DECONFINEMENT PHASE TRANSITION IN RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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We discuss the energy dependence of hadron production in relativistic nucleus-nucleus collisions. Several 'anomalies' in the energy dependence have been predicted as signals of the deconfinement phase transition and three these signals are observed at the CERN SPS indicating that the onset of deconfinement in Pb+Pb collisions is located at about 30 A·GeV. For the first time, we seem to have clear evidence for the existence of a deconfined state of matter in nature.

Introduction

The data on nucleus-nucleus (A+A) collisions suggested that there is a significant change in the energy dependence of pion and strangeness yields which is located between the top AGS and SPS energies. Based on the statistical approach to strong interactions, it was speculated that the change is related to the onset of deconfinement at the early stage of A+A collisions, and a simplified quantitative model was developed, the Statistical Model of the Early Stage (SMES) [1]. It assumes creation of the early stage matter according to the principle of maximum entropy. Depending on the collision energy, the matter is in the confined ($E < 30$ A·GeV), mixed ($30 < E < 60$ A·GeV), or deconfined ($E > 60$ A·GeV) phases.

Rich experimental data on Pb+Pb collisions at five energies (20, 30, 40, 80, and 158 A·GeV) were recently recorded by several experiments (NA49, NA45, NA57, NA50 and NA60) at the CERN SPS. The results from the run at 40, 80, and 158 A·GeV are already published, the preliminary results from the 30 A·GeV run are shown for the first time at the conference SQM03, the data at 20 A·GeV are still being analyzed. The energy scan program at the CERN SPS results in an observation of several 'anomalies' in the energy dependence of hadron production in the same domain of collision energy. These 'anomalies' have been predicted as signals of the deconfinement phase transition [1–3] in A+A collisions. In this report, we review the physical arguments which lead us to the proposed signals as well as the experimental status of these signals.

1. Signals of Deconfinement: Model Predictions

Originally two signals of the deconfinement phase transition were proposed within SMES: the energy dependence of mean pion and mean strangeness multiplicities [1]. Recently two new signals were suggested within SMES: the energy dependence of the inverse slope of transverse mass spectrum of kaons [2] and the energy dependence of properly filtered multiplicity fluctuations [3].

An exact nature of the deconfinement phase transition is still debated. On the other hand, it is rather well established in the lattice QCD at zero baryonic chemical potential that very strong changes of the energy density ε take place in a narrow temperature interval $\Delta T \cong 5$ MeV. Within this temperature interval, the energy density changes by about an order of magnitude, whereas the pressure remains approximately unchanged. One may refer to this temperature interval as a 'generalized mixed phase'.

1.1. The Pion Multiplicity

The majority of all particles produced in high energy interactions are pions. Thus, pions carry basic information on entropy created in collisions. On the other hand, the entropy production should depend on the form of matter present at the early stage of collisions. Deconfined matter is expected to lead to the final state with higher entropy than that created by confined matter. Consequently, it is natural to expect that the onset of creation of deconfined matter should be signalled by an enhancement of pion production. Clearly a trivial dependence of the pion multiplicity on the size of colliding nuclei should be removed and thus a relevant observable is the ratio of the mean pion multiplicity $\langle\pi\rangle$ to the mean number of wounded nucleons $\langle N_W\rangle$. The simple intuitive argumentation can be further quantified within SMES assuming generalized Fermi–Landau initial conditions: initial volume is Lorenz-contracted, $V \propto (\sqrt{s})^{-1}$ ($\sqrt{s}$ is the c.m.s. energy per nucleon–nucleon pair), initial energy density is given by $\varepsilon \propto gT^4 \propto (\sqrt{s})^2$ (T is the initial temperature and g is an effective number of internal degrees of freedom at the early stage). The pion multiplicity is proportional to the initial entropy, and the $\langle\pi\rangle/\langle N_W\rangle$ ratio can be thus calculated outside the transition region as [1]:

$$\langle\pi\rangle/\langle N_W\rangle \ \propto V\ g\ T^3 \ \propto\ g^{1/4}\ F\ . \qquad (1)$$

Therefore, the $\langle\pi\rangle/\langle N_W\rangle$ ratio increases linearly with F outside the transition region, and the slope parameter is proportional to $g^{1/4}$ [4]. In the transition region, a steepening of the pion energy dependence is predicted, because of activation of partonic degrees of freedom, i.e. an effective number of internal degrees of freedom in the QGP is larger than that in the hadron gas: $g_{\mathrm{QGP}} > g_{\mathrm{HG}}$.

