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ESSAY:

«Centauro» events

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1 Introduction

From the point of view of the processes of obtaining data on multiparticle processes, the attractiveness of experiments with cosmic rays is due to their high energies and the ability to study the fragmentation region at energies not yet achieved in accelerator experiments.

However, although experiments with cosmic rays allow us to research the fragmentation of the processes of formation of many particles, they face a number of difficulties. A significant problem is the uncertainty of the composition of primary cosmic rays at energies above 10^{15} eV, and the fact that the flux of primary cosmic rays decreases rapidly with increasing energy (см рис. 1).

Air shower. The name itself – Air shower fairly well reflects the phenomenological picture of the phenomenon that occurs when particles of ultrahigh energy cosmic radiation pass through the atmosphere - the formation of cascades of particles.

The existence of atmospheric showers covering an area of thousands of square meters was shown in 1938 by the experiments of P. Auger. The discovery of cascades from a large number of charged particles coincided with the advent of the electron-photon cascade theory, which made it possible to identify broad atmospheric showers with electron-photon cascades arising in the atmosphere from primary ultrahigh-energy electrons(см. рис. 2)

This point of view on the nature of air showers has been generally accepted for a number of years. However, D. V. Skobeltsyn in 1942, analyzing data on the spatial distribution of particles in air showers, suggested that there is an overlap of two distributions - one of these distributions corresponds to the electron-photon cascade theory. The other, broader one, is related to the intervention of additional interactions - hadron interactions.

«Centauro» events. Long-term measurements of the processes occurring with cosmic particles in the Earth's atmosphere, performed by various experimental techniques, have led to the discovery of a number of exotic phenomena that do not fit into the modern understanding of interactions at high and ultrahigh energies. One of the first exotic phenomena observed in the 80s of the last century was an event recorded by a calorimetric type setup. The event, which was registered by Japanese physicists, had many difficult-to-explain phenomena. This event was called «Centauro».[1]

«Centauro» - is a special type of nuclear interaction in which it is assumed that about one hundred baryons (and possibly including anti-baryons) are formed without any significant meson emission. In addition, there is a similar type of event with a large multiplicity of baryons (10-20), which is called «Mini-Centauro»[2], [3].

2 Experimental setups

2.1 Identification of air showers

Electromagnetic component of an Air Shower. Electromagnetic, muon and hadron components are present in a air shower. The electromagnetic component of the shower is the largest in terms of the number of particles and exceeds all the others by about two orders of magnitude. Consequently, conventional Geiger, scintillation or water Cherenkov detectors located on the surface register mainly this component. Most of the setups created for the study of an Air Shower primarily measure the electromagnetic component.

Many of the listed setups also register the muon component. For the selection of muon events, detectors protected by a sufficient thickness of matter to absorb electrons and gamma quanta are used. Basically, these are either underground detectors, or detectors under a thick layer of an absorber (for example, iron), or water Cherenkov detectors of large volume.

