Is the cosmic-ray Centauro quark-matter fireball metastable ?

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Abstract

We discuss the possible metastability of the cosmic-ray Centauro quark-matter fireball in terms of the equalization of the quark-gluon and vacuum pressures and the radius of the fireball, as deduced from the calculated thermodynamic quantities. We obtain the bag-stability curves as a function of T, μ_q and the bag radius R and we find that the Centauro fireball is situated within one standard deviation from these curves. This fact, together with the very high baryon density and binding energy and the low entropy per baryon of the state, prompt us to conjecture that the Centauro fireball may possibly be a metastable state.

Introduction

The model proposed and developed in Ref's [1,2] explains most features of Centauro events, assuming the formation of a lightly-strange quark matter fireball. According to the model, Centauro events are produced in central collisions of ultrarelativistic cosmic-ray nuclei with air nuclei. The collision of the medium-heavy cosmic-ray nuclei occurs at the top of the atmosphere, producing a presumably long-lived deconfined-quark-matter state (DQM) capable of surviving a flightpath of about 15 km to reach mountain-top altitudes (~ 500 g/cm^2). It could decay spontaneously, or by interacting with nuclei in the atmosphere along its trajectory.

A metastable Centauro state would require a mean life of the order of 10^{-9} sec. This means that the fireball may decay via weak interactions, since strong decays occur within 10^{-23} sec. Even so, the lifetime of 10^{-9} sec is unrealistically long for a (nonstrange, normal) quark matter state. However, the very high baryochemical potential and the transformation of the initial quark matter state into a partially-strange quark matter one, with increased spatial concentration of quarks due to the extra fermion flavour, result in an increase of the binding energy. Thus, the extremely large density and binding energy and the exceedingly small volume may result in the formation of a metastable state.

Conditions for Stability of a DQM State

A general condition for DQM-bag stability comes from the equalization of the internal (quark-gluon) and external vacuum (bag) pressures. It is given by eq. (1), in the case of a state with very high quarkchemical potential ($\mu_q >> T$):

$$P_{qg} = (8/45)\pi^2 T^4 + \mu_q^2 T^2 + (1/2\pi^2)\mu_q^4 = B \qquad (1)$$

Another general condition for stability of a DQM-bag is given by eq. (2), which is obtained by requiring minimization of the bag energy (dE/dR = 0) in a spherical DQM-distribution with radius R, containing N_q massless quarks [3]:

$$E = 2.043N_q/R + (4\pi/3)R^3B$$

which gives:

$$B = (2.043N_q/4\pi)(1/R^4) \qquad (2)$$

These two conditions should be equivalent in a general consideration of DQM-bag stability. We may then equate relations (1) and (2) and obtain:

$$(8/45)\pi^2T^4 + \mu_q^2T^2 + \mu_q^4/(2\pi^2) = (2.043N_q/4\pi)(1/R^4) \qquad (3)$$

where μ_q, T are the quarkchemical potential and temperature of a DQM-bag of radius R, containing N_q quarks. For given T (μ_q) eq. (3) gives the corresponding values of μ_q (T) as a function of R for bag stability. Figure 1 (a,b) gives the corresponding curves for fixed T and fixed μ_q, respectively, and N_q = 225. As a numerical example, for T = 130 MeV, μ_q = 600 MeV and N_q = 225, we find from eq. (3) the DQM-bag radius for stability to be R = 1.43 fm. It may be written as $R = r_oN_b^{1/3}$, where r_o = 0.34 fm and N_b = 75 nucleons.