1.2. The Strangeness to Pion Ratio

The energy dependence of the strangeness to entropy ratio is a crucial signal of deconfinement due to its weak dependence on the assumed initial conditions. Within SMES at low collision energies, when the confined matter is produced, the strangeness to entropy ratio steeply increases with collision energy. Due to the low temperature at the early stage ($T < T_C$) and the high mass of the carriers of strangeness ($m_S \cong 500$ MeV, the kaon mass), the total strangeness is: $\langle s + \bar{s}\rangle \propto \exp(-m_S/T)$. On the other hand, the total entropy is approximately $\propto T^3$. When the transition to a deconfined matter is crossed ($T > T_C$), the mass of the strangeness carriers is significantly reduced ($m_S = 130 \div 170$ MeV, the strange quark mass). Due to the low mass ($m_S < T$), the strangeness yield becomes (approximately) proportional to the entropy (both are proportional to T^3), and the strangeness to entropy (or pion) ratio becomes independent of energy. This leads to a "jump" in the energy dependence from the larger value for confined matter at T_C to the value for deconfined matter. Thus, within the SMES, the non-monotonic energy dependence of the strangeness to entropy ratio is followed by a saturation at the deconfined value which is a direct consequence of the onset of deconfinement taking place at about 30 A·GeV [1].

1.3. The Inverse Slope of m_T Spectra

We discuss another well-known observable, which may be sensitive to the onset of deconfinement, the transverse momentum, p_T, spectra of produced hadrons. It was suggested by van Hove [5] more than 20 years ago to identify the deconfinement phase transition in high energy proton-antiproton interactions with a plateau-like structure of the average transverse momentum as a function of the hadron multiplicity[2]. According to the general concepts of the hydrodynamical approach, the hadron multiplicity reflects the entropy, whereas the transverse hadron activity reflects the combined effects of temperature and collective transverse expansion. The entropy is assumed to be created at the early stage of the collision and is approximately constant during the hydrodynamic expansion. The multiplicity is proportional to the entropy, $S = sV$, where s is the entropy density and V is the effective volume occupied by particles. During the hydrodynamic expansion, s decreases and V increases with sV being approximately constant. Large multiplicity at high energies means a large entropy density at the beginning of the expansion (and consequently a larger volume at the end). Large value of s at the early stage of the collisions means normally high temperature T at this stage. This, in turn, leads to an increase of transverse hadron activity, a flattening of the transverse momentum spectrum. Therefore, with increasing collision energy, one expects to observe an increase of both the hadron multiplicity and average transverse momentum per hadron. However, a presence of the deconfinement phase transition would change this correlation. In the phase transition region, the initial entropy density (and hence the final hadron multiplicity) increases with collision energy, but temperature $T = T_C$ and pressure $p =$

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[1] F is the Fermi's energy measure $F \equiv (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$, where m_N is the nucleon mass. $F \cong (\sqrt{s})^{1/2}$ at high energies.

[2] In the original suggestion [5], the correlation between average transverse momentum and hadron multiplicity was discussed for $\mathrm{p} + \bar{\mathrm{p}}$ at fixed collision energy. Today we have an advantage to use central A+A collisions at different energies [2].

p_C remain constant. The equation of state presented in a form $p(\varepsilon)/\varepsilon$ versus ε shows a minimum (the 'softest point' [6]) at the boundary of the *generalized mixed phase* and the QGP. Consequently the shape of the p_T spectrum is approximately independent of the multiplicity or collision energy. The transverse expansion effect may even decrease when crossing the transition region [5]. Thus, one expects an 'anomaly' in the energy dependence of transverse hadron activity: the average transverse momentum increases with collision energy when the early stage matter is either in pure confined or in pure deconfined phases, and it remains approximately constant when the matter is in the mixed phase [2, 5]. A simplified picture with $T = T_C = \text{const}$ inside the mixed phase is changed if the created early stage matter has a non-zero baryonic density. It was however demonstrated [7] that the main qualitative features ($T \cong \text{const}$, $p \cong \text{const}$, and a minimum of the function $p(\varepsilon)/\varepsilon$ versus ε) are present also in this case. In the SMES model [1], which correctly predicted the energy dependence of pion and strangeness yields, the modification of the equation of state due to the deconfinement phase transition is located between 30 and about 200 A·GeV. Thus, the anomaly in the energy dependence of transverse hadron activity may be expected in this energy range.

