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CAN COSMIC RAYS PROVIDE SIGN OF STRANGELETS?*

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We discuss the possible imprints of Strange Quark Matter (SQM) in cosmic ray data. In particular, we investigate the propagation of SQM through the atmosphere and discuss: *(i)* direct candidates for strangelets, *(ii)* exotic events interpreted as signals of SQM and *(iii)* muon bundles and delayed neutrons in Extensive Air Showers. The physics and astrophysics of SQM is shortly reviewed. We point out the possibility that extreme energy cosmic rays are the results of the decay of unstable primordial objects. Finally, the abundance of possible candidates for strangelets and their mass spectrum are estimated and compared with the astrophysical limits, and prospects of the possible observation of SQM in accelerator experiments are outlined.

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1. Introduction

In the astrophysical literature [1] one can find a number of phenomena which can be regarded as a possible manifestation of the existence of the so called Strange Quark Matter [2] (existing in the form of lumps called strangelets). This is extremely interesting possibility of apparently new stable form of matter (it can decay only via weak interactions, which for a bulk of matter consisting strangelet are very inefficient in reducing its size). In particular one observes (*cf.* [3] for relevant references):

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- anomalous cosmic ray bursts from *Cygnus X-3*,
- extraordinary high luminosity gamma ray burst from the *supernova remnant N49* in the Large Magellanic Cloud,
- or the so called *Centauro* events, which are characterised by anomalous composition of secondary particles with almost no neutral pions present.

There were also attempts to find lumps of SQM, called *strangelets,* in terrestrial experiments devoted to search for the Quark Gluon Plasma (QGP) state of matter but so far without apparent success (*cf.* Ref. [1] and last section below). This fact, however, does not preclude sensibleness of searching for strangelets in cosmic ray experiments, which deal with strangelets formed in completely different astrophysical mechanisms [2], besides one witnesses their production proceeding in collisions of the original CR flux with atmospheric nuclei [4]. However, any SQM produced at very early stage of the history of the Universe would have evaporated long time ago due to the action of weak interactions [5]. On the other hand SQM is probably continuously produced in neutron stars with a super-dense quark surface and in quark stars with a thin nucleon envelope [2]. Collisions of such objects could, therefore, produce small lumps of SQM, strangelets with $10^2 < A < 10^6$, permeating the Galaxy and possibly reaching also Earth, *i.e.*, *a priori* being detectable here. In this presentation we demonstrate how strangelets (not much different in size from the similar lumps of normal nuclear matter) can still penetrate deeply in the atmosphere. We estimate the initial flux of strangelets entering the atmosphere, and finally, we point out the possibility that extreme energy cosmic rays are the results of the decay of unstable primordial objects which can possibly be identified with strangelets. We shall list also the presently running and planned experiments looking for SQM being produced already at accelerators and summarise results obtained so far.

2. Some features of strangelets

Typical SQM consists of roughly equal number of up *(u),* down *(d)* and strange *(s)* quarks, and it has been found to be the true ground state of QCD [5], *i.e.*, it is absolutely stable at high mass numbers A and, because the energy per baryon in SQM could be smaller than that in ordinary nuclear matter, it would be more stable than the most tightly bound ^{56}Fe nucleus. The measure of stability of strangelets is provided by the so called separation energy dE/dA, *i.e.*, energy which is required to remove a single baryon from a strangelet. There exists some critical size given by a critical value of $A = A_{\rm crit}$ (vary from $A_{\rm crit} = 300$ to 400 depending on the various choices of parameters [5]) such that for $A > A_{\rm crit}$ strangelets are absolutely stable against neutron emission [6]. Below this limit strangelets decay rapidly by evaporating neutrons.

The small value of the charge to mass ratio, $Z/A \sim A^{1/3}$, expected in the case of strangelets [5,7], provide us with the main criterion for their discrimination among other debris when searching cosmic rays for such nuclearities.

As we have demonstrated in [3] the rescaled radius r_0 of strangelets (which follow A-dependence typical for nuclei, *i.e.*, $R = r_0 A^{1/3}$) is comparable to this of ordinary nuclei. Considering a lump of SQM visualised after [5] as Fermi gas of u, d and s quarks, with total mass number A which is confined in a spherical volume $V \propto A$, the rescaled radius r_0 is determined by the number density of strange matter [5]. For the values commonly accepted for SQM (like the mass of the strange quark $m \cong 150$ MeV and the chemical potential $\mu \cong 300$ MeV), the values of r_0 of the strangelets are comparable with that for the ordinary nuclear matter [3] (being only a bit smaller, with differences not exceeding 10%–20%). However, because the mass number A of strangelets is much larger than the mass number of ordinary nuclei, their expected geometrical cross sections are also much larger than those for normal nuclei.

3. Propagation of strangelets in the atmosphere

It does not mean, however, that some form of SQM does not penetrate deep in the atmosphere to be finally, registered. The apparent contradiction between its "normal" size and strong penetrability can be resolved in very simple manner. Strangelets reaching so deeply into atmosphere are formed in many successive interactions with air nuclei following one of the proposed possible scenarios:

(*i*) either an initially small strangelet picks up mass from the collisions with air atoms which during its passage through Earth atmosphere [8],

(*ii*) or an initially very heavy lump of SQM entering our atmosphere (with A of the order of 10^3) decreases due to subsequent collisions with air nuclei, until its mass reaches a critical value $A_{\rm crit}$ at which point it disintegrates [3,9].

