Black Holes *versus* Strange Quark Matter

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1 Introduction

The interpretation of Centauro-like events, observed by cosmic-ray mountain experiments [1,2] still remains the open question. A lot of models proposed to explain Centauros and other related phenomena have been described and discussed in [4]. To this list the new ideas based on DCC mechanism [3,11] or mini black holes evaporation [5,6] should be added. The last ones are based on the scenarios with large extra dimensions in which the fundamental Planck scale could be in TeV range. One of the most exciting consequences of a low fundamental Planck scale is the possibility of producing black holes and observing them in future colliders or in cosmic ray experiments [7]. The purpose of this work is to compare the strange quark matter and mini black hole scenarios and in particular to give some comments to the paper [6].

2 Are Black Holes the best explanation of the Centauro events?

If gravity propagates in $d + 4$ dimensions while the other fields are confined to a 3-brane, the 4-dimensional Planck scale is given by $M_{pl}^2 = M_P^{d+2} V_n = G_n^{-1} V_n$, where $M_P$ and $G_n$ are respectively the fundamental Planck scale and the gravity constant in $4 + n$ dimensions and $V_n = (2\pi R^n)^n$ is the volume of the n-torus of the compact space [9]. In models with large extra dimensions $R$ the fundamental Planck scale can be of the order of 1 TeV and the black holes could be produced at LHC energies. It is expected that these mini black holes (MBH) will decay very rapidly, with a lifetime $\tau \sim 1/M_P \sim 10^{-27}$ s for $M_P \simeq 1$ TeV, in several stages. The semiclassical Hawking evaporation will provide a high multiplicity of particles $^1$ and a characteristic black-body type spectrum. Emission of all degrees of freedom are equally probable. It is expected that after evaporation they can leave remnants which are some excited stringy states. A. Mironov, A. Morozov and T.N. Tomaras [6] argue that the signals expected from the evaporation of mini black holes, predicted by TeV-Gravity models, are similar to the characteristics of the Centauro events [3]. Moreover, they suggest that this interpretation is better, or at least not worse than any other proposed so far because "its advantage is the potential to explain all the CLE $^2$ properties at once (no worse than the other approaches, targeted at these properties) and, furthermore it offers somewhat less freedom to arbitrarily adjust different predictions".

We agree that the evaporating mini black holes are good candidates for the origin of unusual cosmic-ray events, however, to draw the above cited conclusion, this scenario needs much more detail studies and answering some important questions. The detailed calculations and simulations of the production and decay of mini black holes are necessary to compare the characteristics of simulated events with experimentally observed Centauros as well as to design the future accelerator experiments to be sensitive to such objects production and detection. It is true that more recently the simulations of cascades, generated by the decay of mini black holes formed in the ultra high energy collisions of the cosmic ray particles with the atmospheric nuclei have been done [8]. The simulations have been performed for several

1In some scenarios the expected multiplicity from black holes decay is quite low and it can be further reduced by quantum gravity effects [10], even at LHC energies is only $\sim 6$ [3].

2Centauro like events.
values of the large extra dimensions and for a variety of altitudes of the initial interactions, and compared with the standard events. However, to settle the Centauro question, much more detailed work, and especially consideration of the signals from the black holes produced rather close to the detector (at heights smaller that $\sim 1000\, \text{m}$ above the chamber) should be done.

Majority of the proposed models, as it was stressed in [2], are not able to explain simultaneously all features of the Centauro-like events and they are mainly concentrated on the interpretation of the basic Centauro anomaly, i.e. the enormous hadron-rich composition. The exception are, however, the Strange Quark Matter (SQM) based scenarios, such as the model proposed and described in [11] and supplemented with the idea of formation and passage of strangelets through the matter [12, 13]. At this stage of investigation, it offers more complete and quantitative description of the cosmic ray exotic phenomena than other approaches, among them also the mini black holes scenario. However, the mini-black hole concept has also some interesting points and it is worth of further considerations. The common advantage of both scenarios is the expectation of the threshold energy necessary for generation of Centauro-like phenomena. Let us try to compare and discuss some essential points.

2.1 Multiplicities and hadron rich composition

The main, widely known feature of the Centauro-like events is their anomalous hadronic to photonic ratio and additionally rather small observed multiplicity, as compared to that expected from nucleus-nucleus collisions at the same energy range.

