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Explosive quark matter and the "Centauro" event

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We study the hypothesis that the "Centauro" event found by the Brazil-Japan cosmic-ray emulsion collaboration is initiated by the explosion of a metastable glob of highly compressed hadronic matter present in the primary spectrum. A crude liquid-drop model is formulated to investigate the properties of the equation of state necessary to support such a hypothesis. The evolution of such a glob as it moves through the atmosphere and eventually explodes is described. Two other variants are also discussed: one is that the glob contains an unconfined, massive quark, while the other is that the lowest-mass fractionally charged hadron has large baryon number. In that case, the Centauro event consists of fragmentation of a nucleon primary into such objects. The most prominent experimental consequences of our speculations appear to be the existence of peculiar explosive events at high altitudes at a rate $\lesssim 10^3$ m^{-2}yr^{-1}, and/or penetrating particles of high ionization density at sea level containing fractional charge.

I. INTRODUCTION

The celebrated "Centauro" event[1] found in the Mt. Chacaltaya emulsion exposures by the Brazil-Japan collaboration continues to resist rational interpretation. The event is described in terms of production of a leading "fireball," with the parameters listed in Table I. The main properties of this event have been inferred from the data, and are not here called into question.

The absence of π^0's in the event would suggest a high-Z primary nucleus as the source. This interpretation, however appears to be untenable since there is a negligible probability that a nucleus would penetrate so deeply into the atmosphere. Furthermore, the mean transverse momentum of the secondaries is much larger than the value typical of a nuclear fragmentation.

These objections, however, offer no obstacle to another interpretation: that the primary object initiating the collision is a glob of nuclear matter of very high density.[2-15] Since the $\langle p_\perp \rangle$ is ~3–5 times the normal value typical of a nucleus, we might expect a density ~30–100 times that of ordinary nuclear matter. This highly compressed glob would have a radius 3–5 times smaller than that of an ordinary nucleus. If the larger transverse momentum is of the same order as the binding energies possessed by the constituents of the dense nuclear matter, these binding energies would be much greater than those of conventional nuclear matter. Thus, were such globs of primordial superdense nuclear matter to exist, the reduced geometrical cross section and increased binding energy might allow these globs to penetrate 500 g/cm^2 of atmosphere and initiate events of the Centauro type.

The high multiplicity of the Centauro event suggests that the mechanism of fragmentation is in fact explosive. Indeed it is *a priori* unlikely that superdense nuclear matter exists in a free state. We might expect, however, that globs of superdense matter could be metastable. If the density of the glob is 30–100 times ordinary nuclear matter density, we would almost certainly expect that the matter would be in the quark phase. In a central collision of an air nucleus with the metastable glob of quark matter, the glob might become sufficiently excited for it to "boil" or explode. This would lead to the high multiplicity, high $p_\perp$, and the predominance of baryons in the final state.

In this paper we explore this hypothesis.[16,17] In Sec. II, we describe the structure of the quark glob and the properties of quark matter necessary for the existence of such a glob. In Sec. III, we describe the evolution of the glob as it penetrates the atmosphere and (perhaps) explodes. Finally in Sec. IV, we address the question of how well the above scenario accounts for the Centauro event, as well as for other cosmic-ray phenomena. We also speculate on mechanisms of formation, including the possibility of the presence of an unconfined quark in the glob as an aid to stabilization of such a highly compressed state of hadronic matter.

II. A QUARK GLOB

A number of authors[3-15] have described matter at very high densities in terms of quarks. Within the context of quantum chromodynamics (QCD), Collins and Perry[4] first suggested that at very high densities, matter is an ideal quark gas. This observation follows from the asymptotic freedom of quark interactions,[18] that is, the decrease in the strength of quark interactions at short distances. At lower densities, quark interactions are increasingly important. At some density the quarks should condense into droplets of hadronic matter.

Calculations using renormalization-group-im-

TABLE I. Properties of the Centauro event.

