TRANSFORMATIONS OF THE HADRONIC AND SUBHADRONIC SUBSTANCES UNDER EXTREME CONDITIONS

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Very dense and/or hot hadronic substance (e.g. the one with energy density greatly exceeding that of a normal nucleus) transforms itself into a subhadronic substance which obeys macroscopic classical physics, in particular suffers phase transitions. The most popular Single Phase Transition Model (SPTM) assumes that the new phase is the Quark Gluon Plasma (QGP) consisting of deconfined, chiral symmetric, pointlike "current" quarks $q$ and gluons $p$ of Quantum Chromodynamics (QCD). This paper is devoted to another, Double Phase Transition Model (DPTM) according to which hadronic substance ($H$) and QGP transform one into another via an intermediate phase consisting of deconfined constituent massive quarks $Q$ which for brevity sake we call also equivalently valons ($Q$, valonic phase) with broken chiral symmetry (plus pions as Goldstone particles). I.e. we consider the phase transformation chain $H \leftrightarrow Q \leftrightarrow QGP$ instead of usually assumed $H \leftrightarrow QGP$. The phase transition $H \leftrightarrow Q$ is the Hagedorn one and corresponds to the Hagedorn temperature. Connection with the relativistic heavy ion collision is discussed. $H \leftrightarrow Q$ transformation may take place even at low (e.g. Dubna) energies.

1 Introduction

There still exist two prejudices.

1) Classical treatment of hadronic matter at extreme conditions is considered a rough vulgarisation while it is actually fully proper. Two simplest arguments for this are:
   i) Here in a single collision very many particles appear, i.e. the number of excited degrees of freedom becomes huge as well as the total quantum numbers leading to classical physics.
   ii) In strong interaction field theory all elements of the Fock column are equally important. Even the vacuum becomes filled up by spontaneously appearing particles, its energy density $\epsilon$ and pressure $p$ are estimated within QCD as $-\epsilon_{vac} = p_{vac} \simeq 0.5 - 1 \text{ GeV/fm}^3$, i.e. average energy density of a continuous medium of close packed nucleons, $\epsilon \approx \epsilon_N \approx 0.5 \text{ GeV/fm}^3$. Thus in certain cases the ultramicroworld may be described by macrophysics. One can even suggest that any field theory at high $\epsilon$, if interaction becomes strong, should reduce to the classical one.

2) After appearance of QCD with its pointlike massless quarks $q$ overwhelming majority of high energy physicists seemingly forgot about massive
constituent quarks (or *valons*) $Q$ with which the quark idea had begun. Systematics and many properties of baryons (three valons) and mesons ($Q\overline{Q}$) were explained with masses $m_{Q(u)} \approx m_{Q(d)} \approx 310 – 340$ MeV, $m_{Q(s)} \approx 510$ MeV and average radius $r_Q \approx 0.3$ fm. As a meaningful exclusion one can mention Kennet Wilson Ohio University group who recently reported on “the fruit of four years struggle and effort to build a bridge between constituent quark model and QCD.”

In the present paper, similarly to $^2-^6$, $Q$ is treated as a real particle (imagined as $q$ dressed by a dense cloud of $q\overline{q}$ pairs and gluons) and phases of hadronic nature substance are considered classically.

2 Single Phase Transition Model (SPTM).

SPTM follows from the Hagedorn observation $^7$ that the mass spectrum of existing hadrons obeys $\rho(m)dm \sim exp\left(\frac{m}{T_H}\right)dm$ (supported later in various theoretical approaches). According to latest fitting, $T_H \approx 150$ MeV $^8$. Since Boltzman average of any function $f(m)$ is $\overline{f} \sim \int f(m)\rho(m)exp(-\epsilon(m)/T)dm_q$ it diverges at $T \geq T_H$. Thus $T_H$ is the maximum possible temperature for hadronic phase $H$. Above it we must have another phase practically unanimously believed to be $QGP$. Thus $T_H$ should coincide with temperatures of deconfinement, $T_d$, and chiral symmetry restoration, $T_{ch}$: $T_d = T_{ch} \equiv T_H$.

3 Double Phase Transition Model (DPTM).

However various arguments, e.g. existence of $Q$, point to existence of additional mass scale and thus to possibility of $T_d \neq T_{ch} ^9$. Field theoretical analysis shows $^{10,11}$ that if so then $T_{ch} \geq T_d$. In fact, consider a simple pattern $^{12}$. Let a nucleus with its $\epsilon_A = 0.15$ GeV/fm to be compressed nearly thrice when its $\epsilon$ becomes equal to a nucleon one, $\epsilon_N = 0.5$ GeV/fm $^3$ i.e. until all nucleons are close packed. Now each $Q$ confined within them can go over to any adjacent nucleon, i.e. becomes *deconfined* and they all form a gas of massive valons (plus pions as Goldstone particles). Further compression up to $\epsilon = \epsilon_Q \sim \frac{1}{4}m_Q\pi r_Q^3 \sim 3$ GeV/fm$^3$ makes $Q$ close packed and enables $q$ quarks to go over from one valon to any adjacent one thus deconfining them and forming $QGP$. This simplified scheme clarifies attempts $^2-^6$ to construct a bag type model in which $Q$ phase was expected to be intermediate. However their results showed negligible role of $Q$ phase.

