Evidence for stabilized strange-quark matter in cosmic rays?

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Centauros, mini-Centauros, Geminion events, halo events, . . . are interpreted as manifestations of the formation of strange-quark matter in collisions of heavy primaries with the atmosphere. The experimental information is compatible with "conventional" ideas on formation and properties of quark matter as well as its stabilization in the form of strange matter.

In this article we propose a unified interpretation of abnormal cosmic-ray fireballs: Centauros, mini-Centauros, Geminion events, halo events, etc.[1] We argue that they have a common origin: the formation of stable or almost stable strange-quark matter in the collision of heavy cosmic-ray primaries with air nuclei near the top of the atmosphere. We show that their formation, propagation through the atmosphere and their experimental signature can be understood in terms of "consensus" ideas regarding the formation and properties of quark matter.[2] Although Centauro events have been previously associated[3–6] with the existence of quark matter, we demonstrate that their origin could be traced back to conventional air showers indiced by heavy primaries and is not necessarily astrophysical.[5] That is, one should not automatically conclude that they are part of the primary cosmic-ray beam,[4,6] e.g., as debris of neutron stars. If our scenario for anomalous cosmic-ray fireballs could somehow be confirmed by ongoing cosmic-ray experiments, it would add considerable impetus for the construction of heavy-ion colliders. It should be pointed out, however, that cosmic-ray experiments by their very nature would observe the phase transition to quark matter of the fragmenting nucleus[7] rather than its formation in the central region of the colliding nuclei studied by a collider.

For definiteness we discuss Centauro I, although one has to keep in mind that an event that spectacular could exhibit properties which have fluctuated far from their average value. The primary energy of the event producing Centauro I is estimated to be about 300 TeV. In this region the primary cosmic-ray beam definitely contains heavy nuclei,[8] although their exact abundance is still a matter of debate. According to present estimates[2] a heavy nucleus, e.g., Fe, colliding with an air nucleus would undergo a phase transition to quark matter. In the fragmentation region of the Fe nucleus a quark glob is formed which moves with Feynman $x_F \simeq 1$ down the atmosphere. There is some experimental support for this prediction. It has been argued that the fragmentation region of the 100-TeV Si-emulsion event observed by the Japanese-American cooperative emulsion experiment[8] (JACEE) exhibits indeed the signatures of a phase transition.[9] In general, the expectation that nuclei in this energy range form quark matter is more than a guess; various other hints in the data support this assumption.[10] If Centauro I is the result of a head-on Fe-air collision, the atomic number of the quark-matter glob is readily estimated on geometrical grounds to be $A \simeq 30$ (air has an average atomic number of 14). It has recently been estimated "that a significant fraction of quark droplets with A not too large may actually consist of strange-quark matter."[11] The increase of the ratio of net strangeness (S) to A,

$$f_s = \frac{S}{A}\ , \tag{1}$$

from its zero initial value is due to the fragmentation of u,d quarks near its surface into K,Λ particles. The estimates are based on ideas familiar in jet physics. Nonstrange u,d quarks near the surface are emitted from the colored plasma. The chromoelectric flux tube linking u,d quarks near the surface to the glob fragments into π's when the energy of the remaining quark has become less than $E_{\min}$. The remaining quark (not antiquark) retracts into the glob. Whenever this quark is strange rather than nonstrange, the net strangeness of the quark matter is increased. The probability that a quark glob has $f_s \gtrsim 0.5$ can be as large as 50%, especially when A is not too large (e.g., 30).[11] This point is central to our discussion. The substitution of u,d quarks by s quarks in the quark nugget reduces the Fermi pressure because of the exclusion principle operative between the nonstrange quarks. Thus stabilized strange globs can have very long lifetimes;[12] they are possibly stable in the ground state.[6] Such strange-quark nuggets formed near the top of the atmosphere can penetrate down to observation level and be the origin of abnormal cosmic-ray events. We discuss this next.

Our general picture is that strange-quark matter formed in the initial collision will immediately drop to its ground state with $T=0$ and then successively collide with air nuclei building up its atomic number from $A=30$ to 75 at observation level. As a result of this it becomes unstable and explodes. Current estimates for properties of strange-quark globs with $A=30$–75 are summarized in Table I.