The hadron rich composition of the events can be easily understood by assuming the existence of the strange quark matter. Such state of matter, containing a comparable fraction of $u$, $d$ and $s$ quarks, initially proposed by E. Witten [14] is recently the subject of many theoretical works. The main argument for the stability of such system is the introduction of a third flavour what creates an additional Fermi well and thus reduces the energy relative to a two-flavor system. It should be stressed that a lot of cosmic ray anomalies, such as massive and relatively low charged objects [15, 16, 17], muon bundles from CosmoLEP [18], delayed neutrons observed with EAS instalation “Hadron” [19], Centauro related phenomena [11, 12, 13, 20, 21] are proposed to be explained by assuming the presence of strangelets in cosmic ray spectrum [22]. To this list the seismic events with the properties of the passage of SQM droplets through the Earth [23] and the candidate for a metastable strangelet found with the AMS detector [24] should be added.

According to the model developed in [11] Centauro arises through the hadronization of a SQM fireball, produced in a nucleus-nucleus collision in the upper atmosphere. The fireball formed in the forward rapidity and high baryon density environment initially consists of $u$ and $d$ quarks and gluons only. The high baryon chemical potential inhibits the creation of $u\bar{u}$ and $d\bar{d}$ quark pairs, resulting in the fragmentation of gluons predominantly into $s\bar{s}$ pairs. This leads to the strong suppression of pions and hence of photons in the process of its hadronization. To form a pion, $q$ and $\bar{q}$ must exist. Large baryon chemical potential $\mu_b = 3\mu_q$ suppresses the production of $\pi$ and $\bar{d}$ quarks because

$$N_{\pi} \propto \exp(-\mu_q/T). \tag{1}$$

In addition, the production of quarks is strongly prohibited due to the Pauli blocking.
Thus, the number of pions, formed by created $q\bar{q}$ pairs, is proportional to
\[ N_{\text{pions}} \propto \exp\left(-\frac{4\mu_q + m_\pi}{T}\right), \]  
and the pion–to–nucleon ratio is proportional to
\[ \frac{N_{\text{pions}}}{N_{\text{nucl.}}} \propto \frac{3}{2}\left[-\frac{4}{3}\mu_b - m_\pi + M_\mu\right]/T \simeq 7 \times 10^{-6}. \]

Such estimate has been obtained in [11] by assuming that nucleons are formed by existing $u, d$ quarks. The values of thermodynamical quantities, such as the energy density $\varepsilon = 2.4$ GeV/fm$^3$, the quark chemical potential $\mu_q = 600$ MeV and the temperature $T = 130$ MeV are not free model parameters but they have been extracted from analysis of experimental characteristics available for the five “classical” Chacaltaya Centauros. So, in the SQM fireball picture the strong suppression of the electromagnetic component is the natural consequence of the nucleus-nucleus collisions at energies high enough to produce, at the forward rapidity region, the fireball of the high baryon density quark gluon plasma. The mechanism of the fireball formation proposed in [11, 12] does not need any additional assumptions and fitted parameters and successfully (and quantitatively) explains the features of Centauros detected at mountain top cosmic ray experiments (i.e. hadron multiplicity $N_h \sim 75$, suppression of electromagnetic component, shape of a pseudorapidity distribution). The Monte Carlo generator of Centauro events, CNGEN, constructed on the basis of this model not only satisfactorily describes the main features of cosmic ray Centauros but also gives quantitative predictions concerning these events possibly produced at LHC accelerator [2, 25].

The authors of [6] suggest that the strong suppression of electromagnetic component observed in Centauro events could be the result of evaporation of MBHs. In this process all kinds of particles of the Standard Model can be produced, so the resulting photon/hadron ratio should be lower than for ordinary hadronic interactions. According to [7, 10] the hadron to lepton ratio is about 5:1, what leads to a hadronic to photonic ratio of about 100:1. No constraint on isospin in the final state of MBH is the additional argument, given in [4], for possibility of appearance of large fluctuations in the ratio of charged to neutral pions. However, at the present level of the study, above mentioned arguments have strictly qualitative character. It was not shown for what values of the parameters the MBH scenario could quantitatively describe the observed characteristic features of Centauros, such as for example the observed multiplicity of electromagnetic and hadronic component, and in particular if the understanding of the extreme situation, the so called clean Centauros (with the totally reduced electromagnetic component) could be possible. According to [6] the number of emitted particles $N_{\text{obs}} \simeq M_{\text{BH}}/2T_{\text{BH}}$ (where $M_{\text{BH}}$ and $T_{\text{BH}}$ are the mass and temperature of the black hole respectively) and the multiplicity of the particles observed $N_{\text{obs}}$ should be calculated using fragmentation functions and will strongly depend on the BH parameters.

