Centauro as Probe of Deeply Penetrating Component in Cosmic Rays

G. Wilk\textsuperscript{a} and Z. Wlodarczyk\textsuperscript{b}
\textsuperscript{a}Soltan Institute for Nuclear Studies, Nuclear Theory Department, Warsaw, Poland
(e-mail: wilk@fuw.edu.pl)
\textsuperscript{b}Institute of Physics, Pedagogical University, Kielce, Poland
(e-mail: wspfiz@sabat.tu.kielce.pl)

The requirements for observing Centauro-like phenomena and their role as possible probes of deeply penetrating component in Cosmic Rays are discussed.

1 Introduction

The Centauro and mini-Centauro events, characterized by the extreme imbalance between hadronic and gamma-ray components among the produced secondaries\textsuperscript{3}, are the best known examples of numerous unusual events reported in Cosmic Ray (CR) experiments\textsuperscript{2}. There are numerous attempts to explain them as: (i) different types of isospin fluctuations or formation of disoriented chiral condensate (DCC)\textsuperscript{3}; (ii) multiparticle Bose-Einstein correlations\textsuperscript{4}; (iii) strange quark matter formation or interaction\textsuperscript{4}. All of them reproduce many features of Centauros in a single collision but fail to explain the substantial number of interactions contributing to the development of families observed at mountain altitudes among which Centauro were observed.

We demonstrate that families produced at mountain altitudes are insensitive to any isospin fluctuations mentioned above (cf.\textsuperscript{3}). This means that Centauro must originate from some very penetrating projectiles. We discuss two scenarios leading to such enhanced penetrability: fluctuations of elementary cross sections\textsuperscript{3} and propagation of chunks of Strange Quark Matter (SQM) (strangelets) in the atmosphere\textsuperscript{3}.

2 Centauros in atmospheric cascades

Isospin fluctuations is characterized by the ratio of neutral to total pion production yields

\[ r = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+\pi^-}} = \frac{N_{\pi^0}}{N} \]  

where \( N \) denotes total pion multiplicity. If isotopic spin is to be conserved \( r \) should be distributed according to binomial distribution (BD) (which for large \( N \) is well approximated by a gaussian with width \( \sigma = 1/\sqrt{3N} \) widely used in most Monte Carlo generators. However, models\textsuperscript{2,3} predict a strong deviations from simple BD formula, namely for large \( N \) one has

\[ P(r) = \frac{1}{2\sqrt{r}}, \]  

i.e., \( r \) differs substantially from the naive value of \( \langle r \rangle = 1/3 \). The natural question therefore arises: does this fact influence also characteristics of atmospheric families observed in the same experiments? To answer this question we have calculated (using standard RR-Y00 model from SHOWERSIM software\textsuperscript{2}) distributions \( P(\varepsilon) \) of the energy fraction

\[ \varepsilon = \frac{\sum E_{\gamma}}{\sum E_{\gamma} + \sum E_h} \]  

of electromagnetic (\( \sum E_{\gamma} \)) and hadronic (\( \sum E_h \)) components of gamma-hadron families (with total visible energy \( \sum E_{\gamma} + \sum E_h \geq 100 \) TeV) recorded in emulsion chambers at mountain altitudes. The results are shown in Fig. 1 where \( P(\varepsilon) \) for DCC type of fluctuations\textsuperscript{3} essentially coincides with the standard behaviour of families described by BD distribution. It means that all scenarios of isospin fluctuations lead to essentially \textit{the same} families at mountain altitudes. (We have checked it for \( P(r) \) ranging from the pure Centauro-Anticentauro production case corresponding to \( P(r) = \frac{1}{3} \delta(r - 1) + \frac{2}{3} \delta(r) \) to the broadest smooth distribution of the form \( P(r) = 2(1 - r) \): the same conclusion holds also for distributions of the corresponding multiplicity fractions \( P(\eta) \), \( \eta = N_{\pi^0}/(N_{\pi^0} + N_h) \)). It means that Centauros need projectiles of the unusually large
penetrability in the atmosphere. We shall discuss now two possible scenarios leading to such a large penetrability: (i) fluctuation of hadronic cross sections \[7\] and (ii) propagation of strangelets in the atmosphere \[8\].

2.1 Fluctuations of hadronic cross sections

Origin of the cross section fluctuations (CSF) is traced down to the compositeness of hadrons and their extension. Depending on the temporal and space configurations of partons (quarks and gluons) composing both colliding hadrons one can have different interaction cross sections for a given interaction with the mean value being equal to \(\sigma_{hh}\). In \[7\] CSF allowed to explain the so called long flying component of CR, in accelerator data they manifest themselves in the diffraction dissociation events. The significance of the CSF in present situation is illustrated in Fig. 1 where out of the two \(P(\varepsilon)\) distributions of DCC type \[2\] only that with CSF - dotted line and including CSF - dashed line - are compared with data from 135 Chacaltaya families \[10\] (squares).

![Figure 1](image.png)

Figure 1. Distributions \(P(\varepsilon)\) for gamma-hadron families detected at mountain altitudes. Results for the standard BD distribution (solid line) and DCC one as given by eq.(2) (without CSF - dotted line and including CSF - dashed line) are compared with data from 135 Chacaltaya families \[10\] (squares).