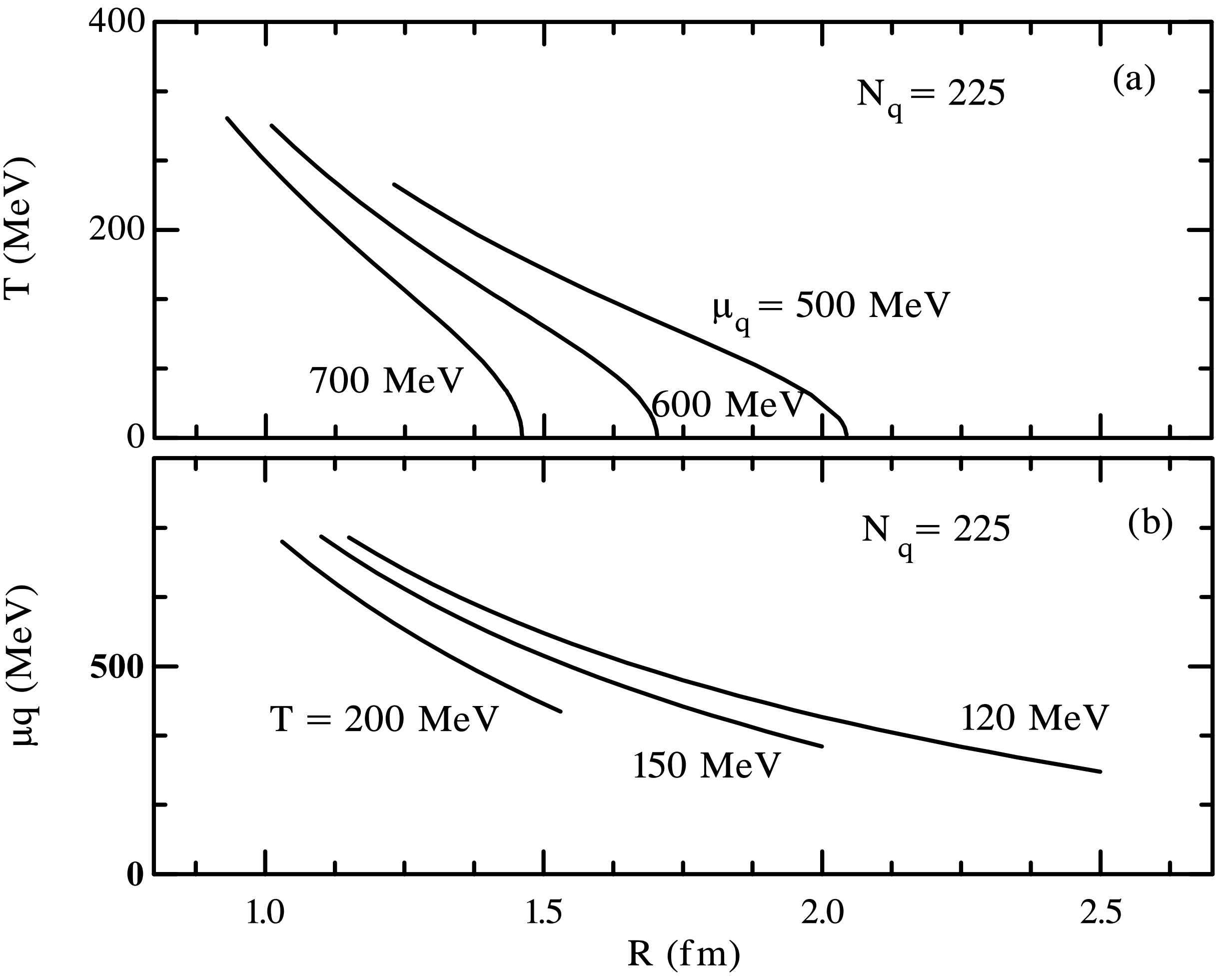

Fig. 1. Plot of eq. (3): (a) T as a function of R for fixed μ_q = 500 – 700 MeV; (b) μ_q as a function of R for fixed T = 120 – 200 MeV; N_q = 225 in both cases.

