SUMMARY OF THE MEETING*

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(Received March 18, 2002)

A (very personal) summary of the meeting is presented.

PACS numbers: 25.75.–q

1. Excuses

It does not seem possible to cover here all ideas presented during the conference. First, they were numerous. Second, being incompetent, I did not fully understand many of them. Third, this volume contains most of the talks and thus the reader can consult them directly. Therefore, I shall restrict myself to those few things which were close enough to my own interests.

2. General remarks about data

Data from CERES and from all four RHIC experiments were presented.

It was rather re-comforting to see that the new, more precise data from CERES [1] confirm the earlier findings: definitely, the excess of dileptons in the mass region below the ρ peak is here to stay (see Fig. 1). And it represents a real challenge for the theory. At the moment, the only viable idea is the shift of the ρ mass in the high density environment [2]. But it will require some more work to be fully acceptable. I feel that, given this situation, it would be very useful to perform a serious calculation of dilepton production from parton-like systems (QGP, the quark–antiquark gas *etc.*). This could provide a necessary alternative to the present hadron-like theories and give a hint as to the future direction of the experiment.

* Presented at the Cracow Epiphany Conference on Quarks and Gluons in Extreme Conditions, Cracow, Poland, January 3–6, 2002.

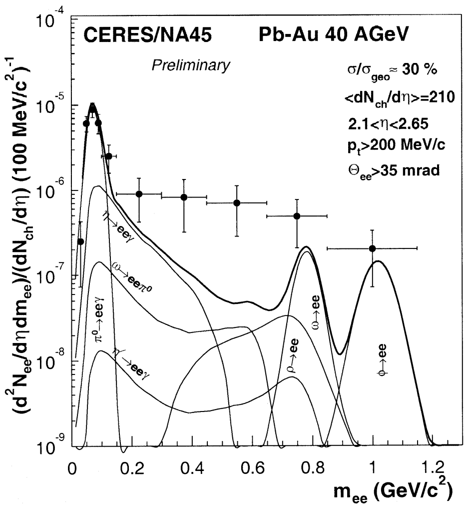

Fig. 1. Recent data from the CERES experiment [1].

The RHIC experiments [3–6] impress everybody, I think, by the speed at which they produced the results and by the quality of the data. In fact, one of the most amazing things is that, as we have seen, the measurements from all four experiments do agree with each other (where they overlap). There is obviously no point to review these results here (they are included in this volume), so I shall restrict myself to two remarks.

First, as shown in numerous examples, all MC codes used in data analysis fail to describe correctly the experimental results. An illustration is shown in Fig. 2 [3], where one sees that none of the three popular models can

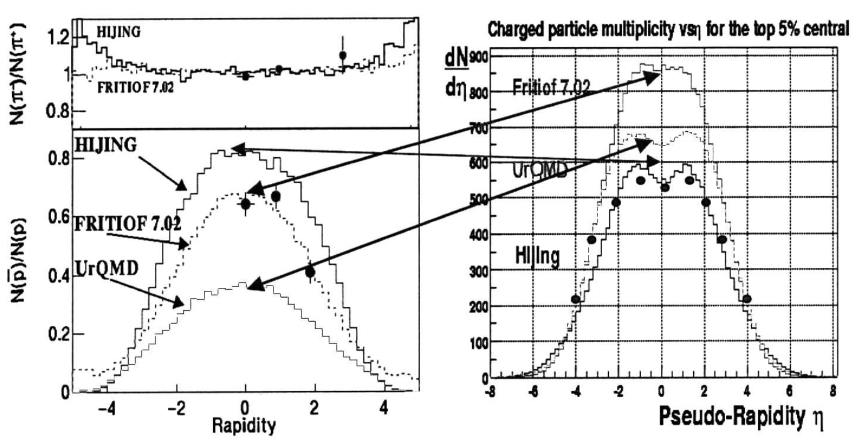

Fig. 2. Comparison of several MC codes to the data from the BRAHMS experiment at RHIC [3].

describe at the same time the charge particle and the net baryon density at the mid-rapidity. One can conclude either that more work must be done to tune the existing codes to the data, or that, perhaps, the proposed approach is too ambitious and some simpler ideas must be tried first. That is to say, one should first of all determine the relevant variables, which decide about the nature of a nuclear collision.

This second point of view is substantiated by the observation that some simple parameterizations employing the quantities like the number of collisions and/or the number of wounded nucleons (called now, *incorrectly*, the number of participants[1]) do work very well. I personally find far from trivial, that the concepts which were developed many years ago to describe the phenomena of a rather different character, are still relevant in this entirely new situation. One example of such parametrization is presented in Fig. 3, taken from [5]. Assuming that the nucleon–nucleon interactions can be split into "hard" and "soft" phenomena, one arrives at the formula [7]

$$\frac{dN}{d\eta} = \left(\frac{dN}{d\eta}\right)_{NN} \left[(1-x)\frac{w}{2} + x\nu\right], \tag{1}$$

where w denotes the total number of wounded nucleons and ν the number of binary collisions. One sees from Fig. 3 that (1) describes reasonably the centrality dependence of the data, although some deviations are perhaps seen at largest centralities. The fraction x of "hard" collisions represents about 10% of the total.