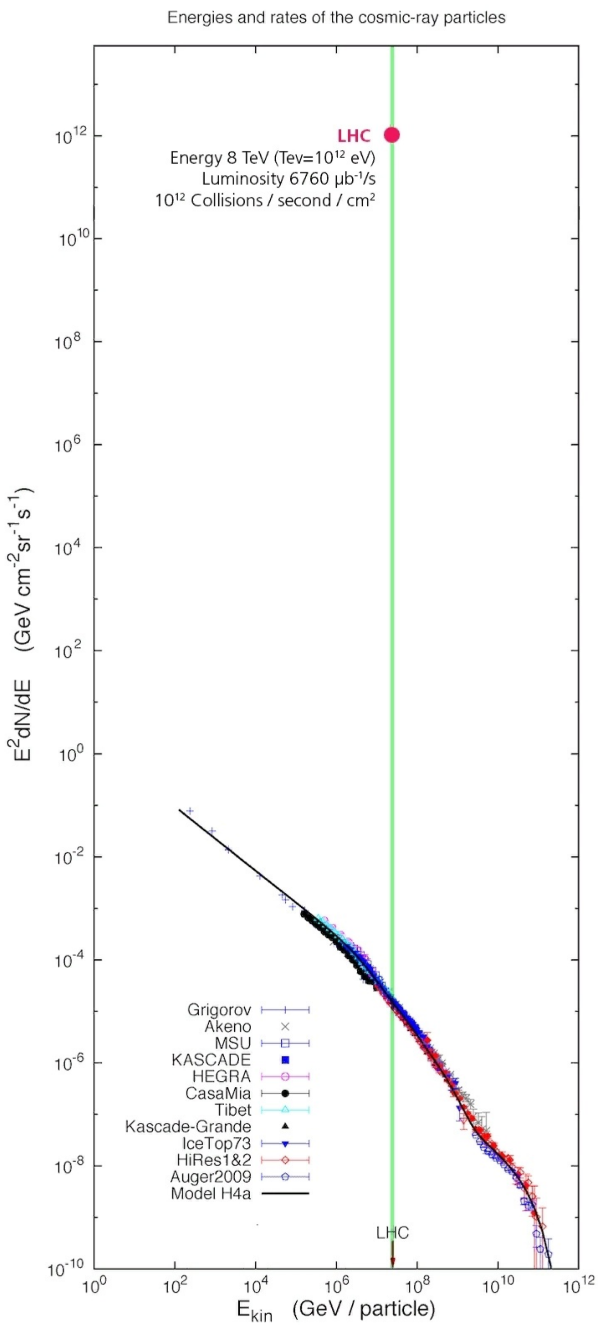


Рисунок 1: Visual comparison of collider experiments and experiments with cosmic rays.

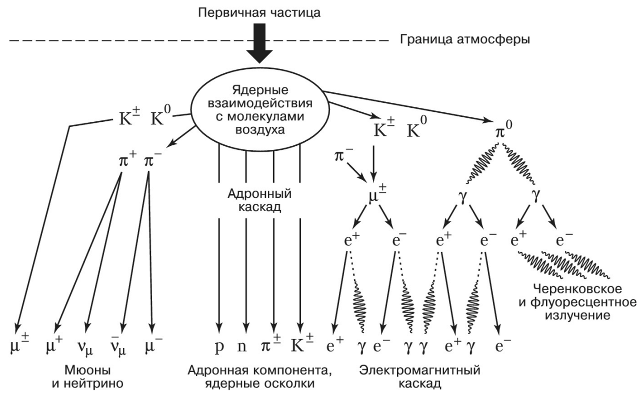


Рисунок 2: **A sketch of the development of a Air shower**: $K^{\pm}$ and K^0 are charged and neutral K-mesons, $\pi^{\pm}$ and π^0 are charged and neutral π -mesons, $\mu_{\pm}$ – muons, p – proton, n – neutron, γ – photon

The hadron component of an Air Shower. The situation is much worse with the hadron component. To study it, X-ray films and nuclear emulsions were used in experiments on Chakaltaya and Pamir, ionization calorimeters, neutron monitors. The main problem in the study of the hadron component is the complexity and high cost of the detectors used, and as a consequence their small number compared to conventional air-shower detectors. Most of the setups that register air shower do not have hadron detectors at all. And in those setups where there are such detectors, their area is not comparable with the size of the studied showers and the area of the electromagnetic component detectors (no more than several hundred square meters).

The hadron component in the depths of the atmosphere mainly consists of protons, neutrons and pions. The proportion of pions in the cosmic ray flux depends on the energy and height. At low energies, pions decay rapidly, and their flow in the atmosphere is small. As the energy of the pions increases, the probability of decay decreases, and at a certain critical energy, the nuclear interaction becomes more likely than decay. At energies significantly exceeding the decay of pions, it plays a small role, and their flow is large.