In what follows we explore the second scenario developed by us recently. In this way one can accommodate both the most probably "normal" mean free paths for successive interactions and final large penetrating depth. Such scenario is fully consistent with all present experiments [9]. The scenario proposed and tested in [3] was that in the interaction of strangelet with target nucleus all quarks of the target (which are located in the geometrical

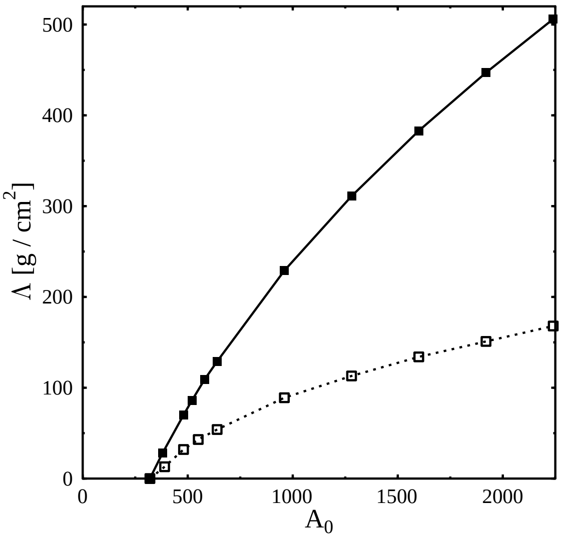

Fig. 1. Atmospheric length Λ after which initial strangelets reaches its critical size $A_{\rm crit} = 320$ drawn as a function of its initial mass number A_0 for SM (solid) and TM (dashed line) models of interaction with air nuclei. Consecutive squares indicate points where $A_0/A_{\rm crit} = 2, 3, \ldots$, (for $A_0 > 600$).

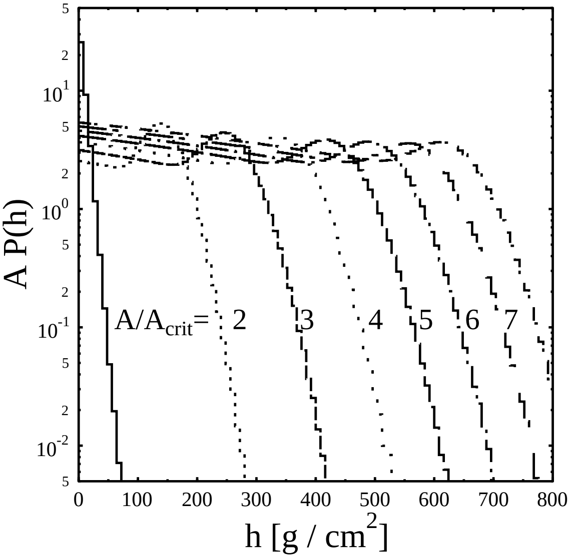

Fig. 2. Number of nucleons released in 1 g/cm^2 at depth h of the atmosphere from the strangelet with mass number ratios $A_0/A_{\rm crit} = 1, 2, ..., 8$, respectively, (in SM model).

intersection of the two colliding nuclei) are involved. It is assumed that each quark from the target interacts with only one quark from the strangelet; *i.e.*, during interaction the mass number of strangelet is diminished to the value equal to A–A_t at most. This procedure continuous unless either strangelet reaches Earth or (most probably) disintegrates at some depth h of the atmosphere reaching $A(h) = A_{\mathrm{crit}}$. This result, in a first approximation (in which $A_t \ll A_{\mathrm{crit}} < A_0$), in the total penetration depth of the order of $\Lambda \cong 4/3\Lambda_{NA_t}(A_0/A_t)^{1/3}$. Fig. 1 shows at what depth strangelets start to become critical whereas Fig. 2 exposes the expected number of nucleons released from strangelet at depth h of the atmosphere.

In numerical estimations provided in [3,9] in addition to the above Standard Model (SM) of collisions of strangelets with the air nuclei, we have also considered the so called "tube-like model" (TM) in which all quarks from geometrical intersection region, both from projectile and target, participate in the collision. However, this variant, which leads to the maximal possible destruction of quarks in strangelets, *i.e.*, to their maximal decreasing, cannot describe adequately experimental data (*cf.* Fig. 3).