With increasing the collision energy, the energy density at the early stage increases. At low and high energies, when the pure confined or deconfined phase is produced, this leads to an increase of the initial temperature and pressure. This, in turn, results in increase of transverse expansion of matter and consequently a flattening of the transverse mass spectra of final state hadrons. The experimental data on transverse mass, $m_T = (m^2 + p_T^2)^{1/2}$, spectra ($m$ is a particle mass) are usually parameterized by a simple exponential dependence:

$$\frac{dN}{m_T dm_T} = C \exp\left(-\frac{m_T}{T^*}\right) , \qquad (2)$$

where the inverse slope parameter T^* is sensitive to both the thermal and collective motion in the transverse direction. In parameterization (2), the shape of the m_T spectrum is fully determined by a single parameter, the inverse slope T^*. In particular, the average transverse mass, $\langle m_T\rangle$, can be expressed as

$$\langle m_T\rangle = T^* + m + \frac{(T^*)^2}{m + T^*} . \qquad (3)$$

Simple hydrodynamical parameterization of the transverse flow leads to the result (T_{kin} is a kinetic freeze-out temperature and v_T is the collective transverse flow velocity):

$$T^*_{\text{low}-p_T} = T_{\text{kin}} + \frac{1}{2} m \, \overline{v_T^2} . \qquad (4)$$

The linear mass dependence (4) of T^* is supported by the data for hadron spectra at small p_T. However, for $p_T >> m$, the hydrodynamical transverse flow leads to a mass-independent blue-shifted 'temperature':

$$T^*_{\text{high}-p_T} = T_{\text{kin}}\sqrt{\frac{1+v_T}{1-v_T}} . \qquad (5)$$

The simple one-parameter exponential fit (2) is quite accurate up to $m_T - m \cong 1$ GeV for K^+ and K^- mesons in A+A collisions at all energies. This means that the energy dependence of the average transverse mass $\langle m_T\rangle$ (3) and average transverse momentum $\langle p_T\rangle$ for kaons is qualitatively the same as that for the parameter T^*. Note that the simple exponential fit (2) neither works for light π-mesons ($T^*_{\text{low}-p_T} > T^*_{\text{high}-p_T}$) nor for heavy (anti)protons and (anti)lambdas ($T^*_{\text{low}-p_T} < T^*_{\text{high}-p_T}$). This means that the average transverse masses, $\langle m_T\rangle$, and their energy dependence for these hadrons are not connected to the behavior of the slope parameters in the simple way described by Eq. (3): one should separately consider both $T^*_{\text{low}-p_T}$ and $T^*_{\text{high}-p_T}$ slopes (see [8, 9] for details).

1.4. Entropy Fluctuations

In thermodynamics, the energy E and entropy S are related to each other through the equation of state, EoS. Thus, various values of the energy of the initial equilibrium state lead to different, but uniquely determined, initial entropies. When the collision energy is fixed, the energy which is used to hadron production still fluctuates. Consequently, simultaneous event-by-event measurements of both the entropy and energy yield an information on the EoS. Since EoS shows an anomalous behavior in the phase transition region, the anomaly should be visible in the ratio of entropy to energy fluctuations [3].

According to the first and the second principles of thermodynamics, the entropy change δS is given as $T\delta S = \delta E + p\delta V$. If we fix the collision geometry, choosing e.g. only a sample of central A+A collisions, we can expect $\delta V \cong 0$. Within SMES, the ratio of entropy to energy fluctuations can be then easily calculated and presented as a simple function of the p/ε ratio [3]:

$$R_F \equiv \frac{(\delta S)^2/S^2}{(\delta E)^2/E^2} = \left(1 + \frac{p}{\varepsilon}\right)^{-2} . \qquad (6)$$

Thus, it is easy to predict a qualitative dependence of the R_F ratio on collision energy. Within the model, the confined matter, which is modelled as an ideal gas, is created at the collision early stage below the energy of 30 A·GeV. In this domain, the ratio p/ε and consequently the R_F ratio are approximately independent of collision energy and equal about 1/3 and 0.6, respectively. The model assumes that the deconfinement phase transition is of the first order. Thus, there is the mixed phase region corresponding to the energy interval 35÷60 A·GeV. At the end of the mixed phase, the p/ε ratio reaches minimum (the "softest point" of EoS [6]). Thus, in the transition energy range, the R_F ratio increases and reaches its maximum, $R_F \approx 0.8$, at the end of the transition domain. Further on, in the pure deconfined phase which is represented by an ideal quark-gluon gas under bag pressure, the p/ε ratio increases and approaches its asymptotic value 1/3 at the highest SPS energy 160 A·GeV. An estimate of entropy fluctuations can be obtained form the analysis of multiplicity fluctuations as proposed in [3].