In experiments with cosmic rays, the cross section of the inelastic interaction is measured, i.e. the interaction is considered to be the birth of at least one additional particle, charged or neutral. In this case, one of the important parameters is multiplicity. The total multiplicity is the sum of charged and neutral particles.

Рисунок 3: **Emulsion experiment on the city of Chakaltaya (Andes, Bolivia).**Unique characteristics of the setup - the height of the location (4370 m above sea level); the world's largest ($\sim$ 1000 m^2) solid-state tracking camera with high spatial resolution ($\sim$ 10 microns) and with a high threshold for particle registration ($\sim$ 4 TeV)

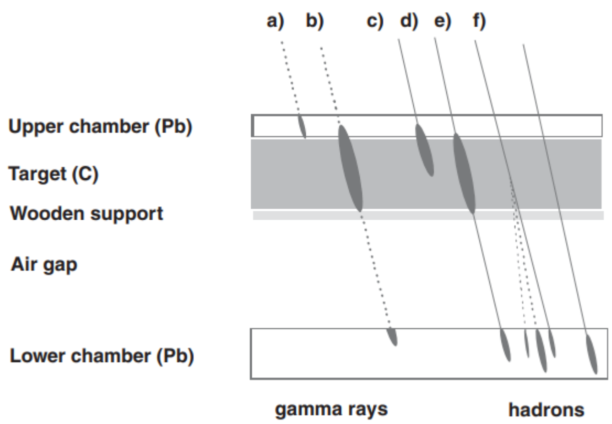


Рисунок 4: **The main structure of the Chakaltaya chamber.** Air shower identification - (a) beam continuation track; (b) track with continuation; (c) Pb-jet in the upper chamber without continuation; (d) Pb-jet in the upper chamber with continuation; (e) showers from the C-jet in the target; (f) Pb-jet in the lower chamber.

When analyzing the passage of cosmic radiation particles through matter, it is necessary to know the spectra of hadrons that are formed in nuclear interactions. One of the important properties of strong interactions is the limitation of the average transverse momentum of secondary particles. The experiment shows that the transverse momentum of secondary pions weakly increases from 0.3 GeV/s to 0.42 GeV/s. The average transverse momentum is greater in those events where the multiplicity is greater.

In hadron interactions, the inelasticity coefficient plays an important role, which is defined as the fraction of the energy of the primary particle carried away by secondary particles. At high energies, the process of deeply inelastic collisions manifests itself. As a result of hadronization, they turn into hadron beams - jets having large transverse immomentum. At high energy, a quark, in the process of hadronization, manages to emit a gluon, and then three jets can occur (the so-called three-jet events).

The measured cross sections in experiments with cosmic rays contain systematic errors caused by the complex composition of cosmic radiation, depending on energy (outside the atmosphere - a complex isotopic composition of primary particles, in the depths of the atmosphere - an admixture of pions). The independence of the energy of interacting nucleons of the partial coefficient of inelasticity in interactions with lead nuclei, as well as the absorption path of nuclear cascade avalanches of nucleons with an energy below 10 TeV, indicate the preservation of scale invariance in collisions of nucleons with nuclei up to the above energy.

2.2 Chakaltaya Observatory

The design of the experimental setup is a heterogeneous calorimeter made of plates of nuclear photoemulsion and lead absorbers. Gamma radiation or an electron, either entering the calorimeter from the outside or generated inside the chamber itself, creates an electron-photon-positron shower. Photoemulsion plates superimposed on each other record tracks of the electromagnetic cascade.

The structure of the entire detector in Chakaltaya consisted of four parts:

- upper detector;
- absorber layer;
- air gap;
- lower detector

The detector that reported the exotic signal was not designed to hunt for events like «Centauro». Initially, the detector was designed to study the multiple formation of pions formed by the interaction of cosmic ray hadrons with carbon. This determined the specific type of detector.