### 2.2 Transverse momentum of produced secondaries

Transverse momentum $p_T$ of particles produced in the Centauro-like events is also surprising. The experimental data indicate that we observe two components of the transverse momentum.
• The first one constitutes the particles with high transverse momentum, estimated to be \( \langle p_T \rangle \sim 1.7 \text{ GeV/c} \) for Centauros and \( \langle p_T \rangle \sim 10-15 \text{ GeV/c} \) for Chirons. These values have been obtained from the formula:

\[
p_T \simeq R \cdot K_\gamma \cdot E/H
\]

where \( R \) is the distance of the particle from the family centre, \( K_\gamma \) is the inelasticity coefficient, \( E \) is the energy of the electromagnetic shower produced in the apparatus, and \( H \) is the height of the interaction point.

We should remember, however, that estimated in this way values of the transverse momenta were obtained by assuming the gamma inelasticity coefficient \( K_\gamma \simeq 0.2 \) and they suffer from some experimental ambiguities. First of all the measurement of the height of the interaction point above the chamber is the serious problem [2]. The heights have been measured directly, through the shower geometry, only for a few exotic events found in Chacaltaya chambers (for three Centauros, two Mini-Centauros and three Chirons). The transverse momenta of secondaries in the other events have been estimated in a more speculative way.

• The second component is seen in the narrowly collimated jets of particles (called mini-clusters) firstly observed in Chirons, later also in other Centauro-type events. The ratio of \( \langle E(\gamma)R \rangle \) of hadron cascades in Centauro-like events to the \( \langle E(\gamma)R \rangle \) in mini-clusters has been found to be surprisingly large (\( \sim 300 \)) and their intrinsic \( p_T \) is supposed to be extremely small (\( \sim 10 - 20 \text{ MeV/c} \)). In addition, the mini-clusters are characterized by very strong penetrative power in the matter (see the next subsection).

In the SQM model [11, 12, 13] the high transverse momentum of secondaries can be the result of the explosive decay of the Centauro fireball and the highly collimated clusters of cascades could be a natural consequence of the evaporation of cold strangelets, during their passage through the apparatus matter. In [2, 25, 26] we have presented the results of the simulations done by means of our Centauro event generator, CNGEN, and in particular, we have shown that the average transverse momentum of the Centauro fireball decay products is several times higher than that for normal events. For example the average transverse momentum of particles coming from the decay of the Centauro fireball characterized by a temperature \( T = 130 \text{ MeV} \) \(^3\) and produced in \( PbPb \) collisions at LHC energies (\( \sqrt{s} = 5.5 \text{ A·TeV} \)) is 1.6 GeV/c, in comparison with \( p_T \simeq 0.44 \text{ GeV/c} \) obtained for conventional events (HIJING generator).

The question of the existence and the understanding of the exotic features of mini-clusters, and in particular, their surprisingly small lateral spread is not considered by authors of [6] in the MBH scenario. It is not clear what mechanism connected with the MBH phenomenon could be responsible for the production of very narrow and strongly penetrating jets of particles?

On the other hand the appearance of the particles with high transverse momenta is strongly stressed by authors of MHB scenarios. They predict that the decay of MBHs looks like a typical fireball situation, but its temperature is very high, \( T_{BH} \sim 1 \text{ TeV} \). The simulations done in [9] for the \( pp \) and \( PbPb \) collisions at the LHC energies showed that hadrons

