STATE RESEARCH CENTER OF RUSSIA

INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 2002-8

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MODEL OF CENTAURO AND STRANGLET PRODUCTION IN HEAVY ION COLLISIONS

Submitted to *Physics of Atomic Nuclei*

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Protvino 2002

UDK 539.12.142 M–24

Abstract

Angelis A. L. S. , Gładysz-Dziaduś E. , Kharlov Yu. V. et al. Model of Centauro and Stranglet Production in Heavy Ion Collisions: IHEP Preprint 2002-8. – Protvino, 2002. – p. 14, figs. 11, tables 4, refs.: 12.

We discuss the phenomenological model of Centauro events production in realitivistic heavy ion collisions at the accelerator LHC. This model predicts quantitative kinematic observables, baryon number and mass of the Centauro fireball and its decay products. Centauro decays mainly into nucleons, strange hyperons and strangelets. The simulation of Centauro events for the CASTOR detector is performed. The signatures of these events are discussed in details.

Аннотация

Ангелис А.Л.С., Гладыш Е., Харлов Ю.В. и др. Модель образования Центавр-событий и стренджлетов в столкновениях тяжелых ионов: Препринт ИФВЭ 2002-8. – Протвино, 2002. – 14 с., 11 рис., 4 табл., библиогр.: 12.

Обсуждается феноменологическая модель образования Центавр-событий в столкновениях релятивистских тяжелых ионов на ускорителе LHC. Эта модель дает количественные предсказания кинематических наблюдаемых, барионного числа и массы Центавр-файербола и его распадных свойств. Центавр распадается в основном на нуклоны, странные гипероны и стренджлеты. Проведено моделирование Центавр-событий для детектора CASTOR. Обсуждаются сигнатуры этих событий.

Introduction

In this paper we present the generator of Centauro events based on the phenomenological model [1,2,3] and discuss the first results on Monte Carlo simulations of Centauro events for the CASTOR detector of the ALICE experiment at LHC [4]. Originally the model of Centauro event production was based on experimental facts from cosmic ray studies and assumptions of some geometrical characteristics of the events; experimentally observed transverse momenta, energies of different spices of secondary particles and scenario of the Centauro fireball evolution allow to calculate thermodynamical parameters and the lifetime of the Centauro fireball. The extrapolation of this model to the higher energy allowed to estimate some observables of Centauro events, when taking into account the collider kinematics [5].

In this approach we attempt to predict more precisely the characteristics of such kind of events. In the current paper we present this model of Centauro events in heavy ion collisions on assumption of some fundamental characteristics of the Centauro fireball which lead to the predictions of observables in such kind of events. The model is formulated in terms of impact parameter of ion collisions, two thermodynamical parameters (baryochemical potential and temperature) which are assigned to the Centauro fireball produced in the scenario of Centauro event evolution, and the nuclear stopping power. Since we construct the fully quantitative model we have to formalize all assumptions of the original model and introduce some additional assumptions. The event generator CNGEN was written to calculate the Centauro fireball parameters and produces the full event configuration. Thus the model predicts all kinematical parameters of the Centauro events which were observed in cosmic ray experiments.

In section 1 we give the gradual thermodynamical and kinematical description of production and evolution of Centauro-type events in relativistic heavy ion collisions and show characteristic mass, energy and multiplicity distributions of these events.

In section 2 results of the detection simulation of these events with the CASTOR apparatus are given. Centauro events are compared with minimum bias events produced by the HIJING generator. Signatures of Centauro events are discussed.

1. Physics of Centauro events

Centauro fireball evolution. The description of Centauro events [6] was introduced in papers [1,2,3]. According to this model Centauro events occur in nuclear collision in the projectile fragmentation region when the projectile nucleus penetrating through the target nucleus transforms its kinetic energy into heating and forms a slightly hot quark matter with high baryochemical potential [2,3]. We refer to this quark matter as a primary Centauro fireball. On the first stage of its evolution it contains u- and d-quarks and gluons. The high baryochemical potential results in impossibility for gluons to fragment into $u\bar{u}$ and $d\bar{d}$-pairs due to Pauli blocking [2]. Therefore gluons quickly fragment into $s\bar{s}$-pairs. The partial chemical equilibrium is achieved by coupling $\bar{s}$-quarks with u and d-quarks and emission of K^+ and K^0 from the primary fireball which decreases the temperature and entropy. After this stage the Centauro fireball becomes a slightly strange quark matter (SQM) with relatively long lifetime ($\tau \sim 10^{-13}$ sec) [3]. Finally the SQM fireball decays explosively into baryons and some light metastable strange matter objects with $A > 6$ called as strangelets.

Baryon number of Centauro fireball. We consider collisions of nuclei with atomic numbers A_1 and A_2 and charges Z_1 and Z_2 respectively with impact parameter b. The impact parameter is roughly restricted by

$$0 < b < R_1 + R_2,$$

where $R_i = 1.15 A_i^{1/3}$ fm ($i = 1, 2$) are radii of colliding nuclei. Centauro fireball is produced in a region of the two nuclei overlapping. The baryon number N_b of the fireball can be estimated from a simple geometrical consideration. We assume that all nucleons of the projectile nucleus which occur in the overlapping region with the target nucleus can interact. Really only the most central part of the overlapping region of the projectile forms the fireball. Assuming the uniform distribution of nucleons in a nucleus one can find N_b through the volume ratio of overlapping region $V_{\rm ovrlp}$ and the whole projectile nucleus V_1:

$$N_b = 0.9\, A_1 \frac{V_{\rm ovrlp}}{V_1}. \tag{1}$$

Here the factor 0.9 gives the most central part of the overlapping region. In other words the primary fireball baryon number N_b is defined by a number of nucleons of the projectile nucleus which impacts in the interaction region.

