ALICE / PHY - 99 –17

On the Metastability of the Cosmic-Ray Centauro Quark-Matter Fireball

Olga P. Theodoratou and Apostolos D. Panagiotou

Nuclear and Particle Physics Division
Physics Department, University of Athens
Panepistimiopolis, Zografou GR-157 71 Athina, Hellas

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 find that, due to the very high baryon density and binding energy and the very small volume of the fireball, it may be possible that it becomes a metastable state, with presumably sufficient lifetime to travel a distance of about 15 km, from the point of creation to the altitude of decay or interaction.

I. Introduction

Cosmic-ray induced interactions can be satisfactorily described in terms of standard ideas regarding hadronic interactions below the energy $E \sim 1000$ TeV . Above this threshold various "anomalies" appear such as exotic events called Centauros, Mini-Centauros, Chirons, superfamilies with "halo", etc. [1]. These anomalies are not rare occurrences but they manifest themselves at approximately the 5% level. Monte Carlo simulations show that they could not originate from any kind of rare statistical fluctuations of normal hadronic interactions.

The model proposed and developed in Ref's [2,3], 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 state, capable of surviving a flightpath of about 15 km to reach mountain-top altitudes (~ 500 g/cm^2). It could decay either by interacting with nuclei in the atmosphere, or spontaneously.

The interaction length of the Centauro fireball in the atmosphere was estimated to be $\bullet_{fb} > 150$ g/cm^2 [3], in accordance with experimental observations. The extremely long interaction length of the fireball, which is about 38 times larger than that of a normal nucleus ($\bullet \sim 4$ g/cm^2 for $A \sim 75$), could be attributed to its very high binding energy and much reduced geometrical cross section [#1]. The estimated volume of the Centauro fireball is about 18 times smaller than that of an ordinary nucleus with the same A.

#1 Note that for protons at comparable energies, $\bullet_p \sim 60 - 70$ g/cm^2.

If the Centauro fireball is a metastable state decaying spontaneously, it would require a mean life of the order of 10^{-9} sec to have a probability to survive a flightpath of about 15 km and reach mountain top altitudes. This means that the fireball would have to 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.

The Centauro fireball is a very different object from the light- or medium-mass strangelets, whose possible (meta)stability has been studied by many authors [4]. The main differences are the following:

- The Centauro fireball temperature is of the order of 150 MeV, compared to T = 0 considered for the strangelet,
- the value of the fireball-bag constant, $B^{1/4}$, is about twice as large as that required for strangelet stability,
- the energy per baryon, E_b, is also more than two times larger than that corresponding to strangelet stability,
- the strangeness content of the fireball, f_s, is very much smaller, and
- the mass of the fireball is substantially larger than the considered strangelet masses.

The practical and customary measure of the stability of a strangelet is provided by the separation energy, $dE/dA \sim E_b$, i.e., the energy required to remove a baryon from the object. Since, in the case of the Centauro fireball, E_b is much larger than even m• , we should turn our investigation to other properties of the fireball in order to deduce indications for possible metastability of the state, such as its very large quarkchemical potential, baryon density and binding energy, as well as its exceedingly small volume and entropy per baryon.

In Section II we discuss the deconfinement of nuclear matter at zero and finite temperatures, both at large quarkchemical potential. The aim is to gain a qualitative understanding of the situation arising in the Centauro fireball. In Section III we study the pressure equalization conditions between the DQM-matter and the surrounding bag, in terms of the thermodynamic quantities: temperature (T), quarkchemical potential ($\bullet_q$) and the radius of the bag (R). In Section IV we present the cosmic-ray Centauro characteristic quantities and compare them to the DQM-stability conditions, discussed in III. Finally, in Section V we discuss our findings and conclude that, due to its characteristics, the Centauro fireball has very possibly attained the requirements for metastability.

