TRACING DECONFINEMENT IN NUCLEUS–NUCLEUS COLLISIONS*

Marek Gaździcki

Institut für Kernphysik, University of Frankfurt
August Euler Str. 6, 60486 Frankfurt, Germany
and
Swiętokrzyska Academy, 25-406 Kielce, Poland

(Received September 29, 2003)

The basic ideas which motivated the search for a deconfinement phase transition in high energy nucleus–nucleus collisions are reviewed. The main results obtained within the energy scan programme at the CERN SPS are presented. Several anomalies in energy dependence of hadron production predicted as signals of deconfinement phase transition are observed and they indicate that the onset of deconfinement phase transition 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.

PACS numbers: 24.85.+p

1. A brief history of ideas

Phase transitions are fascinating physical phenomena. Small changes in temperature (pressure, energy density) lead to dramatic changes in macroscopic properties of matter. Common examples from our daily lives are transitions between solids, liquids and gases such as when water freezes and boils. Properties of substances surrounding us, and the transitions between their various phases, are determined by electromagnetic interactions of atoms and molecules. In the case of atomic nuclei which are built out of nucleons their properties are governed by strong interactions. Thus the questions which arise are: What are the phases of strongly interacting matter? At which temperatures (energy densities) do the transitions between phases take place? What do these transitions look like?

It is likely that successive transitions between various phases of strongly interacting matter took place during the expansion and cooling of the early

* Presented at the XLIII Cracow School of Theoretical Physics, Zakopane, Poland, May 30–June 8, 2003.

Universe, approximately 1 microsecond after the Big Bang. Strongly interacting matter is believed to fill the interior of compact stellar objects such as neutron or quark stars. However, a systematic study of the properties of strongly interacting matter requires a method to create it under well controlled conditions in the laboratory. The study of collisions of two heavy nuclei gives us this opportunity. One expects that during such a collision, a droplet of strongly interacting matter at high energy density is created. Unfortunately, the life time of this so-called fireball is very short, about 10^{-22} seconds. It quickly expands, cools down and finally decays into hadrons and a few light nuclei. These decay products are measured by detectors located around the collision point.

Naturally one expects that with increasing collision energy, the energy density of the fireball would also increase. Thus, as when water heats and successive transitions between its phases are observed, we hope that with increasing collision energy we will be able to observe successive transitions between various phases of strongly interacting matter created at the early stage of a collision. Over the past decades extensive studies of collisions of heavy nuclei have been carried out at several accelerators. These cover a broad energy range from energies $\sqrt{s}_{NN} \approx 2$ GeV (the collision energy in the center of mass of a nucleon–nucleon pair, 1 GeV $= 1.6 \times 10^{-10}$ J) at the BEVALAC at Berkeley and SIS at Darmstadt to the most energetic collisions presently produced at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) $\sqrt{s}_{NN} = 200$ GeV.

Indications of the first phase transition of strongly interacting matter, between a nuclear liquid and a nuclear gas, were reported from the analysis of collisions at low energies ($\sqrt{s}_{NN} \approx 2$ GeV) [1]. The transition temperature was estimated to be about 6×10^{10} K (5 MeV).

Emerging results from the study of high energy collisions of nuclei indicate the existence of the second phase transition of strongly interacting matter, the so–called deconfinement phase transition. Let us briefly report how this phase transition was looked for, and what are the main results of this search.

For more than 30 years it is known that hadrons consist of more elementary particles, *i.e.* quarks and gluons. Thus far nobody has observed an isolated quark or gluon. They always seem to be confined in the interior of hadrons. However arguments against this general statement were presented already in the 1970s, soon after formulation of the confinement idea and the development of quantum chromo-dynamics (QCD), the theory of strong interactions. One of the pioneering papers argued [2]: "A neutron has a radius of about 0.5–1 fm (1 fm $= 10^{-15}$ m), and so has a density of about $8{\times}10^{14}$ g cm^{-3}, whereas the central density of a neutron star can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. **Therefore, we suggest that matter at such densities is a quark soup.**" Thus the creation of matter in a deconfined phase (quark gluon plasma, QGP) may be the only possibility to "see" quarks and gluons moving freely in a large volume.

