Open and hidden strangeness with kaons and φ-mesons in Bjorken energy density approach for central ccollisions from SPS to LHC

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С целью сравнения вкладов в плотность энергии Бьоркена мы используем имеющиеся данные о значениях $< dN/dy >$ и $< p_T >$ для адронов, в том числе для $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \overline{p}$, $K^*(892)^0$, $\overline{K}^*(892)^0$ и φ-мезонов, зарегистрированных в области нулевых быстрот ($|y| < 0.5$) в интервале центральности 0-5% столкновений $Au + Au$, $Pb + Pb$ и $Xe + Xe$ в широком диапазоне энергий. Частицы типа странно-нейтрального φ-мезона (система $s\overline{s}$ кварков) и K-мезона (содержащего одиночный s-кварк) представляют особый интерес, поскольку они могут иметь разные механизмы рождения и чувствительности к свойствам кварк-глюонной плазмы.

We use the available data on $< dN/dy >$ and $< p_T >$ for the identified hadrons including $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \overline{p}$, $K^*(892)^0$, $\overline{K}^*(892)^0$ and φ-mesons, registered at midrapidity ($|y| < 0.5$) in 0-5% central $Au + Au$, $Pb + Pb$ and $Xe + Xe$ collisions in a broad range of energies. The goal is to compare the relative contributions to the Bjorken energy density. Particles, like strangeness-neutral φ-meson (a system of $s\overline{s}$ quarks) and K-meson (containing single s-quark), are of specific interest because they might have different production mechanisms and differ in sensitivity to the properties of the QGP-medium formed in relativistic heavy-ion collisions.

PACS: 44.25.+f; 44.90.+c

Introduction

According to the prediction by J.Rafelski and B. Müller [1], an enhanced production rates of strange particles in high energy heavy nuclei collisions could be considered as a signature for the formation of quark-gluon plasma (QGP) - a new phase consisting of almost-free quarks and gluons. In the

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QGP, the formation of s and $\overline{s}$ quarks can be increased due to the multiple gluon-gluon and light quark-antiquark fusion processes $gg \rightarrow s\overline{s}$ and $u\overline{u}$, $d\overline{d}$ $\rightarrow s + \overline{s}$ [1]. The enhancement can be observed as an increase in relative strange particle abundances as compared to pp or $p + Be$ collisions at the same collision energy per nucleon-nucleon pair. For the comparison, strange particle yields are often divided by the number of nucleons participating in the collision (Npart). The latter is also used to characterize centrality of $A + A$ collisions. Centrality intervals and relevant mean N_{part} values are being usually defined in the standard Glauber model approach in the procedure of fitting the minimum bias charged particles multiplicity distribution. Another indication of the increased strangeness production might be found in ratios of yields of identified strange hadrons to those of non-strange particles like pions. The monotonic increase of these ratios with final state event multiplicity in hadronic collisions could be an indication of the QGP formation.

The first convincing experimental evidence for an enhanced production of strange and multi-strange particles in Pb+Pb collisions at SPS were provided by NA57 [2]. It was found that the enhancement increases with the collision centrality and with the strangeness content of the hyperons [2]. Besides the first NA57 [2] data, the decisive role of open strangeness as a characteristic feature and signal of the formation of quark-gluon plasma was also confirmed by the NA61/SHINE [3–5] at SPS (CERN) and by STAR [6], [7] at RHIC (BNL). An increased yield of strangeness was found later by ALICE at the LHC in the high multiplicity collisions of small systems (pp and $p + Pb$) [8].

As to the strangeness content of the produced particles, the short-lived φ-meson is of particular interest since it is the lightest of the vector mesons with hidden strangeness. This strangeness-neutral φ-meson (a system of $s\overline{s}$ quarks) may have the production mechanism and interaction with the QGP different from that of particles with open strangeness. The quark composition of φ-meson can be thought of as a mixture of $s\overline{s}$, $u\overline{u}$ and $d\overline{d}$ states, but it is considered to be very close to the pure $s\overline{s}$ state. The OZI rule [9] strongly influences the production rate of φ-meson, also suppressing its decay to three pions and causing it to predominantly decay in a pair of K^++ K^- mesons. Additionally, it was suggested [10] that the absence of OZI suppression can lead to a significant increase in the production of φ-mesons in the QGP. One can find a review of measurements of φ-meson yields in [11]. We present below a comparative analysis and discuss the $\sqrt{s_{NN}}$ dependence of the contributions by the identified particles like φ-mesons, $K^*(892)^0$, $\overline{K}^*(892)^0$, K^++ K^-, π^++ π^- and p+ $\overline{p}$ to the Bjorken energy density in the interaction region for the most central (0-5%) nucleus-nucleus collisions.

