Possibility of observing "Centauro" events at the BNL Relativistic Heavy Ion Collider

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A phenomenological model for the production of "Centauro"-type cosmic-ray events is developed, assuming a nucleus-nucleus interaction in the upper atmosphere. The model is used to estimate, in a self-consistent way, several thermodynamic and kinematical quantities, characterizing the observed Centauro events. On the basis of this model, we describe a typical "Centauro" event, possibly produced in the fragmentation rapidity of an $A+A$ central collision at $\sqrt{s}=200A$ GeV at the BNL Relativistic Heavy Ion Collider. We suggest several characteristic signatures for these events, as well as the possibility of observing "strangelets."

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I. INTRODUCTION

In the past twenty years, cosmic-ray experiments have detected numerous most unusual events, whose nature is still not well understood [1–3]. Some of these events, the so-called "Centauro" and "mini-Centauro" [1], show complete absence of, or very much reduced, electromagnetic energy. This fact may be interpreted as complete absence, or strong suppression of all pion species, if isotopic spin is to be conserved. Therefore, these events are considered as predominantly baryon-emitting events.

It was shown through Monte Carlo simulations [2,4] that the Centauro events could not originate from any kind of rare statistical fluctuations in the hadronic and photonic (energy-multiplicity) contents of normal hadronic interactions, viz. by pion multiple production or heavy nucleus (normal) hadronic interaction. Therefore, new types of interactions, or the creation of a new kind of matter, quark matter, was conjectured to be responsible for these extremely unusual phenomena [1,2,4].

In this paper we continue the development of the phenomenological model of Ref. [5] for the Centauro events and we also suggest the possible formation of strangelets in the very baryon-rich environment of the fireball (Sec. III). In Sec. IV we calculate several thermodynamic and kinematical characteristic quantities for the Centauro fireball and we check, wherever possible, for internal consistency of the model and of the estimated quantities and discuss them in the light of other estimations. We find that the energy density, baryochemical potential, and temperature of the Centauro fireball are of such magnitude necessary for a phase transition to quark matter. In addition, the very large baryochemical potential and moderate temperature strongly prohibit the creation of pions in the hadronization of the fireball. Finally, in Sec. V we discuss the possible formation of a typical Centauro-type event, produced in $A+A$ central collisions at $200A$ GeV at the BNL Relativistic Heavy Ion Collider (RHIC). We estimate several characteristic thermodynamic quantities and suggest possible signatures for the identification of such an event.

II. PHENOMENOLOGICAL MODELS

Several phenomenological interpretations have been proposed for the qualitative description of the occurrence and properties of the Centauro-type events [5–7]. We shall briefly discuss their main points, predictions, and limitations.

In Ref. [6] it is suggested that the Centauro events are caused by a primary glob of highly dense nuclear or quark matter. This glob may (or may not) be encircled by a single unconfined quark of very large mass, which increases the density and stability of the matter. The glob is metastable and is induced to explode into a predominantly multibaryon final state with large $\langle p_T \rangle$, by repeated collisions in the atmosphere. The baryons in the final state are comprised of about 50% of strange matter. This scenario has some difficulties: It cannot explain adequately the nonexistence of pions; it predicts unacceptably large rates of fractionally charged quarks at sea level and or horizontal air showers, and it cannot explain persuasively the origin of the primary quark-matter glob.

The second reference [7], proposes that the Centauro events are the result of decaying quark-matter fireballs, produced coherently in single diffractive dissociation of very high-energy nucleon primaries. Although this interpretation reproduces correctly some observed quantities of the Centauro events, such as the cross section for Centauro production and the large $\langle p_T \rangle$, it cannot explain the profound suppression of pions in the hadronization of the quark-gluon plasma (QGP) fireball. The conservation of baryon number necessitates the production also of antibaryons in the hadronization of the fireball. However, this in turn necessitates the creation of antiquarks. It is then difficult to understand the total absence of pions.

The suggestion of the possible observation of Centauro-type events in the diffractive dissociation of $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV and $x_F \geq 0.99$, is currently under investigation in an experiment at Fermilab. However, the results of this search so far have not substantiated this Centauro model.

In Ref. [5], a different interpretation of the Centauro and other unusual cosmic-ray events at even higher energies was proposed. It is based on the hypothesis of the formation of a "quark-matter fireball" in collisions of cosmic-ray nuclei with air nuclei and its subsequent hadronization, through an explosive decay, in the fragmentation rapidity. In this scenario, the very large baryochemical potential inherent in the quark-matter fireball plays the determining role: It causes the strong suppression of the pionic and, hence, γ component and induces the hadronization of the quark-matter fireball predominantly into baryons. A question is also posed concerning the possible formation of strangelets out of the $s\bar{s}$ quarks created by the (primary) gluon fragmentation.

A situation as described in Ref. [5] may possibly arise in nucleus-nucleus collisions at incident energies attainable at RHIC. It is, therefore, very interesting to examine in detail the possibility of forming and observing Centauro-type events in controlled laboratory experiments.

III. THE CENTAURO MODEL

In this section we shall develop further the Centauro model described in Ref. [5]. We discuss in detail the basic ingredients and assumptions of the model and justify them on phenomenological grounds and self-consistency. We use the experimental data for the five Centauro events, obtained by the Chacaltaya Collaboration [1].

A. Centauro fireball

We consider the central collision of an ultrarelativistic cosmic-ray nucleus with a nucleus in the upper atmosphere and the formation of a fireball. The observed chemical composition of primary cosmic rays in the mass region of Fe, with energy in the range 10^3–10^4 TeV, is about 15% of the total flux [8]. It is, therefore, reasonable to consider a medium mass primary cosmic-ray nucleus colliding with a stationary ^{14}N nucleus, which constitutes the bulk of the atmospheric nuclei.