\(^3\)\( T = 130 \text{ MeV} \) is estimated from characteristics of the cosmic ray Centauros.
Table 1: Distances $R$ of the high $p_T$ particles from the centre of the family at the detector level

| $R$ [m] | $E$ [TeV] | $H$ [m] | $p_T$ [GeV/c] |
|---------|-----------|---------|---------------|
| 3       | 1         | 100     | 30            |
| 58      | 2         | 100     | 1000          |
| 30      | 1         | 1000    | 30            |
| 580     | 2         | 1000    | 1000          |
| 0.3     | 10        | 100     | 30            |
| 10      | 10        | 100     | 1000          |
| 0.03    | 100       | 100     | 30            |
| 0.1     | 100       | 100     | 100           |
| 1       | 100       | 100     | 1000          |
| 0.3     | 100       | 1000    | 30            |
| 1       | 100       | 1000    | 100           |

from mini black hole decay dominate the background at transverse momenta $p_T \gtrsim 30$ - 100 GeV/c. The consequences of the production of the particles having such enormously large transverse momenta on the characteristics of the Centauro-like events should be very pronounced. At first, only a fraction of the particles radiated by a black hole could be observed in the chambers. The substantial part of them miss the detector. For example the low energy ($\sim 2$ TeV) particle\(^4\) emitted with $p_T \simeq 1$ TeV/c at the height of 1000 m above the detector, reaching the level of the chamber will be distanced at $R \simeq 58$ m from the family centre. Keeping in mind that the areas of typical emulsion chambers used in these experiments are of the order of tens $m^2$ and additionally that the area, scanned for finding the cascades belonging to the same event is usually limited to the circle of a radius $R \simeq 15$ cm\(^5\) such high $p_T$ particles must escape the detection. Only very high energy particles and/or these produced at low height above the chamber have a chance to be seen in the detector. Table 1 illustrates this question.

Thus, the decaying MBHs will produce events, characterized by a very wide lateral spread, much wider than that conventionally limited to the circle of a radius $R = 15$ cm in the standard procedure of measurements. The simulations of the cascades through the atmosphere done in \cite{ref} also support this statement, claiming that the wide lateral distribution will be the most striking signature of a black hole event.

The second important point is that the production angles $\theta_{prod}$ of such extremely high $p_T$ particles are enough big to apparently change the direction defined by the projectile\(^4\) The energy threshold for the X-ray films is $\sim 2$ TeV.\(^5\) In the part of the experimental material, measured by our Cracow group, this area has been increased to $R \simeq 30$ cm.
arrival. In the typical “normal” events, with \( p_T \sim 0.4 \text{ GeV/c} \) the corresponding \( \theta_{\text{prod}} \) is \( \sim 2 \cdot 10^{-4} \text{ rad} \approx 0.01^\circ \) for \( \sim 2 \text{ TeV} \) particles, and smaller for higher energy particles. Thus, the experimental procedure used to identify particles belonging to the same event is based on the requirement of the same flight direction for all members of the family. The experimental uncertainties in the measuring of the zenithal \( \theta \) and azimuthal \( \phi \) angles are much bigger than the change in the particle direction caused by its production angle. As the example, for the X-ray films technique used in the Pamir Experiment, the estimated error in the solid angle \( \Delta \Omega \approx 0.01 \text{ sr} \) \cite{27}. In the typical procedure of elaboration of the events, all the showers with angles the same within the errors (in the Pamir \( \Delta \theta \approx 3^0 \) and \( \Delta \phi \approx 30^0 \) \( \Delta \theta \approx 6^0 \) and \( \Delta \phi \approx 60^0 \)) for photon (hadron) cascades are considered to be the members of the same family.

The situation is different in the case of huge \( p_T \). The particles of energy \( 2 \text{ TeV} \) (10 TeV) and \( p_T \sim 1 \text{ TeV} \), generated in the evaporation of MBHs, will be emitted at \( \theta_{\text{prod}} \approx 0.52 \text{ rad} \approx 30^0 \) \( \theta_{\text{prod}} \approx 0.1 \text{ rad} \approx 5.7^0 \). Such angles are greater than the values of experimental errors imposed on the measured angles. In consequence, the very high \( p_T \) particles could not be recognised as members of the same family.