The main goal was to research the nuclear interactions occurring in the absorber layer, the thickness of which corresponds to 1/3 of the average free path for nuclear interactions. The hadron jet in the experiment was designated as «C-jet», since the main composition of the absorber material in experiments of this type was carbon.

The idea of creating this two-level camera comes from the following three considerations. Firstly, the upper detector works here as a shield from atmospheric gamma rays and electrons entering the absorber and the lower detector. Secondly, the target layer is made of a low I material, so that it is almost transparent to the gamma rays emitted by the C-jet. And, thirdly, the air gap provides sufficient separation of gamma rays from C-jets.

When the electron shower spreads through the sensitive layer in the chamber, it creates a dark spot on the X-ray film. The darkness of the spot is measured using a photometer. A high-energy hadron interacts with lead or carbon nuclei. The photonic component arising in the target layer is recorded as X-rays in the lower detector. A sign of such a process is the decay of pions (π^0), which are generated in these collisions. The decay of pions leads to the formation of γ rays. The threshold for detecting the energy of showers observed in the X-ray film is 1 TeV.

3 Events of the type «Centauro»

«Centauro» - this is a special type of interaction in which about a hundred baryons are formed without any significant meson radiation.

The event was detected first during scanning of the X-ray film on which C-jets were expected. On the X-ray film, a group of several dozen rain spots was visible, grouped in a narrow area with a diameter of 1 cm, with a total visible energy of significantly more than ∼200-300 TeV.[5]

It is assumed that the family of spots in the upper detector is several times larger, both in quantity and energy, than its continuation in the lower detector. The situation with «Centauro-I» was the opposite. The upper half of the event did not allow reconstructing its lower half, and vice versa. Because of this imbalance, the name «Centauro-I» was chosen. According to the initial analysis, the event consisted of only one γ ray and 49 hadrons.[6]

The initial interpretation of the event «Centauro-I» suggested that two families of cosmic rays were associated with this event. It has also been hypothesized that interactions can occur not only in the chamber, but also at high altitudes. The characteristic features that are believed to be relevant to the description of the phenomenon were (1) a large number of hadrons and (2) a small number of γ rays. Another characteristic moment is associated with the proportion of the hadron energy Q_h of the total observed energy of the event. (Thus, four more candidates were found, named Centauro-II, III, IV, V)[7].

3.1 Phenomenology of the event

The observed multiplicity of the five events «Centauro» is in the range of 63-90 hadrons, with an average of 75[8]. Hadrons are isotropically emitted, and their distribution of energy and transverse momentum has an exponential form:

$$\frac{dN}{dp_T^2} \sim exp(-p_T^2/p_{T0}^2)$$

The average observed transverse momentum calculated on the basis of the derived decay point of the fireball of the event «Centauro-I» is $p_T = 0.35 \pm 0.14 \mathrm{GeV/s}$. From here we can estimate the average transverse momentum of events, which is ($p_T = 1.75 \pm 0.7$GeV/s. This is a very large transverse momentum, about three times higher than the average transverse momentum measured for baryons in core-core collisions at $\sqrt{s} = 200.4$GeV in CERN SPS, which leads to the idea of explosive decay of a superdense fireball (fireball), and not the typical nuclear fragmentation [9].

The events «Centauro» were observed in experiments with cosmic rays in the region of low velocities (kinematic value $\frac{1}{2}\ln(\frac{E+p}{E-p})$) and presumably, the distribution of the longitudinal momentum of the fireball obeys the same law scale invariance, described by the empirical formula [10], established at lower energies for large x_F:

$$\frac{dN}{dx_F} \sim (1-x_F)^n$$

The average observed energy of the events was about 348 TeV. If we take the inelasticity coefficient $k_\gamma = 0.2$, then the total average interaction energy of Centauro will be

$$< E_h >= \frac{< E_h(\gamma) >}{k_\gamma} \sim 1740 \quad TeV$$

In the fireball coordinate system, each isotropically emitted particle (nucleon) has energy:

$$< E_n >= \sqrt{\left(\frac{4}{\pi} < p_T >\right)^2 + M_n^2} \sim 2.4 \pm 0.8 \quad GeV$$