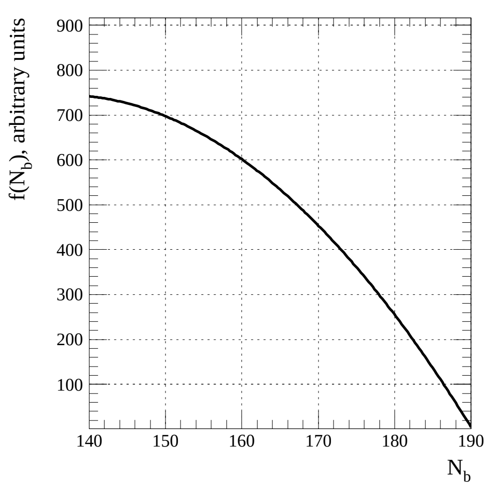

Fig. 1. Baryon number of the fireball produced in Pb-Pb collisions with impact parameters $0 < b < 5$ fm.

It is naturally to assume that projectile and target nuclei are distributed uniformly in the transverse plane, i.e. the squared impact parameter b^2 is distributed uniformly. All cosmic Centauro events were observed with rather high hadron multiplicity ($N_h > 70$), hence in our model we restrict the Centauro fireball production by $N_b > 50$. In our quantitative model we use a simple assumption that each nucleus collision with different impact parameters results in Centauro fireball production with one and the same thermodynamical characteristics. In the real nature it is not so but it seems to be reasonable when the impact parameter varies a little. Central collisions are more likely to produce the Centauro quark matter fireball than peripherial collisions are. Therefore we calculate the distribution of the baryon number of the primary Centauro fireball for Pb-Pb collisions for impact parameters $0 < b < 5$ fm which correspond to the central collisions, the plot is shown in Fig. 1. The form of the distribution $f(N_b)$ is rough enough because of the motivation discussed above. From the other hand this distribution gives the right representation on the baryon number N_b range because N_b is defined strictly for the fixed impact parameter. This remark also concerns shapes of other distributions given in the paper.

Mass of Centauro fireball. The produced fireball is a glob of deconfined quark matter which characterized by a temperature T and baryochemical potential of a nucleon μ_b. As the basic phenomenological model [2,3] predicts, the Centauro fireball has a very high baryochemical potential which does not permit $\bar{u}$ and $\bar{d}$ to be produced. This phase of the Centauro fireball is unstable yet and after $\Delta t \sim 10^{-23}$ sec [3] gluons fragment into $s\bar{s}$-pairs. After that a chemical equilibrium in the fireball is achieved. In the first-order perturbative QCD the energy density of the quark-gluon plasma containing u-, d-, s-quarks and gluons at the temperature T around a critical one T_c is expressed by (see, e.g. [7,8] and references therein)

$$\varepsilon = \varepsilon_g + \varepsilon_q + \varepsilon_s.$$

Here $q = u, d$. Gluon and quark contributions ε_g, ε_q and ε_s are

$$\begin{aligned}
\varepsilon_g &= \frac{8\pi^2}{15}T^4\left(1 - \frac{15}{4\pi}\alpha_\mathrm{s}\right), \\
\varepsilon_q &= \frac{7\pi^2}{10}T^4\left(1 - \frac{50}{21\pi}\alpha_\mathrm{s}\right) + \left(3\mu_q^2T^2 + \frac{3}{2\pi^2}\mu_q^4\right)\left(1 - \frac{2}{\pi}\alpha_\mathrm{s}\right), \\
\varepsilon_s &= \gamma_s\left[\left(\frac{18T^4}{\pi^2}\right)\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) + 6\left(\frac{m_sT}{\pi}\right)^2\left(\frac{m_s}{T}\right)K_1\left(\frac{m_s}{T}\right)\right].
\end{aligned}$$

Here K_i are i-order modified Bessel functions. The strong coupling constant α_s should be taken at a scale $Q \approx 2\pi T$ and equals $\alpha_\mathrm{s} = 0.3$ at a critical temperature $T_c = 170$ MeV [8]. The γ_s is the strangeness equilibration factor ($\gamma_s \approx 0.4$). The net energy density for all degrees of freedom is given by

$$\varepsilon = \frac{37\pi^2}{30}T^4\left(1 - \frac{110}{37\pi}\alpha_\mathrm{s}\right) + \left(3\mu_q^2T^2 + \frac{3}{2\pi^2}\mu_q^4\right)\left(1 - \frac{2}{\pi}\alpha_\mathrm{s}\right) + \varepsilon_s. \tag{2}$$

Here baryochemical potential of a quark μ_q can be expressed via nucleon baryochemical potential μ_b as $\mu_q = \mu_b/3$.

The other thermodynamical quantities of interest, pressure P and quark number density $n_q = N_q/V_\mathrm{fb}$ are obtained from equation (2):

$$P = \frac{1}{3}\varepsilon, \quad n_q = \left(\frac{\partial P}{\partial \mu_q}\right)_T,$$

$$n_q = 2\left(\mu_qT^2 + \frac{\mu_q^3}{\pi^2}\right)\left(1 - \frac{2}{\pi}\alpha_\mathrm{s}\right). \tag{3}$$

Since the number of quarks N_q in the primary Centauro fireball is defined from the collision geometry as $N_q = 3N_b$ one can obtain from (1) and (3) the volume of the fireball V_fb in the order $\mathcal{O}(\alpha_\mathrm{s})$:

$$V_\mathrm{fb} = \frac{3N_b}{2\left(\mu_qT^2 + \dfrac{\mu_q^3}{\pi^2}\right)}\left(1 + \frac{2}{\pi}\alpha_\mathrm{s}\right). \tag{4}$$

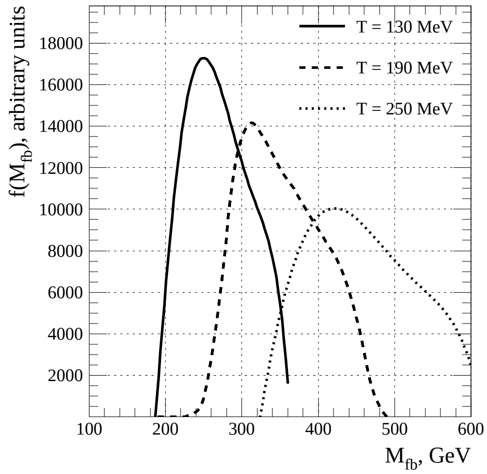

Fig. 2. Mass of the Centauro fireball in Pb-Pb collisions at $\mu_b = 1.8$ GeV and $T = 130$, 190 and 250 MeV.