At the moment, we should invoke the recent papers \cite{28,29,30}, in which authors describe the re-examined Centauro I event. Centauro I was the first and the most spectacular event of this type. It was found, in 1972, in the two-storey Chacaltaya chamber No.15. According to the original analysis \cite{1}, the event consisted of two groups of showers: one group of 7 showers was observed in the lower chamber (called in \cite{28} \( S55 \) family) and the other one of 43 showers \( \text{S}12 \) family) was found in the upper chamber. The authors of the new analysis \cite{28,29,30} claimed that they discovered differences in angles between the cascades registered in the upper and lower blocks. They found \( tg\theta \approx 0.3 \pm 0.1, \phi \approx (130 \pm 10)^0 \) and \( tg\theta \approx 0.4 \pm 0.1, \phi \approx (90 \pm 10)^0 \) for cascades in the lower and upper chambers respectively (according to \cite{28} \( tg\theta = 0.3 \pm 0.1, \phi \approx (130 \pm 10)^0 \) and \( tg\theta \approx 0.3 \pm 0.1, \phi \approx (90 \pm 10)^0 \) for cascades in the lower and upper chambers respectively). In connection with it, the authors of these papers assume that these groups of showers do not constitute the same family but they come from two different primary projectiles, accidentally flying in the very close directions. The further conclusion from \cite{29} is that in the case of the ideal detector, the SQM scenario could be the most plausible explanation, although the authors suggest the Chacaltaya detector problems as the most likely cause of such puzzle event. Then, according to \cite{30} the new physics is not needed for Centauro I explanation, and the event observed in the lower chamber could be the air family passing through a gap between blocks in the upper detector. In such case, however, immediately the question arises about the evidence on anti-Centauro events, artificially produced in the possible gaps between blocks in the lower chamber. The considerations done in \cite{28} lead the authors to the opinion that the Centauro I passed the upper detector with leaving no (or a single) shower in the upper detector and the event seems to be even much more surprising than before. They suggest that the event could be explained by SQM scenario, assuming that large quark globs, present in the primary cosmic ray spectrum, fragment in the atmosphere in smaller quarks lumps and they hit the emulsion chamber.

It seems to us that other possibility of the understanding of this puzzle is to agree with the original analysis of the Centauro I, by allowing the larger errors in the shower direction...
and assuming the same origin of the S55 and I12 groups. The admission of larger errors on the measured azimuthal and zenithal angles is the straightforward consequence of assuming the existence of phenomena in which very high $p_T$ particles are generated, such as MBHs scenario or generally the explosive decay of the large mass fireballs (e.g. the SQM fireball with high T and/or $\mu$).

It should be stressed that Centauro I is not the sole event with such peculiar characteristics. The other one is the Centauro-like event found more recently in Chacaltaya two-storey chamber no. 22. According to descriptions done in [32] no showers in the upper chamber have been observed and although some cascades can be missed in the gaps between blocks, the authors think that it does not seem possible that gaps between blocks could be the reason of missing all showers in the family. May be the particles with very high $p_T$ have been lost?

The phenomenon, which looks like the appearance of two families with very close arrival directions has been also observed by our Cracow group. In particular, doing the final analysis of the Centauro-like event found in the thick Pb emulsion chamber of the Pamir Experiment [33] we have excluded from the event 30 showers having slightly different angles than those measured for other cascades classified as the family members. Except the hadron rich composition, this event has also other exotic feature, i.e. it is accompanied by the surprisingly long many-maxima cascades (see the next subsection).

The appearance of families of showers at the certain apparatus layer, deeply inside the chamber, and a lack of accompanied cascades in the upper part of the deep lead chamber “Pamir 74/75” we have described also in [34]. Unfortunately, in these cases we were not able to exclude the trivial explanation that the observed phenomenon is simply a usual family, reaching the chamber during the time of its assembly. However, the news concerning the Centauro I remind the fact that the family no. 2 ($N_{\gamma} = 2, N_h = 9, \Sigma E_{\gamma} = 5.8$ TeV, $\Sigma E_{\gamma h} = 44.3$ TeV) has been accompanied by the other six cascades (three photon and three hadron showers) with arriving angles only a little different than average $\langle \theta \rangle$ and $\langle \phi \rangle$ measured for the main family.

Could be these observations some signs of the existence of the huge $p_T$ particles?