Primary energy	~	1000 TeV
Production height	~	50 m above apparatus 500 g/cm^2 from the top of the atmosphere
Fireball mass	~	200 GeV
Fireball multiplicity	~	100
Multiplicity of π^0 and e in the fireball	~	0
$\langle p_\perp \rangle$ of secondaries from the fireball	~	1.7 ± 0.7 GeV

proved perturbation theory have given credibility to this scenario. A result of these calculations is that the effects of quark interactions produce an energy-density–density relation of the form

$$\mathcal{E} = A\mathcal{N}^{4/3} + B\,. \tag{1}$$

In this equation $\mathcal{E}$ is the energy density in units of MeV fm^{-3} and $\mathcal{N}$ is the density in units of baryons fm^{-3}. The coefficients A and B are slowly varying functions of $\mathcal{N}$.

This energy-density–density relation is in close correspondence to the relation which holds for the MIT bag model of hadrons in the limit of no interactions between the constituent quarks.[19] In the bag model, A_{bag} and B_{bag} are density-independent constants

$$A_{\text{bag}} \simeq \tfrac{9}{4}\pi^{2/3} \times (200 \text{ MeV fm})\,, \tag{2a}$$

$$B_{\text{bag}} \simeq 58 \text{ MeV/fm}^3\,. \tag{2b}$$

The effect of interactions in QCD is to increase A and B from their ideal-gas values

$$A_{\text{IG}} = \tfrac{9}{4}\pi^{2/3} \times (200 \text{ MeV fm})\,, \tag{3a}$$

$$B_{\text{IG}} = 0 \tag{3b}$$

to values whose numerical value depends on the parameter Λ which characterizes the energy scales of quark interactions in QCD.

At sufficiently low densities, the B term in Eq. (1) becomes comparable in magnitude to the $A\mathcal{N}^{4/3}$ term. At some density, the gas may become unstable since the pressure

$$P = -\frac{d}{dV}\,\mathcal{E}V = \tfrac{1}{3}\mathcal{E} - \tfrac{4}{3}B \tag{4}$$

becomes small. At this density, the quark matter may be unstable with respect to the formation of droplets of hadronic matter. The nature of these droplets of hadronic matter depends on the details of the dynamics of the finite size drop. One possibility is that the droplets are nucleons, another is that they are long-lived metastable globs of quark matter. These globs could have radii of several fermi and contain several hundred quarks.

In the analysis that follows, we shall assume that such globs are formed. We shall attempt to describe these globs by a phenomenological liquid-drop model.

To determine the size and shape of a droplet of quarks of baryon number N, we need the energy E of the droplet for arbitrary volume V and shape S. The energy E should be minimized with respect to V and S to find the equilibrium V_0 and S_0:

$$\frac{\partial}{\partial V_0}\,E(V_0, S_0, N) = 0 = \frac{\partial}{\partial S_0}\,E(V_0, S_0, N)\,. \tag{5}$$

The solutions of these equations gives the energy, $E(N) = E(V_0, S_0, N)$, of the glob as a function of baryon number. In general, Eq. (5) may have many solutions corresponding to objects which are metastable and, therefore, stable with respect to small shape and volume oscillations, but may decay by a large scale oscillation.

The energy of the glob may be written as

$$E(N) = \alpha N - \beta N^{2/3} + \Delta(N)\,. \tag{6}$$

The quantities α and β are constants. The function $\Delta(N)$ is bounded by $N^{2/3}$ for large N but is otherwise arbitrary.

The coefficient α is an extensive parameter which may be determined in the thermodynamic limit $N \to \infty$. Using Eqs. (1) and (4), we obtain

$$\alpha = 4B\left(\frac{A}{3B}\right)^{3/4}\,. \tag{7}$$

In the bag model with no interactions, $\alpha \sim 900$ MeV. In lowest order in perturbation theory, the coefficient A is modified and becomes $A \to A(1 + 2\alpha_s/3\pi)$, $\alpha_s = g^2/4\pi$ is the strong coupling strength. In higher orders A receives positive contributions which are density dependent.

We expect that the "surface term" $-\beta$ should be chosen as negative, $\beta > 0$, since it corrects the positive extensive term α, which arises from repulsive quark interactions. In a finite system, the strength of these interactions should be reduced owing to the presence of a surface. Furthermore, for a finite system there are interactions in addition to the repulsive exchange energy, which are most important in the low-density region near the surface of the glob.

