

## SU(2) x U(1) VACUUM AND THE CENTAURO EVENTS

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## ABSTRACT

We propose that the "fireballs" invoked to explain the Centauro events are bubbles of a metastable superdense state of nuclear matter, created in high energy ( $E \sim 10^{15}$  eV) cosmic ray collisions at the top of the atmosphere. If these bubbles are created with a Lorentz factor  $\gamma \approx 10$  at their CM frame, the objections against the origin of these events in cosmic ray interactions are overcome. A relationship then between their lifetime,  $\tau$ , and the threshold energy for bubble formation,  $E_{th}$ , is derived. The minimum lifetime consistent with such an interpretation is  $\tau \sim 10^{-8}$  sec, while the  $E_{th}$  appears to be insensitive to the value of  $\tau$  and always close to  $E_{th} \sim 10^{15}$  eV. Finally it is speculated that these bubbles might be manifestations of the SU(2) x U(1) false vacuum excited in these collisions. The absence of  $\pi^0$ 's in the Centauro events is then explained by the decay modes of these excitations.

1. Introduction. The Centauro, events (Lattes et al. 1973) are high energy  $\approx 10^{15 \pm 1}$  cosmic ray events detected in nuclear emulsion chambers at high altitudes ( $> 4000$  m) with characteristics which defy explanation in terms of "standard" high energy cosmic ray collisions and subsequent cascading of the produced particles. The characteristics which set these events apart from the typical events expected at these energies ( $\approx 10^{15}$  eV) are the following:

- a. They are observed deep in the atmosphere ( $\approx 500$  g cm $^{-2}$ ), only a few hundred meters above the emulsion chamber detector.
- b. They have very high multiplicity.
- c. They have very large mean transverse momentum,  $\langle P_t \rangle$ , 3-5 times larger than that of a typical nuclear fragmentation interaction.
- d. There is a deficiency of neutral pion production.

Direct nuclear collisions fail to account for any of the above features, especially for the observed rate,  $R \approx 10^{-2}$  m $^{-2}$ sr $^{-1}$ yr $^{-1}$ , since the probability of penetration of strongly interacting particles to such depth is negligible. It was pointed out though, that most of the above features (multiplicity,  $\langle P_t \rangle$ ), could be accounted for in terms of the explosive decay of an unknown state of matter. Bjorken and McLerran (1979) postulate a new metastable form of quark matter, introducing a new component in the cosmic ray spectrum, while Kinnunen and Rubbia (1981) argue that these events cannot be due to high energy cosmic ray interactions, thus in effect agreeing with the previous authors. In the present note we accept the interpretation of the Centauro events as the explosive decays of an unknown yet high energy particle deep in the atmosphere. However, contrary to the previous treatments, we relate the Centauro flux to the flux of high energy cosmic ray particles at the top of the atmosphere, thus avoiding the introduction of a new, unknown component in the primary cosmic ray spectrum. Then, the requirement that Centauros are

due to the explosive decay of a bubble of a metastable superdense nuclear matter, produced in a high energy collision on the top of the atmosphere, leads to a relation between the formation of such a metastable state and to its lifetime. This is done in the next section.

2. The Centauro Event Rate. In relating the Centauro rate to that of high energy cosmic ray interactions, we shall assume that a large fraction of high energy cosmic rays have interacted within  $50 \text{ g cm}^{-2}$  from the top of the atmosphere, which sets the interaction height to about 21 km. Given that the Mt. Chacaltaya detector is at a depth  $\sim 500 \text{ g cm}^{-2}$  or a height of  $\sim 6 \text{ km}$ , the bubbles of metastable matter will have to traverse a distance of about 15 km before they decay. We further assume that any decay at a distance  $d_L > 100 \text{ m}$  from the detector does not classify as a Centauro event, because the ensuing cascade will not have the characteristics of a Centauro (i.e. closeness to the detector, few  $\pi^0$ 's). Then if  $\tau_0$  is the lifetime of the bubble and  $\gamma_L$  its Lorentz factor in the laboratory frame, the decay rate of bubbles as a function of time after the interaction will be

$$N(t) = N_T e^{-t/\gamma_L \tau_0} \quad (1)$$

or in terms of the distance  $d$  from the high energy interaction point,

$$N(d) = N_T e^{-d/c\gamma_L \tau_0} \quad (2)$$

Where  $N_T$  is the rate of bubble production at the top of the atmosphere. Then the differential rate with respect to the pathlength  $d_l$  within which decays are identifiable as Centauro events is