1. Bjorken energy density

Following [12], the Bjorken energy density ϵ is determined at midrapidity through the mean transverse energy density $dE_{\perp}/dy$ by the particles formed in the volume of a cylinder with a cross-sectional area $S_{\perp}$ determined by the overlap between colliding nuclei and the length corresponding to the characteristic particle formation time τ. The majority of Bjorken energy density estimates are widely using the quantity of $\epsilon \cdot \tau$ (1) with the particle formation time $\tau = 1$ fm/c. Our study also follows this approach:

$$\epsilon \cdot \tau = \frac{dE_{\perp}}{dy} \cdot \frac{1}{S_{\perp}} \tag{1}$$

With the transverse mass of an identified hadron $\langle m_{\perp} \rangle = \sqrt{m^2 + \langle p_T \rangle^2}$, one can approximate the mean transverse-energy rapidity density, relevant to the given centrality interval of collisions, with a sum (2) of contributions from different hadrons. In our estimates of components of $\frac{dE_{\perp}}{dy}$, we used the available experimental data on $< dN/dy >$ and $< p_T >$ published in [13–18]. This includes also $K^*(892)^0$, $\overline{K}^*(892)^0$ and φ mesons registered in the central rapidity region in a wide energy range of nucleus-nucleus collisions (from the SPS to the LHC).

$$\frac{dE_{\perp}}{dy} = \frac{3}{2}(\langle m_{\perp} \rangle \frac{dN}{dy})_{\pi^{+}_{-}} + 2(\langle m_{\perp} \rangle \frac{dN}{dy})_{K^{+}_{-},p,\bar{p}} + 2(\langle m_{\perp} \rangle \frac{dN}{dy})_{K^*(892)^0} + (\langle m_{\perp} \rangle \frac{dN}{dy})_{\varphi} \tag{2}$$

The factor of 3/2 accounts for contribution by neutral pions (π^0), while the factors of 2 appear for two other terms due to the mean values of masses and dN/dy values that are being used for the calculations of contributions of yields by $(K^+ + K^-)/2$, $(p) + (\overline{p})/2$ and for $(K^*(892)^0 + \overline{K}^*(892)^0)/2$. In (2) and further below, we are using for simplicity, the notation $K^*(892)^0$ assuming that it includes both $K^*(892)^0$ and $\overline{K}^*(892)^0$.

The quantity of $\epsilon \cdot \tau$ in (2) still contains another parameter - the transverse area $S_{\perp}$, which can not be measured directly. The usual methods to define it are based on the Glauber Monte Carlo (GMC) approach combined with the multiplicity distribution analysis where the estimated mean number of participating nucleons (N_{part}) is considered to be in the relation to the transverse area [3, 8].

In our study, instead of the GMC, we assume that the measured particle production is straightforwardly related to the geometry of partially overlapping nuclei. Calculations, assuming colliding disks of radii R = 6.87 fm [6] for $Au+Au$ collisions (or $R = 7.17$ fm [17] for $Pb+Pb$ collisions), show that in both cases a significant fraction of events selected in a given 0–5% centrality interval will have a noticeable shift of the average impact parameter $< b >$ from 0. The following values were obtained for 0–5% $Au+Au$ central collisions: $< b >= 2.18$ fm, and for 0–5% $Pb+Pb$ collisions: $< b >= 2.26$ fm. In both cases we estimate the accuracy of $< b >$ value to be ~ 0.2 fm. Naturally, this will lead to a smaller value of the overlap area if compared to $< b >= 0$. The GMC calculations for central $Au+Au$ collisions provided similar results for $< b > \sim 2.2$, 2.39, 2.21 fm at three RHIC energies, see [6].