The development of numerical calculation techniques within QCD (lattice–QCD) made it possible to investigate the properties of strongly interacting matter within this approach. Indeed, it was found that there should be a deconfinement phase transition when the energy density of matter exceeds a critical value of about 1 GeV/fm^3 (1.6×10^{35} J/m^3).

Search for the state of deconfined strongly interacting matter already has a long and complicated history. Here we limit our discussion to a path which resulted in the recent data obtained by the NA49 experiment at the CERN Super Proton Synchrotron (SPS), the data which point to the existence of a deconfinement phase transition (and thus the QGP).

In the mid 90s numerous results on collisions of light nuclei at the BNL AGS (beams of Si at 14.6 A GeV) and the CERN SPS (beams of O and S at 200 A GeV) were obtained. The experiments with heavy nuclei (AGS: Au+Au at 11.6 A GeV, SPS: Pb+Pb at 158 A GeV) were just starting. This was the time when the first look at the energy dependence of hadron production in nucleus–nucleus ($A+A$) collisions at high energies was possible. Two compilations, on pion production [3] and on strangeness production [4] resulted in a clear conclusion: the energy dependences of hadron multiplicities measured in $A+A$ collisions and $p+p$ interactions are very different. Further more the data on $A+A$ 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 [5] it was speculated [6] that the change is related to the onset of deconfinement at the early stage of the $A+A$ collisions. Soon after, following this conjecture, a quantitative model was developed, the Statistical Model of the Early Stage (SMES) [7]. 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. The phase transition is assumed to be of the first order.

2. A brief history of the energy scan programme

Based on these ideas in 1997 the NA49 Collaboration proposed to study hadron production in Pb+Pb collisions at the low SPS energies beginning from 30 A GeV [8]. At this energy the SMES predicted a sharp maximum of a strangeness to pion ratio as a characteristic signal of the onset of deconfinement. Following this request the 40 A GeV Pb–beam was delivered to NA49 in 1998 as a test. The 5 weeks long run at 40 A GeV took place in 1999 [1]. The data were registered by NA49, NA45, NA50 and NA57 experiments. The success of this first run at low SPS energy and the exciting preliminary results shown by NA49 justified a continuation of the program. In 2000 a beam at 80 A GeV was delivered for 5 days to NA49 and NA45. The program was completed in 2002 by the run (NA49 and NA60) at 30 A GeV (7 days) and 20 A GeV (7 days).

Numerous experimental results from the run at 30, 40, 80 and 158 A GeV are already published, see *e.g.* [9–11], and presented at conferences see *e.g.* [12, 13]. The data at 20 A GeV are still being analysed.

3. Signals of deconfinement

Originally two signals of the deconfinement phase transition were proposed within the SMES: the characteristic changes in the energy dependence of mean pion and mean strangeness multiplicities [7]. Recently two new signals were suggested within the same approach: the energy dependence of the shape of the transverse mass spectrum of kaons [14] and the energy dependence of properly filtered multiplicity fluctuations [15]. Intuitive arguments which lead us to the proposed signals as well as the experimental status of the signals are reviewed below.

3.1. The pion kink

The majority of all particles produced in high energy interactions are pions. Thus, pions carry basic information on entropy created in the 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 a state with higher entropy than that created in 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 $\langle N_\mathrm{W} \rangle$ (the notation $\langle ... \rangle$ will be used to denote the mean multiplicity in full phase space throughout the paper). This simple intuitive argument can be quantified within the SMES. Due to the assumed generalised Fermi–Landau initial conditions [5] the $\langle \pi \rangle / \langle N_\mathrm{W} \rangle$ ratio increases approximately linear with F [2] outside the transition region. The slope parameter is proportional to

[1] The program was started by 40 A GeV run instead of originally requested 30 A GeV run due to technical SPS reasons.

[2] F is the Fermi's energy measure [5]: $F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}$, where $\sqrt{s_{NN}}$ is the c.m.s. energy per nucleon–nucleon pair and m_N the rest mass of the nucleon.

$g^{1/4}$ [6], where g is an effective number of internal degrees of freedom at the early stage. In the transition region a steepening of the pion energy dependence is predicted, because of activation of a large number of partonic degrees of freedom.