The incident nucleus is highly contracted ($\gamma_{\rm c.m.} \simeq 260$) and has the shape of a cylinder with cross-sectional radius $R = 1.15\langle A_{\rm pr}\rangle^{1/3}$. After the collision, a very compressed and dense fireball is produced, traveling with ultrarelativistic velocity. The very high density of the fireball's matter may allow it to reach and explode above the Chacaltaya detector, situated 5200 m above sea level.

The larger mass of the incident nucleus, compared to the stationary target, causes the colliding-system center of mass to move with almost the velocity of the projectile, since for the average Centauro event:

$$1-\beta_{\rm c.m.}/\beta_{\rm pr} = M_{\rm tg}/(E+M_{\rm tg}) \simeq 7\times 10^{-6} ,$$

where $\beta_{\rm c.m.}$ and $\beta_{\rm pr}$ are the velocity of the center of mass and projectile, respectively, in the laboratory frame, E is the incident energy of the heavy nucleus of order 10^6 GeV, and $M_{\rm tg}$, the mass of the target, is of order 10 GeV. We thus consider the produced fireball to contain the nucleons of both the projectile and target nuclei. Since the Centauro fireball decays into baryons, to conserve baryon number we make the assumption that the average mass of the incoming nucleus is approximately

$$\langle A_{\rm pr}\rangle \simeq \langle N_h\rangle - 14 , \tag{1}$$

where $\langle N_h\rangle$ is the measured average Centauro (baryon) multiplicity.[1]

In this highly dense and moderately hot nuclear matter of the Centauro fireball, the hadron states of the compound system dissolve into the state consisting of their deconfined constituents, the quarks and gluons. This new state is characterized by a very large baryon-number density. After the formation of the quark-matter fireball at a moderate temperature, $T^i_{\rm fb} \simeq T_c(\mu_b) \simeq T^f_{\rm fb}$, where $T_c(\mu_b)$ is the critical temperature for the phase transition in this very high μ_b environment and $i(f)$ denote initial (final) stages, the volume may not increase appreciably, since the final entropy (which is $\simeq VT^3$) should be nearly equal to the initial one, in order to conserve baryon number.

The need for quark fragmentation in order to conserve entropy during the hadronization process decreases rapidly with increasing μ_b. This is because the net contribution of baryons to the total entropy grows with the baryon-number density, which in turn grows rapidly with the baryochemical potential as $\exp[-(M_n-\mu_b)/T]$. Actually, the entropy should increase in the hadronization phase in view of the second law of thermodynamics. This increase, which may be realized in the fragmentation of the original gluons into strange quarks only, as will be discussed later, may lead to the formation of strange hadrons and strange-matter globs. It is, however, unaccounted for at present.

B. Pion suppression

The effects of the large baryochemical potential of the fireball on particle production, in particular on the relative pion/nucleon multiplicities, are profound. To form a pion, a quark and an antiquark must exist. A $\bar{q}$ is created together with a q and the large μ_b suppresses the production of both. The number of antiquarks in the Boltzmann approximation is proportional to

$$N_{\bar{q}} \propto \exp(-\mu_q/T) ,$$

which is strongly suppressed for large $\mu_b = 3\mu_q$.

In addition, the production of quarks is also strongly prohibited due to the Pauli blocking. The momentum distribution of thermalized quarks is given by [9]:

$$f_q(k) = (\lambda^{-1}e^{k/T}+1)^{-1} ,$$

where $\lambda = \exp(\mu_q/T)$ is the fugacity, i.e., the amount of saturation of statistical phase space. The Pauli blocking is obtained from the expression

[1]The multiplicity of the Centauro events includes particles with minimum energy of 4 TeV; the remaining, if any, below this threshold are unaccounted for. Therefore, Eq. (1) should be considered in principle.

$$[1-f_q(k)]=e^{k/T}(\lambda^{-1}e^{k/T}+1)^{-1}\exp(-\mu_q/T) \; ,$$

which is proportional to $\exp(-\mu_q/T)$ and, hence, inhibits the creation of quarks in a large baryochemical potential environment.

With the above considerations, the number of pions, formed by the created $q\bar{q}$ pairs, is proportional to

$$N(\text{pion}) \propto e^{-(4\mu_q+m_\pi)/T}$$

and the pion-to-nucleon density ratio is proportional to

$$N(\text{pion})/N(\text{nucleon}) \propto \tfrac{3}{2}\exp\{[-(4/3)\mu_b-m_\pi+M_n]/T\} \; , \quad (2)$$

where the factor $\frac{3}{2}$ comes from the number of the particle species and M_n, m_π are the nucleon and the pion masses, respectively. We assume here that the nucleons are formed by the existing primary u,d quarks.

The (T,μ_b)-pair values in Eq. (2) are obtained from a T vs μ_b phase diagram, with boundary values $T(\mu_b=0)=180$ MeV and $\mu_b(T=0)=1580$ MeV (corresponding to baryon density $\simeq 1.3\ \text{fm}^{-3}$), which satisfies the equal pressure condition at the quark-matter–hadron-matter boundary: $P_{\text{QM}}=P_{\text{HM}}$,

$$(37\pi^2/90)T^4+\mu_q^2T^2+(1/2\pi^2)\mu_q^4-B=(3\pi^2/90)T^4 \quad (3)$$

where $B=508\ \text{MeV fm}^{-3}$ ($B^{1/4}=250$ MeV) is the vacuum pressure. Figure 1 shows the phase diagram in the T vs μ_b plot, Eq. (3).