At the stage of particle freeze-out, the system's entropy is related to the mean particle multiplicity, $S \propto \overline{N}$. Thus, the initial entropy fluctuations are transformed into the fluctuations of the *mean* multiplicity. It is important to distinguish these fluctuations of $\overline{N}$ formed at the initial stage of the A+A reaction, from the statistical fluctuations of N around $\overline{N}$ at the freeze-out (see [3] for details).

2. Signals of Deconfinement: Experimental Results

The Pion Kink. A recent compilation of the data on pion multiplicity in central Pb+Pb (Au+Au) collisions and p+p interactions is shown in Fig. 1.In this figure, the ratio $\langle\pi\rangle/\langle N_W\rangle$ is plotted as a function of F.

One observes that the mean pion multiplicity per wounded nucleon in $\mathrm{p}+\mathrm{p}(\overline{\mathrm{p}})$ interactions is approximately proportional to F; the dashed line in Fig. 1 indicates a fit of the form $\langle\pi\rangle/\langle N_W\rangle = aF$ to the data. For central A+A collisions, the dependence is more complicated and cannot be fitted by a single linear function. Below 40 A·GeV, the ratio $\langle\pi\rangle/\langle N_W\rangle$ in A+A collisions is lower than in p+p interactions (pion suppression), while at higher energies $\langle\pi\rangle/\langle N_W\rangle$ is larger in A+A collisions than in $\mathrm{p}+\mathrm{p}(\overline{\mathrm{p}})$ interactions (pion enhancement). In the region between the AGS and the lowest SPS energy (15–40 A·GeV) the slope changes from $a = (1.01 \pm 0.04)$ GeV$^{-1/2}$ for the fit to the points up to the top AGS energy to $a = (1.36 \pm 0.03)$ GeV $^{-1/2}$ for the fit to the top SPS energy and the RHIC data points (the full line in Fig. 1).

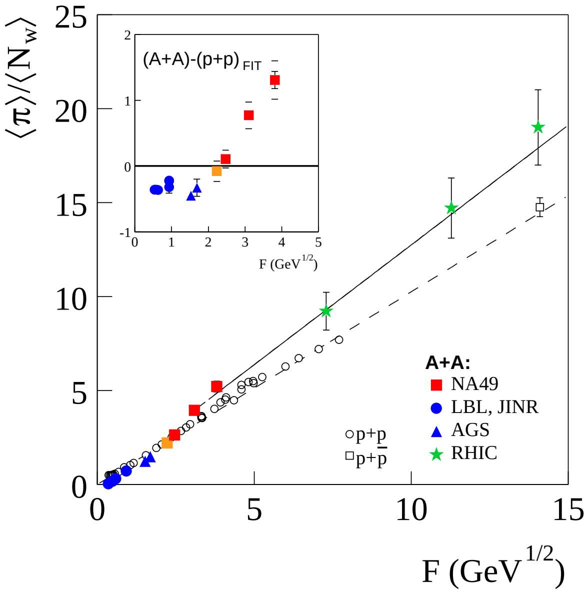

Fig. 1. The dependence of total pion multiplicity per wounded nucleon on Fermi's energy measure F for central A+A collisions (closed symbols) and inelastic $\mathrm{p}+\mathrm{p}(\overline{\mathrm{p}})$ interactions (open symbols)

The measured increase of the slope for A+A collisions by a factor of about 1.3, is interpreted within the SMES as due to an increase of the effective number of the internal degrees of freedom by a factor of $(1.3)^4 \cong 3$ and is caused by the creation of a transient state of deconfined matter at energies higher than 30 A·GeV.

The suppression of pion production in A+A collisions in comparison to p+p interactions is interpreted as due to entropy transfer from mesons to baryons, which is expected to result in a constant shift of the $\langle\pi\rangle/\langle N_W\rangle$ ratio [10]. The transition from pion suppression to pion enhancement is demonstrated more clearly in the insert of Fig. 1, where the difference between $\langle\pi\rangle/\langle N_W\rangle$ for A+A collisions and the straight line parametrization of the p+p data is plotted as a function of F up to the highest SPS energy.