, where M_n is the mass of the nucleon. With the average multiplicity equal to $< N_h >= 75$, the mass of the average fireball becomes:

$$< E_f >=< N_h >< E_n >\sim 180 \pm 60 \quad GeV$$

3.2 Other events similar to the «Centauro» event

In addition to «classical Centauroa», quite reasonable statistics of Centauro-like (or hadron-rich) events were collected by both Chakaltaya and Pamir experiments. Unfortunately, unlike «Centauro-I», some of these events interacted at rather large distances from the detector, so they have a significant share of the electromagnetic component, which was probably generated in nuclear and electromagnetic cascade processes in the atmospheric layer above the chamber. In addition, serious difficulties have arisen in the measurement and analysis of some exotic superfamilies (with very high visible energy, $E_{vis} \geq 500$ TeV), which is very often accompanied by the so-called «halo». The 1 table describes the events of [11].

4 Physical models of Centauro events

4.1 Quark-gluon plasma

Experimentally observables, such as multiplicity, transverse momentum, energy spectra and velocity distributions of secondary particles, inspired the fireball model, through which estimates of thermodynamic parameters [1] were obtained.

At the first stage of evolution, after the collision, the quark-gluon plasma, called the primary fireball, contains $u-$ and $d-$quarks and gluons. The high bariochemical potential prevents the fragmentation of gluons into pairs of $u\bar{u}$ and $d\bar{d}$. Therefore, gluons are fragmented into pairs of $s\bar{s}$ and a state of partial chemical equilibrium is achieved.

During this time, $s-$quarks combine with $u-$ and $d-$quarks, and a certain amount of K^+ and K^0 is emitted from the primary fireball, reducing temperature and entropy. At the end of this stage, the fireball will turn into a ball of quark-gluon plasma with great strangeness and a long lifetime of $\tau \sim 10^{-9}$ sec). In the

Таблица 1: «Centauro» event

Event,	*Collab., Camera.*		N	Energy $[TeV]$	Q_h	$\langle ER \rangle$ $[GeV \cdot m]$	E_{halo} $[TeV]$	E_{th} $[TeV]$	*Approx.*
CENT.	Brasil-	γ	0	0					
NEW	Japan	h	13	51.2	1.			1	
	2-storey								
CENT.	Brasil-	γ	56	361				4	
VI	Japan		157	644					
								2	
	2-storey	h	28	390				4	
			68	496				2	
		tot		751	0.52	735[1]		4	
				1140	0.44	803[1]		2	
CENT.	Brasil-	γ	547	2978				2	Centauro
VII	Japan		265	2179				4	or Chiron
		h	129	2486				2	
	2-storey		74	2328				4	penetr.
		tot		5464	0.46		500	2	cascades
				4506	0.52	842		4	and
					0.8	857[1]		20	mini-
									clusters,
									halo
CENT.	USSR-	γ	15	95		67		4	
PAMIR	Japan		120	298		28.6		1	
		h	22	444		244		4	
	standard		37	476		173		1	
	carbon	tot		539	0.82	495[1]		4	
					0.62			1	
ELENA	Pamir	γ	78	600		360		4	str.pen.
		h	23	1100		885		4	leading
	deep	tot		1700	0.65±0.05				cascade
	carbon	h	22[2]	300[2]		475[2]		4	
C-K	Pamir	γ	74	306		111		~ 1	str.pen.
		h	55	531		195			cascades
	deep			382[3]					
	Pb	tot			0.64				
		γ	27	198				4	
		h	22	446					
				297[3]					
		tot			0.69				