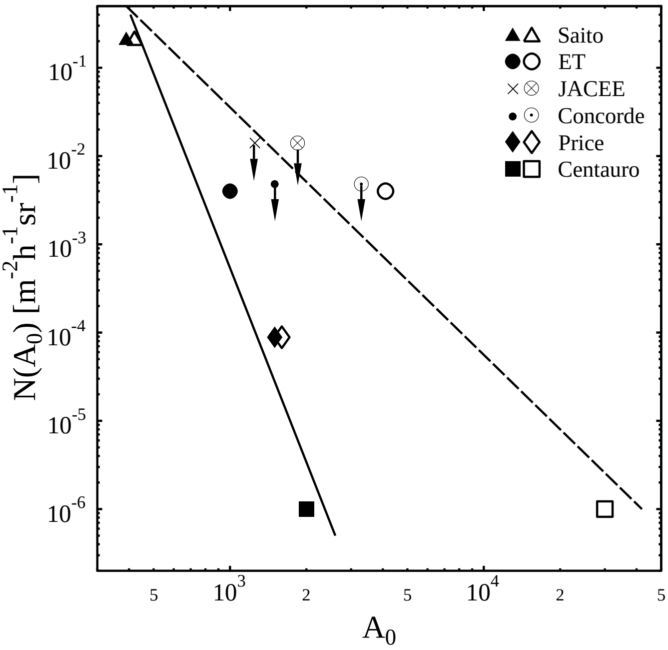

Fig. 3. The estimation of the expected flux of strangelets on the border of atmosphere, $N(A_0)$, as a function of their mass number as obtained from SM (full symbols; solid line for power fits) and TM (empty symbols; dashed line). See [3,9] for further details.

4. Cosmic nuclearities

There are several reports suggesting direct candidates for SQM. In particular, the following anomalous massive particles, which can be interpreted as strangelets, have been apparently observed in Cosmic Ray (CR) experiments:

(*i*) In counter experiment devoted to study primary CR nuclei two anomalous events have been observed (*Saito*) [10] with values of charge $Z \cong 14$ and of mass numbers $A \cong 350$ and $A \cong 450$, respectively.

(*ii*) The so called Price's event [11] with $Z \cong 46$ and $A > 1000$, regarded previously as possible candidate for magnetic monopole.

(*iii*) The so called Exotic Track (ET) event with $Z \cong 20$ and $A \cong 460$ has been reported in [12]. The name comes from the fact that the projectile causing that event has apparently traversed ≈ 200 g/cm^2 of atmosphere.

It is remarkable that all possible candidates for SQM have mass numbers near or slightly exceeding $A_{\rm crit}$ (it is also argued that *Centauro* [13] event, regarded to be possible candidate for strangelet, contains probably ≈ 200 baryons [14]). Also the values of Z and A mentioned above are fully consistent with the existing theoretical estimations for Z/A ratio, which is characteristic for the SQM [15], *cf.* Fig. 4.

Using our scenario of strangelet propagation [3, 9] and experimental data taken at different atmospheric depths we can estimate the flux of strangelets reaching our atmosphere, *cf.* Fig. 3. The experimental data *Saito, ET* [10,12] and *Centauro* [13] on measured fluxes on different atmospheric depths as well as the corresponding upper limits (no strangelets found so far), *JACEE* [16] and *Concorde* [17] are processed. Notice, that Price's data favour standard model. In terms of fits (for 3 points: *Saito, ET, Centauro*) one gets: $\sim A_0^{-7.5}$ for SM and $\sim A_0^{-2.8}$ for TM (dashed line). The choice of the power-like form of standard model was dictated by the analogy to nuclear fragmentation and the expectation that decay (fragmentation) of a strange star after its collision will result in the production of strangelets with similar distribution of mass.

The analysis [3, 9] of the above listed candidates for SQM indicate that the abundance of strangelets in primary cosmic ray flux is roughly $F_{\rm S}(A_0 = A_{\rm crit})/F_{\rm tot} = 2.4 \times 10^{-5}$ at the same energy per particle.

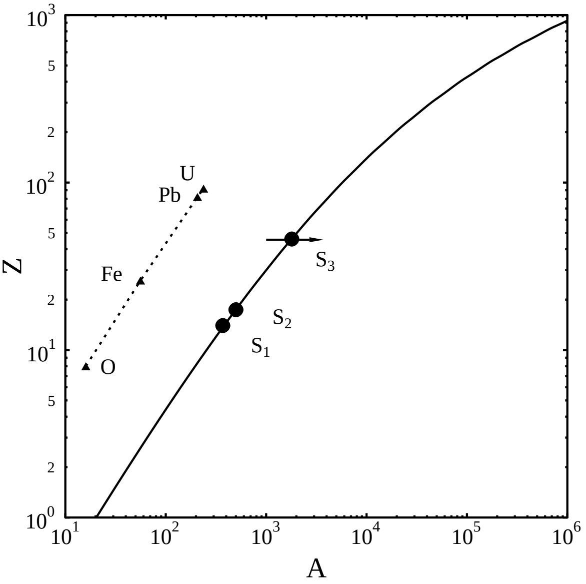

Fig. 4. The relation of Z and A for SQM (solid line) in comparison with the same for normal nuclei (dashed line). Notice that candidates for strangelets ($S1$ [10], $S2$ [12] and $S3$ [11]) lie on theoretical line.

5. Exotic events

We would like to discuss now shortly a number of existing experimental results obtained by Emulsion Chamber experiments, which can be regarded as exotic (*i.e.*, not encountered so far in accelerator experiments and, therefore, still waiting for its proper understanding) [18]. Those are, for example, centauro species, super-families with "halo", the strongly penetrating component, *etc.* As already mentioned, they can hardly be explained in terms of standard ideas about hadronic interactions, which we have learned so far from accelerator experiments. Our Monte Carlo simulations show, however, that these phenomena could not originate from any kind of statistical fluctuations of "normal" hadronic interactions, indicating, therefore, that either some new mechanism of interaction or new primaries might appear in the high energy interactions. Our attitude is to attribute all those effects to action of strangelets.