We first analyze what happens when the glob collides with an air nucleus. Consider the collision in the rest frame of the glob. Again on the basis of geometric arguments the average number of air nucleons absorbed by the 2–3-fm glob is $\langle N_1 \rangle \simeq 2$–4. The nucleons's mean free path inside the quark matter is small (0.27 fm) and it will therefore traverse the glob as three independent quarks

TABLE I. Properties of Centauro-like glob.

$f_s = \frac{S}{A}$	1
$(f_s)_{\text{critical}}$	0.5
Number of quarks density[a] ρ	(2—3)/fm^3
$\lambda_q = 3\lambda_N$	0.81 fm
Mean free path of quark[b]	
A	30—75
R[c]	2—3 fm
E_0	$\simeq A m_\Lambda$

[a](1.5—2) times the density of quarks in a nucleon.
[b]Using ρ and $\sigma_{qq} = \frac{1}{3}\sigma_{qN} = 10$ mb.
[c]Using $\frac{4}{3}\pi R^3 = 3A\rho$.

with mean free path 0.8 fm. Each quark will therefore interact $\langle N_2 \rangle = 3$—4 times. These features are collected in Table II. As Centauro moves down the atomosphere with 300 TeV, the quarks colliding with the glob move nearly upward in its rest frame. They will be emitted as jets at the surface. The number of quarks emitted we crudely estimate as the number contained in the cylindrical volume of a glob traversed by N_1 nucleons of radius $R_N = 0.8$ fm and total interaction length

$$l = \lambda_N + N_2 \lambda_q \ . \tag{2}$$

That is, we just calculate the number of quarks contained in the intersection volume of the glob and the upwards-moving air nucleons. So the number of ejected quarks per collision is

$$n = (l\pi R_N{}^2 \rho + 3) N_1 \ . \tag{3}$$

Here ρ is the number density of quarks given in Table I corresponding to a few times that of quarks in a nucleon.

TABLE II. Traversal of the atmosphere. Example is for Centauro I—type glob traversing 500 g to Chacaltaya chamber.

A	30—75
N_1	2—4
Number of air nucleons absorbed per collision	
N_2	3—4
Number of collisions of quark inside glob	
Number of collisions with atmosphere	10—15
$\Delta f_s = \Delta \left[\frac{S}{A} \right]$	small
per collision	
ΔA	2—4
per collision	
n	30—80
Number of q jets emitted per collision	
$\langle E_{\min} \rangle$ average	0.6 GeV
for π's	0.2—0.4 GeV
for K's	0.5—1 GeV

Therefore, using Tables I and II, $n \simeq 35$ (70) for $A = 30$ (75).

What are the important effects of each encounter of the glob with an air nucleus? The quark jets emitted from the surface fragment. As discussed before, when the flux tube is fragmented down to $E_{\min} = 0.2$—1 GeV (depending on the quark flavor), the remaining quark retracts in the glob, thus increasing its energy. The energy after collision is

$$E = nE_{\min} + E_0 \tag{4}$$

with the ground-state energy

$$E_0 \simeq \left[A - \frac{n}{3} \right] m_\Lambda \ .$$

Furthermore, the baryon number of the glob is on the average increased by N_1, the number of air nucleons absorbed. The strangeness will increase somewhat due to emission of quarks originating from the air nucleons. Quarks emitted from the glob will be strange, say, $\frac{1}{3}$ of the time; this loss in S should be roughly compensated by the increase of S due to the fact that roughly $\frac{1}{3}$ of the emitted quarks will increase S, as previously discussed. There is however a net increase of S due to the $3N_1$ air quarks fragmenting about $\frac{1}{3}$ of the time as a strange particle left inside the glob. Overall the change in $f_s = S/A$ in a collision should therefore not be very large, as both numerator and denominator increase proportional to N_2. We will see further on that these conclusions are compatible with the observed properties of Centauro events.

Now we tackle the final question: when and how will the glob explode? We discuss the stability of the glob on the basis of the bag model.[12] Figure 1 shows the ground-state energy as a function of the radius R for a given A. There is an energy barrier of height E^* at $R = R^*$. If in a collision $E < E^*$ [E is given by Eq. (4)], the quark matter will return to its $T = 0$ ground state and then contract to $R = R_0$, e.g., by rearrangement. If, however, $E \gtrsim E^*$, the glob will expand from $R = R_0$ to $R = R^*$ and