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 $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle$ is plotted as a function of F. One observes that the mean pion multiplicity per wounded nucleon in $p+p(\bar{p})$ interactions is approximately proportional to F; the dashed line in Fig. 1 indicates a fit of the form $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle = aF$ to the data. For central $A+A$ collisions the dependence is more complicated and cannot be fitted by a single linear function. Below 40 AGeV the ratio $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle$ in $A+A$ collisions is lower than in $p+p$ interactions (pion suppression), while at higher energies $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle$ is larger in $A+A$ collisions than in $p+p(\bar{p})$ interactions (pion enhancement). In the region between the AGS and the lowest SPS energy (15–40 AGeV) 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).

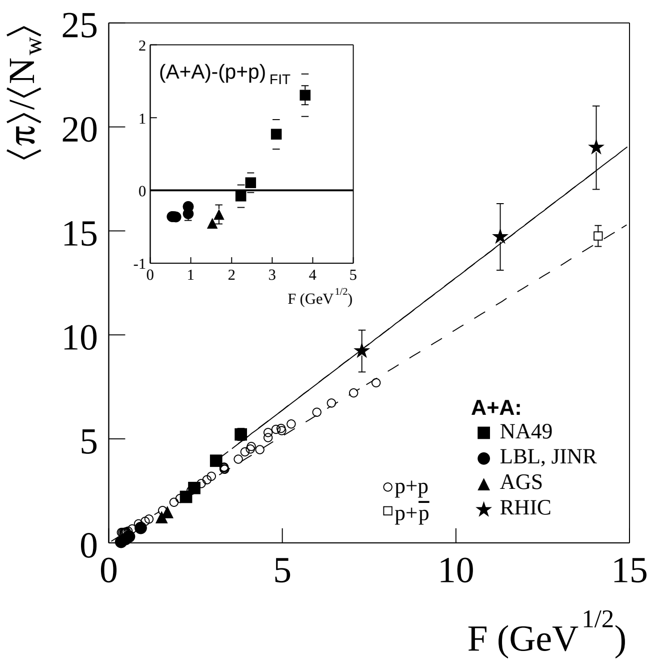

Fig. 1. The dependence of total pion multiplicity per wounded nucleon on Fermi's energy measure F for central $A+A$ collisions (closed symbols) and inelastic $p+p(\bar{p})$ interactions (open symbols).

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 $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle$ ratio [16]. The transition from pion suppression to pion enhancement is demonstrated more clearly in the insert of Fig. 1, where the difference between $\langle\pi\rangle/\langle N_{\mathrm{W}}\rangle$ 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.

3.2. The strange horn

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 [7]. Within the SMES at low collision energies, when confined matter is produced, the strangeness to entropy ratio steeply increases with collision energy, due to the low temperature at the early stage ($T < T_{\mathrm{C}}$) and the high mass of the carriers of strangeness ($m_{\mathrm{S}} \cong 500$ MeV, the kaon mass). When the transition to deconfined matter is crossed ($T > T_{\mathrm{C}}$), the mass of the strangeness carriers is significantly reduced ($m_{\mathrm{S}} \cong 170$ MeV, the strange quark mass). Due to the low mass ($m_{\mathrm{S}} < T$) the strangeness yield becomes (approximately) proportional to the entropy, and the strangeness to entropy (or pion) ratio is 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 measured 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 AGeV.

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 $E_{\mathrm{S}} = (\langle\Lambda\rangle + \langle K+\overline{K}\rangle)/\langle\pi\rangle$ ratio. The energy dependence of both ratios is plotted in Fig. 2 for central Pb+Pb (Au+Au) collisions and $p+p$ interactions. For $p+p$ interactions both ratios show monotonic increase with energy. However, very different behaviour is observed for central Pb+Pb (Au+Au) collisions. The steep threshold rise of the ratio characteristic for confined matter then settles into saturation at the level expected for deconfined matter. In the transition region (at low SPS energies) a sharp maximum is observed caused by a higher strangeness to entropy ratio in confined matter than in deconfined matter. As seen in Fig. 2 the measured dependence is consistent with that expected within the SMES.