Figure 2 shows the plot of the pion-to-nucleon multiplicity, Eq. (2), as a function of μ_b. We observe a profound suppression of pions relative to nucleons with increasing baryochemical potential, of many orders of magnitude for large μ_b values. The size of the effect depends on the choice of the boundary values.

Another important effect of the baryochemical potential may be the reduction of the particle multiplicity in the hadronization of a quark-matter fireball with large μ_b. Since pions constitute, in general, the bulk of the multiplicity, a strong suppression of their production by the large baryochemical potential will cause a reduction of the event multiplicity. Thus, we may observe—contrary to common expectations—the hadronization of a "quark-matter fireball," produced with very large μ_b in $A+A$ collisions, to exhibit a smaller multiplicity than a normal hadronic fireball of the same energy. The stored energy in the quark-matter fireball will show up in the explosive decay as very large average transverse momentum of the hadronization products.

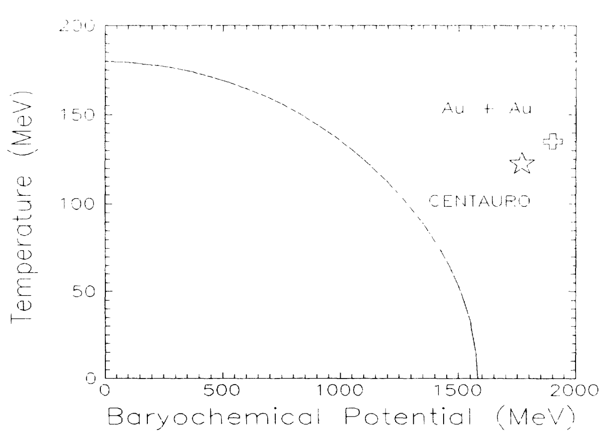

FIG. 1. The calculated phase diagram in a T vs μ_b plot, Eq. (3). The boundary values are given in the text. The star and cross denote the location of the corresponding values for the average cosmic-ray Centauro and (Au+Au) events, respectively (see Sec. IV I, V B of text).

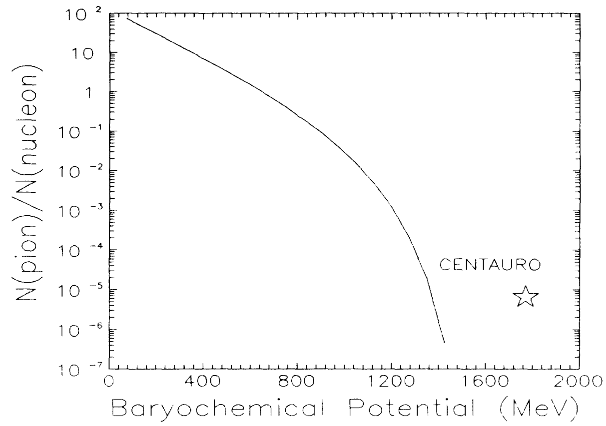

FIG. 2. The calculated particle ratio vs μ_b, Eq. (22). The star denotes the location of the corresponding values for the average Centauro event (see Sec. IV J of text).

C. Strangelet production

The strong suppression of new u,d (anti) quarks raises an interesting question as to what happens to the original gluons is the quark-matter fireball. In the flux-tube model [10], the relative probability of gluon fragmentation into a quark pair of mass m_i, is controlled by the parameter

$$x_i=C\exp(-m_i^2/\kappa) \; ,$$

where $\kappa \simeq 1\ \text{GeV fm}^{-1}$ is the QCD string constant and the normalization constant

$$C=1/[2+\exp(-4m_s^2/\kappa)]\simeq 0.39$$

for three quark flavors with current masses $m_u=m_d=0$ MeV, $m_s\simeq 170$ MeV. This leads to $x_u=x_d\simeq 0.39$ and $x_s\simeq 0.22$ in normal hadronic interactions.

In the case of the Centauro fireball with very large baryochemical potential, the creation of $u,\bar{u}$ and $d,\bar{d}$ is prohibited, thus allowing predominantly for $g\rightarrow s,\bar{s}$ fragmentation. To get a feeling for the relative probability of gluon fragmentation, we may take indicatively $m_u=m_d\simeq u_q\simeq 600$ MeV, which we calculate later on to be the fireball quark chemical potential. We find that $x_u=x_d\simeq 1.2\times 10^{-3}$ and $x_s\simeq 0.998$. Therefore, in the quark-matter fireball there are the primary (constituent) quarks for each flavor (u,d) and the $s,\bar{s}$ quarks generated by gluon fragmentation. Since the fireball hadronizes predominantly into baryons, there will remain an excess of (anti) strange matter, which cannot hadronize[2] and may form strangelets, i.e., stable baryonic states with very high mass to charge ratios [11]. These strange-matter states should be created and sustained more easily in a low-temperature and high-density environment, prevailing in the Centauro fireball. The existence of this kind of matter is, however, still not undoubtedly verified experimentally [12].

IV. CENTAURO CHARACTERISTICS

In the following we shall discuss the observed characteristics of the five Centauro events and we shall estimate several thermodynamic and kinematical quantities characteristic of the "quark-matter fireball," based on the outlined Centauro model. The calculation will be carried out assuming no interaction between the quarks. We shall also discuss very briefly the quantitative effects of quark interaction on some of the estimated quantities.

A. Centauro multiplicity

The observed multiplicity of the five Centauro events [1] is in the range 63–90 hadrons, with an average $\langle N_h \rangle = 75$. Since no primary γ showers were identified, one may conclude that, in order to conserve isospin, these hadrons cannot contain pions. It had been, therefore, widely accepted that the hadrons must be baryons. The hadrons are emitted isotropically from the fireball and their energy and transverse-momentum distributions have an exponential form.