When the volume of the fireball is defined one can easily obtain the mass of the fireball from the energy density (2):

$$M_{\rm fb} = \varepsilon V_{\rm fb}. \qquad (5)$$

The distribution of the Centauro fireball mass produced in Pb-Pb collisions with $\mu_b = 1.8$ GeV and $T = 130$, 190 and 250 MeV is shown in Fig. 2.

Kinematics of the fireball. Centauro events were observed in cosmic ray experiments in the very forward region [6]. We suppose that the longitudinal-momentum distribution of the fireball obeys the scaling law of secondary particles production which is described by empirical formula established at lower energies at large x_F:

$$dN/dx_F \sim (1 - x_F)^n, \quad n \approx 3.$$

The transverse momentum of the fireball should have a value of the order of the intrinsic motion momenta of a nucleon inside a nucleus.

Each constituent quark of the projectile nucleus participating in the fireball formation comes though the scattering off the target nucleus. The transverse momentum distribution of a quark in the fragmentation region can be expressed by the form

$$dN_q/dp_T^2 \sim \exp\left(-\frac{p_T^2}{p_0^2}\right)$$

with the slope $p_0 = 0.3$ GeV$/c$. Vector summation of all transverse momenta of interacting quarks gives the transverse momentum of the produced Centauro fireball.

The rapidity range of the produced fireball can be obtained from the following consideration. The maximum rapidity of the fireball is reached when it carries the whole energy of the projectile nucleus fragment, $E_{\rm max} = E_{\rm beam} N_{\rm b}/A_{\rm beam}$:

$$y_{\rm max} = \ln \frac{2E_{\rm max}}{M_{\rm fb}}.$$

For example for central Pb-Pb collisions at $\sqrt{s} = 5.5$ TeV/nucleon $N_{\rm b} = 0.9\, A_{\rm beam} = 186$, fireball mass at $T = 190$ MeV and $\mu_b = 1.8$ GeV is $M_{\rm fb} = 466$ GeV$/c^2$ and the maximum rapidity is

$$y_{\rm max} = 7.69.$$

But the nuclear stopping is an essential effect as it is expected in heavy ion collisions. The nuclear stopping power shows the degree to which the energy of relative motion of the two incident nuclei can be transferred into thermodynamical degrees of freedom. The nuclear stopping can be expressed by the rapidity shift $\Delta y_{\rm n.s.}$ of produced particles compared to NN collisions. Thus the actual rapidity of the Centauro fireball is defined by the equation

$$y_{\rm fb} = y_{\rm max} - \Delta y_{\rm n.s.}.$$

The value of $\Delta y_{\rm n.s.}$ is a crucial parameter of the model which the observance of the Centauro events depends on. The average of HIJING [10] and VENUS [11] prediction gives $\Delta y_{\rm n.s.} = 2.3$ but values in the range $2.0 < \Delta y_{\rm n.s.} < 3.5$ can take place [3].

Recoil system. Since the kinematics of the fireball is defined one can calculate the momentum of the recoil system which consists of secondaries from the target nucleus. Defining the 4-momentum of the Centauro fireball as $p_{\rm Cn}$ and the 4-momentum of the recoil system as $p_{\rm rec}$ we have the momentum conservation law as

$$p_{\rm proj} + p_{\rm targ} = p_{\rm Cn} + p_{\rm rec}.$$

Let $\sqrt{s_{aa}}$ to be the c.m.s. collision energy of overlapping fragments of the beam nuclei. Obviously for the collision energy per nucleon $\sqrt{s_{NN}}$ we have $\sqrt{s_{aa}} = N_b\sqrt{s_{NN}}$ with N_b defined by equation (1). Neglecting the mass of the Centauro fireball in comparison with $\sqrt{s_{aa}}$ we get the mass of the recoil system $M_{\rm rec}$ to be defined by the expression

$$M_{\rm rec} = \sqrt{s_{aa}}(1-\delta)^{1/2},$$

where $\delta \approx 2M_{\rm fb}\cosh(y_{\rm fb})/\sqrt{s_{aa}}$. For the rapidity of the recoil system $y_{\rm rec}$ the equation is as follows:

$$\sinh y_{\rm rec} \approx \frac{\delta/2}{(1-\delta)^{1/2}}.$$

For the values of the rapidity shift $\Delta y_{\rm n.s.}$ of several units $\Delta y_{\rm n.s.} = 2-3$ one can conclude that the recoil system carries almost the total energy of the nuclear collision $\sqrt{s_{aa}}$. In this approximation it is easy to obtain that value of δ vanishes, hence, the mass of the recoil system $M_{\rm rec}$ is very close to the value of $\sqrt{s_{aa}}$ and $y_{\rm rec}$ is small. To feel the amount of recoil mass and rapidity we give Table 1 which represents these values in central Pb-Pb collisions at $\sqrt{s} = 5.5$ TeV/nucleon, $\sqrt{s_{aa}} = 1140$ TeV when the Centauro fireball mass is $M_{\rm fb} = 530$ GeV/c^2, at different values of $\Delta y_{\rm n.s.}$. From this table it follows that the recoil system is produced in the central rapidity region and, therefore, the secondary particles can be detected by the central detector of any experiment. The contents of the recoil system is still unknown because of the mechanism of the Centauro fireball production is not understood well enough.

Table 1. Recoil system mass $M_{\rm rec}$ and rapidity $y_{\rm rec}$ in Pb-Pb collisions at different values of the rapidity shift due to nuclear stopping of the Centauro fireball $\Delta y_{\rm n.s.}$.