These works were reconsidered within the same bag type thermodynamical model (calculation of partition function for three phases with bag constants...
$B_Q$ and $B_q$ for $Q$ and $QGP$ phases). Herefrom for each $T$ and chemical potential $\mu$ the stable phase can be determined as the one with largest pressure. However the physical approach to the choice of the free parameter $B_q$ was different. It was put equal to $p_{vac}$. This DPTM has given expected result [13]: the phase transition $H\leftrightarrow QGP$ proceeds via the intermediate valon phase, $H\leftrightarrow Q\leftrightarrow QGP$. At some set of the model parameters considered as "standard" ($B_Q = 50\text{MeV/fm}^3$, $B_q = p_{vac} = 0.5\text{GeV/fm}^3$, $r_Q = 0.3\text{fm}$) two phase transitions for $\mu = 0$ occur at $T_d(\equiv T_H) = 140\text{ MeV}$, $T_{ch} = 200\text{ MeV}$ (Fig.1). The width of the $Q$ corridor at almost any $\mu$ is few tens MeV.

Special efforts were directed to testing stability of this conclusion against variation of free parameters. Increase of $B_Q$ narrows the corridor (Fig.2) but leaves result qualitatively unchanged at least for $\mu \leq 1\text{ GeV}$ (this can be compensated by assuming $p_{vac} \sim 1\text{ GeV/fm}^3$: increase of $B_q$ widens the corridor). Variation of $H$ phase description within Hard Core Model (HCM) and Mean Field Approximation (MFA) with two versions of nucleon interaction potential (Fig.3), account in the $H$ phase of exciting 30 resonances (Fig.4) besides initially taken into account merely $N, \Lambda, \pi$ and $K$, as well as variation of $r_Q$ do not tell to any extent essentially.

4 Further results

1) Duration of various phases in the process of expansion of initial fireball generated by two nuclei collision as well as of mixed phases at $T_d$ and $T_{ch}$ calculated according to the Bjorken simplified hydrodynamics is presented in Fig.5. In DPTM it markedly differs from SPTM. Since $T_d$ is very close to freeze out temperature $T_f \approx 130\text{ MeV}$ the pure $H$ phase lasts very short time. A predominantly longer time is spent for $Q$ and mixed $H+Q$ phases. This should tell quantitatively on direct photon and dilepton and strangeness production.

2) As has been noticed in [15], the entropy per baryon $S/N_B$ is not continuous at phase transition is SPTM. The same holds for DPTM. This was cured in SPTM by making $B_q$ depending on $T$ and $\mu$. In our treatment this is hardly proper since $B_q = p_{vac}$. Accordingly in DPTM the same was done only for $B_Q$ by making it $T$ and $\mu$ dependent within $T_d \leq T \leq T_{ch}$.

3) Relative content of strange particles $K^-, \Lambda^-, \Sigma^-$ within DPTM is smaller than in SPTM (due to lower temperature of hadronic phase appearance), save the special case of $K^+\pi^-$, here it is also smaller for $\mu \leq 200\text{ MeV}$ but for $\mu > 200\text{ MeV}$ overcomes (\pi production in SPTM by hadronic resonance decay plays more important role than in DPTM, again due to lower $T$).
5 Concluding remarks.

The above said seemingly supports the idea of existence of the valonic $Q$ phase and two phase transitions with $T_d \neq T_{ch}$. The decisive condition for it is sufficiently large ratio $\beta \equiv \frac{B_Q}{m} \geq 5$. One of the most dubious elements of this thermodynamical approach is the assumed independence of the valon mass $m_Q$ of temperature. It seems plausible that, like for other hadrons, it depends on quark condensate, $m_Q \sim \langle 0|\bar{q}q|0\rangle^{1/3}$ and diminishes with $T$ increasing within $T_d < T < T_{ch}$. Physically this can be imagined as undressing of $Q$, loosing parts of its $q\bar{q}$ cloud. Estimates show that diminishing of $m_Q$ displaces $T_{ch}$ to higher values. However on the other hand the assumed constancy of $B_Q$ within the same interval is also dubious. Diminishing of $m_Q$ means its development in direction to $g$ mass, and thus of $B_Q$ to $B_g$ which influences $T_{ch}$ in inverse sense. These effects are now under investigation.

It deserves stressing that $\epsilon \sim 3\epsilon_A$ necessary for coming to $Q$ phase needs central collision of two identical nuclei Lorentz contracted only $\sim 1.5$ times (even if we neglect additional contraction due to shock wave). I.e. it can take place even at rather low energies, $E_{Lab} \geq 4$ GeV/nucleon.

It is to be added that recently O.K. Kalashnikov build a field theoretical model starting from the complex Lagrangian and imposing a special condition on coupling constant behaviour. This quite a different approach also gave a wide $Q$ phase corridor in $\mu - T$ plane (with smaller $Q$ masses).

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Figure 1: The $\mu - T$ phase diagram according to SPTM (dashed) and DPTM (solid lines) with $\beta = 10$. Dots bound the $Q$-phase for $\beta \approx 3$.

Figure 2: DPTM transition curves from 13 with $B_Q = 50$ MeV/fm$^3$ (solid) and $B_Q = 100$ MeV/fm$^3$ (dashed).
Figure 3: DPTM transition curves for various nucleon interaction description: HCM (solid) and two versions of MFA potential for H-phase from (dashed and dotted).

Figure 4: DPTM (solid) and SPTM (dashed) transition curves for HCM with and without (dots) accounting for 30 resonance in the H phase.
Figure 5: Schematic illustration for space-time evolution of hot matter according to SPTM (a) and DPTM (b) within Bjorken hydrodynamical version. Initial energy density of the fireball assumed to be $\epsilon_0 \approx 4\text{ GeV/fm}^3$. 