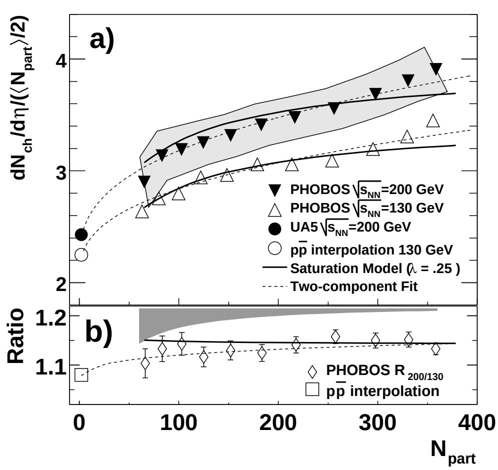

Fig. 3. Centrality dependence of the hadron multiplicity from the PHOBOS experiment at RHIC [5].

[1] Some of the nucleons *participating* in collisions scatter only elastically. They should not be (and are not) counted as "participants". Thus "a participant" is a misnomer.

I think that the analyzes of this type will continue to give an interesting insight in the mechanism of the processes in question, particularly if performed in a broad range of kinematic variables. For example, a similar analysis of the suppression of the high $p_\perp$ particles, presented at this meeting [4], would be certainly very informative.

Surely, this is not the only possibility and other variables may also turn out to be relevant, as suggested in some old [8] and recent [9, 10] work.

3. *NN* and *NA* collisions

New data and analyzes about baryon number transfer and stopping were shown for NN [11], as well as for NA and πA [12] collisions.

It has been demonstrated for the first time [11] that B–$\bar{B}$ pairs produced in pp collisions cannot be identified with p–$\bar{p}$ pairs (as it is usually assumed). Other isospin states contribute substantially to the observed proton spectrum. This contribution (about 1/2 of that coming from p–$\bar{p}$) changes qualitatively the estimate of the transparency of the system (one obtains more transparency, increasing with energy of the collision). Moreover, this new analysis dramatically affects the strange $\bar{B}/B$ ratios and thus provides a new challenge to the models of strangeness production.

Baryon stopping in nucleon–nucleus collisions has been analyzed in [12]. Combining the pA and πA data, the author was able to reconstruct the "genuine" proton spectrum for various centralities of the collision, as is seen in Fig. 4. These results show that, at least for SPS energies, there is no qualitative difference between baryon spectra observed in pA and AA collisions

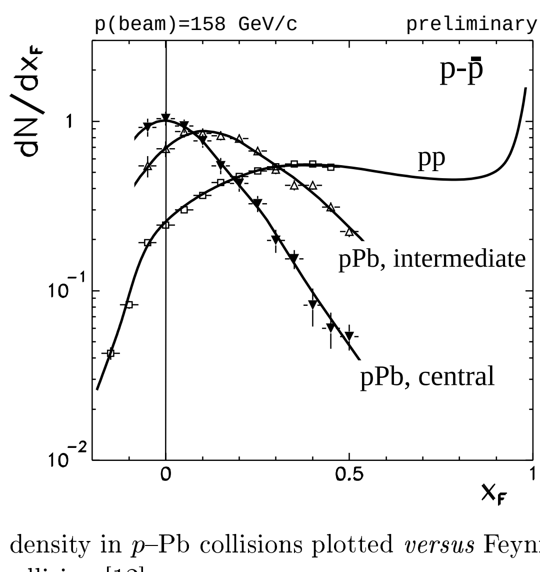

Fig. 4. Net proton density in p–Pb collisions plotted *versus* Feynman x for various centralities of the collision [12].

at comparable centralities. It would be interesting to verify this observation at RHIC energies, once the data on *pp* and *pA* are available.

Let me also call attention of the reader to the very extensive review of the emulsion data [13]. It is, of course, impossible to summarize it here.

4. Hydrodynamics and thermal hadronization

An impressive success of the thermal hadronization model was confirmed at this meeting for RHIC data [14–17]. An excellent agreement is found for particle ratios (shown in Fig. 5 [15]) and for transverse momentum spectra of which one example [16] is shown in Fig. 6.