II. Critical Conditions for Deconfinement of Nuclear Matter

II-1. T = 0

We discuss firstly the deconfinement of quarks in cold nuclear matter. Figure 1 shows the phase diagramme of matter. The curve, defining the limit of the hadronic phase, is the projection on the (T-$\bullet_q$) plane of the intersection of the critical surface of the Strangenessincluding Statistical Bootstrap Model (SSBM), with the Strangeness neutrality surface [5]. Nuclear matter is situated at zero temperature and at quarkchemical potential of about 225 MeV.

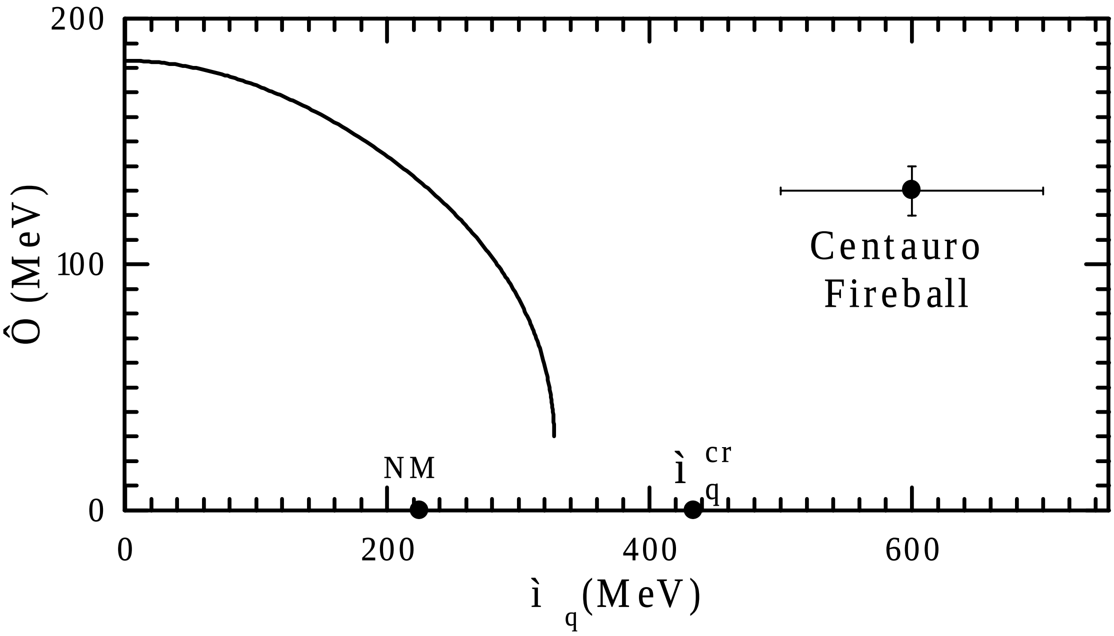

Fig. 1. Phase diagramme of nuclear matter obtained from the SSBM.

The thermodynamic characteristics of nuclear matter are summarized below (h = c = 1):

$$n_b \sim 0.145 \text{ fm}^{-3}$$
$$n_q = 3n_b \sim 0.435 \text{ fm}^{-3}$$
$$\mu_q^{nm} = [\pi^2 n_q/2]^{1/3} \sim 225 \text{ MeV}$$
$$\varepsilon_{nm} \sim 0.136 \text{ GeV/fm}^3$$

The value of the baryon number density, n_b, suggests that each nucleon is associated with an effective volume $V_o = 1/n_b \sim 6.9$ fm^3 ($R_o \sim 1.18$ fm), whilst the nucleon itself has a volume $V_n \sim 2.1$ fm^3 ($r_n \sim 0.8$ fm). Thus, the distance between the centers of adjacent nucleons in nuclear matter is $R = 2R_o \sim 2.36$ fm. If we compress the nucleus so that $R_o \sim r_n$, the effective volume V_o shrinks and becomes equal to the nucleon volume V_n, bringing neighboring nucleons in touch. This results in an increase of the quarkchemical potential to the value $\mu_q \sim 250$ MeV. If we further compress the nuclear matter so that the nucleon volumes start to interpenetrate and overlap (by at least 2.5%), the physical vacuum is totally expelled and the quark and gluon content of each nucleon is freed into the larger volume of the (compressed) nucleus. A new state of matter is now formed, the deconfined-quark matter state, DQM. For this to happen in general, the pressure of the degenerate (u,d)-quark gas must exceed the bag pressure:

