General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA

Technical Memorandum 86082

SU(2) X U(1) VACUUM AND THE CENTAURO EVENTS

D. Kazanas
V. K. Balasubrahmanyan
R. E. Streitmatter

APRIL 1984

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

D. Kazanas[1,2], V. K. Balasubrahmanyan[2]

and

R. E. Streitmatter[2]

[1]Dept. of Physics and Astronomy, U. of Maryland, College Park, MD. 20742
[2]NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD. 20771.

ABSTRACT

We propose that the "fireballs" invoked to explain the Centauro [1] 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 $\gamma \simeq 10$ at their CM frame, the objections against the origin of these events in cosmic ray interactions are overcome. Assuming further, that the Centauro events are due to the explosive decay of these metastable "bubbles", a relationship between their lifetime, τ, 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 τ and always close to $E_{th} \sim 10^{15}$ eV. Finally it is speculated that if the available CM energy is thermalized in such collisions, these bubbles might be manifestations of excitations of the SU(2) x U(1) false vacuum. The absence of π^{o}'s in the Centauro events is then explained by the decay modes of these excitations.

Introduction

The Centauro, [1] mini-Centauro and other "unusual" cosmic ray events (Chiron, Geminion) are high energy ($\approx 10^{15\pm1}$ eV) 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 [2]. We presently focus our attention on the so called Centauro events which have been the subject of controversy over many years. 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 (≈ 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.

It was immediately realized that direct nuclear collisions failed 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 probabilty of penetration of a strongly interacting particle to such depths is negligible. It was also pointed out though, that most of the above features (multiplicity, $\langle P_t \rangle$) as well as those of other "unusual" events [3], could be accounted for in terms of the explosive decay of an unknown state of matter. Bjorken and McLerran [4] for instance, postulate a new metastable form of quark matter, introducing a new component in the cosmic ray spectrum, while Kinnunen and Rubbia [5] 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.

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 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 g cm^{-2} or a height of $\sim$ 6 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 dL > 100 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 π^{o}'s). Then if τ_0 is the lifetime of the bubble and γ_L its Lorentz factor in the laboratory frame, the decay rate of bubbles as a function of time after the interaction will be

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

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

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

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

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

and the Centauro event detection rate should be

$$R = \frac{dl}{c\gamma_L \tau_0} N_T e^{-d/c\gamma_L \tau_0} \tag{3}$$

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

$$N_T = R \frac{\gamma_L c \tau_0}{dl} e^{d/c\gamma_L \tau_0} \tag{4}$$

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

$$N_T = \eta K E_i^{-1.7} = \eta \, 1.1 \, 10^4 \, E_i^{-1.7} \quad m^{-2} \, Sr^{-2} \, s^{-1} \tag{5}$$

with E_i measured in GeV. The factor η 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 ($\eta \approx 1$). The only thing now needed is a relation between E_i and γ_L so that we obtain a relation between E_i and τ_0. 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 $\gamma_{CM} = (\frac{E_i}{2m_p})^{1/2}$

Consequently the Lorentz factor of the bubble in the laboratory frame, γ_L, will be

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

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

$$E_i = [\frac{1}{\eta\kappa} \frac{R}{aT} \ (\frac{E_i}{2})^{1/2} f \, \tau_0 \exp (d/c \ (\frac{E_i}{2})^{1/2} f \, \tau_0)]^{-0.59} \quad (7)$$

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

$$E_i = [\frac{1}{\eta} 5.68 \times 10^8 \ E_i^{1/2} f \, \tau_0 \exp (7.07 \ 10^5/E_i^{1/2} f \, \tau_0)]^{-0.59} \equiv F (E_i, \tau_0) \quad (7a)$$

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 familes of curves $F(E_i, \tau_0)$ are shown as a function of E_i with $f\tau_0$ as a parameter. The study of these curves points out two major features: (i) For sufficiently small values of the parameter $f\tau_0$ (<10^{-8}) no solution to equation (7a) exists. This means that for sufficiently small bubble lifetimes ($f\tau_0$ <10^{-8}) not enough of them will survive deep enough in the atmosphere to account for the observed Centauro flux, (ii) For $f\tau_0$ >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 $E_i = 10^6$ GeV for a wide range of values of the paramter $f\tau_o$, $(10^{-6}\text{-}10^{-8})$, which corresponds to a CM energy of $\simeq 1$ TeV. The lower energy solution however shifts quickly to much lower energies (CM energies < 100 GeV for $f\tau_o > 10^{-7}$ sec.). Center of mass energies much smaller than 100 GeV however may have to be excluded on the basis of lack of such events in accelerator experiments. One should also note the dependence on the assumption $n \simeq 1$. If $n \ll 1$ the whole figure would shift downward thus indicating longer lifetimes and lower threshold energies.