$\Delta y_{\rm n.s.}$	2.0	2.5	3.0	3.5
$M_{\rm rec}/\sqrt{s_{aa}}$	0.93	0.96	0.97	0.98
$y_{\rm rec}$	−0.07	−0.04	−0.03	−0.02

Strange quark matter fireball. As it was mentioned earlier gluons in the primary Centauro fireball fragment into $s\bar{s}$-pairs to achieve the chemical equilibrium. The strange quark number density is given by the equation [9]:

$$n_s = 1.37\cdot 10^{-3}\ \text{GeV}^3 \left(\frac{T}{200\ \text{MeV}}\right) K_2\left(\frac{m_s}{T}\right), \tag{6}$$

where $K_2(x)$ is a modified Bessel function of the second order. Being multiplied by the Centauro fireball volume $V_{\rm fb}$ (4) the equation (6) gives the number of $s\bar{s}$-pairs inside the fireball and, hence, the number of emitted K-mesons:

$$N_{\bar{s}} = N(K^+) + N(K^0) = n_s V_{\rm fb}. \tag{7}$$

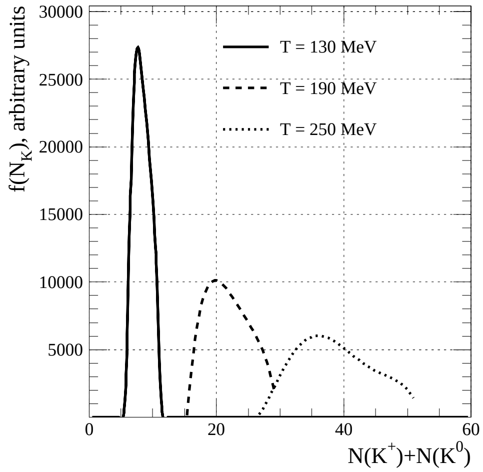

Fig. 3. Number of K^+ and K^0 emitted from the Centauro fireball produced in Pb-Pb collisions at $\mu_b = 1.8$ GeV and $T = 130$, 190 and 250 MeV.

Fig. 3 shows the distribution of kaon numbers emitted from the Centauro fireball with $\mu_b = 1.8$ GeV and $T = 130$, 190 and 250 MeV. Before emitting kaons from the fireball the total number of quarks is $N'_q = 3N_b + 2N_{\bar{s}}$. Hence, the average energy per a constituent quark at this stage is

$$\epsilon'_q = \frac{M_{\rm fb}}{N'_q}. \tag{8}$$

After $2N_{\bar{s}}$ quarks have been emitted with kaons the mass of the remaining SQM fireball is defined by the average quark energy (8) and the number of quarks in the fireball N_q:

$$M'_{\rm fb} = N_q \epsilon'_q = M_{\rm fb}\left(1 - \frac{2N_{\bar{s}}}{N_q}\right).$$

The emission of anti-strangeness is described as an isotropic decay of the primary fireball into $N_{\bar{s}}$ kaons and the SQM fireball with the mass $M'_{\rm fb}$.

Decay of SQM fireball. After emission of kaons the primary Centauro fireball transforms into a slightly strange quark matter which can have a long life-time, of the order of 10^{-13} sec [3]. At the final stage of its evolution the SQM fireball decays into baryons and strangelets. The latter are light drops of strange quark matter with $A > 6$, high strangeness-per-baryon ratio $S/A \approx 1$ and small charge-to-mass ratio $Z/A \approx 0$. In our model for simplicity the only one strangelet is produced in the SQM fireball by random choosing u-, d- and s-quarks from all quarks of the fireball. Not all strangeness of the SQM fireball can be transferred to the strangelet, the rest of s-quarks forms strange hyperons. Baryons are formed in the fireball by the random picking sets of three quarks from the quarks of the fireball matter. The priority is given to the formation of nucleons and all quarks which cannot be coupled to nucleons produce strange hyperons. The decay of the SQM fireball is performed isotropically. We use the well-known event generator Jetset [12] to perform further decays of kaons and strange baryons.

General characteristics of Centauro events. Table 2 shows characteristics of Centauro events in Pb-Pb collision at $\sqrt{s} = 5.5$ TeV/nucleon. At a given impact parameter b, temperature T and baryochemical potential μ_b we calculate baryon number N_b, energy density ε, quark number density n_q, volume of the fireball $V_{\rm fb}$, mass of the primary fireball $M_{\rm fb}$, mass of the SQM fireball $M'_{\rm fb}$, strange quark number density n_s and number of emitted kaons $N(K^{+,0})$. With some initial parameters of the model, especially for central collisions ($b = 0$) and high temperature Centauro events are featured by a high mass and a large number of kaons. Nuclear collisions with large impact parameters could also produce Centauro-type events but these events are characterized by a residual strange component.

The Centauro events as they were observed in cosmic ray experiments are featured by a total or almost total absence of photonic component among secondary particles. Since our model is based on the assumption that the Centauro fireball mostly consists of u-and d-quarks

Table 2. Centauro events properties at some fixed impacts parameters, temperature and barychemical potential.

b	μ_b	T	N_b	ε	n_q	$V_{\rm fb}$	$M_{\rm fb}$	$M'_{\rm fb}$	n_s	$N(K^{+,0})$
fm	GeV	MeV		GeV/fm^3	fm^{-3}	fm^3	GeV	GeV	fm^{-3}	
0	1.8	130	186	4.3	6.7	83	357	344	0.13	11
		190	186	7.7	9.2	61	466	423	0.48	28
		250	186	13.6	12.5	45	607	515	1.14	50
	1.5	130	186	2.7	4.4	125	334	316	0.13	16
		190	186	5.3	6.5	86	460	402	0.48	40
		250	186	10.4	9.2	60	626	503	1.14	68
5	1.8	130	114	4.3	6.7	51	219	212	0.13	6
		190	114	7.7	9.2	37	286	260	0.48	17
		250	114	13.6	12.5	27	372	315	1.14	31
8	1.8	130	53	4.3	6.7	24	102	98	0.13	3
		190	53	7.7	9.2	17	133	120	0.48	8
		250	53	13.6	12.5	13	173	147	1.14	14