The effect of the negative surface energy term is to destabilize globs of arbitrarily large N. This term induces a condensation down to globs of finite but as yet undetermined baryon number.

There is finally the contribution of $\Delta(N)$. This term summarizes all the finite-size corrections to $E(N)$ not already included in the volume and surface terms. The constraints on $\Delta(N)$ are that for $N = 1$, corresponding to a proton,

$$E(1) = m_p\,. \tag{8}$$

We assume that for $N > 1$

$$E(N) > Nm_p , \tag{9}$$

so that the globs are not absolutely stable with respect to decay into nuclear matter. The condition that the glob be stable with respect to single-nucleon emission is

$$\frac{dE}{dN} < m_p \tag{10}$$

for some range of baryon number. Using Eqs. (6) and (10), this stability condition is

$$\tfrac{2}{3}\beta N^{-1/3} - \frac{d\Delta}{dN} > \alpha - m_p . \tag{11}$$

Using Eq. (11), we see that the globs are always unstable for baryon number N greater than some upper limit N_0. For $N < N_0$ the globs are stable with respect to nucleon emission. This stability will be maintained unless, for some baryon number N_c, the term $d\Delta/dN > \frac{2}{3}\beta N^{-1/3} + m_p - \alpha$. In this case, the system would be metastable for $N_c < N < N_0$ and would spontaneously decay for $N < N_c$ or $N > N_0$. Such a hypothetical situation is shown in Fig. 1.

The actual situation may, of course, be much more complicated than the scenario described above. There may be various regions of metastability, or the region of metastability could extend from $1 < N < N_0$. If we require that the glob explodes for some finite range of baryon number, $1 < N < N_c$, then there must be at least one region of metastability.

A mechanism for producing stable globs of quark matter has been suggested by De Rújula, Giles, and Jaffe (DGJ).[20] They have discussed the properties of quantum chromodynamics when the color symmetry is slightly broken so that the color field is of large but finite range. Under these circumstances, the conventional conjecture of perfect confinement of quarks and other color-bearing particles (e.g., diquarks and gluons) no longer holds. The quark in such a model is expected to be a complex object of relatively large mass (indeed, as the range of the color force tends to infinity, so does the quark mass) and large size (of order of the range of the color field). The long-range color field of such a highly massive quark should attract nucleons via an induced color dipole moment. If such a quark is produced in a dense environment of nuclear matter, it might pick up an amount of nucleons comparable in mass to that of the original quark. Indeed, DGJ estimate that in the most stable configuration, the nuclear matter has a mass ~80% of the quark mass. The presence of a quark excess in the conjectured superdense glob of nuclear matter may therefore provide an attractive force and aid in compressing the glob to high density and in maintaining it in a stable state. Finite-size effects may, as was the case of the

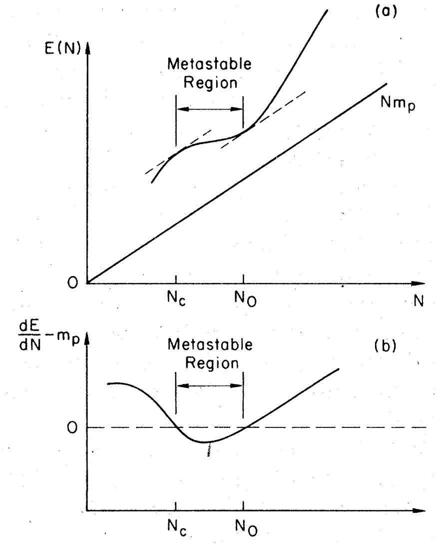

FIG. 1. (a) Conjectured energy of a spherical glob of quark matter as function of its baryon number N. The fact that the curve lies above $E(N) = Nm_p$ implies that such globs are not absolutely stable. (b) The slope of $E(N)$. The region for which $dE/dN < m_p$ is the region of metastability, i.e., where the glob cannot decay by single-baryon emission.