5.1. Mini-cluster

The transition curves of anomalous cascades exhibit surprising features: a strong penetrating nature associated with very slow attenuation and appearance of many maxima with small distances between them (about 2 to 3 times smaller than the calculated distances for the "normal" hadron cascades). We investigate [19] the possible connection between this extremely penetrating component, frequently accompanying the cosmic ray exotic phenomena, and the hypothesis of the formation of strangelets taking place in the process of strangeness distillation, being the last stage of the evolution of the quark matter droplet. We find that many-maxima long-range cascades observed in the homogeneous lead emulsion chamber experiments can be produced in the process of strangelet penetration through the apparatus. The bundle of hadrons provides the possible explanation for the anomalous (strongly penetrating) showers. In order to explain the mutual distance distribution of the sub-showers maxima positions, we need only a few (~ 7) hadrons concentrated in the very forward region. The assumption of strangelet with $A = 15$ penetrating through the chamber and evaporating neutrons leads to the formation of the long-range many-maxima cascades similar to those observed in the experiment.

The existing experimental data, however, are not sufficient to decide if they are produced by (stable or unstable) strangelets. The CASTOR detecting system, proposed as a subsystem of the ALICE experiment at LHC could help in solving the existing uncertainties [20].

5.2. Centauros

The Centauro and mini-Centauro events, characterised by the extreme imbalance between hadronic and gamma-ray components among the produced secondaries, are the best known examples of numerous unusual events reported in cosmic-ray experiments. There are many attempts to explain them (different types of isospin fluctuations or formation of disoriented chiral condensate, multiparticle Bose–Einstein correlations, strange quark matter formation or interaction). It was shown that families recorded at mountain altitudes are insensitive to any isospin fluctuations. Centauro-like phenomena require deeply penetrating component in cosmic rays. We claim that they can be products of strangelets penetrating deeply into atmosphere and evaporating neutrons [21]. Both the flux ratio of Centauros registered at different depths and the energy distribution within them can be successfully described by such concept.

5.3. Coplanar emission

Phenomenon of alignment of structural objects of gamma-hadron families near a straight line in the plane at the target diagram was first observed during examination of multicore halos and, later, when observing distinguished energetic cores (*i.e.*, halos, energetic hadrons, high energy gamma quanta or narrow particle groups) [22]. The excess of aligned families found in these cases exceeds any known conventional concept of interaction. Many attempts to interpret this phenomenon of coplanar emission were undertaken. However, up to now no satisfactory explanation exists. The trouble is that this alignment occurs in spite of the fact that there is always substantial number of interactions contributing to family formation. The long-flying component with mean free path of the few hundreds of g/cm^2 is required. As a tentative explanation the arrival of strangelets with high spin ($J \sim A^2$) and gradual dispersion of mass $A(h)$ along their way through the atmosphere can be given.

6. Families and EAS induced by strangelets

The characteristic features in strangelets propagation in the atmosphere are illustrated in Figs. 1 and 2. Many characteristics of the families and EAS are sensitive to existence of primary strangelets. As an illustration we show in Fig. 5 our expectations for the corresponding distributions of hadrons in EAS detected at Chacaltaya. Analysis of gamma-ray families induced by cosmic rays also shows significant differences between SQM and "normal" hadronic matter. On Fig. 6 we show differences in $f = E/\sum E$ distribution in families with $\sum E = 100$–200 TeV initiated by primary protons and SQM. Families from SQM are characterised by soft energy spectrum (being also

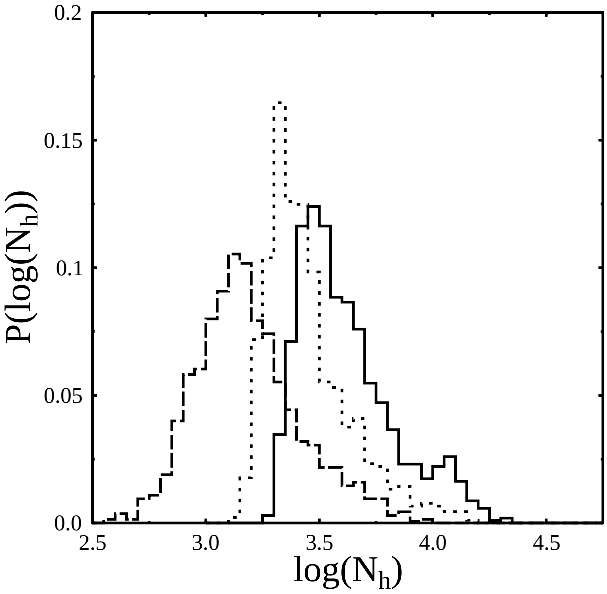

Fig. 5. Multiplicity distribution of hadrons in EAS with size $N_e = 10^6$–10^7 detected at Chacaltaya and initiated by primary protons (dashed line), iron nuclei (dotted line) and strangelets with $A_0 = 400$ (solid line).