2.3 Strongly penetrating component

In [2] we emphasized the very important and up to now rather weakly known experimental aspect of the cosmic ray exotic phenomena, i.e. relation between Centauro species and the long-flying (strongly penetrating) component. In fact, the strongly penetrating component has two faces. At first, it has been observed in the apparatus in the form of strongly penetrating cascades, clusters or the so called halo, frequently accompanying the hadron-rich events. This phenomenon manifests itself by the characteristic energy deposition pattern revealed in shower development in the calorimeters indicating the slow attenuation and many maxima structure in homogenous thick lead chambers. The second face is connected with the strong penetrability of some objects in the passage through the atmosphere. Both aspects can be connected one to each other and could be the different manifestation of the same phenomena.

\[\text{\footnotesize{After excluding 30 cascades with slightly different angles, the multiplicity of the photonic and hadronic showers of energy above 1 TeV is } N_{\gamma} = 74, N_{h} = 55 \text{ respectively.}}\]
MBHs in cosmic rays can be produced by cosmic neutrinos colliding with atmospheric particles [7]. The authors of [6] claim that “a possible neutrino-MBH origin of Centauro like events would explain their deep-penetration property, i.e. the fact that events are observed deep in the atmosphere close to the detectors.” In that case “there should not be any dependence of the probability of creating MBHs on the altitude above sea level.” The experimental data seem to contradict this statement. The non-observation of Centauro like events at Mt. Fuji (3750 m a.s.l.) and the observed smaller intensity of such events at Mts. Pamir (∼4300 m a.s.l.) than at Mt. Chacaltaya (5200 m a.s.l.) indicate the dependence of their flux on the altitude in the atmosphere. Contrary to the expectation from the neutrino origin MBHs, if Centauro species were born in nucleus-nucleus collisions or if they were the strongly penetrating objects, produced at the top of the atmosphere or somewhere in the extra-galactic region, then the decrease of their flux with the atmosphere depth is quite plausible. According to [31] the estimated flux ratio of Centauro events $N_{\text{Pamir}}/N_{\text{Chacaltaya}} \simeq 0.07$, what agrees with experimental observations.

The other serious problem of the MBH scenario seems to be connected with its ability to explain the second form of the strongly penetrating component, i.e. the unexpectedly long showers observed in the emulsion chambers. They are frequently accompanying the Chiron and Centauro-type events. Fig. 1 shows the example of such cascade found among many other hadron cascades, produced in the Centauro-like event [33] and detected in the multilayer homogenous thick Pb chamber (60 cm Pb) of the Pamir experiment. This exotic cascade passed a very thick layer of lead ($109 X_0$) and escaped through the bottom of the chamber. Its transition curve is very exotic: 11 maxima satisfactorily described by individual electromagnetic cascade curves can be revealed.

The question is if and how the MBH scenario could explain the slow attenuation and many-maxima structure of such cascades? It is true that MBHs are expected to produce an excited stringy states which according to [6] could play the role of the projectiles with unusual behaviour and potentially be responsible for the so-called halo events. However, such statement should be explained more precisely. At the moment, it is unclear, even qualitatively, what would be the nature of these exotic remnants of the MBH decay, and in particular which their features could be responsible for the strong penetrating power and the hump structure?

Contrary to the scenario based on MBH, the main advantage of the models based on the idea of the SQM is their potential to understand the connection between the observation of hadron-rich events and the strongly penetrating component, in both above mentioned forms. The models proposed in [11, 12, 20, 21] explain the deep penetration in the atmosphere, the model [11, 12] extended in [13] additionally describes the strongly penetrating component seen in the apparatus. We are able to understand not only Centauros but also numerous hadron-rich families accompanied by highly penetrating cascades, clusters or halo by assuming the same mechanism of the formation of a strange quark matter fireball and its successive decay into predominantly baryons and strangelet(s).

The strong penetrative power of the Centauro-like objects can be connected both with the small interaction cross section (in comparison with that of a nucleus of comparable A) of a strangelet and/or with big concentration of its energy in a narrow region of phase space. This energy could be liberated into conventional particle production in many consecutive evaporation (or interaction) acts.

In the model described in [11, 12] strangelets are formed in the process of strangeness
distillation at the last stage of the Centauro fireball evolution. It is important to stress the following points:

1. Characteristic features of the quark-matter nuggets, coming from the Centauro fireball decay, have been estimated on the basis of experimentally measured Centauro characteristics.

