higgs-like mechanism. In QCD vacuum the color-electric flux is squeezed into an almost one-dimensional object such as string due to the dual Meissner effect caused by condensation of scalar particles [3], which provide the dual superconductor picture of QCD vacuum [4].

We develop an effective Abelian model of $SU(3)$ with the infra-red properties of the vacuum, where the scalar dilatons associated with spontaneous breaking of scale (conformal) symmetry are appear. The approximate scale invariance is manifested at high energies, but is spontaneously broken at a scale f close to the QCD scale.

The physical approach to the QCD critical phenomena is done via the influence fluctuations of Bose-Einstein (BE) correlations for two observed particles to which the chiral end mode couples. The clear signature of the phase transition is a singular behavior of BE correlations characteristics which are rather sensitive to the proximity of CEP, and they could be measured with the magnitude of the fluctuations strengths.

2. Dilaton and scale symmetry breaking

A light CP-even scalar dilaton ϕ may arise as a generic pseudo-Goldstone boson from the breaking of the conformal strong dynamics. We start with partition function

$$Z = \int \mathbf{D}\phi_i \, \exp\left[-\int_0^\infty d\tau \int d^3x L(\tau,\vec{x})\right],$$

$$L(x) = \sum_i c_i(\mu)\, O_i(x),$$

where $c_i(\mu)$ is running coupling, the operator $O_i(x)$ has the scaling dimension d_i. Under the scale transformations $x^\mu \to e^\omega x^\mu$, one has $O_i(x) \to e^{\omega d_i} O_i(e^\omega x)$, $\mu \to e^{-\omega}\mu$. This gives for the dilatation current $S^\mu = T^{\mu\nu}x_\nu$

$$\partial_\mu S^\mu = T^\mu_\mu = \sum_i \left[c_i(\mu)(d_i-4)O_i(x) + \beta_i(c)\frac{\partial}{\partial c_i}L\right],$$

where $T^{\mu\nu}$ and $\beta_i(c)$ are the energy-momentum tensor and the running β-function, respectively. At energies below the conformal breaking scale f: $c_i(\mu) \to (\phi/f)^{4-d_i}\, c_i(\mu\,\phi/f)$. The theory would be nearly scale invariant if $d_i = 4$ and $\beta(c) \to 0$.

Thus, the breaking of chiral symmetry is triggered by the dynamics of nearly conformal sector.

3. Dual model. Flux tubes

The dual Lagrangian density in $SU(3)$ is

$$L_{eff} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{i=1}^{3}\left[\frac{1}{2}|D^{(i)}_\mu \phi_i|^2 - \frac{1}{4}\lambda_\phi\left(\phi_i^2 - \phi_{0_i}^2\right)^2\right],$$

$$G_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu - i\,g[C_\mu, C_\nu],\;\; D^{(i)}_\mu\phi_i = \partial_\mu\phi_i - ig[C_\mu,\phi_i],$$

$$C_\mu(x) = \sum_{a=1}^{8} C^a_\mu(x)\, t_a.$$

In the confinement phase the dual gauge symmetry is broken due to dual scalar mechanism, and all the particles become massive. A quantum of C_μ acquires a mass $m \sim gf$, hence the dual theory is weakly coupled at distances $r > 1/mass$, where the denominator being either the mass of C_μ or the mass $m_\phi \sim \sqrt{2\lambda_\phi}\, f$ which is the threshold energy to excite the dilaton in the dual QCD vacuum.

The excitations above the (classical) vacuum are flux tubes connecting a quark-antiquark pair in which the electric flux is confined to the narrow tubes of a radius $\sim m^{-1}$, at whose center the scalar condensate vanishes. The probability distribution related to the ensemble of systems containing a single flux tube with $N(R)$ number of configurations of the flux tube of the length R is [5]

$$Z_{flux}(\beta,R,m) = \sum_\beta \sum_R N(R)\, e^{-\beta E(m,R)} D(|\vec{x}|,\beta;M),$$

$$E(m,R) \sim m^2 R[a + b\, \ln(\tilde{\mu} R)].$$

C_μ develops an infinite fluctuation length $\xi \sim m^{-1}$ in the proximity of CEP with the critical temperature T_c, $m^2(\beta) \sim g^2(\beta)\,\delta^{(2)}(0)$. The function D in Z_{flux} is also valid at $T > T_c$: $D(|\vec{x}|,\beta;M) = \exp[-M(\beta)\,|\vec{x}|]$, where

$$M(\beta) = M^{LO}(\beta) + 4\,\pi\,\alpha\, T\, y_{n/p}(N) + O(\alpha^{3/2}T, \alpha^2 T),$$

$$M^{LO} = \sqrt{4\pi\alpha\left(\frac{N}{3}+\frac{N_f}{6}\right)}T + N\alpha T \ln\sqrt{\frac{1}{12\pi\alpha}\left(N+\frac{N_f}{2}\right)}.$$

At high T and at large distances the correlator $\omega(\tau,\vec{x}) = \langle O(\tau,\vec{x})O(\tau,0)\rangle$ of two gauge-invariant operators $O(\tau,\vec{x})$, associated with observables is

$$\omega \sim \frac{T}{V_W}\sigma_0\xi^2\left[\frac{1}{\xi}\sqrt{\frac{8\pi}{\sigma_0}} - N\ln\left(\xi\sqrt{2\pi\sigma_0}\right) + 4\pi y_{n/p} + ...\right],$$

where $\sigma_0(\beta) \sim m^2(\beta)\,\alpha(\beta)$ is the running string tension and $y_{n/p}$ reflects the non-perturbative contributions (for details see [5]). The correlator ω is different from zero at small fluctuation length ξ (low T) and has a singular behavior at large fluctuations ($\xi \to \infty$) when CEP is approached. Physically ξ is the penetration depth of color-electric field (or, approximately, the radius of the flux tube), while the inverse dilaton mass $l = m_\phi^{-1}$ stands for the coherent length of the scalar field (condensate).