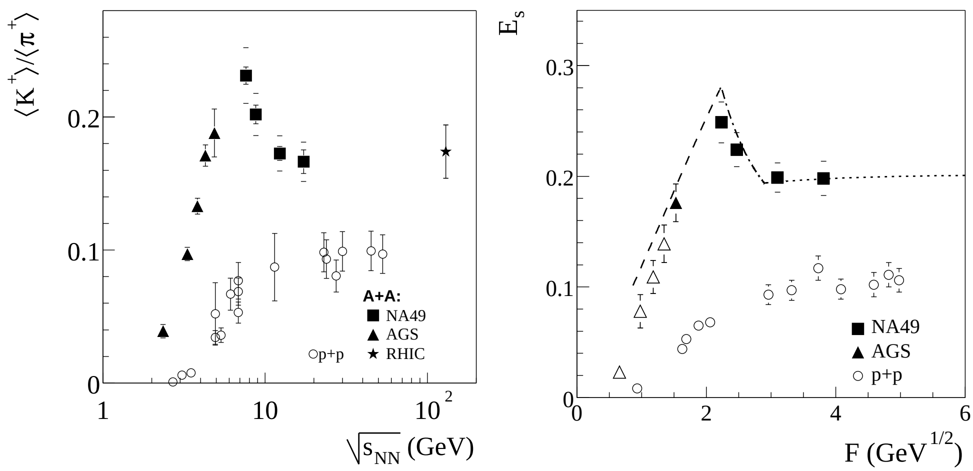

Fig. 2. The dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ (left) and $E_{\rm S}$ (right) ratios on the collision energy for central $A+A$ collisions (closed symbols) and inelastic $p+p$ interactions (open symbols). The predictions of SMES for the $E_{\rm S}$ ratio are shown by a line. Different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

3.3. The step in slopes

With increasing collision energy the energy density at the early stage increases. At low and high energies, when pure confined or deconfined phases are 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 transverse mass spectra of final state hadrons. In the phase transition region the initial energy density increases with collision energy, but temperature $T_0 = T_{\rm C}$ and pressure $p_0 = p_{\rm C}$ remain constant. Consequently the shape of the $p_{\rm T}$ spectrum is expected to be approximately independent of collision energy in the transition region. Thus one expects a characteristic 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 [14, 17].

The energy dependence of the inverse slope parameter fitted to the K^+ (left) and K^- (right) transverse mass spectra at midrapidity for central Pb+Pb (Au+Au) collisions is shown in Fig. 3 [14]. The striking features of the data, not observed in $p+p$ interactions [18], can be summarised and interpreted as follows.

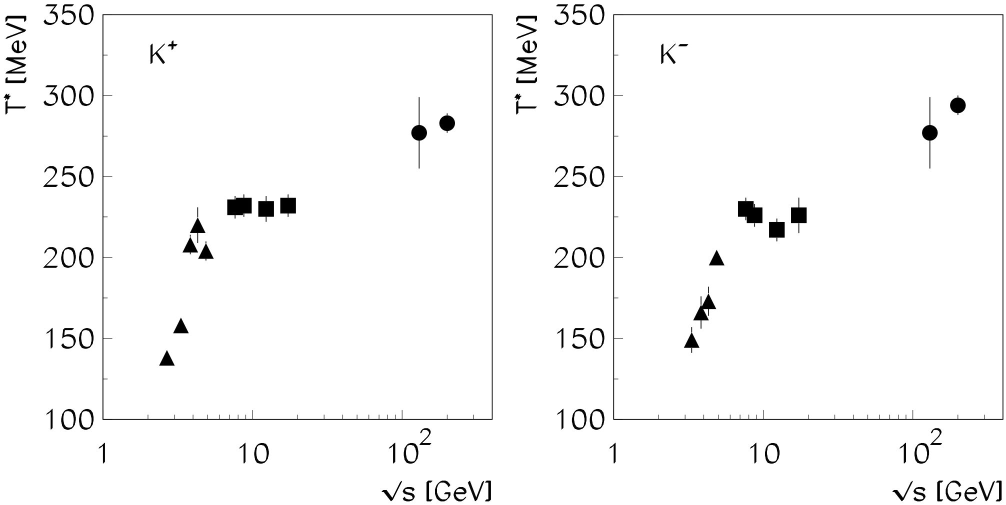

Fig. 3. The energy dependence of the inverse slope parameter T^* for K^+ (left) and K^- (right) mesons produced at mid-rapidity in central Pb+Pb (Au+Au) collisions at AGS (triangles), SPS (squares) and RHIC (circles) energies.

The 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 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 increasing 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 increase of T^* with energy.