with a small amount of $s\bar{s}$-pairs, the most of secondaries particles are baryons. Kaons which are emitted from the primary fireball can decay into pions which give, in turn, photons. Therefore the amount of electromagnetic fraction of such an event is suppressed very much. Fig. 4 shows the ratio of hadron multiplicity to the total multiplicity (hadrons + photons) in Centauro events with $\mu_b = 1.8$ GeV and $T = 190$ MeV produced at LHC in Pb-Pb collisions. The ratio is very close to unity with mean value $\langle N_h/N_{\rm tot}\rangle = 0.93$ and the deviation of this value from 1 is caused by electromagnetic particles. Fig. 5 gives the ratio of summary energy of hadrons to the total energy in the same events. This value is close to 1 with average value $\langle \sum E_h / \sum E_{\rm tot}\rangle = 0.99$. Certainly these ratios depend on thermodynamical characteristics of the Centauro fireball, e.g. the higher the temperature, the more kaons and therefore, the more photons are produced and these ratios become more different from 1.

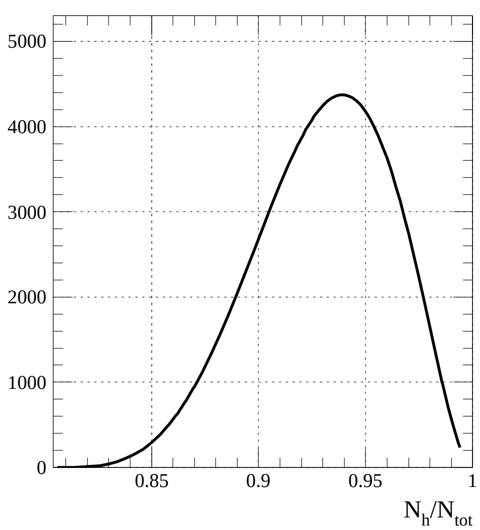

Fig. 4. Ratio of hadron to total multiplicities (hadrons + photons).

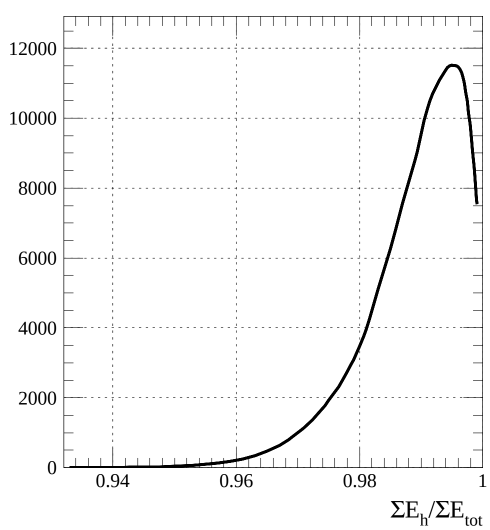

Fig. 5. Ratio of hadron to total summary energies.

Secondary particles in the Centauro events associated with the Centauro fireball decay have a larger mean transverse momentum in comparison with ordinary hadron interaction. The mean p_T observed in cosmic rays [6] is $\langle p_T \rangle = 1.75$ GeV/c. Fig. 6 shows the transverse momentum distribution of hadrons in Centauro events at LHC with 3 sets of baryochemical potential μ_b and temperature T: ($\mu = 1.8$ GeV, $T = 190$ MeV), ($\mu = 1.8$ GeV, $T = 250$ MeV) and ($\mu = 3.0$ GeV, $T = 250$ MeV). The average p_T in such events is $\langle p_T \rangle = 1.34$ GeV/c, 1.47 GeV/c and 1.75 GeV/c respectively. Usual hadron events, as the model HIJING predicts have the average transverse momentum $\langle p_T \rangle = 0.44$ GeV/c which is $2 - 4$ times smaller than that in Centauro events.

Rapidity distribution of decay products of the Centauro fireball certainly depends on the nuclear stopping power $\Delta y_{\text{n.s.}}$. In Fig. 7 rapidity distributions of secondary particles are shown for three values of $\Delta y_{\text{n.s.}} = 2.0$, 2.5 and 3.0. Obviously all secondary particles from the Centauro fireball decay are distributed in the very forward region as it was observed in cosmic rays. However, the whole event which the Centauro fireball is produced in, contains the particles of the recoil system which occupy the central region, $y \approx 0$ according to the Table 1.

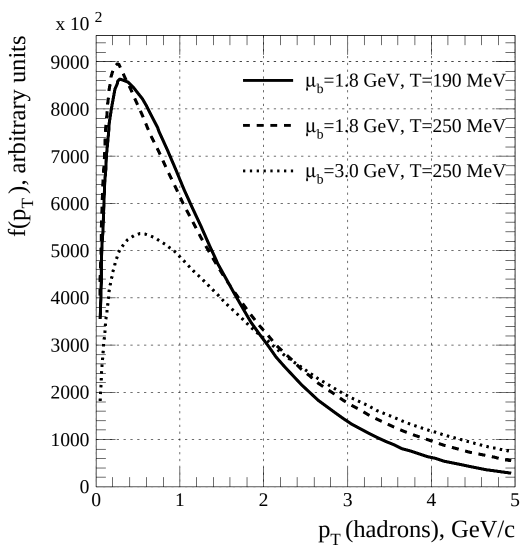

Fig. 6. Transverse momentum distribution in Centauro event with $\mu = 1.8$ GeV, $T = 130$ MeV; $\mu = 1.8$ GeV, $T = 190$ MeV and $\mu = 3.0$ GeV, $T = 250$ MeV.

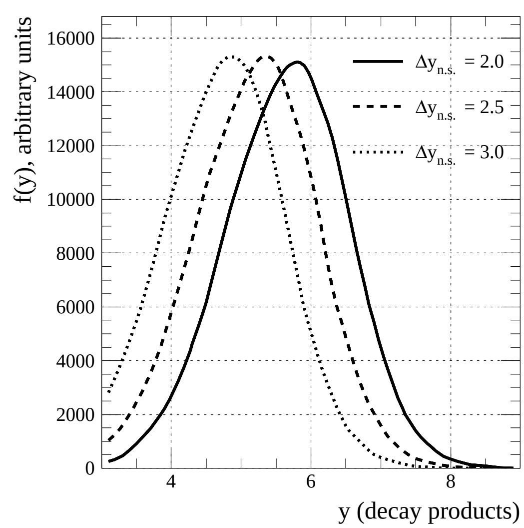

Fig. 7. Rapidity distribution of decay products of Centauro events for three values of $\Delta y_{\text{n.s.}} = 2.0$, 2.5 and 3.0.