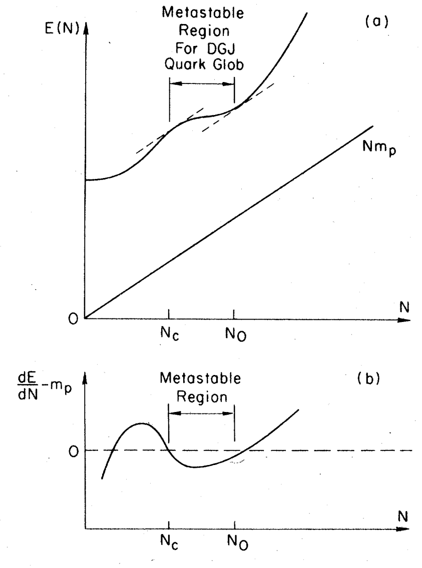

FIG. 2. (a) Conjectured energy $E(N)$ of a spherical glob of quark matter containing an unconfined quark, i.e., the total charge of the glob is assumed to be fractional. (b) The slope of $E(N)$.

glob without an excess quark, produce metastable configurations.

In the DGJ picture, the glob would have the quantum numbers of a quark. The collisions with air nuclei would be, in almost all respects, similar to collisions of a glob with no excess quark. The only obvious difference is that below a certain baryon number, the binding energy per nucleon will monotonically increase (cf. Fig. 2). The quark and a few tightly bound nucleons would necessarily penetrate to sea level.

III. INTERACTION OF THE GLOB WITH THE ATMOSPHERE

We now can construct a qualitative description of the glob as it falls through the atmosphere. Upon entering the atmosphere, the glob collides with air nuclei. This process heats the glob, and it cools either by radiation of mesons or evaporation of baryons. The boiling off of baryons decreases the baryon number, and if the region of metastability extends only to baryon number N_c, the glob will eventually explode after N has decreased below this critical value. If the region of metastability extends all the way down to baryon number 1, the glob will not explode and will collide with air nuclei until it is evaporated.

In the latter case where the glob does not explode, there are two possible scenarios. If $dE/dN - m_p \rightarrow 0$ as N decreases, $N \rightarrow 1$, the glob will evaporate much more rapidly the further it penetrates into the atmosphere. In this case, a central collision of an air nucleus with the loosely bound glob would simulate an explosion. If $dE/dN - m_p$ increases as $N \rightarrow 1$, the evaporation rate will decrease as the glob penetrates more deeply into the atmosphere.

We shall use a simple model of the glob as a droplet, consisting of an ideal degenerate Fermi gas of quarks to obtain an order-of-magnitude estimate of the energy transferred to the glob per collision and to estimate the evaporation rate. We shall carry computations out in the rest frame of the glob. In this frame the air nucleus appears to be a Lorentz-contracted pancake. Assuming that the surface air nucleons completely shield those nucleons which reside in the interior of the air nucleus, the quarks in the glob will see $N^{2/3}$ nucleons. The typical baryon number of an air nucleus is that of nitrogen, $N \sim 14$.

In the average collision, however, only a fraction of the glob overlaps with the air nucleus. The average path length of nucleons through the glob is also reduced from the maximum value of the diameter of the glob, $2R_g$. With comparable sizes of air nucleus and glob, an elementary estimate yields a reduction factor $\sim\frac{1}{6}$.

In addition to this geometrical reduction in the fraction of quarks in the glob excited in the collision, there is a dynamical reduction arising from the Fermi exclusion principle. If a nucleon imparts momentum p to a quark of momentum k, then in order for scattering to occur, the scattered quark must have an energy $|\vec{p}+\vec{k}| > k_F$. The cross section is reduced, therefore, by a factor

$$\Delta = \frac{1}{\frac{4}{3}\pi k_F{}^3} \int d^3k \, \theta(k_F - k)\theta(|\vec{p}+\vec{k}| - k_F) , \qquad (12)$$

which for $p \ll k_F$ is

$$\Delta \sim \frac{3}{4} \, \frac{p}{k_F} \, . \qquad (13)$$

The energy ΔE imparted to the glob per collision is therefore

$$\Delta E \sim \tfrac{1}{6} p \left(\frac{3}{4} \, \frac{p}{k_F} \right) 2R_g N^{2/3} \sigma_{qp} \rho \, . \qquad (14)$$

