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ARE CENTAURO EVENTS A MANIFESTATION OF AN UNUSUAL TYPE OF PHASE TRANSITION?*

by

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SUMMARY

We argue that the Centauro events found in cosmic rays by the brazilian-japanese collaboration could be the manifestation of an unusual phase transition in which a new ordered phase of quarks separated from antiquarks takes place at extremely high densities. This new phase should then be followed by yet another disordered phase which might correspond to freeing the quark components.

Key-words: Centauro; Phase transition; Cosmic rays.

It is now over ten years since the brazilian-japanese collaboration working at Chacaltaya first reported a Centauro event[1] but its origin still remains quite mysterious in spite of the many hypotheses that have been put forward to explain it[2,3,4,5]. Whereas more experimental evidence keeps accumulating from cosmic ray data[6,7], no direct confirmation from high energy accelerators has yet been obtained[8]. This suggests that these events may indeed be of a totally different nature from the usual hadronic interactions (but clearer evidence should soon come from the Fermilab Teratron).

Let us briefly recall that the most relevant property of Centauro events is the appearent lack of π^0's from the hadronic shower in which they materialize. Barring the possibility of a gigantic breaking of charge symmetry, the absence of π^0's entails the absence of mesons altogether, so that one is led to conclude that the hadrons in which the Centauros decay are just baryons (and/or antibaryons).

This conclusion would tend to favor such conjectures as that by Bjorken and McLerran[2] suggesting that the primary object initiating the collision is a glob of nuclear matter of ultrahigh density[9].

From the fact that $\langle p_t \rangle$ is $\sim 3-5$ times larger than the values typical of a nucleus, one expects a density $\sim 30 - 100$ times that of ordinary nuclear matter with the glob radius $3-5$ times smaller than that of an ordinary nucleus.

The speculation that this glob should be made of quark matter is then exploited in ref. 2 to account for the Centauro properties.

Assuming, however, as it seems likely, that the glob was formed subsequent to the big bang, "...the problem of glob origin remains a serious one..."[2].

In this paper we do not wish to address ourselves the question of under what conditions of unusually high density the glob may be formed, but simply ask ourselves whether or not it is at all conceivable that globs of superdense quark or antiquark matter may be formed after the QCD transition from ordinary hadronic to quark matter has already taken place[10]. In a nutshell, our suggestion is the following: under extreme conditions of superhigh densities, the quark-antiquark phases may separate and the ensuing "ordered" phase may have a lower energy than the disordered one where the quarks and the antiquarks coexist. If this is the case, we are back to case one (i.e. to ref. 2) and the quark glob can be the initiator of a Centauro event in which baryons only are produced.

It should be stressed that the phase transition we are envisaging here, has nothing to do with the usual phase transition of QCD leading from hadronic to $q\bar{q}$ matter[10]. The latter is credited to lead to a quark-gluon plasma whose density, 5 to 10 times the one of nuclear matter, is still almost an order of magnitude smaller than the one we are considering here. In our case, we believe we are working in a situation when the quark-antiquark phase has already established itself and we are considering the possibility that a further separation of these two components (quarks and antiquarks) may occur, with increasing densities. For this reason the QCD coupling constant is not likely to play anymore the role of temperature in our case since the hadronic phase has already disappeared and asymptotic freedom is already at work (unless, of course, we imagine that we go beyond QCD over to the scenario when quarks themselves are composite).

The questions behind such a conjecture are many and varied. Just to list a few: i) if a phase transition occurs, what is the equivalent of the free energy in terms of which this occurrence is usually studied? ii) what is the equivalent of the intensive parameter (as for example the temperature), which is variated to obtain the phase transition? iii) what plays the role here of the "order parameter"? Last but certainly not least, how can we implement such a picture as to make it a working one?

Clearly, we can not give any rigorous answer to these questions but we may try to give at least plausible and partial answers.

We visualize the process under discussion as follows: imagine more and more energy is pumped in a finite volume (typically the volume of a hadronic interaction or, more likely, of a glob). As we pass from the hadronic to the quark phase, an extremely dense soup of quarks *and* antiquarks (and of gluons, of course) is created. Until the total density $\rho_q + \rho_{\bar{q}}$ (where ρ_q and $\rho_{\bar{q}}$ are the quark and antiquark densities) is not exceedingly higher than that at which the transition to quark-antiquark phase occurs (i.e. until the density is of the order of 5 to 10 times that of nuclear matter), we may expect an "ordinary" behavior when this energy is finally released, i.e. mostly an evaporation of $q\bar{q}$ pairs (mesons) as the soup cools off. This situation when q's and $\bar{q}$'s coexist will be called the desordered phase.