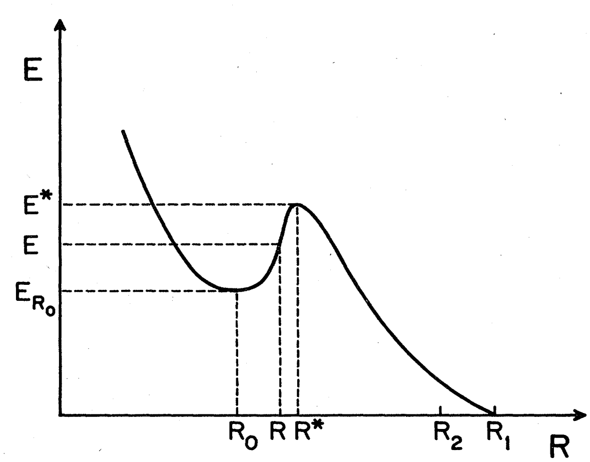

FIG. 1. Sketch of the ground-state energy of stabilized quark matter as a function of the radius R of a quark glob.

then "explode" to $R = R_1$ with large acceleration in the radial direction due to the decrease of "potential energy." At $R = R_1$ the initial energy E will become radial energy of the quarks; this is the origin of the anomalously large transverse momentum of Centauro events. In this picture the barrier energy E^* should therefore be closely related to the energy E reached in the ultimate collision when the glob explodes, i.e.,

$$E \gtrsim E^* , \qquad (5)$$

where E is given by Eq. (4). In previous interactions $E < E^*$ and the glob returns to its new ground state and continues its path down the atmosphere.

The energy E of the glob, calculated from Eqs. (2)—(4) and Tables I and II, is shown in Fig. 2 as a function of A. We took an average value of $E_{\min}$, $\langle E_{\min} \rangle = 0.6$ GeV. This is a nominal value between 0.2—0.4 GeV, the cutoff energy to produce π fragments, and 0.5—1.5 GeV required to produce K's or Λ's. The corresponding value of E^* can be obtained from the data; it is the energy released in the last collision and can be reconstructed from the observed Centauro events,

$$E^* = [\langle p \rangle^2 + M_\Lambda{}^2]^{1/2} A \qquad (6)$$

with

$$\langle p \rangle \sim (\tfrac{3}{2})^{1/2} \langle p_T \rangle \; . \qquad (7)$$

E^* is shown as a function of A for the Centauro events using as input in Eqs. (6) and (7) the $\langle p_T \rangle$ and the multiplicity of tracks ($\simeq A$) measured.[1] Notice that all observed events fall in the intervals

$$A < 21 \; , \quad A > 63 \; . \qquad (8)$$

In our picture this must indicate that somehow the energy barrier E^* is very large for $20 \lesssim A \lesssim 60$, and that the quark nuggets in this E range cannot be destabilized in collision.

Calculations in the general framework of the MIT bag model show that strange-quark matter can be stable for a wide range of values of the strange-quark mass, the bag constant, and the strong coupling α_s [see Fahri and Jaffe (Ref. 12)]. The same calculations suggest that strange-quark matter is stable in nuggets provided $A > A_{\min}$, where $A_{\min}$ can be as low as 10 within the range of parameters. This is consistent with our observations. In the bag model the likelihood of finding stable nuggets with smaller A is reduced; the increased binding in $20 < A < 60$ range is therefore difficult to account for. In the region $A \simeq A_{\min}$ realistic calculations even in the context of the bag model are however difficult. Alternatively the absence of events in this region could just be a reflection of the low statistics of the data. In the bag model quark nuggets are neutral in the flavor symmetric limit that the numbers of u, d, and s quarks are equal. The nonzero mass of the strange-quark results in a positive charge with Q/A rather small. The nuggets will therefore not interact very strongly with ordinary matter. We discuss this further on.

We can now reconstruct the history of Centauro I and check if it is consistent with its observation just above the Chacaltaya chamber. As argued earlier, it is produced at the top of the atmosphere with $A \simeq 30$. So its size is 2 F (but increases to 3 F when $A \simeq 75$) and it will interact on the average 12 times in 500 g of atmosphere.[4] In each interaction the atomic number A increases by 3.2 so that at observation level $A \simeq 75$. We here used the estimates of Ref. 4 for the mean free path of a glob of size 2—3 fm for $A = 30$—60. In successive collisions the energy E (increasing with A) fluctuates around the value shown in Fig. 2. The glob only explodes when A comes close to 70 where E is not much smaller than E^*; see Fig. 2. Fluctuations are of course large, as both N_1 and N_2 fluctuate around their average values shown in Table II. Using Eqs. (2)—(4), we compute that E is indeed 125 GeV from $E_{\min} = 0.5$—0.6 GeV provided $N_1 = 9$—12. So Centauro I exploded because in the last collision more than $\langle N_1 \rangle = 4$ air nucleons were absorbed. This value agrees with the "measured" value computed from Eqs. (6) and (7) shown in Fig. 2. No π^0 or other mesons are produced in the expansion from $E \simeq E^*$ since the temperature of the glob is zero at $R = R^*$. Even if π mesons would be produced in an expanding nugget cooling in hydrodynamic equilibrium, they are likely to be reabsorbed and the final pion yield will again be very small.