The Strange Horn. One can argue that the strangeness to entropy ratio is closely proportional to the two ratios directly measured in experiments: the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio and the $E_S = (\langle\Lambda\rangle + \langle K + \overline{K}\rangle)/\langle\pi\rangle$ ratio. The energy dependence of both ratios is plotted in Fig. 2 for central Pb+Pb (Au+Au) collisions and p+p interactions.

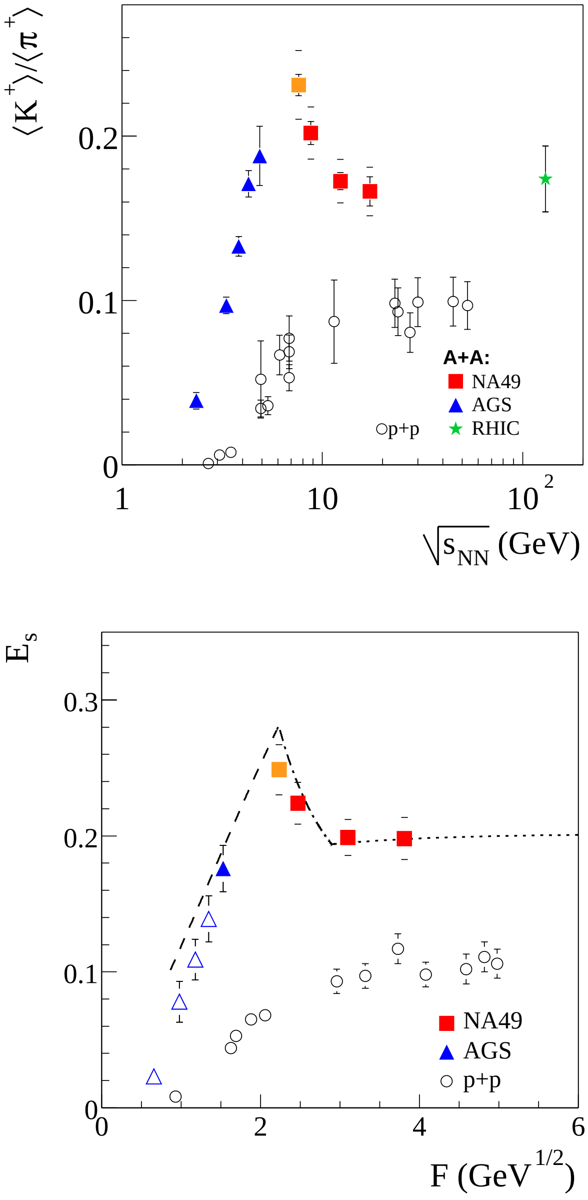

Fig. 2. The dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ (left) and E_S (right) ratios on the collision energy for central A+A collisions (closed symbols) and inelastic p+p interactions (open symbols). The predictions of SMES for the E_S ratio are shown by a line. Different line styles indicate predictions in the energy domains in which confined matter (dashed line), mixed phase (dash–dotted line), and deconfined matter (dotted line) are created at the early stage of the collisions

For p+p interactions, both ratios show a monotonic increase with energy. However, very different behavior is observed for central Pb+Pb (Au+Au) collisions. The steep threshold rise of the ratio characteristic of confined matter then settles into saturations at the level expected for deconfined matter. In the transition region (at low SPS energies), a sharp maximum is observed to be caused by a higher strangeness to entropy ratio in confined matter than that in deconfiend matter. As seen in Fig. 2, the measured dependence is consistent with that expected within the SMES.

The Step in Slopes. The energy dependence of the inverse slope parameter fitted to the K^+ (left) and K^- (right) transverse mass spectra for central Pb+Pb (Au+Au) collisions is shown in Fig. 3 [2]. The striking features of the data can be summarized and interpreted as follows.

The T^* parameter increases strongly with collision energy up to the lowest (30 A·GeV) SPS energy point. This is an energy region where the creation of confined matter at the early stage of the collisions is expected. Increasing the collision energy leads to an increase of the early stage temperature and pressure. Consequently the transverse activity of produced hadrons, measured by the inverse slope parameter, increases with energy. The T^* parameter is approximately independent of the collision energy in the SPS energy range. In this energy region, the transition between confined and deconfined matter is expected to be located. The resulting modification of the equation of state "suppresses" the hydrodynamical transverse expansion and leads to the observed plateau structure in the energy dependence of the T^* parameter. At higher energies (RHIC data), T^* again increases with collision energy. The equation of state at the early stage becomes again stiff, the early stage temperature and pressure increase with collision energy. This results in the increase of T^* with energy.