In ref. [4] the possibility for the existence of stable collapsed nuclei is discussed. A collapsed nucleus is a highly dense nuclear matter state, the nucleon density being more than

20 times larger than that corresponding to a normal nucleus, with binding energy per nucleon of hundreds of MeV and even up to the nucleon mass (for T = 0). In this condition, a collapsed nucleus is a cold deconfined-quark-matter state . It is found that, in the saturating quark model, the radius of a collapsed nucleus is $R_c = r_c A^{1/3}$, with $r_c \sim 0.4$ fm. From Fig. 1 we see that the radius parameter of a pressure-equalized DQM-bag is $r_o < 0.4$ fm, for T > 120 MeV and $\mu_q > 500$ MeV. This is of the same magnitude as the collapsed-nuclear radius parameter r_c. One may then consider the pressure-stabilized DQM-states at very high baryochemical potential as collapsed-matter states (at T > 0) of extremely high density.

The Centauro DQM State

From the analysis of the cosmic-ray Centauro events [1] it was deduced that the mean number of emitted baryons is 75, the mean mass of the DQM fireball is about 180 $\pm$ 60 GeV and the mean energy per baryon is approximately 2.4 $\pm$ 1 GeV. Thus, the mean energy per quark in the fireball is: $\langle E_q \rangle = \langle E_b \rangle/3 \sim 800 \pm 300$ MeV. Hence, the energy density of the fireball is (we assume $\alpha_s = 0$):

$$\varepsilon_{fb}^{cnt} = n_q^{cnt} \text{ x } \langle E_q \rangle = 8.34 \text{ (fm}^{-3}\text{) x } 800 \text{ (MeV)} = 6.7 \pm 3.6 \text{ GeV/fm}^3$$

where

$$n_q^{cnt}(T,\mu_q) = 2(\mu_q T^2 + \mu_q^3/\pi^2) = 8.34 \pm 3.3 \text{ fm}^{-3}$$

for T = 130 $\pm$ 10 MeV and $\mu_q = 600 \pm 100$ MeV, estimated for the Centauro fireball. From this we deduce the volume of the fireball: $V_{fb} = M_{fb}/\varepsilon_{fb} = 27 \pm 16$ fm^3, and the radius, $R_{fb} = r_o A^{1/3} \sim 1.85 \pm 0.36$ fm, with $r_o \sim 0.44 \pm 0.08$ fm, assuming spherical shape. Note that the fireball radius parameter, r_o is very close to that of a collapsed nucleus, $r_c \sim 0.4$, and that $n_b^{cnt}/n_b^{nm} \sim 19$.

