Two – component – liquid model for quark – gluon plasma

V.I. Zakharov (ITEP, Moscow),
based on collaborations with
M. N. Chernodub (Tours), A.S. Gorsky (ITEP),
A. Nakamura (Hiroshima), H. Verschelde (Gent)

QUARKS 2010
Kolomna
07.06.10

Model, reminder

In hydrodynamic approximation:

$$
\begin{aligned}
j^{\mu} &= n u^{\mu} + f^{2}\partial^{\mu}\phi \\
T^{\mu\nu} &= (\epsilon + P)u^{\mu}u^{\nu} + P\eta^{\mu\nu} + f^{2}\partial^{\mu}\phi\partial^{\nu}\phi \\
u^{\mu}\partial_{\mu}\phi &= \mu
\end{aligned}
\qquad (1)
$$

u^{μ} is 4-velocity,
ϕ is a scalar field

Two independent motions,

$$\rho_{tot} = \rho_{n} + \rho_{s}$$

Outline of the talk

1. Why at all?
2. where is the scalar field in QCD?
3. possible crucial test

A. Equation of state

$$\epsilon(T) \approx (\epsilon(T))_{ideal\ gas}(1-\delta)$$

$\delta \approx 0.1 - 0.15$

Close to the ideal gas

Known since long from lattice simulations

“lost decades"(E.V. Shuryak)

Viscosity η

(like friction, enters hydrodynamic $T^{\mu\nu}$)

Fits to the RHIC data:

$$\left(\frac{\eta}{s}\right)_{plasma} \approx \frac{1}{4\pi}$$

It is the lowest viscosity among all known liquids
(or, the plasma is closest to the ideal liquid)

For ideal gas:

$$\eta_{ideal\ gas} \longrightarrow \infty$$

Low η/s is confirmed now on the lattice

C. Quantum effects

From kinetics:

$$\frac{\eta}{s} \sim k_B^{-1} \tau_{relaxation} \cdot \left(\frac{\epsilon}{n}\right)$$

From uncertainty principle

$$\left(\frac{\epsilon}{n}\right) \cdot \tau_{relaxation} \sim \bar{h}$$

since ϵ/n is energy per particle

$$\frac{\eta}{s} \sim \frac{\tau_{relaxation}}{\tau_{quantum}}$$

It is a challenge to explain points A)-C) which show in opposite directions

Two components?

What is special about the viscosity?

If there are two components

$$\frac{1}{\eta_{tot}} = \frac{c_1}{\eta_1} + \frac{c_2}{\eta_2} \qquad (*)$$

where $c_1 + c_2 = 1$, $c_{1,2}$ are phase-space factors
Indeed, η is like resistance

$(*)$ is true for classical solutions ($c_{1,2}$ are concentrations)

$(*)$ is supported by superfluidity example

Two components:

1. One component dominates E.o.S., $c_1 >> c_2$
2. The other dominates η_{tot} if $\eta_2 << \eta_1$
3. if one component superfluid, large quantum effects are 'explained'
4. unlike non-relativistic case,
   in field th. seems no limit on temperature

   Indeed, from dimensional reduction:

$$\lim_{T\to\infty} c_2 \sim \frac{1}{(\ln T)^3}$$

To summarize: two components seem to work qualitatively

Scalar field?

To realize superfluidity, need a scalar fields.
Constraints:

1. complex field,
   $\phi \neq \phi^*$,
2. condensed,
   $\langle\phi\rangle \neq 0$,
3. no known quantum number is allowed
   to be violated by $\langle\phi\rangle \neq 0$,
4. rather $3d$ field, $\phi(\mathbf{r})$
   $(\partial_t \phi = \mu)$

Thermal scalar

Scalars do arise within string-based approaches
Near Hagedorn transition, $\beta < \beta_H$ single mode with mass

$$m_\beta^2 = \frac{\beta_H(\beta_H - \beta)}{2\pi^2(\alpha')^2}$$

dominates. At $\beta = \beta_H$ becomes tachyonic.

$$F = = \beta \ln Z \approx \beta \int_0^\infty \frac{dL}{L} \frac{\exp(-m_\beta^2 l_s L)}{(l_s L)^{d/2}}$$

Sum over random walks

1. of length L
2. with steps l_s (related to the string tension)
3. in d dimensions

Thermal scalar vs constraints

IF thermal scalar condensed at $T > T_c$
our constraints were satisfied:

1. $\phi \neq \phi^*$ (sum over closed loops)
2. 3d field (from explicit calculations, strings static)
3. quantum number related to the field is topological (wrapping around the time direction)

Gauge/string correspondence

Duals to YM: strings in extra curved dimensions

Generic features:

1. Thermal scalar condensation changes geometry
2. various lower-dimensions defects exist
3. at $T > T_c$ defects become time oriented (strings static)
4. 3d projections of time-oriented strings
   do produce scalar fields
5. Deconfinement phase transition
   as a change of geometry from 4d to 3d already at
   $T = T_c$

Lattice data

provide independent support for theoretical picture above

In particular, 2d defects become time oriented at $T > T_c$ (known since long)

At a time slice their projection forms an infinite cluster that is,

scalar condensation is observed in geometric language

To summarize:

there is strong evidence in favor of existence of

3d scalar field at $T > T_c$

both from continuum (dual models) and lattice.

Deconfinement phase transition as
transition from 4d to 3d in non-perturbative sector.

Static correlator of momentum densities operators

Consider

$$G_R^{0j,0i}(k) = i \int d^4x e^{-ikx} \theta(t) < |T^{0j}(x), T^{0i}(0)| >$$

in the static case:

$$G_R^{0j,0i}(\omega = 0, \mathbf{k}) = \frac{k_i k_j}{\mathbf{k}^2} G^L(\mathbf{k}) + (\delta^{ij} - \frac{k_i k_j}{\mathbf{k}^2}) G^T(\mathbf{k})$$

Theorems known:

$$\lim_{\mathbf{k}\to 0} G^T(\mathbf{k}) = -(sT + \mu\rho_n)$$

and

$$\lim_{\mathbf{k}\to 0} G^L(\mathbf{k}) = -(sT + \mu\rho_{tot})$$

In other words,

$$\lim_{\mathbf{k}=0} G^{0j,0i}(\mathbf{k}=0) \;=\; \rho_s \frac{k_i k_j}{\mathbf{k}^2}$$

Superfluidity brings in non-analyticity at small $\mathbf{k}$.
All quantities are static
and could, therefore, be measured directly on the lattice

The two-component model has not failed so far.

Could be crucially tested in the future