In the discrete space of a dilaton condensate $N(R) = V\, l^{-3}\, exp[s(R/l)]$ [5], hence Z_{flux} becomes

$$Z_{flux}(\beta, R, m) = \frac{V}{l^3} \sum_R \exp(-E_{flux}\beta), \quad (1)$$

$$E_{flux}(\beta) = \sigma_{eff}(\beta)\, R,$$

$$\sigma_{eff}(\beta) = \sigma_0 - \frac{s}{l\beta} + \frac{|\vec{x}|}{R\beta} M(\beta).$$

The chiral symmetry is restored at $T = T_c$; $s = E_{tot}/T$, and $E_{tot} \sim O(m_{q\bar{q}})$ with $m_{q\bar{q}}$ being the mass of a quark-antiquark bound state.

The interactions between flux tubes are defined by the scalar and gauge boson fields profiles. The vacuum criterium is given by the Ginzburg-Landau-like parameter $k_{GL} = \xi/l$:
- $k_{GL} < 1$ (type-I vacuum), the attracted forces can appear between two (parallel) flux tubes;
- $k_{GL} > 1$ (type-II vacuum), the flux tubes repel each other in the vacuum.

The phase transition, if occurred, must be seen through the singularity once partition function is calculated. The singularity of Z_{flux} (1) may arize when the vacuum criterium obeys the following condition

$$k_{GL} > L_W\, M(\beta) \left(\frac{\xi}{\beta}\right),$$

where L_W is the spatial Wilson loop which has an area law behavior below and above T_c. The critical temperature is $T_c \simeq 167$ MeV for pions ($N_f = 3$), while the value of baryon (chemical) potential μ is compared to the dilaton mass m_ϕ for strings with $m_{q\bar{q}}R \sim O(1)$, $\mu \simeq 0.35$ GeV for QCD scale $\Lambda \simeq 0.5$ GeV.

4. Two-particle correlations

The fluctuations of some modes in the vicinity of CEP can not be measured in experiments. These fluctuations can affect the observables either in direct channel or in indirect reactions. One of the examples is the BE correlation phenomenon, where the strength of the correlation between two particles may have the influence fluctuations.

At finite temperatures the correlation between two Bose-particles with momenta p_1 and p_2 is given by the function (see for details [6])

$$C_2(q,\beta) \simeq \eta(n) \left\{1 + \lambda(\beta) e^{-q^2 L_{st}^2} \left[1 + \lambda_1(\beta) e^{+q^2 L_{st}^2/2}\right]\right\},$$

$$\eta(n) = \langle n(n-1)\rangle / \langle n \rangle^2, \quad q = p_1 - p_2,$$

where L_{st} is the measure of the space overlap between two identical particles (flux tubes) affected by stochastic forces in the vacuum characterized by k_{GL}.

The following theoretical effects of CEP on the size L_{st} of particle emission source and the correlation strength $\lambda(\beta)$ are obtained.
Evolving size. L_{st} is strongly dependent on $\lambda \sim (1+\nu)^{-2}$, the transverse momenta k_T, the hadron mass m_h and T. At low temperatures L_{st} decreases with k_T and increases with particle multiplicity n ($\nu(n) \to 0$).

At higher T there is a nontrivial singular behavior of $L_{st} \sim \left[\nu(n)\, k_T^2\, T^3\right]^{-1/5}$ with $\nu \sim (n\, k_{GL}^2)^{-1}$ [7]. No the dependence of both μ and m_h are found, and $L_{st} \to \infty$ as $\nu(n) \to 0$ with $n \to \infty$, when $\xi \to \infty$.

Correlation strength. The correlation strength $\lambda(\beta)$ decreases with k_T. The result of smooth decreasing of λ with k_T with slight increasing of the values of λ at small n has been already demostrated by CMS [8]. In the phase of deconfinement we propose $\lambda = 1$, $\lambda_1 = 0$ as $T \geq T_c$ and the fluctuation length $\xi \to \infty$ (or $L_{st} \to \infty$).

5. Conclusions.

The following phenomenological quantities can show the occurrence of phase transition (CEP is approached):
- L_{st} blows up as $T \to T_c$ (due to $\nu(n) \to 0$, $m_h \to 0$), L_{st} singularity is evident;
- large enough fluctuation length ξ ($\nu(n) \to 0$, chiral symmery is restored);
- C_2 - function being non-monotonous function of k_T at low T does not deviate from 1 as $T \geq T_c$;
- the correlation strengths $\lambda = 1$ (fully chaotic source) and $\lambda_1 = 0$ as $T \geq T_c$;
- the allocation of CEP satisfies $C_2 \sim \lambda \sim 1$ relevant to ($\mu - T$) phase diagram.

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