Therefore, in our approach we take into account this partial overlap and use the following corrected values of the mean initial transverse area $S_{\perp}$

for 0–5% central $Au + Au$ and $Pb + Pb$ collisions: $118.5 \pm 2.9\ fm^2$ and $129.5 \pm 2.2\ fm^2$. Naturally, this results in about 20% higher values of $\epsilon \cdot \tau$ then in the usually applied GMC where the transverse area $S_\perp$ is finally defined for 0–5% central collisions as πR^2. For centrality interval of 0–10% of $Au{+}Au$ collisions at $\sqrt{s_{NN}}$=200 GeV the value of $< b >= (2.26{\pm}0.2)$ fm and $S_\perp = 104.7 \pm 2.5\ fm^2$. We may also argue that our straightforward approach should give a smaller systematic bias on the final results then Glauber-based. In case of collisions of the deformed Xe nuclei ($\beta = 0.18 \pm 0.02$) at 5.44 TeV, we used the efficient value of the transverse overlap area $S_{eff\perp}$. This was done due to the obvious uncontrollable orientation of two deformed colliding nuclei. We took the assumption that the data on the energy density obtained for $Xe + Xe$ collisions at $\sqrt{s_{NN}} = 5.44$ TeV should be very close to the $Pb + Pb$ data at $\sqrt{s_{NN}} = 5.02$ TeV. Using the fitting function obtained for the energy dependence of $\epsilon \cdot \tau$ for pions below $\sqrt{s_{NN}} = 5.02$ TeV, we made the extrapolation to the energy of $\sqrt{s_{NN}} = 5.44$ TeV. After the normalization to this extrapolated value of $\epsilon \cdot \tau$ for pions, we obtained $S_{eff\perp} = 70.1\pm$ 15.6 fm^2, that is used further to calculate the contributions to $\epsilon \cdot \tau$ by $K^+ + K^-$, $p + \overline{p}$, $K^*(892)^0$, $\overline{K}^*(892)^0$ and φ-mesons for 0-5% central $Xe + Xe$ collisions at $\sqrt{s_{NN}} = 5.44$ TeV.

Results

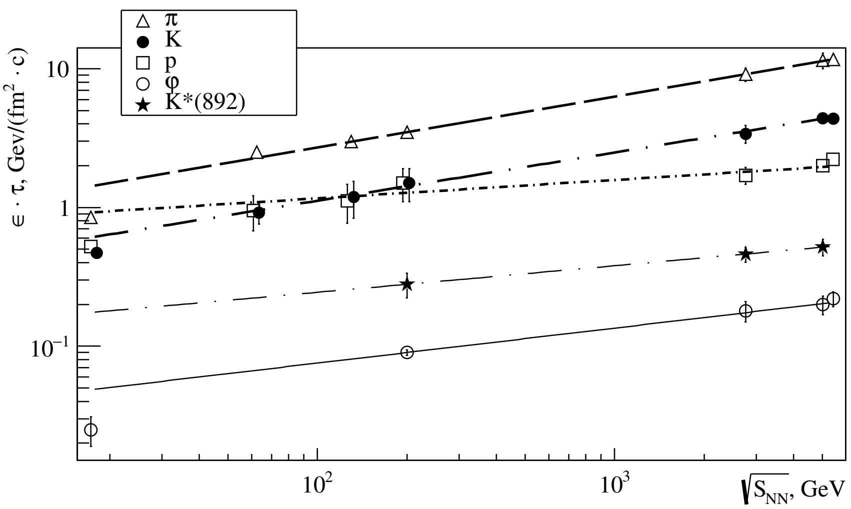

Fig. 1. Values of Bjorken $\epsilon \cdot \tau$ with $\tau = 1$ fm/c in $0 - 5\%$ $Au + Au$, $Pb + Pb$ and $Xe + Xe$ collisions as a function of $(\sqrt{s_{NN}})$ for identified hadrons (including $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \overline{p}$, $K^*(892)^0 + \overline{K}^*(892)^0$ and φ-mesons). Estimates were done using published data on $< p_T >$ and $< dN/dy >$ measured in [13–18] at midrapidity $((|y| < 0.5)$, except for data at 17.3 Gev, where $(|y| < 0.6))$. Lines – are the results of power-law fits (3). We show only statistical uncertainties. We estimate total systematic uncertainties to be $\leq 11\%$ for $Au{+}Au$ and $Pb{+}Pb$ data and $\leq 25\%$ in case of $Xe + Xe$.

