A NEW LOOK AT THE QCD PLASMA

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Abstract

The possibility of a bound-state effect in the quark-quark interaction is discussed. If such dynamical diquarks exist, they should play a role in the formation and decay of a QCD plasma, as probed in relativistic heavy-ion collisions. In an intermediate temperature range, just above the critical temperature, a diquark plasma component is expected to be important. Quantitative results within a particular model, the Stockholm diquark model, are presented. Possible experimental signatures of such a diquark plasma are suggested.

1. Introduction

A Stockholm group (S. Fredriksson and myself, previously also M. Jändel and T.I. Larsson) has for the past few years investigated the hypothesis that there exist a bound state in the quark-quark interaction, a *diquark*. So far the model has been confronted with data from deep inelastic lepton-nucleon scattering[1,2], e^+e^- annihilation[3], and hadron-hadron scattering[4,5]. It is in line with world data, and for some phenomena diquarks seem to provide the best explanation on the market.

The Stockholm diquark model prescribes that two quarks of unequal flavour and colour can form a scalar diquark. Excited states do not seem to be needed to account for the data, so for simplicity and economy we assume that only the ground state is bound, i.e. a diquark has colour 3^* and $J^P = 0^+$.

Since diquarks are not colour singlets, they are subject to confinement, but they could occur

- inside hadrons,
- in the fragmentation process, or
- in a QCD plasma,

on an equal footing with single quarks.

Diquarks are expected to occur inside spin-½ baryons (as well as in multiquark states, such as dibaryons). We assume that $p = u(ud)$ and $n = d(ud)$.

Since the diquark is an extended object, the interaction amplitude is suppressed by a form factor. This Q^2 dependence can explain the scaling violation in deep inelastic structure functions[1,2], as well as the p_T and θ dependences of high-p_T proton production in hadron-hadron collisions[4,5].

Here I will focus on the third possible arena for diquarks in physics : *the QCD plasma*. If diquarks are bound, it is energetically favourable for two quarks in the plasma to form a diquark. However, for very high temperatures, i.e. $T \gg$ diquark binding energy, we expect that most diquarks will dissociate into two quarks. It is in an intermediate temperature range, just above the critical temperature, that diquarks could conceivably be an important component in the plasma. Thus, it is possible that the experimentally observable decay of the plasma, which reflects the plasma properties at "low" temperatures, is influenced by the presence of diquarks.

In the following, I present a model of the plasma, in order to arrive at a quantitative estimate of the fraction of quarks in the plasma that are bound in diquarks.

2. Model of the plasma

Regard a QCD plasma with N_i particles of type i in a volume V as an ideal relativistic gas of fermions and bosons. Consider the process

$$u + d \rightleftarrows (ud) \tag{1}$$

as a chemical reaction, and use thermodynamics to calculate the relative abundances, assuming thermal and chemical equilibrium. In this approach, the gluonic degrees of freedom are regarded as an effective "heat bath", which is responsible for the thermalisation.

We have contributions to the grand canonical partition function Ξ from particles of type i :

$$T \ln \Xi_i = \int \sigma_i(E) \left(\exp \frac{E-\mu_i}{T} \pm 1\right)^{-1} dE \ , \tag{2}$$

where T is the temperature and μ is the chemical potential. The plus sign is applicable for fermions and the minus sign for bosons. The integrated one-particle state density function is

$$\int_{m_i}^{E} \rho_i(E)\ dE = \sigma_i(E) = \eta_i \int_{\varepsilon_i < E} \frac{V\, d^3p}{(2\pi)^3} = \frac{\eta_i}{6\pi^2}\, V\, (E^2 - m_i^2)^{3/2} \tag{3}$$

for $E > m_i$. η_i is the degeneracy factor, ε_i the energy, and m_i the mass of one particle of type i.

For the particle number densities $n_i = N_i/V$ and the pressure P of the plasma one gets

$$n_i = \frac{1}{V} \frac{\partial}{\partial \mu_i} (T \ln \Xi_i) = \frac{1}{V} \int_{m_i}^{\infty} \rho_i(E) \left(\exp \frac{E-\mu_i}{T} \pm 1\right)^{-1} dE \ , \text{ and} \tag{4}$$

$$P = \frac{1}{V}\, T \ln \Xi = \frac{1}{V} \sum_i \int_{m_i}^{\infty} \sigma_i(E) \left(\exp \frac{E-\mu_i}{T} \pm 1\right)^{-1} dE \ . \tag{5}$$

The condition for chemical equilibrium is

$$\mu_u + \mu_d = \mu_D , \tag{6}$$

where we have introduced the notation D for the (ud) diquark, and the condition of total quark-number conservation

$$2 n_D + n_u + n_d = n , \tag{7}$$

where the quark-number density n is the total net number of quarks (including those bound in diquarks) per unit volume.

For the effective quark and diquark masses we use m_q = 400 MeV and m_D = 500 MeV , corresponding to a diquark binding energy of 300 MeV. This choice can be motivated by comparing the nucleon (qD) mass ≅ 900 MeV to the delta (qqq) mass ≅ 1200 MeV. Also, from classical considerations one can show[6] that when two objects of mass 400 MeV bind to form a state of mass 500 MeV, the radius of the system becomes 0.25 fm, which is the value favoured by our earlier analyses of μp and pp scattering[1,5].