B. Interaction energy

The five Centauro events have an average observed energy $\langle E_h(\gamma) \rangle = 348$ TeV. If we take the γ inelasticity coefficient $k_\gamma = 0.2$, the total average Centauro interaction energy is $\langle E_h \rangle = \langle E_h(\gamma) \rangle / K_\gamma = 1740$ TeV. It should be noted that the incident energy is at least equal to (and probably larger than) this interaction energy. Assuming that the incident nuclei have an average mass $\langle A_{\rm pr} \rangle \simeq 60$, Eq. (1), the interaction energy in the N-N center-of-mass system is $\sqrt{s_{N\text{-}N}} = 233$ GeV. The total interaction energy in the c.m. is equal to

$$\sqrt{s} = (M_{\rm pr}^2 + M_{\rm tg}^2 + 2M_{\rm tg} \langle E \rangle)^{1/2} = 6760 \text{ GeV}$$

corresponding to $\gamma_{\rm c.m.} = [\langle E \rangle + M_{\rm tg}]/\sqrt{s} = 257$. The above energies should be considered as *lower limits.*

[2] φ, K^+, K^0 mesons should also be created copiously. Their subsequent decay into channels containing π^0's (68%, 31%, and 33%, respectively) might not have been identified in the Chacaltaya chamber, due to their large lateral dispersion and the high-energy threshold of the detector. In addition, strange baryons $(\Lambda, \Sigma, \Xi \ldots)$ should also be produced, within baryon-number conservation.

C. Transverse momentum

The average observed transverse momentum, as estimated from the deduced fireball decay point of the Centauro I event, is $\langle p_T(\gamma) \rangle = 0.35 \pm 0.14$ GeV/c. Taking $K_\gamma = 0.2$, the average transverse momentum of the Centauro events is $\langle p_T \rangle = \langle p_T(\gamma) \rangle / K_\gamma = 1.75 \pm 0.7$ GeV/c. This is a very large transverse momentum, about three times larger than the average transverse momentum measured for baryons in nucleus-nucleus collisions at 200A GeV at the CERN SPS [13]. It necessitates the notion of an explosive decay of the superdense fireball rather than of a typical nuclear fragmentation.

D. Mass of the fireball

In the fireball frame each isotropically emitted particle (nucleon) has an energy given by

$$\langle E_n \rangle = \{[(4/\pi)\langle p_T \rangle]^2 + M_n^2\}^{1/2} = 2.4 \pm 0.8 \text{ GeV} ,$$

where M_n is the nucleon mass. With the average multiplicity being $\langle N_h \rangle = 75$, the mass of the average Centauro fireball becomes:

$$M_{\rm fb} = \langle N_h \rangle \langle E_n \rangle = 180 \pm 60 \text{ GeV} . \quad (4)$$

E. Volume of the fireball

Our picture of the Centauro event assumes the collision of a Lorentz-contracted incident nucleus, $\langle A_{\rm pr} \rangle \simeq 60$, with a ^{14}N nucleus in the upper atmosphere and the production of a quark-matter fireball from the combination of the two nuclei. The quark-matter fireball retains the contracted, cylinderlike shape of the incident heavy nucleus, with volume

$$V_{\rm fb} \simeq d\pi R^2 \simeq 75 \text{ fm}^3 , \quad (5)$$

where we have used $R = 1.15 \langle N_h \rangle^{1/3}$ fm, and $d \simeq 1$ fm, equivalent to the formation time $\tau_0 = 1$ fm, since $2R/\gamma_{\rm c.m.} \ll 1$ fm. This volume is a *lower limit,* since there should be a number of unidentified strange particles and some expansion of the fireball before hadronization. It is, however, about five times smaller than the volume of a nucleus with $A = 75$.

We can make another estimate of the fireball volume in terms of the freeze-out volume, accepting that the freeze-out radius $R_{\rm F} \simeq \lambda_h$, the hadron mean free path. More precisely, in the Centauro case where the hadrons are mostly baryons, $\lambda_b \lesssim R_{\rm F} < \lambda_\pi$, where the baryon mean free path $\lambda_b \simeq \frac{3}{4}\lambda_\pi$, for $1 < p < 20$ GeV/c, as obtained from π-p and p-N total cross sections. Since the freeze-out radius $R_{\rm F} \simeq 0.7 (dN/dy)^{1/2}$ [14], we calculate $65 < V_{\rm fb}^{\rm F} < 115$ fm^3, in agreement with Eq. (5).

F. Energy density of the fireball

The average energy density of the Centauro fireball can be estimated from the fireball mass and volume:

$$\varepsilon_{\rm fb} = M_{\rm fb} / V_{\rm fb} = 2.4 \pm 1 \text{ GeV fm}^{-3} . \quad (6)$$

The uncertainty in the energy density is calculated assuming a 30% variance in the volume estimation. The magnitude of the fireball energy density is—despite the large error—sufficiently high for the phase transition from (the incident) nuclear matter to the quark matter. Recent lattice QCD calculations [15] have shown that for a two-flavor QGP, the critical temperature and energy density have been reduced to the range of 150 MeV and 1 GeV fm^{-3}, respectively. This reduction of the critical quantities is even larger if heavier quarks are included.

The energy density is fundamental in the estimation of many other thermodynamic quantities of the fireball and its accurate knowledge is very desirable. The energy density varies as $\langle N_h \rangle^{1/3}$ and hence even a large increase of $\langle N_h \rangle$, say by a factor of 2, will produce only about a 25% change in ε.