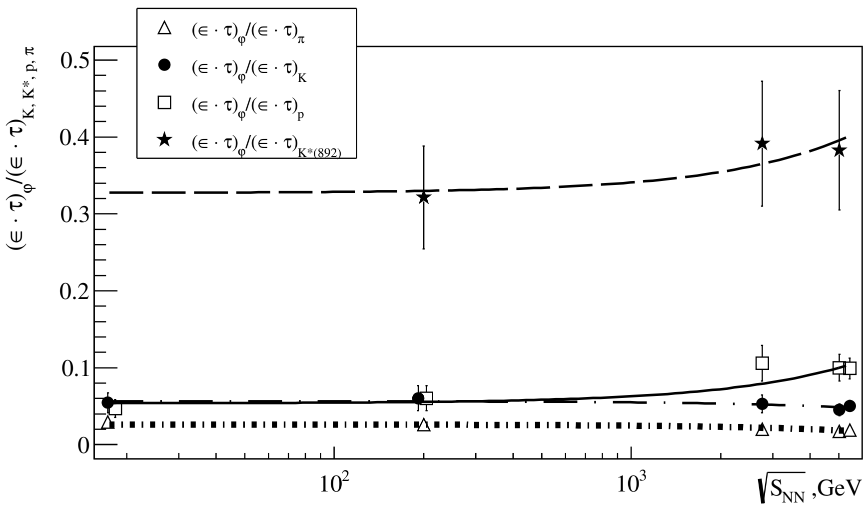

Fig. 2. Energy dependence for ratios of fractional values of Bjorken energy densities: $(\epsilon{\cdot}\tau)_{\varphi}/(\epsilon{\cdot}\tau)_{(\pi^{+}+\pi^{-}),(K^{+}+K^{-}),(p+\overline{p}),(K^{*}(892)^{0}+\overline{K}^{*}(892)^{0})}$. Lines are linear fits $A{+}B{\cdot}(s)$ (see Table 2).

We show in Fig. 1 the results of energy dependence of fractions of $\epsilon \cdot \tau$ as defined in (2) and obtained in our study for the identified hadrons including $\pi^{+}+\,\pi^{-}$, $K^{+}+\,K^{-}$,$p+\,\overline{p}$, $K^{*}(892)^{0}\,+\overline{K}^{*}(892)^{0}$ and φ-mesons. Only statistical uncertainties are shown. The main contributions to systematics uncertainties are: (i) experimental uncertainties for the measured yields of particle species and mean transverse momenta, that go into the estimates of the mean transverse energy and which contribute $\sim$ 10%; (ii) the systematic uncertainty of the cross-sectional area $S_{\perp}$ is estimated in our approach for 0-5% central $A + A$ collisions to be below 3%. So the total systematic uncertainty for Bjorken energy density is about 11% for $Au+Au$ and $Pb+Pb$ data and 25% for $Xe+Xe$.

The identified hadrons were measured at midrapidity in central 0-5% $Au + Au$, $Pb + Pb$ and $Xe + Xe$ collisions in a broad range of collision energies. We have to note that the Bjorken energy density approach may not be entirely accurate at the energies below RHIC, because the formation time (τ) should be larger than the time of passage of the colliding nuclei through each other [19]. Therefore, we will use in our analysis of $\epsilon \cdot \tau$ excitation functions only data in the region from the top RHIC energy to the LHC.

Power-law fits (3) were performed for $\epsilon \cdot \tau$ vs. $\sqrt{s_{NN}}$ data in the region of $\sqrt{s_{NN}}$ from 200 GeV to 5.02 TeV. One may find the fit parameter values in Table 1.

$$\epsilon \cdot \tau = Q \cdot (s_{NN})^{n} \tag{3}$$

From Fig.1 and Table 1, one can see that the s-dependence of $\epsilon{\cdot}\tau$ demonstrates different behavior for identified particles under study, and the power-law indices are different. In particular, in case of pions, the s-dependence of $\epsilon \cdot \tau$ is growing faster ($s^{0.184\pm0.015}$) then the power-law behavior in case of the