2.2 Strangelets in the atmosphere

In \[8\] we have proposed scenario of the extraterrestrial strangelets penetrating deeply in the atmosphere in which heavy lumps of strange quark matter of mass number \(A_0 \sim 1000\) arrive at the top of atmosphere and degrade in the successive interactions with air nuclei until reaching some critical value of \(A_{\text{crit}} \sim 320\). Below this value they simply desintegrate into nucleons \[8\]. Centauro events \[1\] interpreted in terms of this approach would correspond to \(A_0 = 2000\) if detected at Chacaltaya \((540 \text{ g/cm}^2)\) and to \(A_0 = 2350\) if detected at Pamir altitudes \((600 \text{ g/cm}^2)\). For the mass spectrum \(N(A_0) \equiv \exp(-A_0/130)\) discussed in \[8\] the above mass numbers correspond to the observed flux ratio of Centauro events, \(N_{\text{Pamir}}/N_{\text{Chacaltaya}} \approx 0.066\) explaining nicely the small number of Centauros detected at Pamir altitude. The observed 5 events on the area 200 m² yr and 1 event on the area 600 m² yr from the Chacaltaya and Pamir experiments respectively, \[11\], lead to the observed flux ratio equal to \(N_{\text{Pamir}}/N_{\text{Chacaltaya}} = 0.06\).

![Figure 2](image.png)

Figure 2. Integral distribution of fractional energy of hadrons in Centauro event \[1\] (squares) compared with our predictions for \(E_h = \text{const}\) and fluctuating partial inelasticity \(k_\gamma\) distributed according to UA5 Monte Carlo algorithm for nuclear interactions \[12\].

In this scheme Centauros are baryon-emitting events. Nucleons evaporated from the strangelet emitting when its \(A < A_{\text{crit}}\) deeply in the atmosphere are recorded in the emulsion chamber. Despite the fact that energies \(E_h\) of all evaporated baryons are very close to each other, the observed visible energies \(E_h^\gamma\) can still exhibit be-
haviour observed experimentally. In Fig. 2 we show the integral distribution of fractional energy $x = E^\gamma / \sum E^\gamma_h$ of hadrons detected in the Centauro event [1] compared to our predictions. In our simulations we start with sampling energy of such hadrons from the initial distribution $N(E_h) \approx \delta(E_h - E_0)$ and transform it into $E^\gamma_h = k_\gamma E_h$ with the help of the partial inelasticity $(k_\gamma)$ distribution given by

$$f(k_\gamma) \, dk_\gamma = \frac{1}{\Gamma(\alpha)} \left( \frac{k_\gamma}{\beta} \right)^{\alpha-1} \exp \left( -\frac{k_\gamma}{\beta} \right) \frac{dk_\gamma}{\beta}$$

(4)

with $\alpha = 1.05$ and $\beta = 0.145$ obtained by using UA5 Monte Carlo algorithm as a model of nuclear interactions [2]. In such approach the energy distribution in Centauro event reflects just the partial inelasticity distribution.

3 Summary and conclusions

Centauros can occur either as pionic events or as purely baryonic ones. In the first case they can be described by some apparent strong isospin fluctuations. However, their occurrence at mountain altitudes indicates additional strong penetrability of the projectile causing such event. We claim that in this case such penetrability could be provided by the CSF mechanism, cf. Fig. 1. In the second case we show that they can be products of strangelets penetrating deeply into atmosphere. Both flux ratio of Centauros produced at different experiments and energy distribution within them can be successfully described by such concept.

References

[1] C.M.G.Lattes et al., Phys. Rep. 65 (1980) 151; A.S.Boriso et al., Phys. Lett. B190 (1987) 226.

[2] Z.Wlodarczyk, 23th ICRC, Calgary (1993), eds. D.A.Leahy et al., WS Singapore (1994) p. 355.

[3] R.Attallah and J.N.Capdevielle, J.Phys. G19 (1993) 1381; M.Martinis et al., Phys. Rev. D51 (1995) 2482; J.D.Bjorken, Int. J. Mod. Phys. A7 (1992) 4189 and Acta Phys. Polon. B23 (1992) 637.

[4] S.Pratt and V.Zelevinsky, Phys. Rev. Lett. 72 (1994) 816.

[5] J.D.Bjorken and L.D.McLerran, Phys. Rev. D20 (1979) 2353; A.D.Panagiotou et al., Phys. Rev. D45 (1992) 3134; M.N.Asproli et al., Astropart. Phys. 2 (1994) 167.

[6] G.Wilk and Z.Wlodarczyk, J.Phys. G19 (1993) 761.

[7] G.Wilk and Z.Wlodarczyk, Phys. Rev. D50 (1994) 2318.

[8] G.Wilk and Z.Wlodarczyk, [hep-ph/9606401] to be published in J. Phys. G (1996) and Proc. of STRANGENESS’96, Budapest 1996, to be published in Heavy Ion Phys. (1996), [hep-ph/9606401].

[9] A.Wrotniak, Report No. 85-191, Univ. of Maryland (1985).

[10] E.Navia et al. Nuovo Cim. A108 (1995) 1341.

[11] Pamir, Fuji and Chacaltaya Coll., Nucl. Phys. B191 (1981) 1.

[12] M.Tamada, J. Phys. G20 (1994) 487.