Mini-Centauros are produced by the same mechanism, but their parent collision being less central or the incident nucleus being less heavy (e.g., C, N, O), their original A value at the top of the atmosphere is much less than 30 and they can fluctuate to critical energy E^* in the small-A region of Fig. 2. Using the same procedure as for Cen-

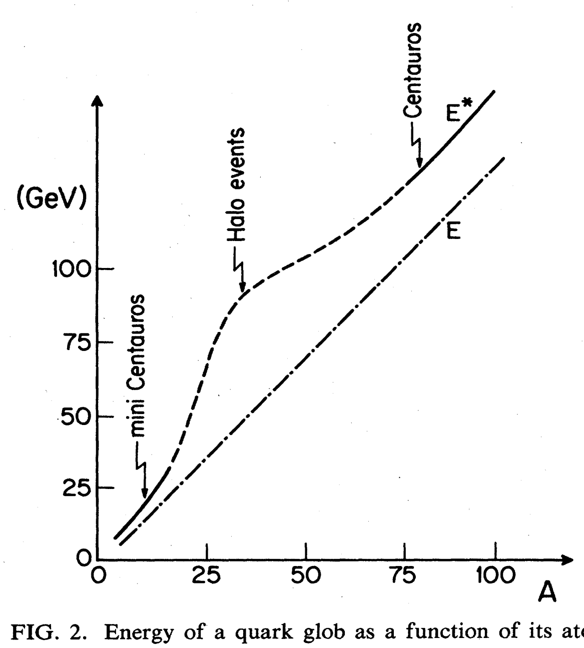

FIG. 2. Energy of a quark glob as a function of its atomic number A calculated according to Eqs. (2)—(4) and Tables I and II (dash-dotted line). Energy of the observed mini-Centauro and Centauro events calculated from their measured $\langle p_T \rangle$ and A values using Eqs. (6) and (7) (solid curve). Speculation for the increased binding energy in the $20 < A < 60$ range (dashed curve).

tauro I, we calculate $E \simeq E^* \simeq 12$ (24) GeV for mini-Centauros with $A = 8$ (17), which agrees with observed values 12 (28) GeV calculated from their $\langle p_T \rangle$ and multiplicity.[1] The extra π^0's observed in these events could have various origins, e.g., E could have fluctuated significantly above the barrier energy E^*. Alternatively, some of the released potential energy could go into particle production if their final radius R_1 is slightly larger than the radius R_2 where transition to hadronic matter occurs.

What happens to globs which remain stable in the $A = 20-60$ range? They reach the detector and penetrate the hadron block and x-ray films of the detector. The attenuation from layer to layer would be very small, as a glob with energy 10^2-10^4 TeV loses at most a small fraction of its energy in each collision. It is accompanied by a halo of particles due to the large number of jets emitted in each collision with the atmosphere before reaching the detector. As previously described, several tens of quark jets are emitted in each of some ten collisions. Such events have been observed by several groups;[1] the halo is of order 1 cm and does exactly reflect the $\langle p_T \rangle \simeq 0.6$ GeV of the jets which are emitted in collisions at different depths.

Finally, let us remark that our picture predicts delayed events at an observable ratio. Binocular events,[1] which have been difficult to accommodate into the standard framework of QCD high-p_T jet production, could be the result of the fission of the globs described in this paper. The observed multiple halo events would obviously fall in the same category.

We previously noted[5] that the pattern of anomalies observed in cosmic-ray interactions above 100 TeV is very suggestive of quark-matter formation by heavy primaries. The theoretical observation that quark matter could be stabilized in its strange form solves the basic problem that some manifestations of quark matter are observed deep in the atmosphere. These anomalous fireballs in emulsion show indeed features of strange-quark matter.

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