2. Detection of Centauro events with CASTOR

Here we present a simple detection efficiency calculation for the detector CASTOR of the ALICE experiment at LHC. The detector is installed in a very forward region at the distance 10.5 m apart from the interaction point of incoming nuclei. The detector has an approximate central symmetry and installed as much as possible close to the beam pipe, i.e. it has a central hole with the radius $R_{\text{in}} = 4$ cm, the outer radius is $R_{\text{out}} = 23$ cm. Therefore, the detector covers pseudorapidities $4.5 < \eta < 6.2$. The detector is capable to measure charge particle and photon multiplicities and deposited energy of hadronic and electromagnetic components.

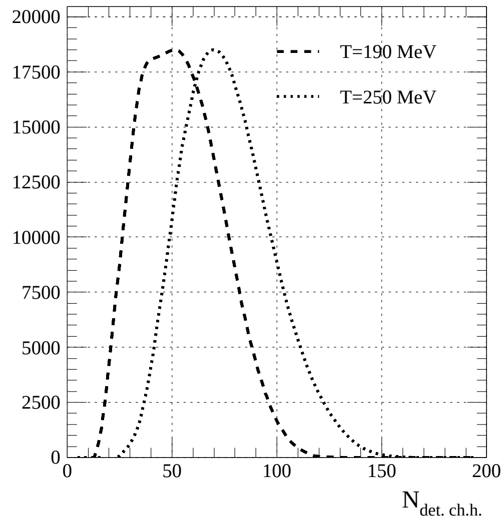

Fig. 8. Charged hadron multiplicity in the detector at $\Delta y_{\rm n.s.} = 2.5$, $\mu = 1.8$ GeV and two values of $T = 190$ and 250 MeV.

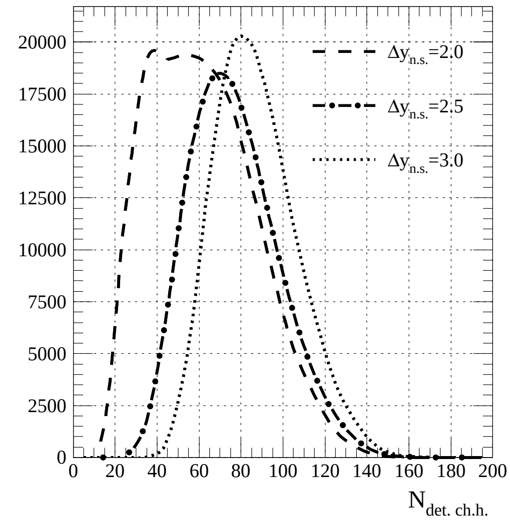

Fig. 9. Charged hadron multiplicity in the detector at $\mu = 1.8$ GeV, $T = 250$ and three values of $\Delta y_{\rm n.s.} = 2.0$, 2.5 and 3.0.

The detection of Centauro events strongly depends on parameters of the model, namely thermodynamical variables μ and T which influence the mass of the fireball and rapidity shift due to nuclear stopping $\Delta y_{\rm n.s.}$. We compare detection possibilities of the Centauro fireball at different T and fixed μ and $\Delta y_{\rm n.s.}$, as well as at different $\Delta y_{\rm n.s.}$ with fixed thermodynamical parameters. Fig. 8 gives charged hadron multiplicity distribution in the detector with fixed $\Delta y_{\rm n.s.} = 2.5$ and $\mu = 1.8$ GeV and two values of the fireball temperature $T = 190$ and 250 MeV. The dependence of the charged hadron multiplicity on the rapidity shift at fixed $\mu = 1.8$ GeV and $T = 250$ MeV is shown in Fig. 9: curves correspond to $\Delta y_{\rm n.s.} = 2.0$, 2.5 and 3.0. The number of detected charged hadrons at each set of parameters has to be compared with the total number of charged hadrons generated in event. The forth column of Table 3 shows the average efficiency of charged hadron detection $\epsilon_{\rm ch.had.}$ in terms of μ, T and $\Delta y_{\rm n.s.}$.

Table 3. Detection efficiency of charged hadron and strangelets in terms of μ, T and $\Delta y_{\rm n.s.}$.

μ, GeV	T, MeV	$\Delta y_{\rm n.s.}$	$\epsilon_{\rm ch.had.}$	$\epsilon_{\rm str.}$
1.8	130	2.5	0.56	0.23
1.8	190	2.5	0.69	0.29
1.8	250	2.5	0.79	0.39
1.8	250	2.0	0.65	0.22
1.8	250	3.0	0.88	0.61
3.0	250	2.5	0.81	0.62

The charged hadron multiplicity of the Centauro-type events in the detector is rather small, not more than 120 with the mean values $30 - 60$. Photon multiplicity is much smaller as it is seen from Fig. 4.

Small multiplicity in the Centauro events seems to be anomalous for nuclear collisions. In ordinary hadron events the multiplicity is expected to be of the order of some thousand. Fig. 10 shows the charged hadron multiplicity in ordinary hadron events detected by CASTOR as predicted by HIJING. The multiplicity in the minimum bias events is several times higher that that in Centauro-type events, the mean detected multiplicity in hadron events is 1500 which is about 30 times more in comparison with Centauro events.

Because of their higher mass strangelets are boosted forward more than ordinary hadrons are. Therefore strangelets have a tendency to fly closer to the beam. The distribution of the radius of strangelet hits on the detection plane at $\mu = 1.8$ GeV, $T = 250$ MeV and $\Delta y_{\mathrm{n.s.}} = 2.5$ is shown in Fig. 11. The shadowed area corresponds to the detector surface. The efficiency of strangelet detection $\epsilon_{\mathrm{str.}}$ at different values of the model parameters is given in the last column of Table 3.