In particular, the strange quark density and thus a strangelet mass number $A_{str}$ have been calculated from the formulas:

$$A_{str} \simeq N_s = \rho_s V$$  \hspace{1cm} (5)

where $\rho_s$ is $s$–antiquark density and depends on the temperature by the relation [35]:

$$\rho_s \simeq 0.178\left(\frac{T}{200\text{MeV}}\right)K_2\left(\frac{150\text{MeV}}{T}\right).$$  \hspace{1cm} (6)

For $T=130$ MeV, which is the temperature for cosmic-ray Centauros, $\rho_s \simeq 0.14\text{ fm}^{-3}$. Evaluating a volume of the Centauro fireball $V \sim O(100\text{ fm}^3)$ the number of created $s\bar{s}$ pairs and thus $A_{str}$ is $\sim 14$.

2. The indicated above value of a strangelet mass number $A_{str} \simeq 14$ is consistent with that we estimated independently by using the other method and other piece of experimental information (analysis of the shape of the strongly penetrating many-maxima cascades [13]).
3. The long many-maxima cascades observed in the thick lead emulsion chambers [33, 36] have been satisfactorily described by the strangelet scenario [13].

Commenting the statement from [6], “The models involving strangelets ... depend, in addition, on *ad hoc* assumptions about properties of hypothetical strange matter (both its formation and decay)”, we would like to explain the following points:

- **The signal produced in the thick emulsion chamber/calorimeter by the strangelet passage through the apparatus does not depend on the mechanism of a strangelet formation.**

It does not matter, if the strangelet is produced via strangeness distillation, coalescence mechanism, or in other quite different process. The single strangelets born by any mechanism will give the same signals in the detector.

It is true that different patterns can be obtained if the strangelet formation is accompanied by production of other species. However, the conclusion from our studies is that both the strangelets born among other conventionally produced particles and the strangelets produced via the Centauro fireball decay give the signals quite different from usual events and resembling the experimentally found cascades, strongly penetrating through the apparatus. In the papers [2, 37] we have shown the simulated signals produced by single strangelets as well as by strangelets born among other conventionally produced particles, during their passage through the deep tungsten calorimeter. In [26] the strangelets being the remnants of the Centauro fireball explosion have been investigated. In this case the resulting signal is the sum of the strangelet, other Centauro decay products and the conventional background. In each of the considered cases the resulting signal is very characteristic and it can be easily distinguished from the conventional background. We have done calculations at energies predicted for PbPb collisions at LHC collider and for the CASTOR calorimeter [38], being the subsystem of the CMS experiment. The upper picture at the Fig. 2 shows the example of the simulated transition curves produced in the calorimeter by the stable strangelet \((A_{str} = 20, E_{str} = 20 \text{ TeV})\) (full line), the other Centauro decay products (dashed line), and the HIJING estimated background of conventionally produced particles (hatched area). The lower picture shows the summed signal of these three contributions (full line) in comparison with the average signal in the other (not being hit by the strangelet) calorimeter sectors (dashed line) and also with the predictions of the HIJING model (histogram).

- **The strong penetrating power through the apparatus is the feature of long-lived as well as short-lived strangelets.**

We found in our simulations [13] that the long many-maxima cascades can be produced in thick emulsion chambers independently of the strangelet lifetimes. We expect also that the nature of the baryons being the strangelet decay products weakly influence the shape of the produced showers. In Fig. 3 three examples of many-maxima long range cascades, obtained in simulations of the passage of different kinds of strangelets through the emulsion chamber, are shown.

The thickness of the emulsion chambers used in the cosmic ray mountain experiments is too small to distinguish between the stable and unstable strangelet decay scenario. On the other hand, our simulations done for the CASTOR detector [38] allow to
Figure 2: Transition curves produced by the Centauro and the strangelet being its remnant, during their passage through the deep calorimeter (proposed for the CASTOR detector). The energy deposits in the calorimeter versus its depth expressed in the number of the calorimeter layers (one calorimeter layer $\sim 1.8 \ (3.7) \ X_0$ in electromagnetic (hadronic) part of the calorimeter) are shown in the sector hit by the strangelet.

Unstable strangelet decaying into a bundle of 7 neutrons ($E_{\text{n}} \approx E_{\text{str}}/A_{\text{str}} \approx 200 \ \text{TeV}$).

Metastable strangelet ($A_{\text{str}} = 15, E_{\text{str}} = 200 \ \text{A TeV}, \tau \sim 10^{-15} \ \text{s}$).

Long-lived strangelet ($A_{\text{str}} = 15, \mu_q = 600 \ \text{MeV}$).