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 ref. [5] against the origin of Centauros in high energy cosmic ray collisions. The latter authors have reached that conclusion by noting that the kinematics of the Cenaturo event demand $\gamma \simeq 10^4$ and $M_{fireball} \simeq 200$ GeV. Assuming further (as they did) that all the primary energy goes into making the rest mass energy of the fireball (i.e. $\gamma_L = \gamma_{CM}$), they derived from the latter figures a primary energy $E_i \simeq \gamma_{CM}^2 \ M_{fireball} \simeq 10^{17}$ 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 $f \simeq 10$ then $\gamma_L = 10^4$ implies $\gamma_{CM} \simeq 10^3$ and hence a primary energy $E_i \simeq 10^{15}$ eV, which provides sufficient flux to account for the observed rate.

Discussion - Conclusions

Motivated by the extraordinary properties of the Centauro events we have reexamined the "fireball" hypothesis. In contrast to the previous treatments, we have tried to avoid the introduction of a new component in the primary

cosmic rays, but we have instead examined the possiblity of producing the metastable high density phase of matter needed to account for the "fireballs" in high energy cosmic ray collisions on the top of the atmosphere. Establishing such a connection leads to the relation of fig 1 between the threshold energy for the production of the metastable bubbles and their lifetimes.

The next question one is called to answer is the nature of these "fireballs". A clue to this question comes from the large P_t observed in these events. The value of P_t observed indicates, as pointed out [ref. 4], a superdense state of matter with mean particle separation, ℓ, 3-5 times smaller than that of quarks in a nucleon. Since the corresponding energy density is expected to be $\epsilon \sim n^{4/3} \sim (1/\ell)^4$, (n is the quark number density) it would correspond to energy densities $\sim$ 80-600 times those of nuclear matter. Hence the matter is expected to be in the quark-gluon phase. Unfortunately the phase transition from the quark to nuclear matter is considered to take place at much lower energy densities, a few GeV fm^{-3}, and therefore does not appear to account for the observed magnitude of P_t. Also the decay of such quark-gluon balls should produce π°'s contrary to observation.

In search of another scale at higher energy densities, the intriguing possibility of the SU(2) x U(1) $\rightarrow$ U(1) symmetry breaking scale has been considered. If the symmetry is restored there is a contribution to the energy density from the SU(2) x U(1) vacuum. The total energy density, ϵ, 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

$$P = \eta \frac{d\epsilon}{d\eta} - \epsilon = \frac{4}{3} A\eta^{4/3} - \rho .$$

One can now observe that for $A\eta^{4/3} \simeq \rho$ (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 $T \simeq T_c$ 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 $T \gtrsim T_c$ [6]. Neglecting surface effects, the bubbles are in pressure equilibrium between the positive particle pressure and the negative vacuum tension. These bubbles would presumably survive as long as the false vacuum state is preserved and does not decay to its minimum energy state (true vacuum). From the formal point of view the SU(2) x U(1) vacuum acts in a similar way as the constant bag energy density of QCD (which presumably is due to the SU(3) vacuum; see ref. 7), to form bound metastable objects. The difference is that the SU(2) x U(1) vacuum is metastable and these objects will decay with the decay of the false vacuum. However for this situation to occur the energy density achieved in the collision should be of the order of that required to restore the SU(2) x U(1) symmetry. This is roughly the energy density corresponding to black body radiation of temperature equal to the critical temperature for SU(2) x U(1) breaking. This is expected to be $T \sim m_H$, where m_H is the mass of the Higgs boson. This mass cannot be determined from the theory and it is currently unknown. Taking however at face value the observed P_t for the Centauro events, and assuming as a working hypothesis, that is due to the decay of metastable vacuum into Higgs particles which further decay into Kaons, one is

lead to $m_H \sim 2p_t$ or 2-3 GeV. It is interesting to note that this value for m_H naturally accounts for the large observed multiplicity, since an object similar to that considered to account for the Centauros with M ~ 100 GeV will decay into ~ 50 Higgs particles which will further decay into ~ 100 $K\bar{K}$ (see further discussion). One should mention at this point that there is a lower limit to the mass of the Higgs boson within the minimal (one Higgs doublet) standard model, of the order of $m_H \gtrsim 10$ GeV [8]. However models with extended Higgs sector [9], [10] can actually circumvent this limit. It has actually been suggested [10] that the particle $\xi(2.2)$ observed in the decay $J/\psi \rightarrow \gamma + \xi(2.2)$ might indeed be the long sought Higgs boson. It is encouraging that this value is consistent with the observed value of P_t as argued earlier.