$$P_q = (1/2\pi^2)\,\mu_q^4 > B \qquad (T = 0) \qquad (1)$$

which gives

$$\bullet_q > (2\bullet^2 B)^{1/4} \tag{2}$$

For the nucleon [$R = r_n \sim 0.8$ fm, $N_q = 3$, $B^{1/4} \sim 206$ MeV (see Section III)], the critical quantities for deconfinement assume the values (at T = 0):

$$\begin{aligned} \bullet_q^{cr} &> 434 \text{ MeV.} \\ n_q^{cr} &= (2/\bullet^2)\,\bullet_q^{cr\,3} > 2.16 \text{ fm}^{-3} \\ n_b^{cr} &= n_q^{cr}/3 > 0.72 \text{ fm}^{-3} \\ V_n^{cr} &< 1.39 \text{ fm}^3 \\ r_n^{cr} &< 0.69 \text{ fm} \end{aligned} \tag{3}$$

That is, to achieve deconfinement on the nucleon scale, the normal nucleon volume V_n (~ 2.1 fm^3) must be reduced by ~ 35%.

For a nucleus with N_b nucleons, the critical volume and radius for deconfinement can be written as:

$$V_{nm}^{cr} = N_b/n_b = (3\bullet^2/2)\,N_b/\bullet_q^{cr\,3}$$

$$R_{nm}^{cr} = (9\bullet/8)^{1/3} N_b^{1/3}/\bullet_q^{cr} < 0.69\,N_b^{1/3} \qquad (\bullet_q^{cr} \geq 434 \text{ MeV})$$

or in general,

$$R_{nm}^{cr} < 0.723\,N_b^{1/3}\,B^{-1/4} \tag{4}$$

We observe that, to achieve quark deconfinement in a nucleus at T = 0, the nuclear radius must be $R_{nm}^{cr} < 0.69N_b^{1/3}$, where $r_o = r_n^{cr} = 0.69$ fm is the maximum effective radius of the nucleon volume for deconfinement on the nucleon scale. Equivalently, the volume of a nucleus must be reduced by at least five times, in order to ensure the necessary overlap between adjacent nucleons (of uncompressed volume V_n) by more than 2.5%.

Madsen [6] has shown that for bulk strange quark matter (SQM) at T = 0, with $n_u = n_d = n_s$ and $m_u = m_d = m_s = 0$, the critical radius for stability is:

$$R_{SQM}^{cr} = 0.699N_b^{1/3}\,B^{-1/4}$$

Comparing R_{SQM}^{cr} to the critical radius for normal nucleus deconfinement [eq. (4)], we see that $R_{SQM}^{cr} < R_{nm}^{cr}$. For $m_s > 0$, R_{SQM}^{cr} becomes even smaller. The smaller R_{SQM}^{cr} compared to R_{nm}^{cr} is expected, since SQM has lower internal energy compared to normal nuclear matter, due to the extra fermion flavour, the strange quark. Therefore, for the same value of the bag constant, a smaller radius is required to balance the vacuum pressure.

II-2. T > 0

We consider now the hypothetical case where the nucleus is heated without being compressed, keeping the quarkchemical potential fixed at $\bullet_q^{nm} = 225$ MeV. When deconfinement is achieved, the energy density and pressure of the (u,d)-quark and gluon plasma are given by:

$$\bullet_{qg} = (8/15)\bullet^2 T^4 + 3\bullet_q^2\bullet^2 + (3/2\bullet^2)\bullet_q^4 \tag{5}$$

$$P_{qg} = \bullet_{qg}/3 = (8/45)\bullet^{2}T^{4} + \bullet_{q}^{2}\bullet^{2} + (1/2\bullet^{2})\bullet_{q}^{4} \qquad (6)$$

Note that for $\bullet_q >> T$ the production of antiquarks is strongly inhibited due to Pauli blocking. In this treatment we also ignore the contribution of the created strange quarks, which is very small. We estimated the contribution of s-quarks to the pressure to be of the order of 0.1%.