Figure 3: Examples of simulated transition curves recorded in the lead chamber and produced by various strangelets. Numbers of electrons $N_e$ are counted within the radius of 50 $\mu$m.
hope that future collider experiments, using much deeper calorimeters, will be able to distinguish between different strangelet lifetimes.

It is true that predictions concerning the decay modes of such hypothetical objects as strangelets can not be precise and in some points they are simply more or less justified speculations. The same remark concerns of course other exotic objects, among them the black holes. At the moment a weak dependence of the form of the strongly penetrating component on the mechanism of a strangelet formation and its decay modes strongly supports the SQM Centauro model.

- The strong penetrability power in the matter is mainly the result of the big concentration of energy in a small range of the phase space. The strangelets as the dense and cold objects with relatively high mass numbers are reasonable candidates for such species. The small geometrical cross section is the additional factor increasing the penetrability of the long-lived strangelets through the matter.

In [13, 37] we have calculated the mean interaction path of the stable strangelet, basing on [39]. The strangelet was considered as an object with the radius

\[ R = r_0 A_{\text{str}}^{1/3} \]

where the rescaled radius

\[ r_0 = \left( \frac{3\pi}{2(1 - \frac{2\alpha_c}{\pi})[\mu^3 + (\mu^2 - m^2)^{3/2}]} \right)^{1/3} \] (7)

\( \mu \) and \( m \) are the chemical potential and the mass of the strange quark respectively and \( \alpha_c \) is the QCD coupling constant.

The mean interaction path of strangelets in the absorber (e.g. tungsten)

\[ \lambda_{s-W} = \frac{A(W) \cdot m_N}{\pi(1.12A_{W}^{1/3} + r_0 A_{\text{str}}^{1/3})^2} \] (8)

It is clear that the main reason of the long interaction length of a strangelet is its small geometrical radius, being the function of the quark chemical potential \( \mu \). In principle, \( \mu \) is the parameter of the model, however, two points should be mentioned. Firstly, the value of this parameter (\( \mu = 600 \) MeV) has been estimated experimentally from the observed characteristics of cosmic ray Centauros. Morever, we have done simulations for very wide range of values of this parameter (\( \mu = 300 \) and 600 MeV in [13], \( \mu = 600 \) and 1000 MeV in [37]) and we found that the interaction length of the strangelet is always longer than that for the nucleus of comparable mass number \( A \), what results in the unexpectedly long penetrating showers. The examples of the values of the \( r_0 \) and \( \lambda_{s-W} \) for stable strangelet interacting in the tungsten absorber are shown in Table 2.

Fig. 4 shows examples of different stable strangelets, characterized by the values of parameters expected for the LHC energies and conditions (energy \( E_{\text{str}} = 10-40 \) TeV, baryon number \( A_{\text{str}} = 15-40 \), quark chemical potential \( \mu_q = 600, 1000 \) MeV). It is seen that all of them are characterized by very long attenuation pattern and they can be easily distinguished from the conventional events.
Table 2: Stable strangelets interacting in the tungsten absorber

| α | $A_{tg}$ | $A_{str}$ | $\mu$ [MeV] | $\lambda$ [cm] | $r_{str}$ |
|---|---|---|---|---|---|
| 0.3 | 172 | 15 | 7.3 | 1.0 | |
| 15 | 600 | 10.1 | 0.48 |
| 20 | 600 | 9.7 | 0.48 |
| 40 | 600 | 8.9 | 0.48 |
| 20 | 1000 | 11.4 | 0.28 |
| 40 | 1000 | 10.7 | 0.28 |

3 Conclusions

The QGP strangelet mechanism proposed in some of our papers offers a good description of anomalous cosmic ray events. In contrary, at this stage of development, the idea of explanation of Centauro like events via a decay of mini black holes encounters various difficulties when compared with experimental observations. However, some consequences of mini black hole scenario, such as appearance of huge $p_T$ particles, makes this idea worth of further considerations and encourages for more detailed studies.

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13
Figure 4: Transition curves of stable strangelets with energies $E_{str} = 10-40$ TeV, baryon number $A_{str} = 15-40$, quark chemical potential $\mu_q = 600$ MeV (the red lines) and 1000 MeV (the green lines). Energy deposit (MeV) in the calorimeter layers, in the octant containing a strangelet, is shown. Full line histograms show the HIJING estimated background.

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