In this equation we take the quark-proton cross section to be $\sigma_{qp} \sim 12$ mb, the density of quarks in the glob is ρ. With $N \sim 14$, $N_g \sim 100$ and $k_F \sim 1$ GeV, we obtain $E \sim 7$ GeV/collision. Therefore, in a typical collision of a glob of this size the fractional energy loss $\Delta E/E$ is ~3%. With a collision length ~30 g/cm^2 (appropriate for $R_{\text{glob}} \sim R_{\text{air}}$), it follows that the glob penetrates to a range X:

$$X \sim 1\,000 \ln \frac{E}{M} \ \text{g/cm}^{-2}$$

provided it does not explode. For a glob with Centauro parameters $E/M \sim 10^3 - 10^4$ (and still omitting the possibility of explosion), the range is $X \sim 6000-8000$ g/cm^2 and the glob penetrates to sea level. As it penetrates it loses somewhere between $10^3 - 10^5$ GeV/collision. The air shower which forms will have somewhat different characteristics than the typical proton-induced shower. However, before the glob reaches sea level, it may explode. Assuming a few nucleons per collision are evaporated, the glob could easily lose 20–100 nucleons before penetrating 500 g/cm^3. If the glob is metastable, this large evaporation could transform the glob from a metastable to an unstable configuration, and the glob would spontaneously explode. If this is the case, these explosions should occur at a reasonably well-defined depth in the atmosphere. If the primary spectrum is peaked at an optimal baryon number N_0 and ΔN is the mean loss of baryons per collision, the explosion would occur when the number of emitted baryons reduced N_0 to the critical value N_c. This explosion happens at a depth

$$X \sim 30 \left(\frac{N_0 - N_c}{\Delta N} \right) \ \text{g/cm}^2 \qquad (16)$$

in the atmosphere, with a spread

$$\Delta X \sim 30\left(\frac{N_0 - N_c}{\Delta N}\right)^{1/2} \text{ g/cm}^2 . \tag{17}$$

Notice this depth does not depend upon primary energy. However, if nonrelativistic metastable globs impinged on the top of the atmoshpere, they might not be sufficiently energetic to boil away enough baryons to explode. Such globs would penetrate to sea level and survive.

The charge/baryon number ratio Q/N of the glob can be estimated by using an ideal Fermi gas model. At the Fermi energy appropriate to the glob $E_f \sim 1$ GeV, only up, down, and strange quarks should be present in the glob. The lowest energy configuration of the glob has equal Fermi energies of up, down, and strange quarks. The density of each species of quarks is $n_i \sim k_i^3$ so that

$$\frac{Q}{N} = \frac{2k_u^3 - k_d^3 - k_s^3}{k_u^3 + k_d^3 + k_s^3} . \tag{18}$$

For $m_u \sim m_d \sim 0$, $m_s \sim 300$ MeV, and $k_F \sim 1-1.5$ GeV, we find $Q/N \sim 1-2\%$, and the strangeness of the order of the baryon number. Upon explosion, the products of the glob will be primarily Λ's and Σ's with only ~30% nonstrange baryons. The small charge of the glob will also make it difficult to detect by techniques used to identify relativistic high-Z primaries.[16]

If the glob were to contain an unconfined massive quark as envisaged by DGJ[20] but still possess a metastable state which allows Centauro explosions, then the products of such explosions would necessarily include a "stripped" glob of smaller N containing the quark. Such globs would penetrate to sea level. We shall see in Sec. IV that there are in fact rather serious experimental constraints on this hypothesis.

It is interesting to consider what would happen were the binding of nucleons to an isolated quark even stronger than considered by DGJ. If the energy of the system of quark and nucleons is as shown in Fig. 3, with $dE/dN + m_p < 0$ for some region of N, a quark once produced could *spontaneously* decay into the stable system X_N with large baryon number N: $Q \to X_N + N$ baryons + $\cdots$. Such a decay would in fact again look very much like a Centauro final state. Thus if the process

$$\begin{array}{l} p+p \to q+q+q+\text{hadrons} \\ \qquad\qquad\quad \searrow X_N+\text{baryons} \\ \qquad\qquad \searrow X_N+\text{baryons} \\ \qquad \searrow X_N+\text{baryons} \end{array} \tag{19}$$

had for some reason a large cross section at 10^3 TeV, then because of the decay of the "primeval" quarks to the stable glob states of large baryon number one could account for the Centauro phenomenon. In this case the residual glob states X_N containing the net fractional charge and large N would again be expected to penetrate to sea level. Furthermore, in this case the experimental constraints alluded to above are less severe.