The condition for deconfinement in the heated nucleus (for $\bullet_q >> T$) is now:

$$P_{qg} = (8/45)\bullet^{2}T^{4} + \bullet_{q}^{2}\bullet^{2} + (1/2\bullet^{2})\bullet_{q}^{4} > B$$

(7)

Evaluating the temperature from equation (7) with $\bullet_q = 225$ MeV and $B^{1/4} = 206$ MeV gives $T^{cr} > 130$ MeV. Note that this condition for deconfinement (T >130 MeV, $\bullet_q \sim 225$ MeV) is close to the theoretical phase curve of the SSBM, Fig. 1.

In ultrarelativistic nucleus-nucleus interactions, however, the actual trajectory, which the nuclear matter fireball follows to reach the deconfined state, is somewhere in-between the two hypothetical extreme paths discussed.

III. Conditions for Stability of a DQM State

We shall consider and discuss now the conditions which might ensure a metastable state in extreme environments, such as very high quarkchemical potential and much reduced volume.

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 the equality in eq. (7), in the case of a state with very high quarkchemical potential ($\bullet_q >> T$):

$$P_{qg} = (8/45)\bullet^{2}T^{4} + \bullet_{q}^{2}\bullet^{2} + (1/2\bullet^{2})\bullet_{q}^{4} = B$$

(8)

Another general condition for stability of a DQM-bag is given by eq. (9), 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 [7]:

$$E = 2.043N_q/R + (4\bullet/3)R^{3}B$$

which gives:

$$B = (2.043N_q/4\bullet)(1/R^{4}) \qquad (9)$$

These two conditions should be equivalent in a general consideration of DQM-bag stability. We may then equate relations (8) and (9) and obtain:

$$(8/45)\bullet^{2}T^{4} + \bullet_{q}^{2}\bullet^{2} + \bullet_{q}^{4}/(2\bullet^{2}) = (2.043N_q/4\bullet)(1/R^{4}) \qquad (10)$$

where $\bullet_q$, T are the quarkchemical potential and temperature of the DQM-bag of radius R, containing N_q quarks. For given T ($\bullet_q$) eq. (10) gives the corresponding values of $\bullet_q(T)$ as a function of R for bag stability. Figures 2 (a,b) give the corresponding curves for fixed T and fixed •$_q$, respectively, and N_q = 225. As a numerical example, for N_q = 225, T = 130 MeV and •$_q$ = 600 MeV, we find from eq. (10) the DQM-bag radius for stability to be R = 1.43 fm. It can be written as $R = r_o N_b^{1/3}$, where r_o = 0.34 fm and N_b = 75 nucleons.