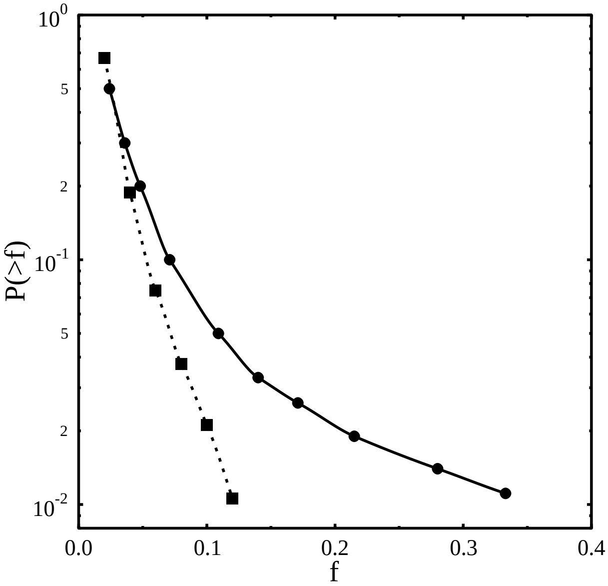

Fig. 6. Integral $f = E/\sum E$ distribution in families with $\sum E$ = 100–200 TeV initiated by primary protons (dots) and SQM (squares).

much broader) then those induced by primary proton. The examples of results obtained for muons in EAS with and without strangelets are presented in Figs. 7 and 8.

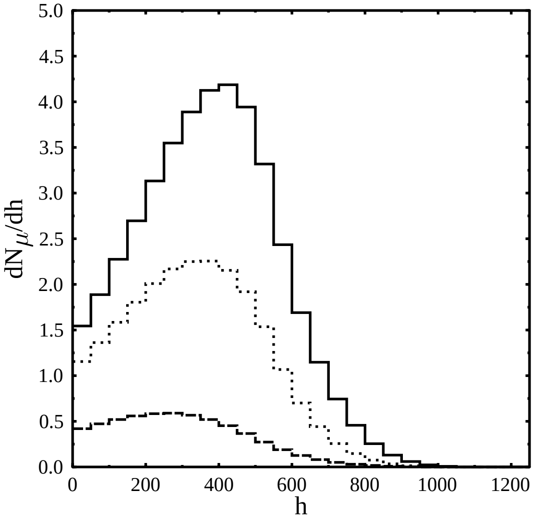

Fig. 7. Depth of origin of muons in EAS originated by primary protons (dashed line), iron nuclei (dotted line) and strangelet with $A_0 = 400$ (solid line).

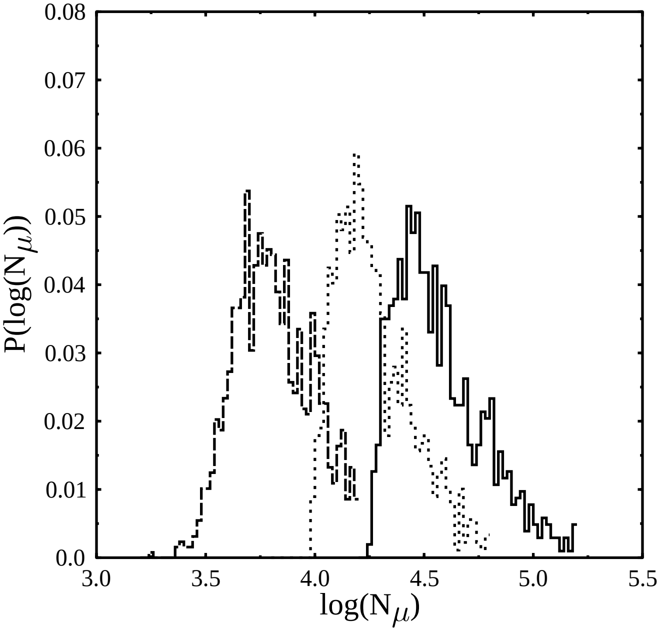

Fig. 8. Multiplicity distributions of muons in EAS with size $N_e = 10^6$–10^7 detected at Chacaltaya and indicated by primary protons (dashed line), iron nuclei (dotted line) and strangelets with $A_0 = 400$ (solid line).

7. Muon bundles from CosmoLEP

We would like to bring ones attention to the data from the cosmic-ray run of the ALEPH detector at the CosmoLEP experiment. Data archives from the ALEPH runs have revealed a substantial collection of cosmic ray muon events [23]. More than 3.7×10^5 muon events have been recorded in the effective run time 10^6 seconds. Multi-muon events observed in the 16 m^2 time projection chamber with momentum cut-off 70 GeV have been analysed and good agreement with the Monte Carlo simulations obtained for multiplicities N_μ between 2 and 40. However, there are 5 events with unexpectedly large multiplicities N_μ (up to 150) which cannot be explained, even assuming pure iron primaries.