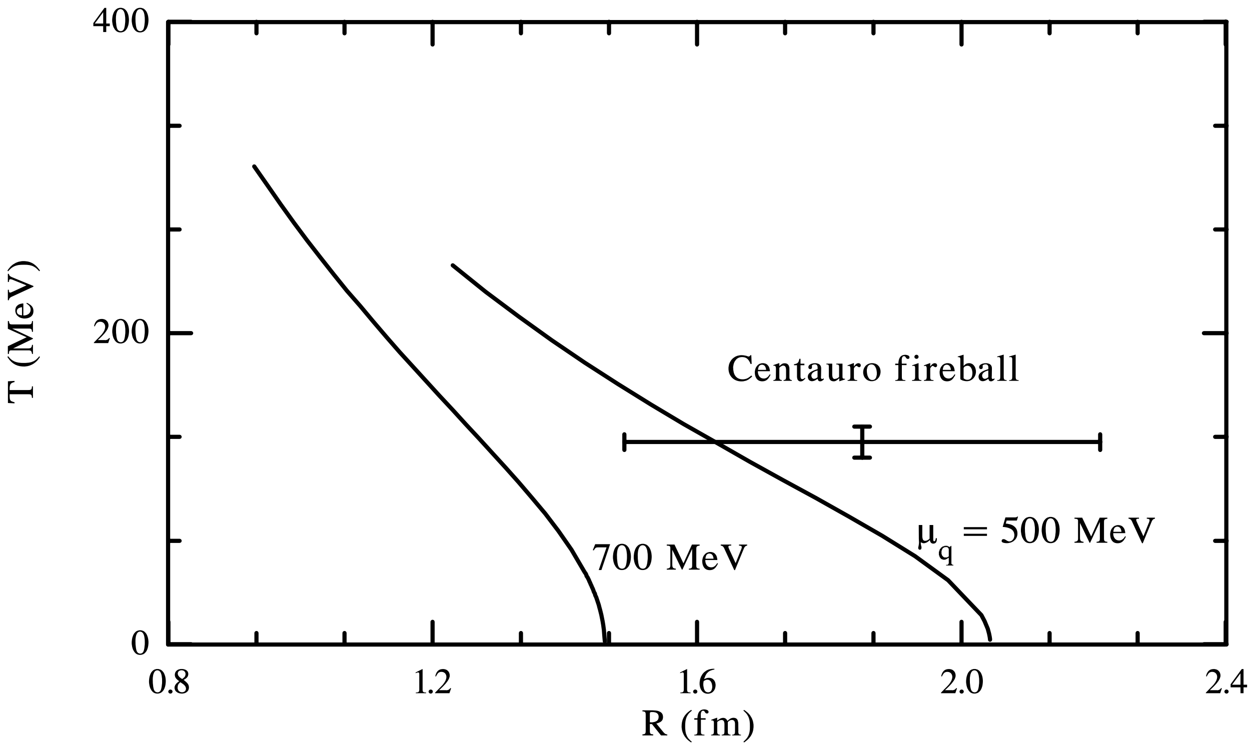

Fig. 2. Plot of eq. (3): T as a function of R for fixed μ_q = 500, 700 MeV; the values correspond to the cosmic-ray Centauro fireball.

Figure 2 depicts the DQM-bag stability curves, eq. (3), of T as a function of R, with $\mu_q = 600 - \Delta\mu_q$ and $\mu_q = 600 + \Delta\mu_q$, corresponding to the cosmic-ray Centauro fireball values. Comparing the Centauro DQM-state quantities [T, μ_q, R_{fb}] with the curves of Fig. 2, we observe that they are within one standard deviation to the stability conditions. It might then be possible that the Centauro fireball is a metastable state.

Discussion

A thermodynamic quantity, which may influence the (in)stability of a DQM fireball, is its entropy per baryon. It is calculated from the relation:

$$S_b = S/n_b = [(32/45)\pi^2T^3 + 2\mu_q^2T]/\{(2/3)[\mu_qT^2 + (1/\pi^2)\mu_q^3]\} \qquad (4)$$

where the entropy is (for $\mu_q >> T$):

$$S = (1/3)d\varepsilon_{qg}/dT = (1/3)d/dT\,[(8/15)\pi^2T^4 + 3\mu_q^2T^2 + (3/2\pi^2)\mu_q^4] = (32/45)\pi^2T^3 + 2\mu_q^2T$$

and $$n_b = (2/3)[\mu_qT^2 + (1/\pi^2)\mu_q^3]$$

Evaluating eq. (4) for T = 130 MeV and μ_q = 600 MeV we find the entropy per baryon for the Centauro fireball to be $S_b \sim 5$. This is a small value and it should not influence adversely the possible metastability of the Centauro state [#2].

In summary, we have examined the conditions for possible metastability of the cosmic-ray Centauro DQM-fireball in terms of the stability between the internal (quark-gluon) and external vacuum pressures. We obtained the DQM-bag stability curves as a function of T, μ_q and the bag radius R and found that the Centauro fireball is situated within one standard deviation from these curves. This fact, together with the exceedingly small volume, the very high baryon density ($n_b^{cnt} / n_b^{nm} \sim 19$) and consequently high binding energy and the rather low entropy per baryon of the state, prompt us to conjecture that the Centauro fireball may possibly be a metastable state.

[#2] Note that the entropy of the Centauro fireball is about 14 fm^{-3} compared to ~ 39 fm^{-3} deduced experimentally for the ^{32}S + Ag interaction at 200A GeV [5].

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