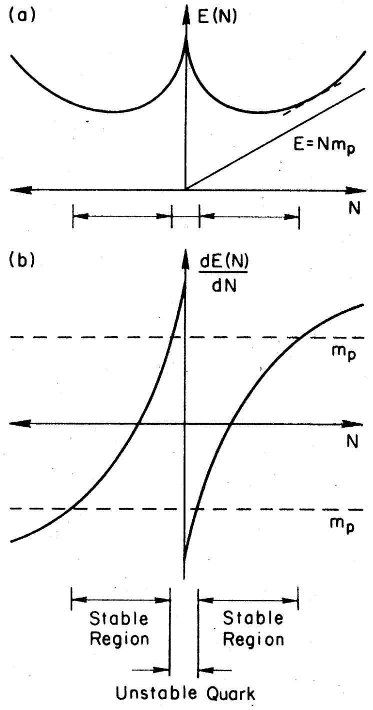

FIG. 3. (a) Highly speculative conjecture of energy of a fractionally charged quark glob as function of baryon number N. If there is a local maximum near $N = 0$, the least massive state has large $|N|$. (b) The slope $E(N)$ versus N. If $|dE/dN| > m_p$, the glob is unstable. The regions of unstability and stability are shown.

IV. PHENOMENOLOGY

How well does the above scenario account for the properties of the Centauro event, in particular the absence of π^0's? We may estimate crudely the number of π^0's as follows: We assume the emitted baryons are predominantly in the $\underline{56}$ of SU(6), according to the appropriate statistical weights. In the symmetry limit, this gives the decay products as listed in Table II. Not all the Λ's, Σ's, and Ξ's decay in the 50 m between production point and detector, and furthermore, relatively few of the decay products are π^0's of energy great enough to be detected. Thus the predominant source of π^0's are the decay products of the Δ and Y^*, which in this picture comprise ~50% of the primary baryons. With one π^+, π^-, or π^0 emitted per resonance decay, the number of π^0's per emitted baryon is $\sim\frac{1}{3}$

TABLE II. Fireball decay products.

n, p	$\frac{4}{56} \sim 7\%$
Δ	$\frac{16}{56} \sim 30\%$
Λ, $\Sigma^{\pm}$, Σ^0	$\frac{8}{56} \sim 15\%$
$Y^*(1385)$	$\frac{12}{56} \sim 20\%$
Ξ^-, Ξ^0	$\frac{4}{56} \sim 7\%$
$\Xi^*(1530)$	$\frac{8}{56} \sim 15\%$
Ω^-	$\frac{4}{56} \sim 7\%$

$\times 50\% \approx 15\%$. In the rest frame of the glob, these should be emitted isotropically with mean momentum of a few hundred MeV. A crude estimate indicates that no more than 30–50% of these should have sufficient energy in the laboratory frame to exceed the 1 TeV threshold energy for detection. Thus we could expect ~5–8 detectable π^0's to accompany the ~100 baryons emitted in a Centauro explosion. This is uncomfortably large, but, given the statistical and systematic uncertainties, perhaps not impossibly large.

In addition to the direct products of the Centauro explosion, there could be additional hadrons produced in the collisions preceding the main event. However, at Chacaltaya altitudes, the collision length for the glob is ~400 m, and other than possibly an enhanced, pionic component (a factor ~3?) from "radiative" cooling, the reaction products in such collision have properties similar to those from the explosion itself. Also, since only a small fraction f (~3%?) of the mass of the glob is emitted per noncatastrophic collision, and since even for the first collision the products will be distributed in a detector area ~10–100 times large as for the products of the explosion, the additional contribution from prior collisions would appear to be small.