The question is now the following, suppose we keep increasing $\rho_q + \rho_{\bar{q}}$. Is it then at all possible that for densities 30 - 100 times greater than the ordinary nuclear matter the two components, quarks and antiquarks, separate giving rise to what we call the ordered phase? In case we can give a positive answer, in the ordered phase only baryons on the one hand and antibaryons on the other hand can be produced which would thus lead to a natural explanation of Centauro events.

Assuming the free energy to still be a relevant variable to deal with, it seems inescapable that the role of the temperature T must be played by some increasing function of the energy density $T = h(\varepsilon)$.

The order parameter η can then, most naturally, be taken to be

$$\eta \propto \rho_q - \rho_{\bar{q}} \tag{1}$$

Strong support to our conjecture would follow if we could give a positive answer to the following question: do we know of any example in which the ordered phase occurs at some temperature *higher* than the desordered phase and, if yes, how can this be described in the conventional language of phase transitions? The answer to the first part of the question is indeed yes, we have examples of the above kind in nature but, most interesting, this can occur only if, *by increasing further the temperature, a further new disordered phase follows the ordered one.*

One such example is provided by the compound $KNaC_4H_4O_6 \cdot 4H_2O$ known as the Rochelle salt.

If our series of conjectures is at all realistic, we should then expect the following picture: At "low" (ordinary nuclear matter) densities, mostly mesons are produced; as we increase the temperature, a quark gluon plasma is formed whereas at even higher temperatures the most favourable state becomes the one in which the quarks separate from the antiquarks and the globs of ref. 2 are produced; as a consequence, only baryons and antibaryons can then be emitted. As we further increase the temperature, however, the desordered phase takes over once again and, presumably, ordinary emission occurs as this soup releases its energy. This last phase could be related to a possible compositeness of the quark themselves.

The above picture may be the long sought explanation of why Centauros not only are so rare events but are also reported[1] to occur in a sort of quantized way (minicentauros with a total c.m. energy of $\sim$ 30 - 40 GeV and Centauros with a total c.m. energy of $\sim$ 300 GeV) and why much higher energies cosmic ray events have not provided any indication of Centauro-like patterns.

Let us now quickly discuss the mathematical aspects of how the previous scenario could work.

Let the free energy be $F(T,\eta,\{\mu\})$ where T is the temperature, η is the order parameter (1) and $\{\mu\}$ denotes all other macroscopic parameters of the system besides T.

Given our assumptions, F must be an even function of η (so that, to a pure quark phase there may correspond a pure antiquark phase). In this case, F can be expanded as

$$F(T,\eta,\{\mu\}) = F_o(T,\{\mu\}) + F_1(T,\{\mu\})\eta^2 + F_2(T,\{\mu\})\eta^4 + \ldots \qquad (2)$$

As a function of T, the system will have to be in a minimum of $\Delta F \equiv F - F_o$ and ΔF will have to be limited in η for reasons of stability. Thus, if we keep only terms up to the order η^4, F_2 must be positive (for all values of T and $\{\mu\}$) whereas F_1 can either be positive or negative. Usually, following Landau[11] one parametrizes most simply F_1 as

$$F_1(T,\{\mu\}) = A(\{\mu\})(T - T_c) \qquad (3)$$

(with $A>>0$) so that F_1 wil be > 0 or < 0 according to whether T is above or below the critical temperature T_c. When $T > T_c$ the minimum is for $\eta = 0$ but when $T < T_c$ there are two symmetrical minima (symmetry $\eta \to -\eta$) located at $\eta = \pm(A(T_c - T)/F_2]^{1/2}$.

The linear choice (3) in T, however, does not suffice to mimick the situation we are interested in since it gives rise to the situation of Fig. 1a whereas within our description of a Centauro event we expect something like Fig. 1b i.e. from a disordered phase we move to an ordered phase followed by yet another desordered phase.