[1] is measured by showers with E (γ) $\geq$ 20 TeV

[2] without a leading cascade

[3] energy is released only in the first peaks

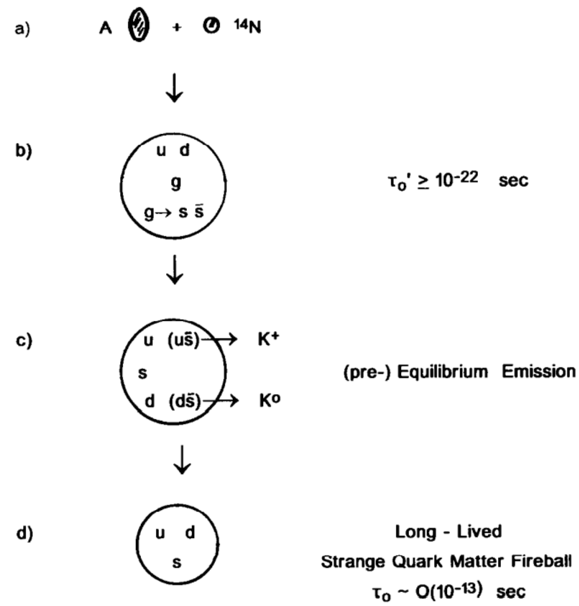


Рисунок 5: A sketch of the evolution of a fireball from quark matter to a strange state before decay.

case of cosmic rays, this is enough to overcome the atmosphere and reach the peaks of the mountains. At the same time, the mechanism of formation of strange particles can lead to the fact that the content of strange quarks in the fireball will accumulate and finally break up into non-strange baryons and light particles of strange quark matter - strangelets. The process is shown in the figure 5

To estimate some parameters, consider collisions of nuclei whose atomic weights are A_1 and A_2, and charges are Z_1 and Z_2. The interaction centrality parameter is limited by natural conditions:

$$0 < b < R_1 + R_2$$

, where $R_i = 1.15A_i^{1/3}$. A fireball is formed in the nuclear overlap region. Since all ejected nucleons from the overlap region participate in the interaction process, the fireball baryon number is also determined. Thus, the baryon number of the fireball N_b can be estimated based on simple geometric considerations. Assuming a uniform distribution of nucleons across the nucleus, it is possible to express N_b in terms of the volume ratio.

$$N_b = 0.9A_1\frac{V_o}{V_1}$$

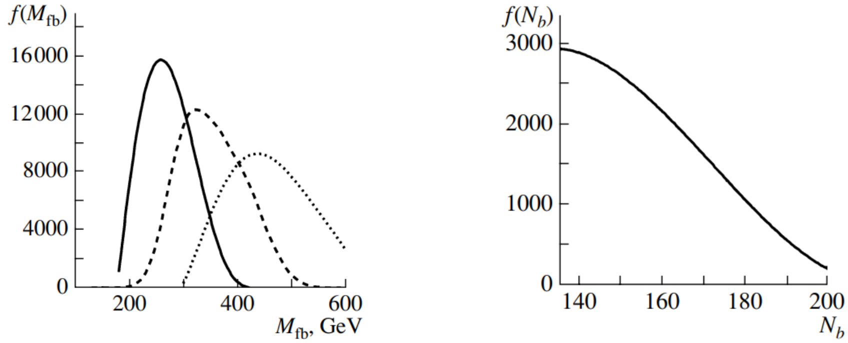
Where a coefficient of 0.9 was introduced in order to exclude the contribution to N_b from the boundary of the overlap area. It is natural to assume that the nuclei of the beam and the target are distributed uniformly along the transverse plane, which is equivalent to a uniform distribution of the impact parameter squared b^2. This assumption determines the shape of all distributions. Also, it should be noted that the fireball «Centauro» should occur more often in central than in peripheral collisions, because the former have a higher content of baryons.