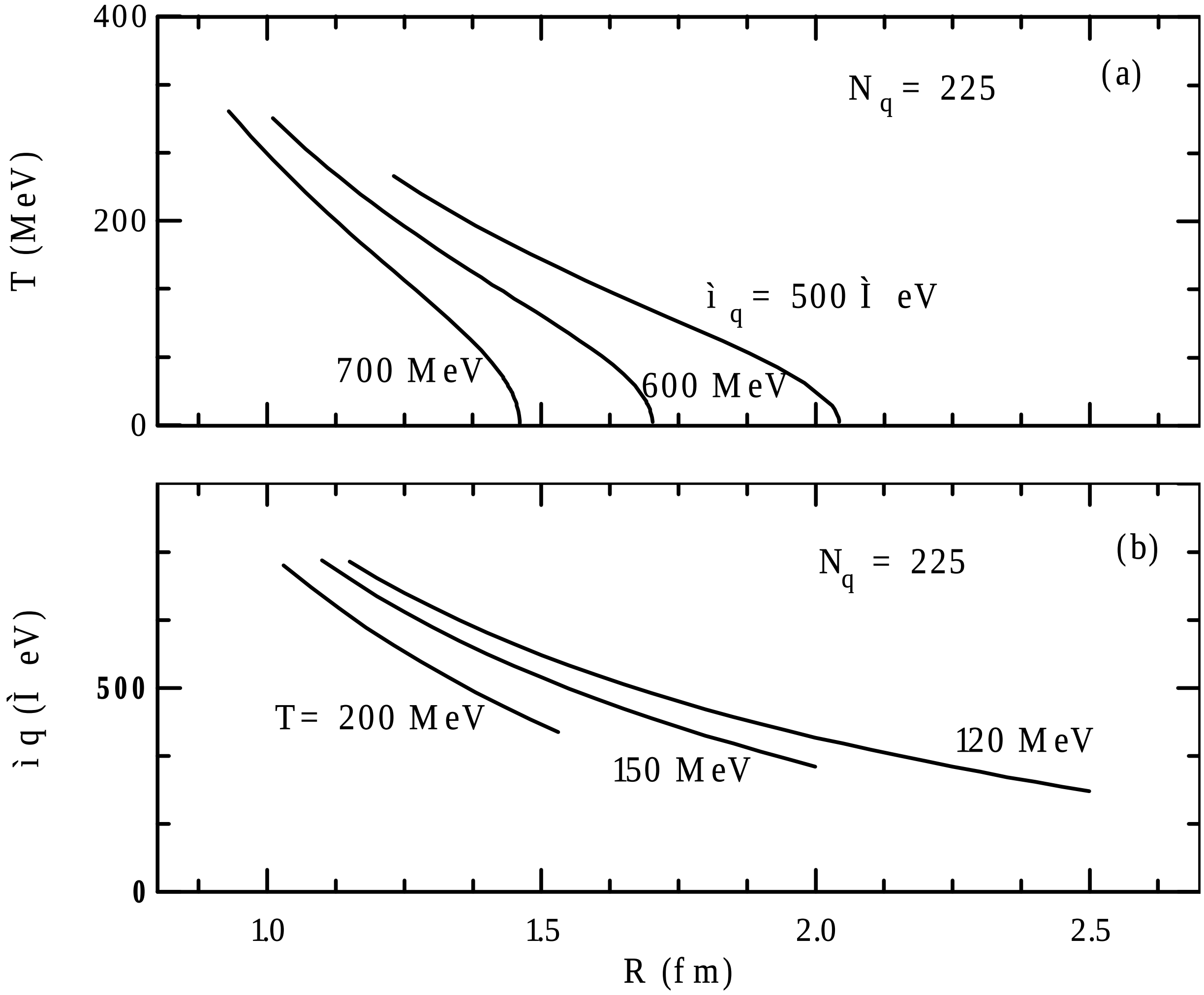

Fig. 2. Plot of eq.(10): (a) T as a function of R for fixed •$_q$ = 500 -700 MeV; (b) •$_q$ as a function of R for fixed T = 120 - 200 MeV; N_q = 225.

In ref. [8] 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 (see discussion in Section II-1). 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 ~ 0.4 fm. From Fig's 2 (and 4) we observe that the radius parameter of a pressure-equalized DQM-bag is r_o < 0.4 fm, for T > 120 MeV and •$_q$ > 500 MeV. This is of the same magnitude as the collapsed-nuclear radius parameter r_c. One may then consider the pressurestabilized DQM-states at very high baryochemical potential as collapsed-matter states (at $T > 0$) of extremely high density.

IV. The Centauro DQM State

From the analysis of the cosmic-ray Centauro events [2] 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. This means that the mean energy per quark in the fireball is: $\langle E_q \rangle = \langle E_b \rangle/3 \sim 800 \pm 300$ MeV. Thus, the energy density of the fireball is (we assume $\bullet_s = 0$):

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

where

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

for $T = 130 \pm 10$ MeV and $\bullet_q = 600 \pm 100$ MeV, estimated for the Centauro fireball. From this we deduce the volume of the fireball: $V_{fb} = M_{fb} / \bullet_{fb} = 27 \pm 16$ 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, $r_c \sim 0.4$.