It is of interest to question whether the air shower produced by a glob has other distinctive characteristics which would provide supportive evidence. We have argued that as the glob propagates through the atmosphere, it will release per collision a fraction f of its rest energy into baryons and mesons. The fraction f is poorly known, but of order of a few percent. Because of the large degree of penetration and short interaction length, this will lead to considerable deposition of energy in the atmosphere. However, because the Lorentz factor γ of the primary is not too large, the γ of the secondary hadrons in the shower will not be large either. This means that the shower should have a more diffuse radial distribution than a proton-induced shower of the same energy. It should, however, be less diffuse than the shower produced by an iron nucleus of comparable energy, inasmuch as in this latter case the γ of secondaries is likewise small and the fragmentation into nucleons occurs at the top of the atmosphere.

We have not carried out any simulations of these air showers. However, because their properties seem to be intermediate between those of iron primaries and of proton primaries, and because the fraction of primaries of a given energy which are these exotic globs is a few percent, it may be difficult to find evidence for or against this hypothetical component from the general characteristics of air showers.

A more hopeful possibility may lie in high-altitude calorimetry, where one sees the entire longitudinal development of the shower. The data from the Tien-Shan calorimeter[21] in particular may be relevant. However, without detailed simulations (which we have not done) it is not clear to us that the increased penetrationof hadron cascades at energies in excess of 100 TeV claimed in that experiment is in fact connected to the phenomenon we discuss here.

If the primary flux of globs has an energy dependence similar to the overall cosmic-ray flux, there should be a sizeable number of lower-energy globs incident. The flux of globs with $\gamma \gtrsim 3$ would be $\lesssim 10^5$ the Centauro rate, or $\sim 10^3\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, and these would again be expected to explode at a depth ~500 $\mathrm{g\,cm}^{-2}$. The products of these explosions would be emitted at quite large angles and low energy (a few GeV), and would be of quite unique character. (Total charged multiplicity ~100, total visible energy ~500 GeV, and mean angles of emission of hadrons ~20°–50°.) Observation of these low-energy, high multiplicity events should be quite feasible with an appropriately designed track chamber placed at appropriately high altitude. It is not known to us whether existing experiments rule out such phenomena.

As mentioned in the previous section, slower globs will not explode at all, and should find their way to sea level. With a flux of $\sim 10^3\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, an accumulation time ~$10^8$ yr, and a mixing depth ~100 m, this implies an average concentration of 10^3 globs/cm^3. The behavior of these globs in matter, because of their low charge, should be similar to that of stable, heavy hadrons carrying a new flavor quantum number. This possibility has been recently reviewed by Dover, Gaisser, and Steigman.[22] The above concentration of globs is not at all restricted by existing experiments.

If data do somehow restrict the flux of globs of energy less than Centauro energy, there does exist an avenue of escape. The glob should have a finite lifetime for spontaneous explosion. This process requires some kind of tunneling phenomenon, and even the logarithm of the lifetime would be difficult to estimate. However, if the lifetime is $\sim 10^6$ yr, then low-energy primordial globs will have decayed out, and the energy spectrum could be cut off at a point only slightly lower than the Centauro energy scale.

If the globs had their origins in the big bang, we might expect the presence of globs in ordinary matter at about the same ratio of globs to ordinary matter in high-energy cosmic rays, which is $\sim 10^{-2}$. This is clearly too large. The limits obtained from searches for stable heavy hadrons,[22] on the other hand, give no better limit than $\sim 10^{-10}$ for this ratio. The assumption of primordial globs and this small limit therefore suggest a finite lifetime $\lesssim 10^8$ yr and a cutoff in the low-energy primary spectrum of globs. Such a finite lifetime would not be required if the globs have their origins in phenomena which occurred subsequent to the big bang. We have no specific suggestion to make here; the problem of glob origin remains a serious one.

Finally, it is also of interest to see what changes occur if there exists a physical quark in the glob which helps to stabilize it, i.e., if the glob itself has fractional charge. The scenario of the Centauro event is essentially unchanged until the explosion occurs. Thereafter, the quark source, stripped of much of its nuclear matter but still possessing large rest mass, must continue to penetrate to sea level and eventually stop underground. The interactions of the residual quark with air nuclei will be not too different from the interactions of the glob.