The initial stage of the evolution of the fireball is unstable, but during the time interval $\Delta t \sim 10^{-21}$, gluons fragment into pairs $s\bar{s}$, after which chemical equilibrium is established. In the first order of perturbative QCD, the energy density of the product of a quark–gluon plasma consisting of u, d, 4 quarks and gluons with a temperature of T is defined as:

$$\epsilon = \epsilon_g + \epsilon_{u,d} + \epsilon_s$$

The mass of the fireball, respectively, will be defined as:

$$M_{fb} = \epsilon V_{fb}$$



(a) Kind of mass distribution

(b) Kind of multiplicity distribution

More precisely, the calculated distributions of mass and baryon multiplicity are shown in Figures 6b and 6a.

4.2 Other Centauro Event models

It is widely believed that the formation of a quark-gluon plasma is a probable mechanism for the formation of events of the type «Centauro». Models based on quark-gluon plasma satisfactorily explain the hadron-rich composition of events like Centaur, but only the fireball model, which decays into baryons and strangelets, offers a simultaneous explanation of all the phenomena associated with the event.

Bose-Einstein condensate: However, a number of other models proposed by various authors should also be mentioned. In the article [13], the authors consider a model of the formation of a pion condensate formed as a result of fragmentation. This model predicts large «Centauro»-like fluctuations in the ratio of neutral and charged pions.

Exotic states Also, a model was proposed by the authors of [15], in which events of the type «Centauro» can actually be interpreted as the diffraction formation of a new, short-lived quasiparticle with a mass in the range of 20-40 GeV and can be attributed to a strongly interacting sextet quark QCD sector.

Evaporation of black holes The authors in [14], analyze the model of evaporating mini-black holes, which may also be good candidates for the origin of unusual events associated with cosmic rays. Also, the cascades generated by the decay of mini-black holes formed during collisions of ultrahigh-energy cosmic ray particles with atmospheric nuclei were simulated.

5 Black hole evaporation model

Black hole evaporation models are based on scenarios with additional dimensions in which the fundamental Planck scale may be in the order of several TeV. Directly, the idea arose [16] due to the fact that attempts to create a Centauro-type event in experiments at the collider were not successful.

One of the most interesting conclusions for the low fundamental Planck scale is the possibility of the birth of black holes and their observation in future colliders or in experiments with cosmic rays. If gravity propagates in $d + 4$ dimensions, while other fields are bounded by a 3-brane. In models with large extra dimensions, black holes can form at LHC energies. It is expected that these mini-black holes will decay very quickly, with a lifetime of $\tau \approx 1/M_P \approx 10^{-27}$. Semi-classical Hawking evaporation will lead to a large multiplicity of particles and a characteristic blackbody spectrum, since radiation of all degrees of freedom is equally likely.

The main, well-known feature of Centauroa events is the anomalous ratio of hadron and photon components, in addition, the observed multiplicity is rather small compared to that expected from inter-nuclear collisions in the same energy range. The strong suppression of the electromagnetic component observed in Centauro-type events could be the result of the evaporation of black holes. In this process, all kinds of particles of the standard model can be obtained, so the resulting photon/hadron ratio should be lower than with conventional hadron interactions. According to the ratio of hadron to lepton is about 5:1, which leads to a ratio of hadron to photon of about 100:1. The absence of isospin degrees of freedom for the final state of evaporated black holes is an additional argument for the possibility of large fluctuations in the ratio of charged and neutral pions. However, at the current level of research, the above arguments are strictly qualitative in nature. However, it is worth considering several papers that attempt to assess the possible observed manifestations of black hole evaporation.

Decaying black holes will cause events characterized also by very wide transverse propagation. Air shower modeling also confirms that a wide transverse distribution over transverse momentum will be the most striking sign of a black hole evaporation event.

The possible neutrino origin of Centauro-type events would explain their property of deep penetration into the atmosphere, that is, the fact that events are observed deep in the atmosphere near detectors. Experimental data still contradict this statement.

And finally, a serious problem with the Hawking radiation scenario seems to be related to its ability to explain a strongly penetrating component, that is, unexpectedly prolonged showers observed in emulsion chambers.