Among measured hadron species, kaons are the best and unique particles for observing the effect of modification of the equation of state due to the onset of deconfinement. The arguments are the following.

- The kaons m_T spectra are only weakly affected by the hadron re-scattering and resonance decays during the post-hydrodynamic hadron cascade at the SPS and RHIC energies [8].

- A simple one-parameter exponential fit (3) is quite accurate for kaons in central A+A collisions at all energies. This simplifies strongly an analysis of the experimental data.

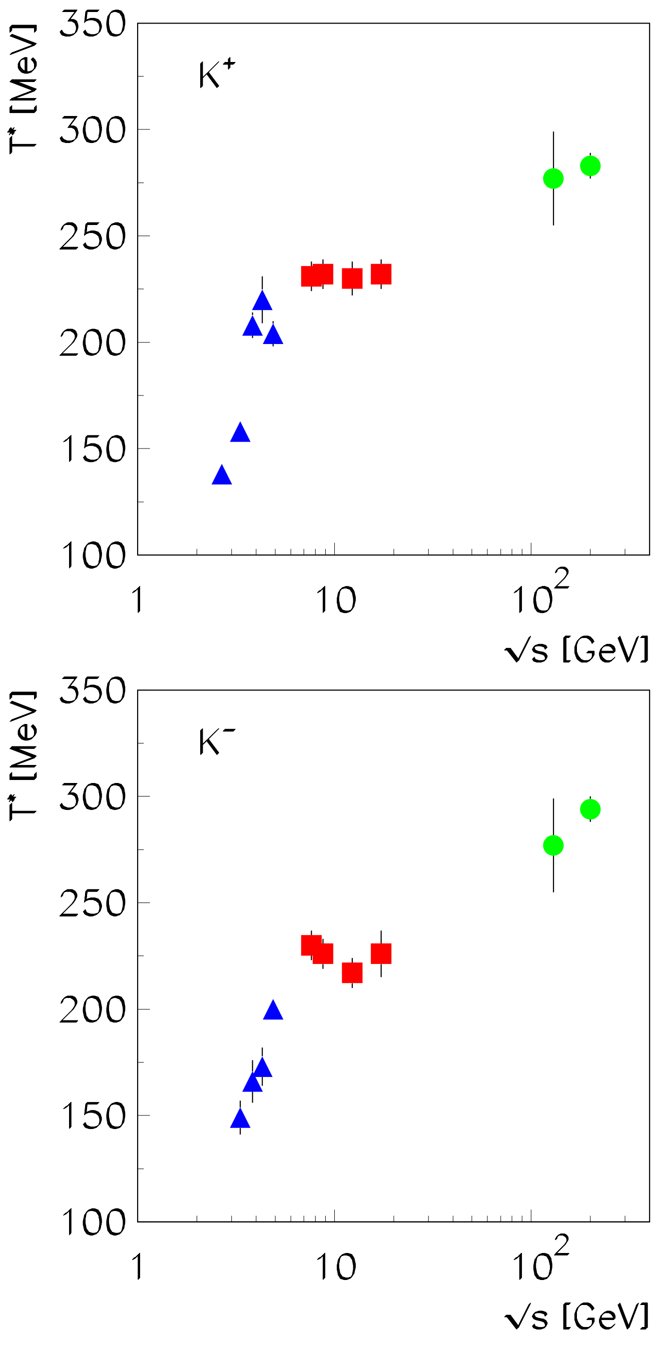

Fig. 3. The energy dependence of the inverse slope parameter T^* for K^+ (left) and K^- (right) mesons produced at mid-rapidity in central Pb+Pb (Au+Au) collisions at AGS (triangles), SPS (squares), and RHIC (circles) energies

- The high-quality data on the m_T spectra of K^+ and K^- mesons in central Pb+Pb (Au+Au) collisions are available in the full range of relevant energies.