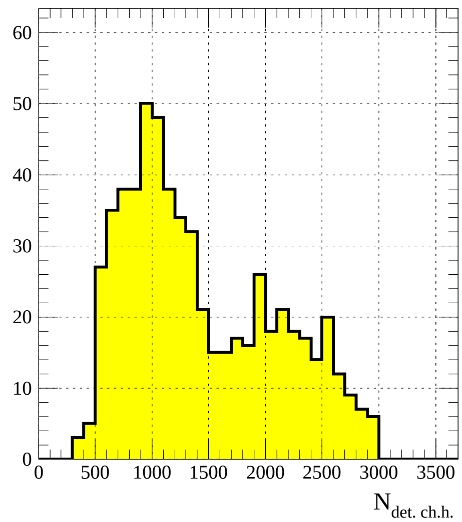

Fig. 10. Charged hadron multiplicity in the detector in minimum bias events predicted by HIJING.

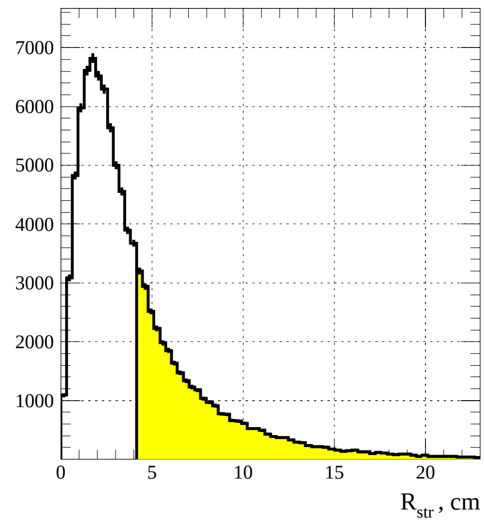

Fig. 11. Distribution of hit radius of strangelets on the detection plane at $\mu = 1.8$ GeV, $T = 250$ MeV and $\Delta y_{\mathrm{n.s.}} = 2.5$. Shadowed area corresponds to the detector surface.

Cosmic ray experiments observed also the high energy collimation in the forward region in Centauro-type events [6]. As the degree of the collimation the ratio of multiplicity and deposited energy in the central core to those total values was taken:

$$\chi_N = \frac{N(R < R_{\mathrm{core}})}{N_{\mathrm{tot}}}, \quad \chi_E = \frac{\sum E(R < R_{\mathrm{core}})}{\sum E_{\mathrm{tot}}}.$$

Certainly the observed values of the multiplicity and energy collimations depend of the detector size. For the small CASTOR detector with radii $4 < R < 23$ cm one can choose the central part of the detector, say, with $R < 10$ cm to measure these values. But if CASTOR can be increased in the outer size, say, up to $R_{\mathrm{out}} = 35$ cm or if it can work along with the mid-rapidity detecor covering central region, the collimation measurement would be more significant. In Table 4 we show the collimations χ_N and χ_E with the central part of the detector of the radius $R_{\mathrm{core}} = 10$ cm in Centauro events with different sets of parameters and in hadron events predicted by HIJING. This table also shows the observed in the detector ratios of hadron-to-total multiplicities and deposited energies in Centauro-like and hadron-like events. This table gives bright signatures to observe Centauro events which are distinguished from the ordinary hadron events by the event collimation parameters and smallness of the electromagnetic component.

Table 4. Degree of the multiplicity and energy collimation χ_N and χ_E and hadron-to-total multiplicity and energy ratios on Centauro and hadron minimum bias events according the HIJING model.

Event type			χ_N	χ_E	$N_h/N_{\rm tot}$	$\sum E_h/\sum E_{\rm tot}$
Centauro events						
μ, GeV	T, MeV	$\Delta y_{\rm n.s.}$				
1.8	130	2.5	0.70	0.83	0.95	0.99
1.8	190	2.5	0.62	0.77	0.93	0.99
1.8	250	2.5	0.54	0.70	0.90	0.98
1.8	250	2.0	0.64	0.79	0.89	0.98
1.8	250	3.0	0.42	0.55	0.91	0.98
3.0	250	2.5	0.52	0.68	0.95	0.99
Hadron events						
			0.38	0.58	0.58	0.75

Conclusion

We presented quantitative results of Centauro events observation in heavy ion collisions at LHC energies. The phenomenological model of Centauro events was originally introduced in papers [2,3] and gives a transparent explanation of such events. On the basis of this model we construct the quantitative model and the event generator CNGEN which provides a tool to estimate detection efficiency of Centauro events and strangelets.

Possibility to observe Centauro events depends strongly on the parameters of the model such as thermodynamical characteristics and the nuclear stopping power. Contrary to hadrons emitted from the Centauro fireball strangelets are harder to detect because of their higher mass in comparison with that of hadrons.

The signatures for Centauro events observation with the CASTOR detector can be summarized as follows:

- small detected charged particles multiplicity, $\langle N_{\rm ch.\ h.}\rangle = 50$ compared to $\langle N_{\rm ch.\ h.}\rangle = 2000$ in minimum bias hadron events;
- significant predominance of the detected hadron multiplicity which is can be characterized by the average hadron-to-all particles ratio $\langle N_h/N_{\rm tot}\rangle = 0.9$ while this ratio is equal to $\langle N_h/N_{\rm tot}\rangle = 0.5$ in hadron events;
- significant predominance of the detected hadron energy deposited in the detector, $\langle \sum E_h/\sum E_{\rm tot}\rangle = 0.99$ with $\langle \sum E_h/\sum E_{\rm tot}\rangle = 0.75$ in hadron events;
- large average transverse momentum, $\langle p_T\rangle > 1$ GeV/c compared to $\langle p_T\rangle = 0.44$ GeV/c in hadron events;
- higher multiplicity collimation with the core radius $R_{\rm core} = 10$ cm, $\chi_N = 0.4\div0.7$ depending on model parameters; hadron events have $\chi_N = 0.4$ which is comparable with Centauro events only at critical values of parameters;
- high energy collimation, $\chi_E = 0.6\div0.8$ while hadron events have $\chi_E = 0.6$ which is also at the lower limit of Centauro events. Both collimations differ much more in Centauro-type and hadron-type events with increasing the detector acceptance, say, up to $R_{\rm out} = 35$ cm or with using the central detector.