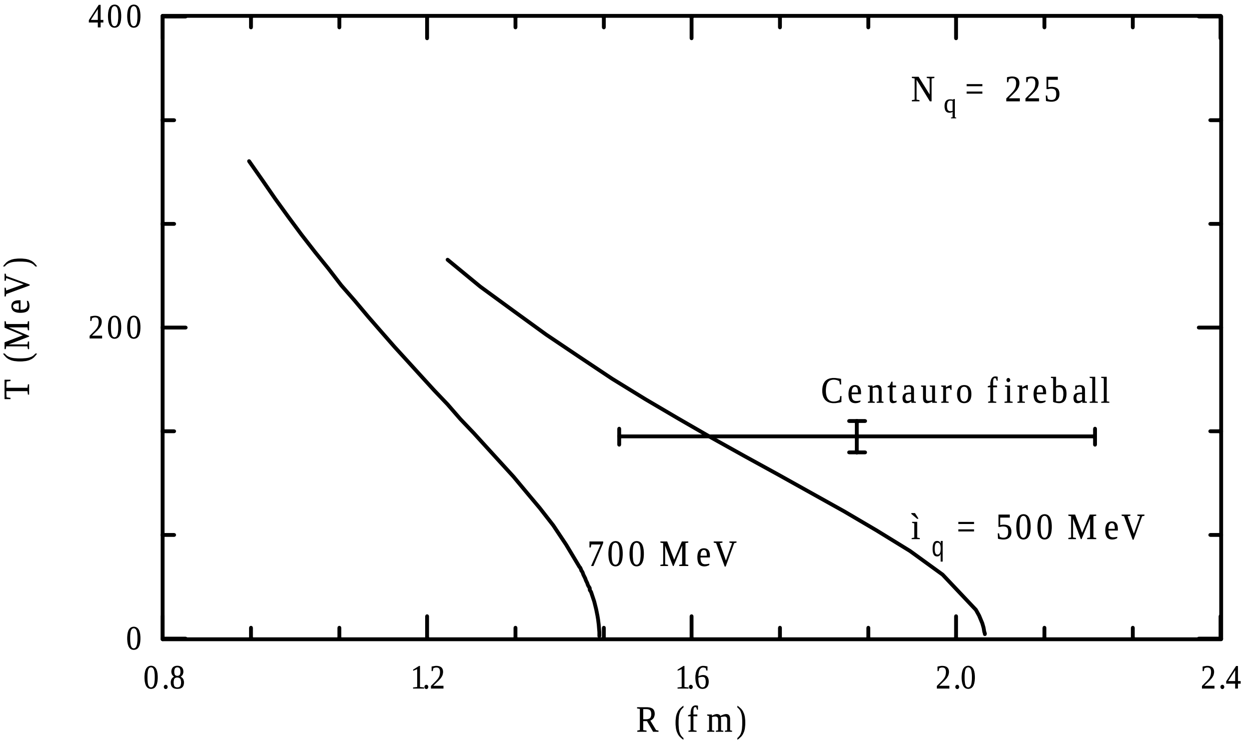

Fig. 3. Plot of eq. (10): T as a function of R for $\bullet_q$ = 500, 700 MeV; values correspond to the cosmic-ray Centauro fireball

Figure 3 depicts the DQM-bag stability curves [eq. (10)] of T as a function of R, with $\bullet_q = 600 - \bullet \bullet_q$ and $\bullet_q = 600 + \bullet \bullet_q$, corresponding to the cosmic-ray Centauro fireball. Comparing the Centauro DQM-state quantities [T, $\bullet_q$, R_{fb}] with the curves of Fig. 3, 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.