3.4. The shark fin in 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 for hadron production still fluctuates. Consequently, simultaneous event–by–

event measurements of both the entropy and energy yield information on the EoS. Since the EoS changes rapidly in the phase transition region this should be visible in the ratio of entropy to energy fluctuations [15].

Within the SMES the ratio of entropy to energy fluctuations is given by a simple function of the p/ε (pressure/energy density) ratio:

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

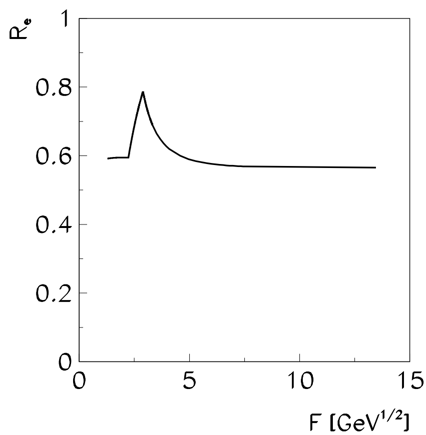

Fig. 4. The collision energy dependence of the relative entropy to energy fluctuations, R_e, calculated within SMES. The non-monotonic behaviour, the "shark fin" structure, is caused by the large fluctuations expected in the vicinity of the mixed phase region.

It is easy to predict a qualitative dependence of the R_e ratio on collision energy. Within the approach, confined matter modelled as an ideal gas is created below $\approx 30A$ GeV beam energy. In this domain, the ratio p/ε, and consequently the R_e ratio, are approximately independent of collision energy and equal to the ideal gas value of about 1/3 and 0.6, respectively. The model assumes that the deconfinement phase–transition is of the first order. Thus, there is a mixed phase region, corresponding to the energy interval $\approx 30 \div \approx 60A$ GeV. At the end of the mixed phase the p/ε ratio reaches a minimum (the "softest point" of the EoS [19]). Thus in the transition energy range the R_e 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 of 160 A GeV. This results in a decrease of the R_e ratio and its saturation at the value of about 0.6.

An estimate of the entropy fluctuations can be obtained from the analysis of multiplicity fluctuations as proposed in [15].

Experimental results on the energy dependence of the R_e ratio are not yet available.

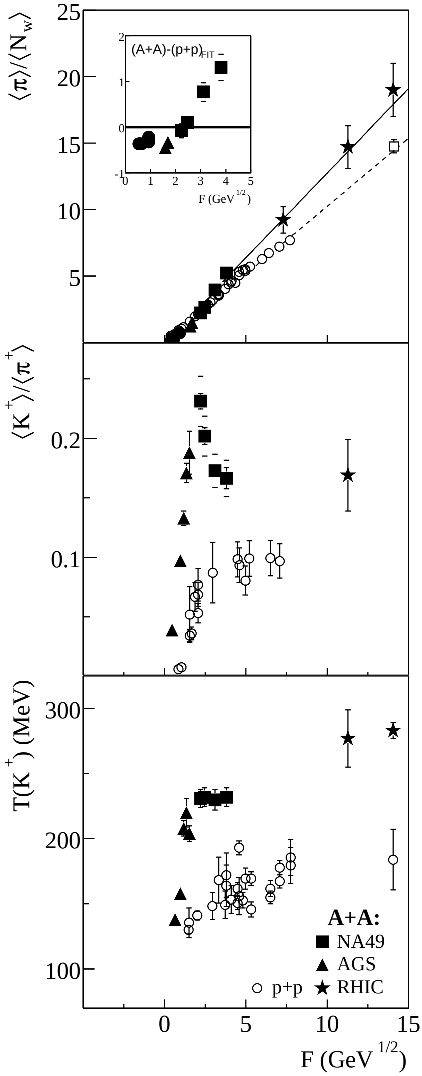

Fig. 5. Collision energy dependence ($F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4}/\sqrt{s_{NN}}^{1/4} \approx s_{NN}^{1/4}$, where m_N is nucleon mass) of various hadron production properties (for details see text) measured in central Pb+Pb and Au+Au collisions (solid symbols) compared to results from $p+p$ reactions (open dots). The changes in the SPS energy range (solid squares) indicate the onset of the deconfinement phase transition.

4. Conclusions and future

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 systematic data on 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, the strange horn and the step in slopes) are observed simultaneously at low SPS energies. The basic results are plotted on the same energy scale in Fig. 5 for a direct comparison.