Table 1. Parameters of power-law $Q \cdot (s)^n$ approximations for fractional values of $\epsilon \cdot \tau$ as a function of $\sqrt{s}$ for ($\pi^+ + \pi^-$), ($K^+ + K^-$), ($p + \overline{p}$), $K^*(892)^0 + \overline{K}^*(892)^0$ and φ-mesons. In the bottom: parameter n for power-law fit in $A + A$ and pp collisions for charged hadrons yield vs $\sqrt{s}$.

	n	Q	χ^2/NDF
π	0.184 ± 0.015	0.50 ± 0.09	0.013/2
K	0.17 ± 0.03	0.23 ± 0.11	0.14/2
p	0.07 ± 0.03	0.6 ± 0.3	0.6/2
$K^*(892)^0$	0.10 ± 0.04	0.10 ± 0.06	0.002/1
φ	0.126 ± 0.020	0.024 ± 0.006	0.05/1
Charged hadrons in $A + A$ collisions [20]	0.155(4)	–	–
Charged hadrons in pp collisions [20]	0.103(2)	–	–

Table 2. Parameters of linear approximations $A + B \cdot (s)$ of ratios of yields of φ-mesons to the relevant yields of ($\pi^+ + \pi^-$), ($K^+ + K^-$), ($p + \overline{p}$) and $K^*(892)^0$ $+\overline{K}^*(892)^0$.

	$(\epsilon \cdot \tau)_\varphi/(\epsilon \cdot \tau)_\pi$	$(\epsilon \cdot \tau)_\varphi/(\epsilon \cdot \tau)_K$	$(\epsilon \cdot \tau)_\varphi/(\epsilon \cdot \tau)_p$	$(\epsilon \cdot \tau)_\varphi/(\epsilon \cdot \tau)_{K^*}$
A	0.026 ± 0.002	0.06 ± 0.01	0.05 ± 0.01	0.33 ± 0.07
B,10^{-6}	-1.5 ± 0.5	-1.6 ± 2.1	9.2 ± 2.7	13.6 ± 21.2
χ^2/ndf	0.8/3	0.4/3	1.8/3	0.15/1

charged particle multiplicities in $Au + Au$, $Pb + Pb$ and $Xe + Xe$ collisions described by the function $s^{0.155}$ [20]. We may note here that such behavior of $\epsilon \cdot \tau$ with the collision energy might be a result of well known growth of the mean $p_\perp$ for charged hadrons, that contributes to the transverse mass. It is not so in case of the hidden strangeness formation. One may see in Fig.1 and with the data in Table 1 that the Bjorken energy fraction of $\epsilon \cdot \tau$, relevant to φ-mesons, is growing much slower with the collision energy ($s^{0.126 \pm 0.020}$) then the one for pions ($s^{0.184 \pm 0.015}$). As to the case of $p + \overline{p}$, we see rather slow growth of $\epsilon \cdot \tau$ ($s^{0.17 \pm 0.03}$) with $\sqrt{s_{NN}}$. Taking into account the fact that masses of φ-mesons and $K^*(892)^0$ – (1020 MeV and 892 MeV) are close to the mass of proton (938 MeV) one may assume that the partonic degrees of freedom in QGP could play a quite different role in the formation of protons and resonances.

Another observation concerns the ratios of fractions of Bjorken energy density $\epsilon \cdot \tau$ values as a function of collision energy obtained in this work for several identified hadrons. In fact, these are the ratios of the relevant fractions of transverse energies. In Fig.2 we show these ratios of values of $\epsilon \cdot \tau$ of φ-mesons to the relevant densities for other hadrons: ($\pi^+ + \pi^-$), ($K^+ + K^-$), ($p + \overline{p}$) and $K^*(892)^0$. In Table 2 we present the parameters of approximation of ratios of particle yields with linear function $A + B \cdot (s)$.

In the whole region of collision energies under study, these ratios of particle yields $(\epsilon{\cdot}\tau)_{\varphi}/((\epsilon\cdot\tau)_{(\pi^{+}+\pi^{-}),(K^{+}+K^{-}),(p+\overline{p},K^{*}(892)^{0})})$ are almost flat versus $\sqrt{s_{NN}}$ (see Fig.2). A similar flat dependence, but *for the ratios of the yields* of φ-mesons to yields of K^{-} was observed earlier in the domain from SPS to RHIC energies (see the compilation of data and analysis in [21]) and at the LHC [22]. Our results for the ratio of yields $2\cdot\varphi/(K^{+}+K^{-})=0.12\pm0.2$ are very close to the mean ratio of yields $\varphi/K^{-}=0.15\pm0.3$ observed in a wide region of collision energies (see in [21] and [22]). However, we would like to stress here that the values of particle yield ratios appear to be different from the Bjorken energy density $\epsilon\cdot\tau$ fractional values shown in Fig.2. One may compare the mentioned above ratio of φ-meson yields to kaons $2{\cdot}\varphi/(K^{+}{+}K^{-})=0.12{\pm}0.2$ to the mean value for relevant $\epsilon\cdot\tau$ values equal to 0.06 ± 0.01 (see Table 2).