We take into account only the particle types i = D and i = q (= u or d), i.e. we neglect strange and heavier quarks, and also pair production of even the lightest quarks. This can be motivated, since production of real quark-antiquark pairs should be negligable when $T \ll 2 m_q$. We are interested in the low-temperature structure of the plasma, and we assume the effective lightest quark mass to be 400 MeV.

For simplicity we consider the isoscalar case

$$n_u = n_d . \tag{8}$$

In this case one also gets

$$\mu_u = \mu_d = \mu . \tag{9}$$

This is applicable to the forward baryon-rich fragmentation region in the CERN SPS heavy-ion programme, with ^{16}O, ^{32}S, and, possibly, ^{40}Ca beams[7].

In order to solve the system (4) - (9) for μ , and get the diquark fraction, the pressure, and the volume of the plasma solely as functions of temperature (and of the initial conditions at plasma formation), we need an additional relation; an equation of state for the cooling plasma. Here I will present results for two cases, namely constant volume or constant pressure. Probably neither of these scenarios is very realistic, and the results should be considered as preliminary. It has been argued, for instance, that $P \propto T^4 + \text{const}$ is a good candidate as the equation of state[8].

3. Results and conclusions

The resulting diquark fractions

$$x_D = n_D/(n_D+2n_q) \tag{10}$$

as functions of temperature are shown in Figures 1 and 2 for some special cases of constant volume and constant pressure, respectively.

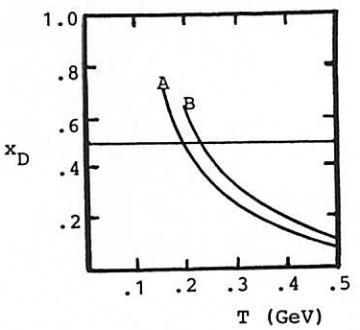

Fig. 1 Diquark fractions in the plasma as functions of the temperature for *constant volume*. Curve A corresponds to the density $n = 4n_0$ and curve B to $n = 7n_0$. n_0 is the density of ordinary nuclear matter.

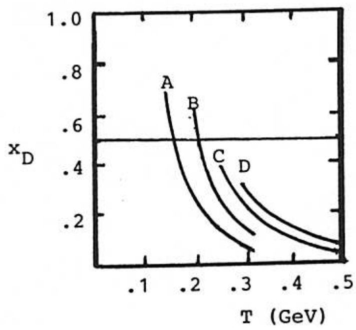

Fig. 2 Diquark fractions as functions of temperature for *constant pressure*. Curves A, B, C, and D correspond to the pressures
A : $P = P(T=.15, n=4n_0)$
B : $P = P(T=.20, n=7n_0)$
C : $P = P(T=.30, n=4n_0)$
D : $P = P(T=.30, n=7n_0)$
(T in GeV)

The line $x_D = 0.5$ has been indicated, since it is of special interest whether x_D is greater than 0.5 or not at the hadronisation temperature. $x_D = 0.5$ corresponds to equal number of diquarks and single quarks, which is the situation we have in spin-½ baryons.

If $x_D > 0.5$ there are "too many" diquarks for the plasma to be able to decay completely into colour-singlet hadrons by baryon and meson formation alone. The excess diquarks do not readily split up into quarks,as the system is too cool. Instead, we expect the formation of *multiquark states*, such as three-diquark systems or dibaryons, as an interesting experimental signature of this type of baryon-number rich QCD plasma decay.

Since the hadronisation temperature is widely believed to be of the order of the pion mass, it seems that all cases depicted in the Figures would lead to this excess-diquark effect. However, one must be careful in noting that those curves were calculated using constant volume or constant pressure, whereas a more realistic equation of state would presumably imply that the pressure and density decrease as the plasma cools. This would tend to disfavour the diquark component. More detailed work is in progress.

To conclude :

- If diquarks are bound, they should occur as a component in the QCD plasma.
- If the binding energy $\gtrsim T$, they should be important.
- If the diquark fraction > 0.5 at the hadronisation temperature, we expect multiquark states such as dibaryons as an experimental signature.

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References

1) S. Fredriksson, M. Jändel and T. Larsson, Z. Phys. C14 (1982) 35.
2) S. Fredriksson, M. Jändel and T. Larsson, Z. Phys. C19 (1983) 53.
S. Ekelin and S. Fredriksson, Phys. Lett. 162B (1985) 373.
3) S. Ekelin et al., Phys. Rev. D28 (1983) 257.
S. Ekelin et al., Phys. Rev. D30 (1984) 2310.
S. Ekelin and S. Fredriksson, Phys. Rev. Lett. (in press).
4) T.I. Larsson, Phys. Rev. D29 (1984) 1013.
5) S. Ekelin and S. Fredriksson, Phys. Lett. 149B (1984) 509.
6) J. Kogut and L. Susskind, Phys. Rep. 8C (1973) 75.
7) R. Stock, Nucl. Phys. A447 (1985) 371c.
8) J.-P. Blaizot and J.-Y. Ollitrault, report Saclay PhT/86-39.