$$\frac{dN(d)}{d_l} = \frac{1}{c\gamma_L \tau_0} N(d)$$

and the Centauro event detection rate should be

$$R = \frac{d_l}{c\gamma_L \tau_0} N_T e^{-d/c\gamma_L \tau_0} \quad (3)$$

Solving this relation for the rate of events at the top of the atmosphere,  $N_T$ , one obtains

$$N_T = R \frac{\gamma_L^c \tau_0}{d_l} e^{d/c\gamma_L \tau_0} \quad (4)$$

Since we expect the formation of bubbles to have a threshold energy  $E_i$ ,  $N_T$  should be the integrated cosmic ray flux at the top of the atmosphere with  $E > E_i$  or

$$N_T = \eta K E_i^{-1.7} = \eta 1.1 \cdot 10^4 E_i^{-1.7} \text{ m}^{-2} \text{ Sr}^{-2} \text{ S}^{-1} \quad (5)$$

with  $E_i$  measured in GeV. The factor  $\eta$  denotes the fraction of these events that produce bubbles of metastable nuclear matter, which we will presently assume to be of the order of 1 ( $\eta \approx 1$ ). If  $M_b$  is the mass (rest energy) of the bubble and  $E_b^*$  its CM energy then its Lorentz factor in the interaction CM frame will be

$$f = E_b^*/m_b$$

Hence the Lorentz factor of the CM will be  $\gamma_{CM} = \left(\frac{E_i}{2m_p}\right)^{1/2}$ . Consequently the Lorentz factor of the bubble in the laboratory frame,  $\gamma_L$ , will be

$$\gamma_L = \frac{E_{b,lab}}{M_b} = \gamma_{CM} f + (\gamma_{CM}^2 - 1)^{1/2} \cdot (f^2 - 1)^{1/2} \cos\theta^* \approx f \left(\frac{E_i}{2m_p}\right)^{1/2} \quad (6)$$

Substituting equations (5) and (6) into equation (4) and solving for  $E_i$  we obtain the transcendental equation

$$E_i = \left[ \frac{1}{n\kappa} \frac{R}{dl} \cdot \left(\frac{E_i}{2}\right)^{1/2} f \tau_0 \exp(d/c \left(\frac{E_i}{2}\right)^{1/2} f \tau_0) \right]^{-0.59} \quad (7)$$

where  $R = 10^{-2} \text{ m}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$  is the Centauro event rate,  $dl = 10^4 \text{ cm}$ ,  $d = 15 \text{ km} = 1.5 \times 10^6 \text{ cm}$ ,  $\kappa$  is defined by equation (5), and  $m_p$  has been taken as 1 GeV. Substituting the numerical values equation (7) reads

$$E_i = \left[ \frac{1}{n} 5.68 \times 10^8 E_i^{1/2} f \tau_0 \exp(7.07 \cdot 10^5 / E_i^{1/2} f \tau_0) \right]^{-0.59} \equiv F(E_i, \tau_0)$$

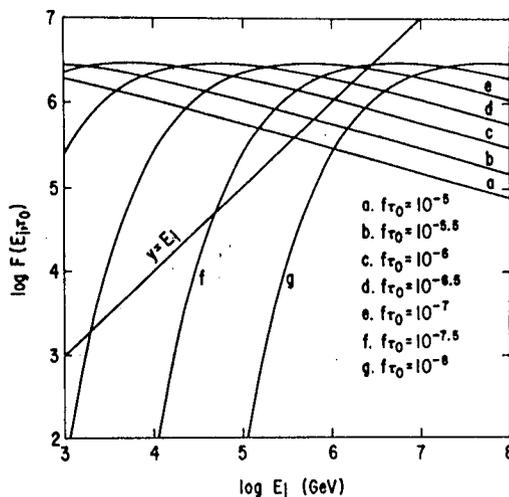


Figure 1

Equation (7a) can be solved graphically by plotting the curves  $y = E_i$  and  $y = F(E_i, \tau_0)$ . The results are shown in figure 1 where the families of curves  $F(E_i, \tau_0)$  are shown as a function of  $E_i$  with  $\tau_0$  as a parameter. One can distinguish two major features: (i) For sufficiently small values of the parameter  $\tau_0$  ( $< 10^{-8}$ ) no solution to equation (7a) exists. This means that for sufficiently small bubble lifetimes ( $\tau_0 < 10^{-8}$ ) not enough of them will survive deep enough in the atmosphere to account for the observed Centauro flux, (ii) For  $\tau_0 > 10^{-8}$  there are always two solutions to equation (7a) since the curve  $y = E_i$  intersects the curve  $y = F(E_i, \tau_0)$