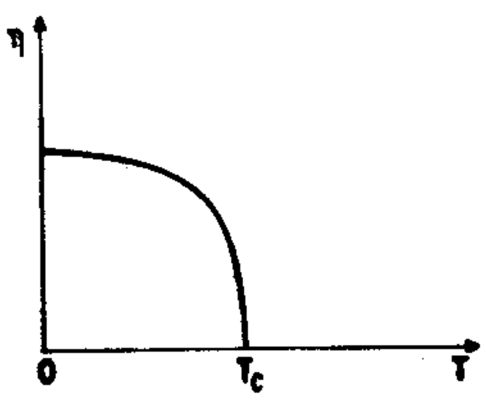

FIG.1a

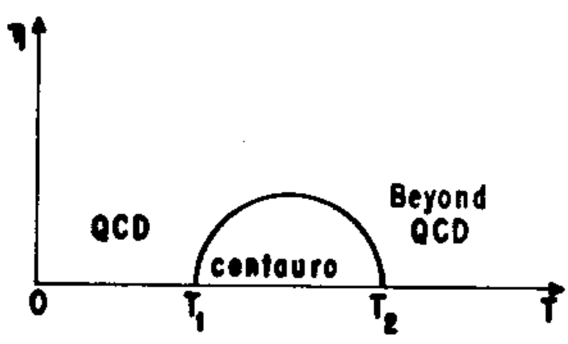

FIG.1b

Thus, we must have $F_1(T)$ at least quadratic in T (Fig. 2)

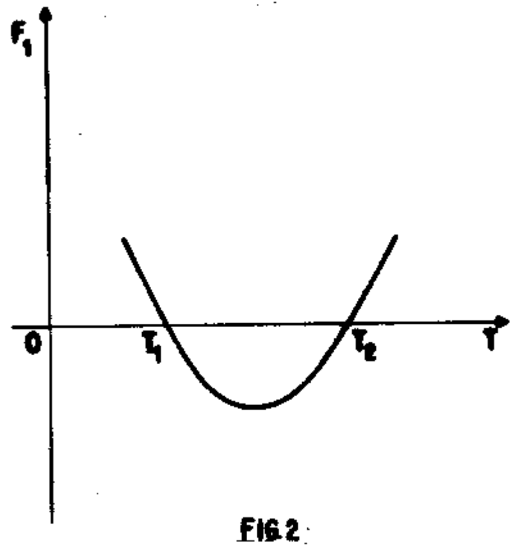

FIG.2

The above picture, unfortunately, has rather limited predictive power or, rather, its predictive power is exactly that something like Centauro events should be seen if the picture is qualitatively correct i.e., first one should see mostly mesons (and a few baryons) produced; at increasing densities there should come a point when essentially only baryons are produced and then, at even higher densities, we expect the production of mesons to take over again. Differently stated, Centauro events should be a transient phenomenon confined between two temperatures T_1 and T_2 but unfortunately we have no way to determine how narrow is this window $T_2 - T_1$. Whether the new disordered phase is related to freeing the quark constituents themselves, remains open to speculation.

Even more complicate situations can be imagined like, for instance, an abrupt increase of the order parameter (first order transition) in which case there would be a region of temperatures where the two phases coexist and both mesons and baryons are produced with comparable abundance. The above complication would demand the expansion (2) to go up to terms η^6 with F_3

positive (for reasons of stability) and F_1 , F_2 of either sign. Convenient choices of functions for F_1 and F_2 could produce an order parameter of the kind of Fig. 1b (but discontinuous).

In conclusions, we have proposed a general scheme in which the production of Centauro events finds a most natural explanation. Even though the main prediction we can make remains that Centauro-like events should occur, within our scheme we also predict[12] that increasing further the density above the Centauro level, these events should not be found anymore; in spite of its being so little predictive, at this stage we consider our scheme very intriguing since it raises many interesting questions. We thus believe that it deserves being further investigated in the many contexts we have merely touched upon such as establishing a better link with the various thermodynamical quantities. It is at present quite unclear to us whether the scheme proposed requires a departure from QCD and whether it could be the very first indirect manifestation of quark compositeness. We hope to return to this questions in a near future.

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12) We can expect there should be an interval in the energy range where both mesons and baryons are produced at a comparable rate if a first order transition occurs.