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.

1. Introduction

Physics target: Study of hot and strongly interacting matter.
Tool: Superconducting accelerator complex NICA (**N**uclotron-based **I**on **C**ollider f**A**cility)
Two modes in operation:
- collider mode (MPD detector), max $p = 13\ GeV/c$ for protons, $L = 10^{27} cm^{-2}s^{-1}$;
- extracted beams (BM@N).

In the proximity of the Critical End Point (CEP):
- matter becomes weakly coupled, color is no more confined;
-chiral symmetry is restored;
-phase transition is associated with breaking of symmetry.

CEP may be clarified through scanning of $(\mu - T)$ phase diagram, where each point on the diagram corresponds to a (metha)stable thermodynamic state characterized by temperature T-dependent gauge-invariant functions at finite baryon density μ.

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?

To realize the program of study the critical phenomena (e.g., to predict the CEP location) the collision energy in relativistic heavy ion machines would not be sufficiently high ($\sqrt{s_{NN}} \simeq 4$ -11 GeV), however the new phenomena would be seeing at high luminosity and high baryon density.

NICA is the best accelerator for such a search.

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 [*Nielsen, Olesen, 1973*]. 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 scalar condensation.

Our message is an effective Abelian model of $SU(3)$ with IR 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 arize as a generic pseudo-Goldstone boson from the breaking of the conformal strong dynamics. We start with partition function

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

$c_i(\mu)$ 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 $S^\mu = T^{\mu\nu} x_\nu$

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

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.

Dual Lagrangian density in $SU(3)$

$$L_{eff} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \sum_{i=1}^{3} \left[\frac{1}{2} \left|D_\mu^{(i)} \phi_i\right|^2 - \frac{1}{4}\lambda_\phi \left(\phi_i^2 - \phi_0^2\right)^2\right],$$

$$G_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu - i\, g[C_\mu, C_\nu], \;\; D_\mu^{(i)}\phi_i = \partial_\mu \phi_i - ig[C_\mu, \phi_i], \;\; C_\mu(x) = \sum_{a=1}^{8} C_\mu^a(x)\, t_a.$$

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 Z_N 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

$$Z_{flux}(\beta, R, m) = \sum_\beta \sum_R N(R)\, \exp\left[-\beta\, E(m, R)\right]\, D(|\vec{x}|, \beta; M),$$

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

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

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

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

At high T and at large distances the correlator of two operators associated with observables is

$$\langle O(\tau, \vec{x}) O(\tau, 0)\rangle \sim \frac{T}{V_W} \sigma_0 \xi^2 \left[\frac{1}{\xi}\sqrt{\frac{8\pi}{\sigma_0}} - N \ln\left(\xi\sqrt{2\pi\sigma_0}\right) + 4\pi y_{n/p} + \ldots\right].$$

The latter 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 $N(R) = V\, l^{-3}\, exp[s(R/l)]$

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

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

The chiral symmetry is restored at $T = T_c$; $s = E_{tot}/T$, and $E_{tot} \sim O(m_{q\bar{q}})$.

The interactions between flux tubes are defined by the scalar and gauge boson fields profiles. 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

$$k_{GL} \geq 1 + \frac{M(\beta)\, T}{\alpha(\beta)\, m^2(\beta)} \frac{L_W}{R}.$$

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 $\Lambda \simeq 0.5$ 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 two-particle BE correlation function is (*G. Kozlov, 2009*)

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

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}.

Theoretical results.

Theoretical effect of CEP on the size L_{st} of particle emission source is explored.

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 ν, where in the scheme with dilaton condensate $\nu \sim (\xi/L_{st})\, (1/k_{GL}^2)$. 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. We find out that 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 was demostrated by CMS at LHC in 2011. Actually, in the phase of deconfinement $\lambda = 1$, $\lambda_1 = 0$ as $T \geq T_c$ with the fluctuation length $\xi \to \infty$ (or $L_{st} \to \infty$).

5. Conclusions. Signatures if the CEP is approached.

Phenomenological quantities to show the occurrence of phase transition:
- 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 symmetry is restored);
- C_2 - function being non-monotonous function of k_T at low T does not deviate from 1 as $T \geq T_c$;
- correlation strengths $\lambda = 1$ (fully chaotic source) and $\lambda_1 = 0$ as $T \geq T_c$;
- the allocation of CEP satisfies to $C_2 \sim \lambda \sim 1$ relevant to $(\mu - T)$ phase diagram.