Among the theoretical models directly focused on medium effects on hidden strangeness production in heavy-ion collisions, we would like to mention just briefly the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach model [21] that was successfully applied to describe the ratios of φ-mesons yield to K^{-} as a function of collision centrality observed earlier in the domain from SPS to RHIC energies. The PHSD model is a non-equilibrium microscopic transport approach for the description of the dynamics of strongly interacting hadronic and partonic matter. At the same time at LHC energies, the ratio of φ-meson yields to kaons K^{-} was described in the different approach of statistical hadronization model [23]. Several other approaches, including EPOS3 and EPOS3 + UrQMD, PYTHIA6, PYTHIA8, EPOS-LHC, and HERWIG MC event generators, were used in [22] in the analysis of data on $K^{*}(892)^{0}$ and φ -meson production at $\sqrt{s_{NN}}=5.02$ TeV. However, these facts show the lack of completeness in understanding the full picture of hidden strangeness production in a wide energy range from SPS to LHC.

We may conclude here that the hidden strangeness production and the medium induced effects on strangeness yields are still not quite understood, and this requires the additional studies with new observables. What we would like to point at, it is the observed rather weak energy dependence of the fractional contribution of different hadrons to the Bjorken energy density that deserves a closer attention.

Conclusions

We calculated the values of mean Bjorken energy density $\epsilon\cdot\tau$ using the available experimental data on $<dN/dy>$ and $<p_T>$ for several identified hadrons including strangeness– neutral φ-meson ($s\overline{s}$ quark system), $K^{*}(892)^{0}$ $+\overline{K}^{*}(892)^{0}$ and $K^{+}+K^{-}$ mesons (containing single s (or $\overline{s}$)-quark) published in [13–18]. We obtained estimates of mean Bjorken energy density $\epsilon\cdot\tau$ in 0–5% central $Au+Au$, $Pb+Pb$ and $Xe+Xe$ collisions in a wide range of $\sqrt{s_{NN}}$ – from 200 GeV up to 5.44 TeV.

We observe different dependences of the ratios of the fractional Bjorken energy densities $\epsilon{\cdot}\tau$ on the collision energy. We found that the one relevant to $(\pi^+ + \pi^-)$ grows with s faster ($s^{0.184\pm0.015}$) then in case of energy dependence of the pion yields ($s^{0.157}$) [20] (see Table 1). This could be explained by the additional contribution to the transverse energy density dE_t/dy by the $< p_T >$ of charged particles (pions) produced at midrapidity in $A+A$ collisions and growing with the energy of collision. At the same time, the results for $(p+\overline{p})$ demonstrate the slowest dependence on the energy of collisions: ($s^{0.07\pm0.3}$). We observe also that *the ratios of the Bjorken energy fractions*, relevant to the identified hadrons - $(\epsilon{\cdot}\tau)_{\varphi}/((\epsilon\cdot\tau)_{(\pi^++\pi^-),(K^++K^-),K^*(892)^0)})$, in all cases, are practically not depending on the collision energy. This behavior looks similar to the one previously observed in *the ratios of φ-meson yields* to K^- mesons, although the values of mean ratios are different. The observed rather weak energy dependence of the ratios of the fractional contribution of different hadrons to the Bjorken energy density deserves a closer attention of further studies.

It is in our plans to include further in the analysis of Bjorken energy densities in relativistic heavy-ion collision the additional data on Λ hyperons yields, as well as of the particles containing two or three strange quarks, and to compare with the dependence on the collision energy of hidden strangeness production observed in this study.

Acknowledgement: Supported by Saint Petersburg State University, project ID: 95413904.

Authors are grateful to Vladimir Kovalenko for useful discussions.

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