V. Discussion

Gilson and Jaffe have shown [9] that for a lump of SQM with high strangeness content ($n_u = n_d = n_s$, $f_s = 1$) at $T = 0$, in which surface effects are ignored, the radius of the bag, which will balance the quark pressure against the vacuum pressure and lead to stability, is given, in terms of the energy per baryon E_b, by:

$$R = 1136\ A^{1/3}/E_b\ [2 + (1 - 9m_s^2/E_b^2)^{3/2}]^{-1/3} \quad \text{(fm)} \tag{11}$$

Although the Centauro state is a lightly-strange QM state, to obtain a feeling for the bag radius we evaluate this relation with the Centauro fireball quantities, where $E_b = M_{fb}/A$ and $A = 75$. It gives $R = 1.42$ fm, for $m_s = 300$ MeV. We observe that the Centauro fireball radius is about 30% larger than the approximate value of the stable SQM-bag radius, $R_{fb} \sim 1.3\ R$. This could be expected, since the Centauro fireball has a small strangeness content ($f_s \sim 0.1$) and finite temperature, resulting in much higher internal energy. Hence, R_{fb} could be larger, even though the value of the fireball-bag constant is higher than the one for the SQM state.

The value of the bag constant, $B^{1/4}$, calculated for the thermodynamic quantities T, $\bullet_q$ of the Centauro fireball, is of the order of 330 MeV. It is about two times larger than the value required for stability of a strangelet at T = 0 [4,6,9]. This is understood, because in the fireball the pressure of quarks and gluons inside the bag at finite T is much higher than for a strangelet and hence it requires a larger vacuum pressure for stabilization. Note also that, the phase curve of Fig. 1, which indicates pressure equalization between hadron gas and DQM state, is drawn for $B^{1/4} = 235$ MeV ($T_o = 183$ MeV) [5].

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

$$S_b = S/n_b = [(32/45)\bullet^2T^3 + 2\bullet_q^2\bullet\ ]/\{(2/3)[\bullet_q\bullet^2 + (1/\bullet^2)\bullet_q^3]\} \tag{12}$$

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

$$S = (1/3)d\bullet_{qg}/dT = (1/3)d/dT\ [(8/15)\bullet^2T^4 + 3\bullet_q^2\bullet^2 + (3/2\bullet^2)\bullet_q^4] = (32/45)\bullet^2T^3 + 2\bullet_q^2T$$

and

$$n_b = (2/3)[\bullet_q\bullet^2 + (1/\bullet^2)\bullet_q^3]$$

Evaluating eq. (12) for T = 130 MeV and $\bullet_q = 600$ MeV we find the entropy per baryon for the Centauro fireball to be $S_b \sim 5$. This is a rather small value and it should not influence adversely the possible metastability of the Centauro state [#2].

#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 [10].

In Pb+Pb interactions at LHC energies ($\sqrt{s}$ = 5.5 TeV/nucleon) we expect the formation of Centauro-type fireballs at very forward rapidities (beam fragmentation) [11]. In very central collisions, Monte Carlo simulations [12] have shown the formation of fireballs with N_b ~ 180, T ~ 210 MeV and μ_q ~ 600 MeV. For these conditions we have calculated the DQM-bag stability curves employing eq. (10), as well as the fireball radius, R_{fb} ~ 2.17 fm (r_o ~ 0.38 fm), Fig. 4. We observe that the Pb+Pb fireball point is about one and a half standard deviations away from the stability curves and it may or may not be a metastable state.