6 Conclusion

The events of cosmic rays of ultrahigh energies lead to the appearance of new states of matter. It is widely believed that the probable mechanism of Centauro formation is the formation of quark-gluon plasma, which has been included in many of the proposed models. They satisfactorily explain the hadron-rich composition of events of the «Centauro» type, but only the fireball model decaying into baryons and strangelets simultaneously explains all the phenomena associated with «Centauro».

At this stage of the study, a more complete and quantitative description of exotic phenomena associated with cosmic rays is needed to consider other more exotic approaches to explaining the phenomenon.

Also, it should be noted that experiments with cosmic rays are related to experiments on modern high-energy accelerators, in particular collisions at an energy of about 1.8 TeV in S.C.M. is equivalent to a cosmic ray particle with an energy of $\approx$2 PeV, and 7 TeV in S.C.M. is equivalent to an energy of $\approx$26 PeV.

All this leads to the understanding that future accelerator experiments at colliders are capable of a more detailed study of new phenomena that are difficult to explain today, to which we receive indications in experiments with cosmic rays.

Список используемой литературы

[1] A.D. Panagiotou et al., Z. Phys. A333 (1989), 355.

[2] A.D. Panagiotou et al., Phys. Rev. D45 (1992) 3134.

[3] M.N. Asprouli, A.D. Panagiotou and E. G ladysz-Dziadu ́s, Astropart. Phys. 2 (1994) 167.

[4] C.M.G. Lattes, Y. Fugimoto and S. Hasegawa, Phys. Rep. 65 (1980) 151

[5] Chacaltaya and Pamir Collaboration, Contributions to 23rd ICRC (Calgary, 19–30 July, 1993), ICRR-Report-295-93-7 (1993)

[6] ALICE Technical Proposal, CERN/LHCC/95-71

[7] Physical Review. D, Particles Fields; ISSN 0556-2821; Worldcat; v. 23(3); p. 771-776

[8] O.P. Theodoratou and A.D. Panagiotou, Astropart. Phys. 13 (2000) 173

[9] M. Martinis, Phys.Rev.D51:2482-2485,1995

[10] Kopenkin, V.; Fujimoto, Y. (2006). "Exotic models are no longer required to explain the Centauro events". Phys. Rev. D. 73 (8): 082001.

[11] Janusz Kempa(Warsaw U. of Tech.), Bryan Pattison(CERN), Ewa Gladysz-Dziadus(Cracow, INP), Lawrence W. Jones(Michigan U.), Rauf Mukhamedshin(Moscow, INR). "Emulsion chamber observations of Centauros, aligned events and the long-flying component". Published in: Central Eur.J.Phys. 10 (2012) 723-741

[12] Aurélie Guilbert-Lepoutre, Anastasios Gkotsinas, Sean N. Raymond, David Nesvorny. "The gateway from Centaurs to Jupiter-family Comets: thermal and dynamical evolution". arXiv:2212.06637 [astro-ph.EP]

[13] J. D. Bjorken, “A Full Acceptance Detector for SSC Physics at Low and Intermediate Mass Scales: An Expression of Interest to the SSC,” Int. J. Mod. Phys. A **7** (1992), 4189-4258 doi:10.1142/S0217751X92001885

[14] Ewa Gladysz-Dziadus. Black Holes versus Strange Quark Matter arXiv:hep-ph/0405115

[15] K. Kang and A. R. White, ‘A Collider Diffractive Threshold, Hadronic Photons and Sextet Quarks,” Phys. Rev. D **42** (1990), 835-847 doi:10.1103/PhysRevD.42.835

[16] A. Mironov, A. Morozov and T. N. Tomaras, “Can centauros or chirons be the first observations of evaporating mini black holes?,” Int. J. Mod. Phys. A **24** (2009), 4097-4115 doi:10.1142/S0217751X09044693 [arXiv:hep-ph/0311318 [hep-ph]].