G. Quark-baryon densities of the fireball

We have considered the Centauro fireball to consist mainly of constituent u,d quarks in the initial stage. Assuming that quarks carry on the average 300 MeV of energy in the rest frame (as in the case of confinement in the nucleon) the quark density of the Centauro fireball is:

$$\langle N_q \rangle = \varepsilon_{\text{fb}}/0.3 = 8\pm 3 \text{ fm}^{-3} .$$

Here we implicitly consider the energy density of the fireball to reside mainly in its quark content. Therefore, the estimated $\langle N_q \rangle$ value is an *upper limit.*

The baryon density can be simply estimated from the quark density:

$$\langle N_b \rangle = \tfrac{1}{3}\langle N_q \rangle = 2.7\pm 1 \text{ fm}^{-3} .$$

This value of the baryon density is approximately 18 times larger than that in nuclear matter (~ 0.15 fm^{-3}). It indicates a fireball of superdense matter with, perhaps, different characteristics (binding energy, collision mean free path, etc.) capable of penetrating down to the Chacaltaya detector altitude and exploding into baryons with very large $\langle p_T \rangle$.

H. Baryochemical potential of the fireball

The energy density of an ideal quark-gluon plasma as a function of the temperature and the baryochemical potential, resulting from both the quark and gluon degrees of freedom, is given by [16]

$$\varepsilon = (\pi^2/30)(N_g + \tfrac{7}{4}N_q)T^4 + N_q \mu_q^2 T^2/4 + (1/8\pi^2)N_q \mu^4 , \tag{7}$$

where $N_g = 16$ and $N_q = 12$ are the gluon and quark degrees of freedom, respectively, for two quark flavors.

To obtain a first estimate of the baryochemical potential, we consider the case $T \simeq 0$. Then the relation contains only the contribution from the quarks (at $T = 0$) and reduces to

$$\varepsilon = (12/648\pi^2)\mu^4 ,$$

which gives $\mu_b = 1.8\pm 0.3$ GeV for $\varepsilon = \varepsilon_{\text{fb}} = 2.4$ GeV fm^{-3}. This is a large quantity and its effects on $q\bar{q}$ production will be profound, as we will discuss later. It should be remembered that for cold nuclear matter the baryochemical potential is $\mu_b = 0.77$ GeV.

If we calculate the baryochemical potential from the relation between quark density, quark chemical potential and temperature,

$$N_q = 2(\mu_q T^2 + \mu^3/\pi^2) , \tag{8}$$

working again in the $T \simeq 0$ limit, we find that $\mu_b \simeq 2\pm 0.4$ GeV. In a more realistic situation with $T > 0$, the baryochemical potential will be smaller, since at high T the first term of (8) causes the baryochemical potential to drop as T^{-2}, if the baryon density remains constant.

I. Temperature of the fireball

The fireball temperature can be estimated from the relation

$$N_q = 2[\mu_q T^2 + \mu^3/\pi^2] .$$

With $\langle N_q \rangle = 8$ fm^{-3} and $\mu_b = 1.8$ GeV, the fireball temperature takes on the value $T_{\text{fb}} = 130\pm 6$ MeV. It is a moderate temperature, which could sustain the quark matter in the large-ε and -μ_b environment. In Fig. 1 we indicate on the phase diagram the location of the point (T_{fb},μ_b) and notice that it is well within the quark-matter phase for any reasonable boundary values.

The value of μ_b was estimated from Eq. (7) assuming $T=0$. If we now substitute in (7) the above-calculated values of μ_b and T_{fb} and require that $\varepsilon = 2.4$ GeV fm^{-3}, we find that μ_b, T_{fb} should be reduced by about 6%.

A comment should also be made concerning the calculated T_{fb} and the $\langle p_T \rangle$ of the Centauro fireball. In a (baryonic) fireball, the relation between the mass of the fireball and its $\langle p_T \rangle$ or T leads to the relation

$$\{[(4/\pi)\langle p_T \rangle]^2 + M_n^2\}^{1/2} = M_n + \tfrac{3}{2}T ,$$

where M_n is the nucleon mass. For the Centauro case, this relation gives an extremely large fireball temperature, $T = 975$ MeV. If this is a true measure of the fireball temperature, then three questions arise: which is the mechanism responsible for creating such a high temperature, since the nuclear stopping is almost null at these incident energies; how does one reconcile this temperature with the previously estimated one of the order of 130 MeV and what is the meaning of the "temperature" or the "inverse slope parameter," as inferred from the $\langle p_T \rangle$ or from fitting to the p_T distribution, respectively.

The meaning of this "temperature" has been a longstanding controversy. The inverse slope parameter, often referred to as "temperature," obtained from a fit to the p_T distribution may give an indication of a thermal-like spectrum, but it is not sufficient; more subtle density-, volume-, and flow-related effects must be found. These effects may drastically modify the "temperature" inferred from the $\langle p_T \rangle$ or p_T distributions [17].

J. Emitted-particle ratios

It was discussed in the Centauro model how the large baryochemical potential, inherent in the quark-matter fireball, will influence the hadronization process. The pion-to-nucleon density ratio was found to be proportional to the expression (2). Evaluating this ratio, taking for the Centauro fireball $\mu_b = 1.8$ GeV and $T_{fb} = 130$ MeV, we find that $N(\pi)/N(n) \simeq 7\times10^{-6}$. Indeed, we observe the total disappearance of pions and, hence, of gammas in the hadronization of the Centauro quark-matter fireball. This is in agreement with the accepted observed final state of the Centauro events. We indicate in Fig. 2 the location of the particle ratio for the average Centauro event.

K. Rapidities

The incident-nucleus rapidity of the Centauro event can be calculated from the average projectile energy per nucleon,

$$y_{pr} = \ln(2\langle E_h\rangle/\langle A_{pr}\rangle M_n) = 11.03 \ , \qquad (9)$$

where $\langle E_h\rangle = 1740$ TeV and $\langle A_{pr}\rangle \simeq 60$, according to our Centauro model. The rapidity is not a sensitive function of the projectile mass, since it varies as $\ln A_{pr}$.