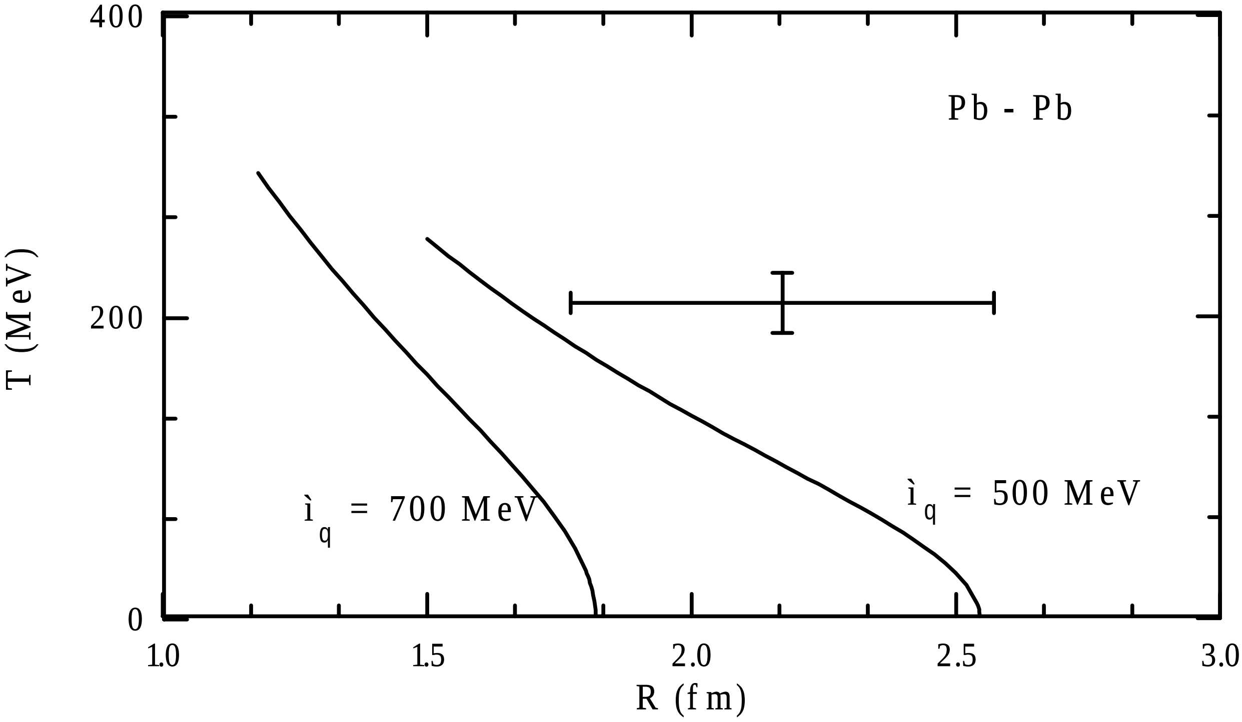

Fig. 4. Plot of eq. (10): T as a function of R for μ_q = 500, 700 MeV; values correspond to a Centauro fireball in Pb+Pb interactions at the LHC.

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 rather low entropy per baryon, the exceedingly small volume and the very high binding energy of the state, prompt us to conjecture that the Centauro fireball may possibly be a metastable state, with sufficient life time to travel about 15 km and decay or interact at mountain-top altitudes. The Centauro-type fireball, conjectured to be produced in Pb+Pb interactions at the LHC, is less possible to be a metastable state.

Acknowledgement
This work is supported in part by the Research Council of the University of Athens.

References

[1] C. M. G. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep.**65**(1980)151.
[2] A. D. Panagiotou et al., Z. Phys. **A333**(1989)335
A. D. Panagiotou et al., Phys. Rev. **D45**(1992)3134.
[3] M.N. Asprouli, A.D. Panagiotou, E. Gladysz-Dziadus, Astroparticle Phys.**2**(1994)167
[4] J. Schaffner-Bielich et al, Phys. Rev C55 (1997)3038 and Ref's therein
[5] A. Kapoyiannis, C. Ktoridis and A. D. Panagiotou, Phys. Rev. **D58** (1998) 034009.
[6] J. Madsen, Astro-ph/9809032 (1998)
[7] C.-Y. Wong, "Introduction to High-Energy Heavy-Ion Collisions" World Scientific
[8] A. R. Bodmer, Phys. Rev. **D4** (1971)
[9] E. P. Gilson and R. L. Jaffe, Phys. Rev. Lett. **71** (1993) 332
[10] CERN – EMU05 Collaboration
[11] A.L.S. Angelis et al, CASTOR draft Proposal, ALICE/CAS-97-07
[12] E. Gladysz-Dziadus et al, ALICE/PHY-97-06