Centauro events can be accompanied by highly penetrating object. If these object are connected to strangelets with $A > 6$ they have a rather small detection efficiency. The detection efficiency of other secondaries of the Centauro events has a satisfactory value.

The authors would like to thank Zbigniew Wlodarczyk for useful remarks.

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Received February 28, 2002

Appendix. Centauro event generator

Here we describe the Monte Carlo event generator of Centauro event production, CNGEN. The code of the generator is written in Fortran 77. User interface consists of two subroutines and two common blocks.

`SUBROUTINE CNINIT` — initializes the generator according to initial parameters which can be either taken by default values or changed via common blocks.

`SUBROUTINE CNEVNT` — produces one event.

`COMMON /CNPARS/ ICNINP(8), RCNINP(10)` — common block to define initial parameters of the generator:

`icninp(1)`	beam nucleus atomic number A
`icninp(2)`	target nucleus atomic number A
`icninp(3)`	beam nucleus charge Z
`icninp(4)`	target nucleus charge Z
`icninp(5)`	minimal baryon number of primary fireball
`icninp(6)`	minimal strangeness of strangelet
`icninp(7)`	flag of nuclear density distribution: `=1` for gray disk, `=0` for Wood-Saxon distribution
`icninp(8)`	flag of QCD orders: `=0` for first order, `=1` for $O(\alpha_s)$
`rcninp(1)`	c.m. initial energy of $A-A$ collision [GeV]
`rcninp(2)`	minimum impact parameters [fm]
`rcninp(3)`	maximum impact parameters [fm]
`rcninp(4)`	primary fireball temperature [GeV]
`rcninp(5)`	fireball baryo-chemical potential of baryon [GeV]
`rcninp(6)`	rapidity shift of fireball due to nuclear stopping
`rcninp(7)`	rapidity width of fragmentation region
`rcninp(8)`	strange-quark-matter fireball mean life time [sec]
`rcninp(9)`	strong coupling constant α_s
`rcninp(10)`	width of Gaussian distribition of fireball's p_T [GeV]

`COMMON /CNINFO/ ICNOUT(30), RCNOUT(20)` — common block to retrieve information on produced Centauro fireball after each event:

`icnout(1)`	baryon number of primary fireball
`icnout(2)`	number of protons in primary fireball
`icnout(3)`	number of neutrons in primary fireball
`icnout(4)`	number of quarks in primary fireball
`icnout(5)`	number of u-quarks in primary fireball
`icnout(6)`	number of d-quarks in primary fireball
`icnout(7)`	number of s-quarks in fireball
`icnout(8)`	total number of quarks in fireball after $\bar{s}$ production
`icnout(9)`	number of emitted K^+
`icnout(10)`	number of emitted K^0
`icnout(11)`	number of u-quarks in fireball after K emission
`icnout(12)`	number of d-quarks in fireball after K emission
`icnout(13)`	number of s-quarks in fireball after K emission
`icnout(14)`	baryon number A of strangelet
`icnout(15)`	charge Z of strangelet
`icnout(16)`	number of protons emitted from fireball
`icnout(17)`	number of neutrons emitted from fireball
`icnout(18)`	number of Σ^+ emitted from fireball
`icnout(19)`	number of Λ^0 emitted from fireball

`icnout(20)`	number of Σ^- emitted from fireball
`icnout(21)`	number of Δ^{++} emitted from fireball
`icnout(22)`	number of Δ^- emitted from fireball
`icnout(23)`	number of Ξ^0 emitted from fireball
`icnout(24)`	number of Ξ^- emitted from fireball
`icnout(25)`	number of Ω^- emitted from fireball
`icnout(26)`	`KF` code for beam nucleus
`icnout(27)`	`KF` code for target nucleus
`icnout(28)`	current event number
`icnout(29)`	bad event if `=1`, good event otherwise
`rcnout(1)`	energy density in primary fireball in GeV^4
`rcnout(2)`	quark density in primary fireball in GeV^3
`rcnout(3)`	volume of fireball in GeV^{-3}
`rcnout(4)`	mass of primary fireball
`rcnout(5)`	maximal rapidity of fireball
`rcnout(6)`	average rapidity of fireball
`rcnout(7)`	rapidity of fireball
`rcnout(8)`	transverse momentum of fireball
`rcnout(9)`	strange quark density in GeV^3
`rcnout(10)`	energy per quark in fireball
`rcnout(11)`	mass of strange quark matter fireball
`rcnout(12)`	mass of strangelet
`rcnout(13)`	energy density in primary fireball in $\mathrm{GeV/fm}^3$
`rcnout(14)`	quark density in primary fireball in fm^{-3}
`rcnout(15)`	volume of fireball in fm^3
`rcnout(16)`	strange quark density in fm^{-3}
`rcnout(17)`	collision energy per nucleon in c.m.s.
`rcnout(18)`	impact parameter in current event in fm

Препринт отпечатан с оригинала-макета, подготовленного авторами.

А.Л.С. Ангелис и др.
Модель образования Центавр-событий и стренджлетов в столкновениях тяжелых ионов.

Оригинал-макет подготовлен с помощью системы LaTeX.

Подписано к печати 11.03.2002. Формат $60 \times 84/8$.
Офсетная печать. Печ.л. 1.75. Уч.-изд.л. 1.4. Тираж 160. Заказ 43.
Индекс 3649. ЛР №020498 17.04.97.

ГНЦ РФ Институт физики высоких энергий
142284, Протвино Московской обл.

Индекс 3649

П Р Е П Р И Н Т 2002–8, И Ф В Э, 2002