The average pseudorapidity of the Centauro fireball decay products is calculated from the lateral spread of the family hadrons, measured from the center of gravity of the family (which coincides with the projectile direction) and the height of the interaction point. We estimate the average pseudorapidity of the five Centauro events to be $\langle \eta_{cnt}\rangle \simeq 9.9\pm0.2$. The incident-nucleus rapidity and the mean fireball pseudorapidity enable us to calculate, in a model-dependent way, the Centauro fireball mass using the relation [18]

$$M_{fb} = M_n A_{pr} \exp(y_{pr} - \langle \eta_{cnt}\rangle) \simeq 175\pm20 \text{ GeV} \ ,$$

a value equal to the one calculated from the experimental $\langle p_T\rangle$ of the Centauro events [Eq. (4)]. This shows an internal consistency of the proposed Centauro model.

The midrapidity of the colliding nuclei can be estimated from the relation

$$y_{mr} = \tfrac{1}{2} y_{pr} - \tfrac{1}{2}\ln(A_{tg}/\langle A_{pr}\rangle) = 6.24 \ , \qquad (10)$$

since all target and projectile nucleons participate. The hadronization of the central rapidity for the Centauro I event should be seen at an average angle of approximately 0.22° with respect to the direction of the incoming fireball. This corresponds to about 20 cm away from the family center of gravity. It is not known from the analysis of the Centauro I event if any showers of hadronic and electromagnetic nature are found there and what their characteristics are. One expects to observe both types of showers. There should be no inhibition on $q\bar{q}$ production and consequently on $\pi^{\pm}$ and π^0, since the midrapidity is almost totally free of baryon number density at these incident energies. Such an observation would be very interesting and would give credit to this Centauro model.

Table I summarizes the various observed and estimated characteristic thermodynamic and kinematical quantities of the average cosmic-ray Centauro event.

L. *q-q* interaction

The above Centauro characteristic quantities were calculated assuming an ideal noninteracting quark gas. We consider, in the following, *q-q* interaction, which will result in altering the estimated quantities. We take as the strong coupling constant for two quark flavors $a_s \simeq 0.16$. Then for the energy density we find [16]

TABLE I. Summary of observed and estimated thermodynamic and kinematical quantities characteristic of the cosmic-ray Centauro events.

Hadron multiplicity, $\langle N_h\rangle$	64–90, $\langle 75\rangle$
γ multiplicity	0
Average total incident energy	$\langle E\rangle \geq 1740$ TeV
Total interaction energy in "60+14" c.m.	$\sqrt{s} \geq 6760$ GeV
Total interaction energy in *N-N* c.m.	$\sqrt{s_{N\text{-}N}} \geq 233$ GeV
Average transverse momentum	$\langle p_T\rangle = 1.75\pm0.7$ GeV/c
Mass of fireball	$M_{fb} = 180\pm60$ GeV
Volume of fireball	$V_{fb} = 75-100$ fm^3
Energy density of fireball	$\varepsilon_{fb} = 2.4\pm1$ GeV fm^{-3}
Quark density of fireball	$\langle N_q\rangle = 8\pm3$ fm^{-3}
Baryon density of fireball	$\langle N_b\rangle = 2.7\pm1$ fm^{-3}
Baryochemical potential of fireball	$\mu_b = 1.8\pm0.3$ GeV
Temperature of fireball	$T_{fb} = 130\pm6$ MeV
Predicted particle ratio	$N(\text{pion})/N(\text{nucleon}) \simeq 7\times10^{-6}$
Incident nucleus rapidity in laboratory frame	$y_{pr} = 11.03$
Midrapidity of "60+14" system	$y_{c.m.} = 6.24$
Laboratory pseudorapidity of emitted baryons	$\langle \eta_{cnt}\rangle = 9.9\pm0.2$
Width of pseudorapidity distribution	$\langle \Delta\eta_{cnt}\rangle \simeq 1\pm0.2$

$$\varepsilon'_{\rm fb}=(1-2a_s/\pi)\varepsilon_{\rm fb}\simeq 2.15\ {\rm GeV\,fm^{-3}}\ ,$$

where $\varepsilon_{\rm fb}=2.4$ GeV fm^{-3} [Eq. (6)] is the energy density without q-q interaction. The new energy density is about 90% of the ideal-quark-gas value and still large enough to produce deconfinement.

The baryon density has the same dependence on a_s as the energy density. We find that the q-q interaction reduces N_b by about 10% to a value of approximately 2.4 fm^{-3}. We may also anticipate an increase of the fireball volume due to the q-q interaction

$$V'_{\rm fb}=M_{\rm fb}/\varepsilon'\simeq 85\ {\rm fm}^3\ .$$

We notice that all changes in the thermodynamic quantities due to the q-q interaction are well within the uncertainties of the values in the case of no interaction. Therefore, we shall not consider it any further.

M. Centauro event rate

An important point of the model is the assumption of the collision of a medium-mass cosmic-ray nucleus with a ^{14}N in the upper atmosphere. The rate of incidence of such nuclei is of the order of 15% of the total cosmic-ray flux, in the energy range 10^3–10^4 TeV. To examine the rate expected for nucleus-induced events, let us follow the syllogism: The five observed Centauro events were among about 600 cosmic-ray events recorded in the Chacaltaya chamber [1]. Of the 600 events, about $0.15\times 600=90$ events could be induced by medium-mass nucleus collisions. Therefore, the five Centauro events may constitute about 5.6% of the nucleus-induced cosmic-ray events. Now for these 90 nucleus-nucleus events, the fraction of the total inelastic cross section, $\sigma_{\rm tot}=\pi b_{\rm max}$, which corresponds to central collisions, possibly leading to a Centauro event, is equal to

$$f=\sigma_{\rm DI}/\sigma_{\rm tot}=\pi b^2_{\rm DI}/\pi b^2_{\rm max}$$
$$=(R_{\rm pr}-R_{\rm tg})^2/(R_{\rm pr}+R_{\rm tg})^2=5.4\%\ ,$$

where $R=1.15\ {\rm A}^{1/3}$ and $\sigma_{\rm DI}$ is the "dive-in" cross section. The five Centauro events could be considered as the *central collisions* of the nucleus-induced cosmic-ray events.