They indicate that the onset of deconfinement is located at about 30 AGeV. 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 we are soon expecting first results at 20 A GeV. Many new observables can be studied in the near future. We hope that the properly analysed event–by-event fluctuations may also be sensitive to the onset of deconfinement and can serve as further confirmation of the current interpretation of the data.

The observation of anomalies in the energy dependence of hadron production in Pb+Pb collisions in the SPS energy range requires further study. In the future it would be interesting to extend measurements of the energy dependence to central collisions of light nuclei as well as to proton-proton and proton–nucleus interactions. Such measurements should significantly constrain models of the collision process and, in particular, help us to understand the role played by the volume of the droplet of strongly interacting matter in determining the onset of the deconfinement phase transition.

I would like to thank Mark I. Gorenstein and Peter Seyboth for a very exciting and fruitful period of common search for deconfinement phase transition in nucleus–nucleus collisions. This work was partially supported by Bundesministerium für Bildung und Forschung (Germany) and the Polish State Committee for Scientific Research (KBN) under grant 2P03B04123.

REFERENCES

[1] P.J. Siemens, *Nature* **305**, 410 (1983); J.P. Bondorf, A.S. Botvina, A.S. Ilinov, I.N. Mishustin, K. Sneppen, *Phys. Rep.* **257**, 133 (1995); J. Pochodzalla *et al.*, *Phys. Rev. Lett.* **75**, 1040 (1995).

[2] J. Collins, M. Perry, *Phys. Rev. Lett.* **34**, 1353 (1975).

[3] M. Gaździcki, D. Röhrich, *Z. Phys.* **C65**, 215 (1995).

[4] M. Gaździcki, D. Röhrich, *Z. Phys.* **C71**, 55 (1996).

[5] E. Fermi, *Prog. Theor. Phys.* **5**, 570 (1950); L.D. Landau, *Izv. Akad. Nauk SSSR Ser. Fiz.* **17**, 51 (1953).

[6] M. Gaździcki, Proceedings of NATO Advanced Research Workshop: "Hot Hadronic Matter: Theory and Experiment", Divonne-les-Bains, France, June 27–July 1, 1994, ed. by J. Letessier, H.H. Gutbrod and J. Rafelski, NATO ASI Series B: Physics Vol. 346, Plenum Press, 1995, p. 215; M. Gaździcki, *Z. Phys.* **C66**, 659 (1995); *J. Phys. G* **23**, 1881 (1997).

[7] M. Gaździcki, M.I. Gorenstein, *Acta Phys. Pol. B* **30**, 2705 (1999).

[8] J. Bächler *et al.* (NA49 Collab.), Searching for QCD Phase Transition, Addendum–1 to Proposal SPSLC/P264, CERN/SPSC 97 (1997).

[9] S.V. Afanasiev *et al.* (NA49 Collab.), *Phys. Rev.* **C66**, 054902 (2002).

[10] M.C. Abreu *et al.* (NA50 Collab.), *Phys. Lett.* **B530**, 33 (2002); **B530**, 43 (2002).

[11] D. Adamova *et al.* (NA45 Collab.), *Nucl. Phys.* **A714**, 124 (2003).

[12] for review see Proceedings of the 6th International Conference on Strange Quarks in Matter, Frankfurt, 2001, *J. Phys.* **G28**, 1517 (2002).

[13] C. Alt *et al.* [The NA49 Collaboration], `nucl-ex/0305017`.

[14] M.I. Gorenstein, M. Gaździcki, K. Bugaev, *Phys. Lett.* **B567**, 175 (2003).

[15] M. Gaździcki, M.I. Gorenstein, St. Mrówczyński, `hep-ph/0304052`.

[16] M. Gaździcki, M.I. Gorenstein, St. Mrówczyński, *Eur. Phys. J.* **C5**, 129 (1998).

[17] L. Van Hove, *Phys. Lett.* **B118**, 138 (1982); E.V. Shuryak, O.V. Zhirov, *Phys. Lett.* **B89**, 253 (1979).

[18] M. Kliemant, B. Lungwitz, M. Gazdzicki, `hep-ex/0308002`.

[19] C.M. Hung, E. Shuryak, *Phys. Rev. Lett.* **75**, 4003 (1995).