We shall estimate the production of muon bundles of extremely high multiplicity in collisions of strangelets with atmospheric nuclei [24]. Monte Carlo simulation describes the interaction of the primary particles at the top of atmosphere and follows the resulting electromagnetic and hadronic cascades through the atmosphere down to the observation level. The integral multiplicity distribution of muons from ALEPH data is compared with our

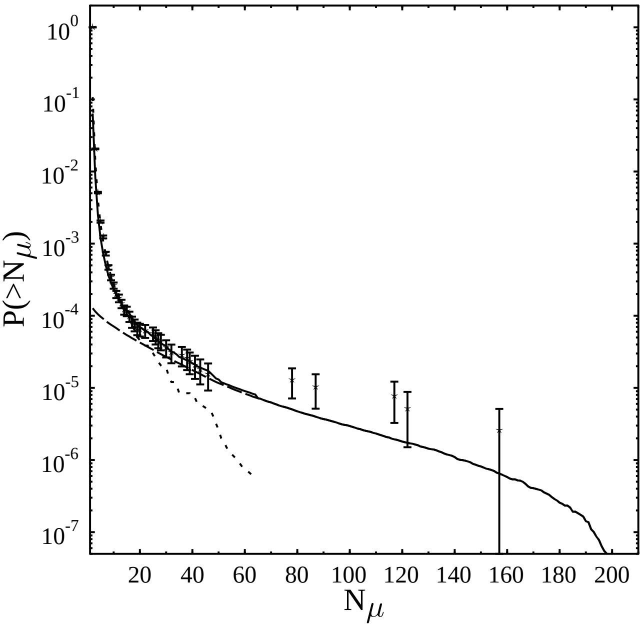

Fig. 9. Integral multiplicity distribution of muons for the CosmoLEP data [24] (stars). Monte Carlo simulations for primary nuclei with "normal" composition (dotted line) and for primary strangelets with $A = 400$ (dashed line). Full line shows the summary (calculated) distribution.

simulations in Fig. 9. We have used here the so-called "normal" chemical composition of primaries with 40% protons, 20% helium, 20% CNO mixture, 10% Ne–S mixture, and 10% Fe. It can describe low multiplicity ($N_\mu \leq 20$) region only. Muon multiplicity from strangelet induced showers are very broad. As can be seen, the small amount of strangelets (with the smallest possible mass number $A = 400$ (the critical mass to be $A_{\rm crit} = 320$ here)) in the primary flux can accommodate experimental data. Taking into account the registration efficiency for different types of primaries one can estimate the amount of strangelets in the primary cosmic flux. In order to describe the observed rate of high multiplicity events one needs the relative flux of strangelets $F_{\rm S}/F_{\rm tot} \simeq 2.4 \times 10^{-5}$ (at the same energy per particle). It can be interesting to point out that the high multiplicity events discussed here (with $N_\mu \simeq 110$ recorded on 16 m^2) corresponds to $\sim$ 5600 muons with $E_\mu \geq 70\,$GeV (or 1000 muons with energy above 220 GeV). These numbers are in surprisingly good agreement with results from other experiments like Baksan Valley where 7 events with more than 3000 muons of energy 220 GeV were observed [25].

8. Delayed neutrons

In the last years some evidences have been found [26] for the existence of abnormal large events in neutron monitors that we shall call delayed neutrons. These phenomena could not be explained by the known mechanisms of hadronic cascades development.

On the other hand such delayed neutrons may appear after decay of small, unstable strangelet, which was created as a result of interaction of primary cosmic rays with air nuclei. Mean lifetime of that strangelet may be few thousands μs long [27, 28]. We calculated arrival time distribution of neutrons, like shown in [29]. We used this distribution for simulation of the time distribution of delayed neutrons which appear after decay of the strangelet. The energy spectrum of evaporated neutrons followed the Planck distribution with $T = 4$ MeV. The integration over energy was performed in the energy interval 1–50 MeV. In Fig. 10 we show experimental data from standard neutron super monitor 18NM64 [30] in comparison with our simulations. If we assume mean lifetime of a strangelet being $\tau \simeq 2000$ μs it describes satisfactorily experimental data.

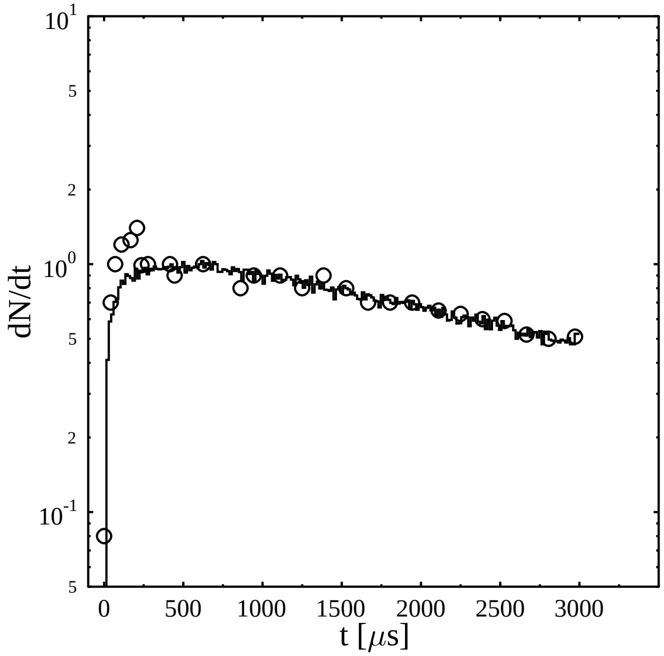

Fig. 10. Temporal distribution of highest multiplicity neutron event (circles) recorded by boron neutron counter [30] compared with Monte Carlo simulations (full line) with mean lifetime of strangelet $\tau = 2000$ μs.