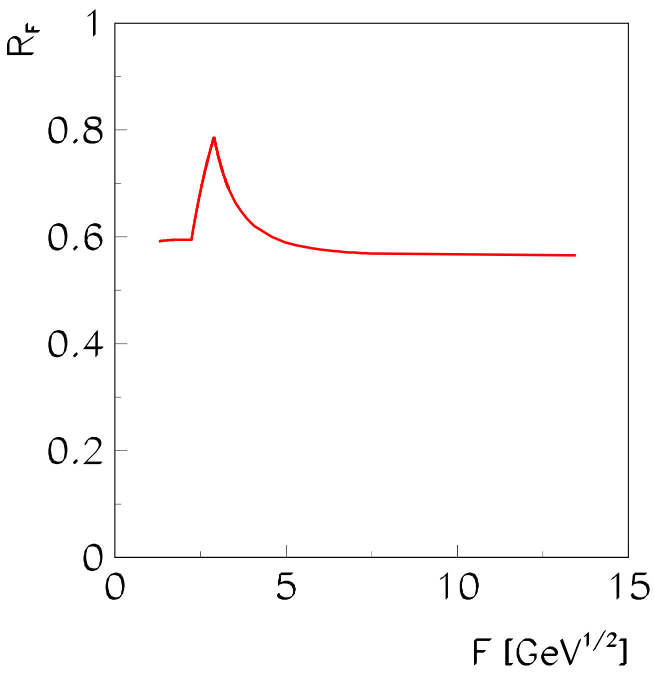

Fig. 4. The collision energy dependence of the relative entropy to energy fluctuations, R_F, calculated within SMES. The non-monotonic behavior, the "shark fin" structure, is caused by large fluctuations expected in the vicinity of the mixed phase region

The Shark Fin in Entropy Fluctuations. Ratio (6) of entropy to energy fluctuations is presented in Fig. 4 [3].

The experimental results on the energy dependence of the R_F ratio are still not available.

Conclusions

The energy scan program at the CERN SPS together with the measurements at lower (LBL, JINR, SIS, BNL AGS) and higher (BNL RHIC) energies yielded the systematic data on the energy dependence of hadron production in central Pb+Pb (Au+Au) collisions. Predicted signals of the deconfinement phase transition, namely anomalies in the energy dependence of hadron production (the pion kink, strange horn, and step in slopes, see [1,2]) are observed simultaneously at low SPS energies. They indicate that the onset of deconfinement is located at about 30 A·GeV. For the first time, we seem to have clear evidence for the existence of the deconfined state of matter in nature. The analysis of the data from the energy scan program is still in progress. In particular, first results at 20 A·GeV are soon expected. Many new observables can be studied in the near future.

We hope that the properly analyzed event–by-event fluctuations (see [3]) may also be sensitive to the onset of deconfinement and can serve as a further confirmation of the current interpretation of the data.

The results presented in this report were to a large extent obtained thanks to my close collaboration with Marek Gaździcki. I would like to thank him for an exciting and fruitful period of joint work. I am also thankful to Walter Greiner for his permanent support and encouraging of these studies.

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ФАЗОВИЙ ПЕРЕХІД ДЕКОНФАЙНМЕНТУ В РЕЛЯТИВІСТСЬКИХ ЯДРА-ЯДЕРНИХ ЗІТКНЕННЯХ

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Резюме

Обговорюється залежність народження адронів від початкової енергії в релятивістських ядра-ядерних зіткненнях. Декілька “аномалій” в цій залежності було передбачено як сигнали фазового переходу деконфайнменту, і три з них було виявлено експериментально на прискорювачі в CERN SPS. Це вказує на той факт, що початок фазового переходу деконфайнменту в Pb+Pb-зіткненнях знаходиться при енергії близько 30A ГеВ. Мабуть вперше ми маємо прямі свідчення про існування в природі матерії в стані деконфайнменту.

ФАЗОВЫЙ ПЕРЕХОД ДЕКОНФАЙНМЕНТА В РЕЛЯТИВИСТСКИХ ЯДРА-ЯДЕРНЫХ СОУДАРЕНИЯХ

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Резюме

Мы обсуждаем зависимость рождения адронов от начальной энергии в релятивистских ядра-ядерных соударениях. Несколько “аномалий” в этой зависимости были предсказаны как сигналы фазового перехода деконфайнмента, и три из них были обнаружены экспериментально на ускорителе в CERN SPS. Это указывает на то, что начало фазового перехода деконфайнмента в Pb+Pb-соударениях расположено при энергии около 30A ГэВ. Кажется, впервые мы имеем прямые свидетельства о существовании в природе материи в состоянии деконфайнмента.