at two points. It is interesting to note that of these two solutions the highest ones are always close to an energy  $E_i = 10^6 \text{ GeV}$  for a wide range of values of the parameter  $\tau_0$ , ( $10^{-6} - 10^{-8}$ ), which corresponds to a CM energy of  $\approx 1 \text{ TeV}$ .

One can of course assume that the increased penetration is due to the smaller cross section of the "bubble". The difference in heights between 21 km (where presumably the metastable state forms) and 5 km where the fireball occurs and corresponds to  $\sim 500 \text{ g cm}^{-2}$  or a cross section  $> 10$  times smaller than that of strong interactions. This corresponds to a linear dimension  $> 3$  times that of a proton and hence a  $P_t \gtrsim 3$  times that of strong interactions as indeed observed.

The assumption that the bubbles of the superdense metastable nuclear

state are produced with a certain kinetic energy at the CM of the collision can actually sidestep the arguments of Kinnen and Rubia (1981) against the origin of Centauros in high energy cosmic ray collisions. The latter authors have concluded so by noting that the kinematics of the Cenaturo event demand  $\gamma \approx 10^4$  and  $M_{\text{fireball}} \approx 200$  GeV. Assuming further (as they did) that all the primary energy goes into making the rest mass energy of the fireball (i.e.  $\gamma = \gamma_{\text{CM}}$ ), they derived from the latter figures a primary energy  $E_i \approx \gamma_{\text{CM}}^2 M_{\text{fireball}} \approx 10^{17}$  eV. The flux of cosmic rays at these energies is much too low to account for the observed Centauro rate. Eq. (6) however shows that if the bubble is created in the CM frame with a Lorentz factor  $f \approx 10$  then  $\gamma_i = 10^4$  implies  $\gamma_{\text{CM}} \approx 10^3$  and hence a primary energy  $E_i \approx 10^{15}$  which provides sufficient flux to account for the observed rate.

3. Discussion - Conclusions. The next question one is called to answer is the nature of these "fireballs". (See Kazanas et al. 1984). We consider the possibility of the SU(2)xU(1) vacuum as a means for producing these "fireballs". At the restoration of the symmetry there is a contribution to the energy density from the SU(2)xU(1) vacuum. The total energy density,  $\epsilon$ , is then

$$\epsilon = An^{4/3} + \rho$$

The first term is the energy density due to the quarks participating in the collision (assumed to be cold) and the second term the energy density of the vacuum. The pressure of the mixture can then be calculated using the thermodynamic relation

$$P = n \frac{d\epsilon}{dn} - \epsilon = \frac{1}{3} An^{4/3} - \rho$$

One can now observe that for  $An^{4/3} \approx \rho$  (i.e. close to the phase transition point) the pressure of the mixture goes to zero and the medium becomes unstable to bubble formation. It is assumed that at  $T \approx T_c$  the two phases with  $\langle \phi \rangle = 0$  and  $\langle \phi \rangle \neq 0$  coexist since the height of the barrier between them is smaller than the thermal energy for  $T > T_c$  (Sher and Flores 1983). Neglecting surface effects, the bubbles are in pressure equilibrium between the positive particle pressure and the negative vacuum tension. The bubbles should therefore decay primarily into Higgs particles. It has been suggested (Willey 1984) that the particle  $\xi(2.2)$  observed in the decay  $J/\psi \rightarrow \gamma + \xi(2.2)$  might be the Higgs boson. Such an identification would indeed fit the signatures of the Centauros. A  $\sim 100$  GeV bubble would decay into  $\sim 50$  Higgs and subsequently into  $\sim 100$  KR ( $\xi(2.2) \rightarrow RK$  dominantly). These K's would have  $P_t \sim 1$  GeV and would explain the absence of  $\pi^0$ 's. Also only explosions close to the detector would classify as Cenaturos since for  $dL > 300$  m the K's would have a chance to decay into  $\pi^0$ 's, and then into photons.

#### 4. References

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