We can expect a somewhat reduced cross section because of the smaller size, but a comparable energy loss $\Delta E/E$ per collision as for the glob. Thus the range of the quark at Centauro energies should be comparable to or larger than that estimated in Sec. III for the glob, $\sim(5-10)\times 10^3$ g/cm^2. The principal empirical consequences for this variant are the presence of quarks in matter at a concentration of $\sim 10^3$ cm^{-3} (as in the previous estimation for integer-charged globs) and the existence of an exotic component in the sea-level cosmic-ray flux. If the primary spectrum of globs extends downward into the TeV energy range, the flux of stripped globs would be $\sim 10^3$ m^{-2} sr^{-1} yr^{-1} at sea level. This is large enough that one might have expected them to have been detected. The characteristic signature is a particle of great penetrating power but producing large energy deposition by hadron production ($dE/dx > 1$ GeV/g cm^{-2}). We cannot cite one experiment that definitely rules out this hypothesis, but would not be surprised if somewhere it has already been performed.

Another constraint comes from data on horizontal air showers.[23] The rate for showers of size $>10^4$ and with zenith angle $>70°$ (corresponding to a depth >3000 g/cm^2) is comparable to the rate for Centauro events at Mount Chacaltaya. In equilibrium, the shower accompanying the stripped glob should have a size

$$N_e \approx \frac{\left(\dfrac{dE}{dx}\right)_{\text{glob}}}{\left(\dfrac{dE}{dx}\right)_{\text{electron}}} \sim \frac{\left(\dfrac{dE}{dx}\right)_{\text{glob}}}{2\ \text{MeV/g cm}^{-2}}\ . \qquad (20)$$

Thus to be observable, $(dE/dx)_{\text{glob}} \gtrsim 20$ GeV/g cm^{-2} or $E_{\text{glob}} > 60$ TeV. Guessing that about half the primary energy went to the stripped glob and the other half to the products of the Centauro explosion, this gives a predicted flux of (observable) horizontal showers $(1000/120)^{1.7} \sim 30$ times the Centauro flux. Thus it would appear that the hypothesis that a stable, heavy hadronic system emerges from the Centauro explosion (such as the stripped glob with a quark core) is difficult to reconcile with known data—unless for some reason the primary spectrum is cut off at energies not much lower than 10^3 TeV.

In Sec. II, we raised the extreme possibility that the most stable fractionally charged hadron had large N. In that case the Centauro event could be interpreted as fragmentation of a primary *proton* into "primeval" unconfined quarks of $|N| = \frac{1}{3}$. The nucleon fireball is then the decay products of these primeval unconfined quarks into globs of large baryon number N. Again in this case these globs would be expected to be quite heavy and to penetrate to sea level. However, now it is reasonable to have a production threshold $E \gtrsim 10^3$ TeV; hence the sea-level flux need not be greater than the flux appropriate for Centauro events themselves. Taking into account attenuation of primary protons in reaching the Chacaltaya altitude (a factor $\sim 10^2$), this would leave a flux of globs at sea level ~ 1 m^{-2} sr^{-1} yr^{-1}. There is still a problem with horizontal air showers. The compatibility with data is a complicated question and may require air shower simulations.

V. SUMMARY

We have sketched a hypothesis that the Centauro event is caused by a primary glob of highly dense nuclear matter or better, quark matter which is metastable and induced to explode into a multibaryon fireball by repeated collisions in the atmosphere. These explosions occur at a reasonably well-defined depth. If the primary flux extends to low velocities with the same spectral index as for proton primaries, then the rate of explosions should allow reasonably direct experimental searches for such events.

We also briefly sketched two variants of the idea involving the additional notion of the existence of heavy fractionally charged unconfined quarks. The first follows De Rújula, Giles, and Jaffe, and assumes an unconfined quark in the glob which might help compress the quark matter to the required high density. This leads to a quite possibly unacceptable flux of quarks at sea level, as well as a probably unacceptable rate of horizontal air showers.

The second variant, even more speculative, supposes the most stable unconfined quark has large baryon number. The Centauro would be fragmentation of a primary proton into unconfined primeval quarks, with subsequent decay (with multibaryon emission) into the most stable globs. The flux of such globs reaching sea level will be significantly reduced relative to the previous variant, but the problems with horizontal air showers remain.

All these considerations are extremely speculative. We entertain them mainly because the Centauro phenomenon appears so difficult to interpret in conventional terms.

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