The most serious problem concerning such an interpretation of the Centauro events is the achievement of energy densities $\gtrsim 100$ times that of ordinary nucleons (or 30-60 GeV fm^{-3}), needed for the restoration of SU(2) x U(1) symmetry, in view of the arguments put forward in ref. [11]. These authors have argued that at high energies the nuclei become transparent to each other thus limiting the maximum energy density achieved in a collision. Since, no definite answer to this question can presently be given and since the required energy density is within an order of magnitude of the ones presently considered achievable we consider that such a possibility exists. Such a point of view is actually supported by the evidence for apparent scaling violation both in high energy cosmic ray interactions [12] and in $p\bar{p}$ collider experiments [13]. It is interesting to note that the energy at which evidence for such violations occurs (as quoted by the above authors) is ~ 10^{15} eV, in good agreement with the threshold energy for Centauro productions as derived graphically in fig. 1.

One can of course always argue that such structures have very long life

times and were created in the early universe [4], since at sufficiently early times the temperatures were high enough for the SU(2) x U(1) symmetry to be restored. Unfortunately this scheme, although it may account satisfactorily for the production of such objects, requires the introduction of several other parameters (their life times, spectrum, number density etc.) in an ad hoc manner. While such a possibility cannot be dismissed it appears to be at least for the present, intractable.

Finally there is one more issue to be addressed, namely the apparent absence or deficiency of neutral pions or photons in these events, which should be explained in terms of the decay modes of the form of matter considered to comprise the fireballs. If our hypothesis is correct and the "fireballs" are due to false vacuum excitations, one would expect them to decay into Higgs particles, since the Higgs field is the agent responsible for the breaking of the symmetry. The Higgs should then subsequently decay, preferably into heavy quarks (Nussinov, private communication) since the coupling of Higgs to fermions is proportional to the square of the fermion mass. It is at this point that the identification of the $\xi(2.2)$ meson with the Higgs boson [10] provides evidence in support of our hypothesis and agreement with observation. If such an identification can indeed be made one would expect the Higgs bosons to decay primarily into the heaviest quarks lighter than the Higgs i.e. into Kaons (which is actually observed in the ξ (2.2) decay). The Kaons have sufficiently long life times (even for K_s, $\tau \sim 10^{-10}$ sec) that with a Lorentz factor $\gamma = 10^4$ (as observed for the Centauro) they would have to traverse ~ 300 m before they would decay into pions. So in this scenario the absence of pions would be accounted for by the closeness of the fireball to the detector (~ 50 m). It is interesting to note that other similar events (mini-Centauros) which apparently release the

fireball energy a few hundred meters from the detector show a deficiency rather than absence of pions, potentially accounted for by the same argument.

We would like to acknowledge discussions with Tom Gaisser, S. Nussinov, Jon Ormes and Quaisar Shafi.

RERERENCES

[1] C. M. G. Lattes, et al. (Japan-Brazil Collaboration), 1973, Proc. 13th ICRC, Denver, $\underline{3}$, 2227; $\underline{4}$, 2671.

[2] T. K. Gaisser and G. B. Yodh, Ann. Rev. Nuc. Part. Sci. $\underline{30}$, (1980) 475.

[3] N. J. Capdevielle et al., Proc. 17th I.C.R.C., Paris, (1981), $\underline{11}$, 112.

[4] J. D. Bjorken and L. D. McLerran, Phys. Rev. D20 (1979), 2353.

[5] R. Kinnunen and C. Rubbia, Proc. 17th I.C.R.C., Paris, (1981), $\underline{11}$, 112.

[6] M. Sher and R. A. Flores, Anny. Phys. 148 (1983), 95.

[7] G. Baym, in "Quark Matter Formation in Heavy Ion Collisions", M. Jacob and H. Satz editors, World Scientific, (1982).

[8] A. D. Linde, JETP Lett. 23 (1976), 64.
     S. Weinberg, Phys. Rev. Lett. 36 (1976), 294.

[9] F. Wilczek, Phys. Rev. Lett. 39 (1977) 1304.

[10] R. S. Willey, Phys. Rev. Lett. 52 (1984), 585.

[11] R. Anishetty, P. Koehler, and L. McLerran Phys. Rev. D22 (1980), 2793.

[12] S. Miyake, Proc. Bartol Conf.(1978) (AIP Conf Proc. No. 49) p 352.

[13] J. Wdowczyk and A. W. Wolfendale, Nature 306 (1983), 609.