N. Comments on the model and estimated quantities

Before presenting and discussing a "typical" Centauro event at RHIC, we shall comment on the plausibility and self-consistency of the developed model and of the estimated quantities for the observed Centauro events.

The values of the various thermodynamic quantities of the Centauro fireball, $\varepsilon_{\rm fb}$, μ_b, $T_{\rm fb}$ were calculated for an ideal QGP, which is not the condition in the Centauro fireball. Although the effect of the (massive) q-q interaction was estimated to change these values by only about 10%, nevertheless it is a weak point which merits further consideration. The values of these quantities are, however, reasonable and within the range necessary for the phase transition from nuclear to quark matter.

The estimation of the mass of the Centauro fireball gives a measure of consistency of the model. The mass was calculated by two methods, one using the accepted experimental value of the average p_T and the other using the model-estimated rapidity of the incident nucleus and the experimentally measured pseudorapidity of the fireball decay products. The two methods gave the same mass for the fireball.

We may attempt to get another estimate of the energy density using the Bjorken formalism,

$$\varepsilon=[\langle m_T\rangle/\tau_0 A_T](\Delta N/\Delta\eta)$$

where $A_T=\pi(1.15\langle N_h\rangle^{1/3})^2\simeq 74$ fm^2, $\langle m_T\rangle=[\langle p_T\rangle^2+M_n^2]^{1/2}\simeq 2$ GeV and $\tau_0\simeq 1$ fm. We take as $\Delta N/\Delta\eta=\langle N_h\rangle/\langle\Delta\eta\rangle$, where $\langle\Delta\eta\rangle$ is estimated from the height of the interaction point and the corresponding distance of the showers measured from the center of family for the five Centauro events [18]. We find: $\langle\Delta\eta_{\rm cnt}\rangle=\langle\eta_{\rm cnt}\rangle_{\rm max}-\langle\eta_{\rm cnt}\rangle_{\rm min}\simeq 10.4-9.4=1\pm0.2$. With these values, the Bjorken formula for the energy density gives $\varepsilon\simeq 2\pm0.4$ GeV fm^{-3}. This is of the same order of magnitude as the previous estimation Eq. (6), showing a consistency of our Centauro model.

Therefore, the syllogism and assumptions made in the formulation of the Centauro model and in calculating the characteristic thermodynamic quantities are reasonable, plausible, and self-consistent.

V. A CENTAURO EVENT AT RHIC

The new Relativistic Heavy Ion Collider at Brookhaven National Laboratory, with colliding beams of nuclei at $\sqrt{s_{N\text{-}N}}=200$ GeV, provides near-optimum conditions for the possible formation of Centauro-type events. We shall describe below the expected features of a typical "Centauro" event at RHIC and give suggestions for possible signatures.

A. Kinematics

We consider a central collision of two Au nuclei incident on each other. The rapidity of each colliding beam is

$$y=\ln(2E/M_n)=5.36\ ,$$

where $E=100$ GeV is the incident energy per nucleon for each Au nucleus. The corresponding γ factor is $\gamma=\cosh y=106$. The shape of the colliding nuclei is a cylinder with cross-sectional radius $R=1.15\ {\rm A}^{1/3}=6.7$ fm. The thickness of the cylinder, d, is taken to be 1 fm, since $2R/\gamma\ll 1$ fm. Then the volume of each contracted nucleus is $V=d\pi R^2\simeq 140$ fm^3, which is about 11% of the volume of an Au nucleus at rest.

We consider central collisions with impact parameters in the range $0<b<5$ fm. The upper limit corresponds to $(0.4\times b_{\rm max})$, that is to about 50% of the maximum number of nucleon-nucleon collisions [19], where $b_{\rm max}=2(0.9\times 1.15\ {\rm A}^{1/3})$, equivalent to an overlap of each nucleus at a point with more than 90% of the nuclear density [20]. With this geometry, covering approximately up to 14% of the total inelastic cross section ($\sigma_{\rm inel}\simeq 5.6$ b), the mean number of participating nucleons in each fireball is *at least* of order 150. According to our model, the mean (baryon) multiplicity of the hadronized fireball in the fragmentation rapidity would be of similar order of magnitude. In this case, however, one should also take account of strange particles, mainly φ, K^+, K^0, Λ, Σ, which should be present.

The transfer of energy from the fragmentation rapidity's initial kinetic and internal energies to the midrapidity will cause the slowing down of the created fireball and the dispersion of baryon number density in the fragmentation rapidity. On the assumption that the $\langle p_T \rangle$ of the fireball decay products is of the order 1.7 GeV/c, as in the case of the Centauro events, we may expect an average pseudorapidity

$$\langle \eta \rangle = y - \ln[(4\langle p_T \rangle / \pi M_n)^2 + 1]^{1/2} \simeq 4.4 ,$$

due to transverse momentum *alone*. Any nuclear stopping will decrease $\langle \eta \rangle$.