9. Interactions with background radiation

In analysis of cosmic rays propagation through the Universe one should consider their interaction with background radiation. In the region of high energies, the main processes are: pair production $p + \gamma \to p + e^+e^-$, photoproduction $p + \gamma \to p + \pi^0$ and nuclei photodisintegration. The energy losses of nuclei with mass A during their interaction with background photons given by [31] shows remarkable Z^2/A behaviour ($\sim A^{-1/3}$ in the case of strangelets). In Fig. 11 we show the energy losses of nuclei and strangelets arised due to interactions with background radiation. As can be seen, because of their large mass number A, strangelets can propagate through the Universe with very small energy losses. Critical energy for strangelets is see-mighty larger then this for protons (*cf.* Fig. 12). This can lead to the idea that extremely energetic cosmic rays are not the result of the acceleration of protons, but rather of the decay of unstable primordial objects. We expect that strangelets may be highly energetic primordial remnants of the Big Bang falling into this category.

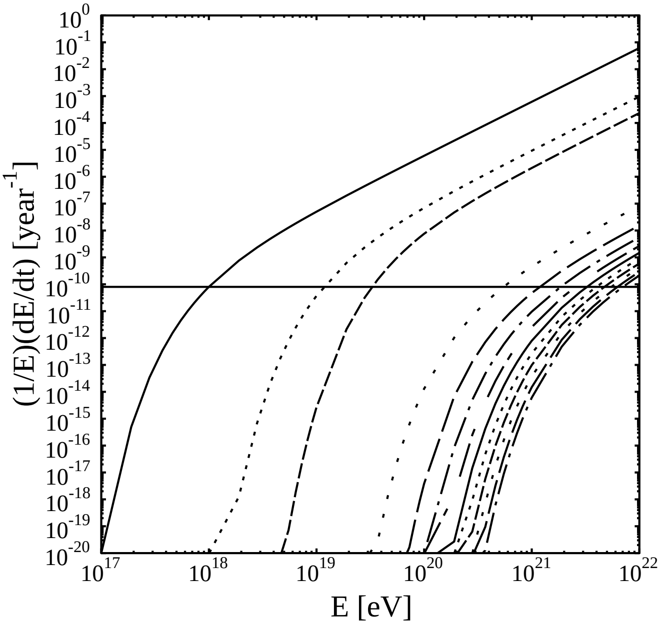

Fig. 11. Energy losses of protons, O, Fe, and some strangelets with mass number $A = 320, 640, ..., 3200$ (respectively, from left) due to interaction with cosmic background radiation. Horizontal line shows red shift limit.

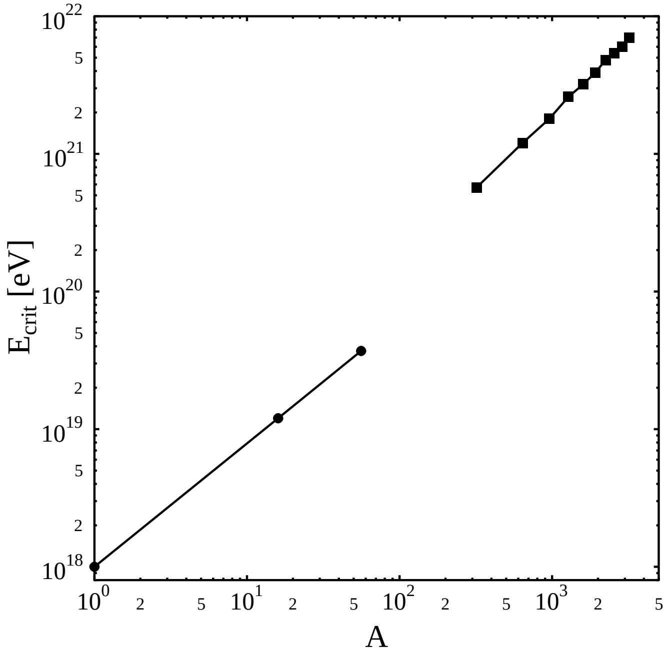

Fig. 12. GZK cutoff $E_{\rm crit}$ as a function of mass number A. Dots represents normal nuclei, squares — strangelets.

10. Abundance of strangelets

We can estimate flux of strangelets on the border of atmosphere using the existing experimental data taken at different atmospheric depths [9]. Interpreting them in terms of our scenarios of propagation of strangelets in the atmosphere, the flux of strangelets hitting the Earths atmosphere as a function of mass is evaluated. The results can be parametrised as follows: $\propto A_0^{-7.5}$. The estimated flux of strangelets is consistent (*cf.* Fig. 13) with the predicted astrophysical limits and the upper limits given experimentally [32].

It is interesting to note that essentially the same power behaviour is observed also for occurrence of normal nuclei in the Universe. Namely, combination of existing data [33] on the chemical composition (for normal nuclei, *i.e.*, $Z < 100$ or $A < 250$) comprising CR (at relativistic energies) and different astrophysical objects (like solar system matter, Earth's core or Sun's atmosphere) can be described by the formula $N(A) \propto A^{-7.5}$ (*cf.* Fig. 14).