The width of the fragmentation region may be taken to be $\Delta\eta \simeq 2$ units of pseudorapidity [21], corresponding to a range of lab angles of the decay products around $\langle \theta \rangle \simeq 4°$. It should be noted that increased nuclear stopping, as predicted by recent event generators (RQMD) [22], will decrease $\langle \eta \rangle$, shift $\langle \theta \rangle$ to larger values and broaden the distribution. In the extreme case of very limited nuclear transparency at RHIC energies, the baryon number density will be distributed in the entire rapidity range and there will be no prominent Centauro event. Even in this case, however, Au+Au central collisions may still produce quark-matter events, at the maximum of the baryon rapidity distribution, with similar—although not so eminent—observables.

B. Thermodynamic quantities

To obtain an estimate of the expected characteristic thermodynamic quantities of the "Centauro" event at RHIC, we make the assumption that the mean transverse momentum is of order 1.7 GeV/c, similar to the cosmic-ray Centauro events. We also assume for simplicity that the fireball retains roughly the cylindrical shape of the colliding nucleus. This may not be exactly true at RHIC in the case of heavy nuclei with large stopping, as it is in fixed target collisions of cosmic rays. We may have, then, to consider lighter-mass systems, say Cu+Cu, for the observation of Centauro events.

The thermodynamic and kinematical quantities take on the approximate values shown in Table II. We notice that the critical quantities, ε, μ_b, T, are all of a reasonable magnitude, within the range required for a phase transition in a large μ_b environment; see Fig. 1.

TABLE II. Characteristic thermodynamic and kinematical quantities of an average "Centauro" event in Au+Au central collisions at RHIC.

$\langle p_T \rangle \simeq 1.7$ GeV/c
$\langle E_n \rangle \simeq 2.4$ GeV
$\langle N_n \rangle > 150$
$M_{fb} \gtrsim 350$ GeV
$\varepsilon_{fb} \simeq 3$ GeV fm^{-3}
$\mu_b \simeq 1.9$ GeV
$T_{fb} \simeq 135$ MeV
$3 \lesssim \langle \eta \rangle \lesssim 5$
$\langle \theta \rangle \simeq 4°$

C. Observables

At RHIC, the Centauro-type event will materialize in the fragmentation regions and should exhibit dramatic signatures of its formation, in terms of both the multiplicity and energy contents. In the fireball fragmentation rapidity we expect [5]:

(i) The hadronic energy to be many times more than the electromagnetic, so that $E_h/E_\gamma \gg 3$. In normal hadronic interactions this ratio is of order 3, in the fragmentation rapidity.

(ii) The hadron multiplicity to be many times larger than the γ multiplicity so that $N_h/N_\gamma \gg 1$, which is roughly the value for this ratio in hadronic interactions.

(iii) The total hadron multiplicity, in the fragmentation rapidity, to be rather small, compared to normal hadronic interactions in central Au+Au collisions. In addition, the bulk of the hadrons should be baryons.

(iv) Strange particles ($\varphi, K^+, K^0, \Lambda, \Sigma$) to be produced copiously and the K^+/π^+ ratio to increase strongly.

(v) The average p_T of the fireball decay products to be considerably larger than what is predicted by simulation codes, whose value is in good agreement with experiment, viz. ^{16}O Au at 200A GeV [13].

Finally, the suggestion of forming "strangelets" with the unpaired and unable-to-hadronize strange (anti) quarks, is an exciting possibility.

VI. SUMMARY

We have developed a phenomenological model, based on the available and accepted information for the Centauro events. Our model attempts to explain the observed features of the average event and to estimate characteristic thermodynamic quantities, such as ε, μ, T, knowledge of which is necessary for an educated suggestion of a possible phase transition to quark matter in a highly dense nuclear system.

The model we presented makes certain plausible assumptions and arguments, which do not conflict with any known theory nor contradict any existing experimental data. The important assumptions are: the collision of a medium-mass cosmic-ray nucleus with a ^{14}N nucleus and the small changes of the fireball entropy, volume, and temperature during the phase transition. The justification of these assumptions is given by the self-consistency of the model and the estimated quantities and the reasonable and plausible values of these quantities, which are also within the range considered to be necessary for the phase transition.

Using this model, we attempt to describe a typical Centauro-type event, possibly appearing in A+A central collisions at RHIC. We find that the characteristic thermodynamic quantities of the produced fireball are of sufficient magnitude to sustain a phase transition to quark matter. The proposed signatures for such an event include particle species and multiplicity, type of energy contents, and large average p_T. Finally we make a speculative suggestion for the possible creation of "strangelets" in the fragmentation region of the fireball.

Our "Centauro" model is (to our knowledge) the only one capable of being tested at RHIC. In view of the highly interesting and still puzzling Centauro events, we believe that every effort should be made to implement appropriate measurements of particle multiplicity, particle identification, energy content, and $\langle p_T \rangle$ in the fragmentation rapidity region. It may give a direct and indisputable indication of quark-matter formation in a highly dense nuclear system and solve the mystery of the Centauro and other exotic cosmic-ray events. At the same time, the possibility of observing "strangelets" adds a new dimension of excitement to these measurements.

Note added in proof. Since the submission of this paper, two items can to our attention. (i) A calculation of a phase transition in very dense nuclear matter by Ellis, Kapusta, and Olive [23]. They find such a phase transition to quark matter to occur at $\mu_b = 1.77$ GeV, $N_b \simeq 2.37\ \text{fm}^{-3}$, and $1.53 < \varepsilon < 3.42\ \text{GeV fm}^{-3}$. Our estimated quantities for the Centauro events are precisely in these ranges. (ii) Long-range cascades, lying in the forward cone in Centauro-type events and penetrating as much as 120 cascade units have been observed [24]. These highly penetrating "particles" may be "strangelets," produced in the Centauro quark-matter fireball [25].

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