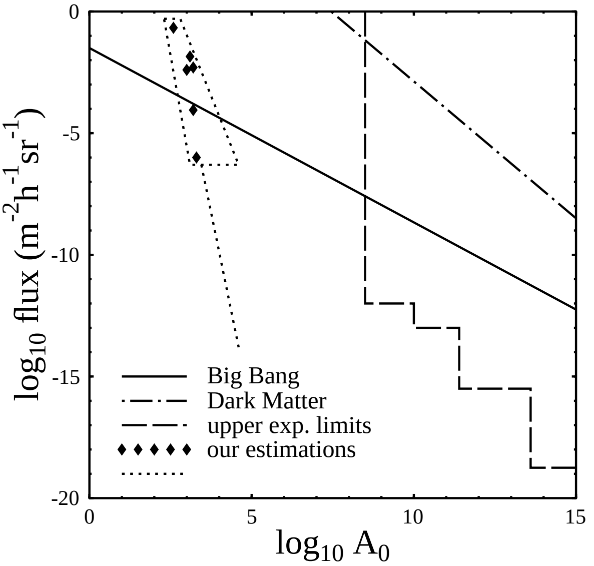

Fig. 13. The expected flux (our results) of strangelets compared with the upper experimental limits, compiled by Price [33], and predicted astrophysical limits: Big Bang estimation comes from nucleosynthesis with quark nuggets formation; Dark Matter one comes from local flux assuming that galactic halo density is given solely by quark nuggets.

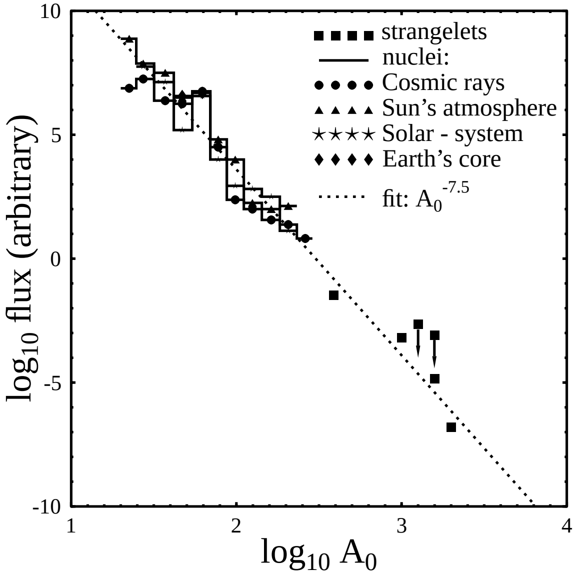

Fig. 14. Comparison of the estimated mass spectrum $N(A_0)$ for strangelets with the known abundance of elements in the Universe [34].

11. Summary and conclusions

Problem of possible Strange Quark Matter existence in the Universe were discussed from many year. There are large amount of phenomena that cannot be explain without assuming of existence of SQM. We demonstrated only few examples from various fields of cosmic ray physics. In particular we showed that extremely high energy cosmic rays, exceeding the usual GZK limit, can indeed exists provided they are composed of strangelets. Strangelets can be, therefore, considered as natural candidates for looked for unstable primordial objects (remnant of the Big Bang), decay of which can provide such energetic cosmic rays.

Let us finally mention a few words on problems of observability of strangelets in heavy-ion collisions. One must stress from the very beginning that those are different objects from the SQM originated astrophysically in what concerns their size. In comparison with the former they will be small, fast decaying (because of the dominance of the surface effects) object. Nevertheless, such strangelets can be to originate in the hadronisation of a QGP fireball of any high-baryon density and baryo-chemical potential, which is formed in ultra-relavistic nucleus–nucleus collisions. Metastable droplets of strange quark matter can be formed during the phase transition. This is due to the production of kaons (containing $\overline{s}$ quarks) in the hadron phase while s quarks remain in the deconfined phase. The $s-\overline{s}$ separation results in a strong enhancement of the s-quark abundance in the quark phase [34]. Several experimental searches for SQM had been carried out at the AGS at the BNL and at the SPS at the CERN.

- The experiment E864 (BNL–AGS) aims to study heavy-ion collisions in an open geometry spectrometer in $11.5A$ GeV Au+Pb collisions [35]. So far no neutral strangelets was found (the upper limit of strangelets obtained is of the order of 10^{-8} per central collisions).

- NA52 is the only dedicated experiment at CERN which searches for strangelets in sulfur–tungsten and lead–lead interactions. Statistics of several 10^{12} interactions have been collected. This data set addresses the question of a short-lived strangelet candidate with mass 7.4 GeV and charge $Z=-1$ [36].

A new experimental approach proposed recently is to search for strangelets by using unconventional strangelet signature, namely by looking at the energy deposition pattern (*cf.* Section 5.1) trying to observe strangelets occurring as deeply penetrating objects. The corresponding detector system CASTOR is proposed as an integral part of the planned CERN–LHC

ALICE experiment [37]. CASTOR will cover the very forward rapidity region ($5.6 < \eta < 7.2$). This is assumed to be a preferred region to create a dense quark matter fireball because it is baryon-rich. This could probe a strangelets separation mechanism like distillation.

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