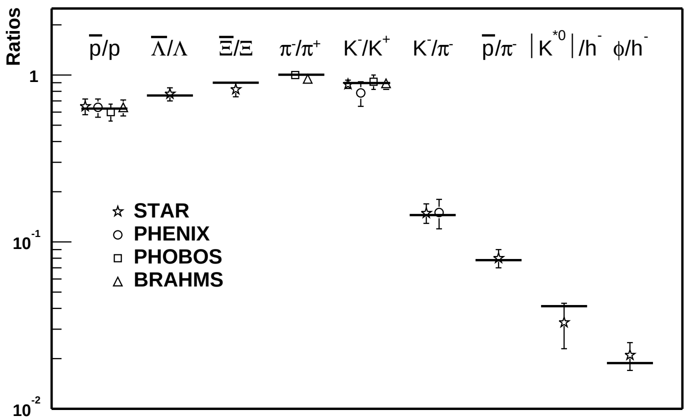

Fig. 5. Particle ratios from RHIC experiments compared to the thermal model [15].

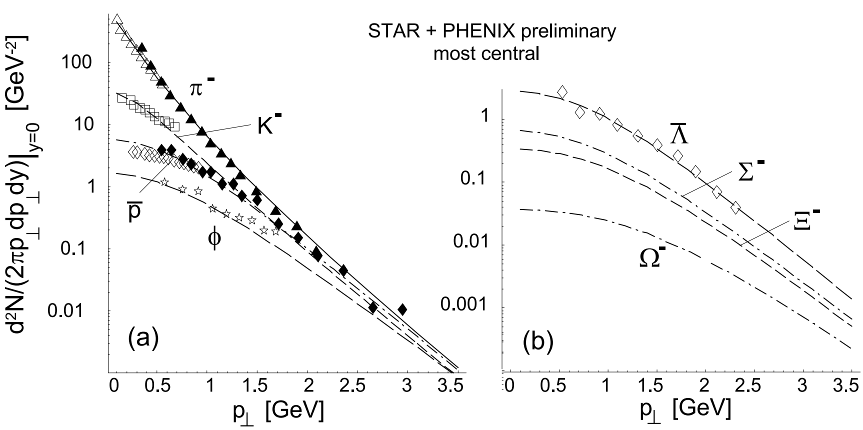

Fig. 6. An example of the transverse momentum spectrum calculated from the thermal model and compared to data from RHIC [16].

Taken together with the thermal fits at lower energies [17], these new analyzes of RHIC data confirm the universal behavior of the freeze-out energy density of 1 GeV/particle. The resulting phase diagram is shown in Fig. 7 [17] and Fig. 8 [14]. Explanation of this amazing universality which seems to have a fundamental (albeit not yet understood) meaning is obviously a great challenge for the theory. It may perhaps reflect some yet unknown features of the QCD vacuum [18].

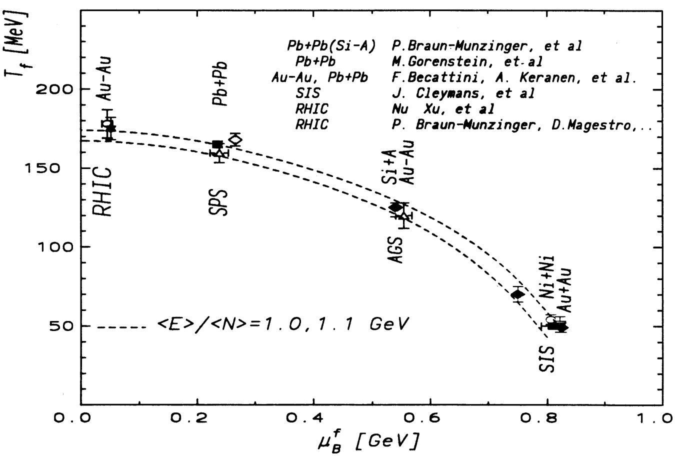

Fig. 7. Phase diagram for parton–hadron transition, as estimated from data at different energies [17].

Not so spectacular[2] but also fairly successful is the hydrodynamic description of the collective motion of the strongly interacting fluid created during the collision of two heavy nuclei [19]. Not only the general features of the flow are reconstructed but also a subtle phenomenon of the elliptic flow is described, at least semi-quantitavely. With the advent of new measurements of the flow, including a new technique wich allows to study higher order moments [20], the hydrodynamic approach shall be soon subject to even more stringent constraints.

Both hydrodynamics and thermal hadronization imply an increasing freeze-out volume with increasing energy of the collision [14, 19, 21]. This is mostly a consequence of the increase of the initial density of the produced system at higher energies. At the same time, the freeze-out parameters measured by HBT interference are practically energy-independent from 2 GeV till RHIC energies [22, 23]. These two facts are difficult to reconcile with the present models of these phenomena [21]. This is yet another challenge for the theory. And a serious one.

[2] Some serious problems were reported in [19].

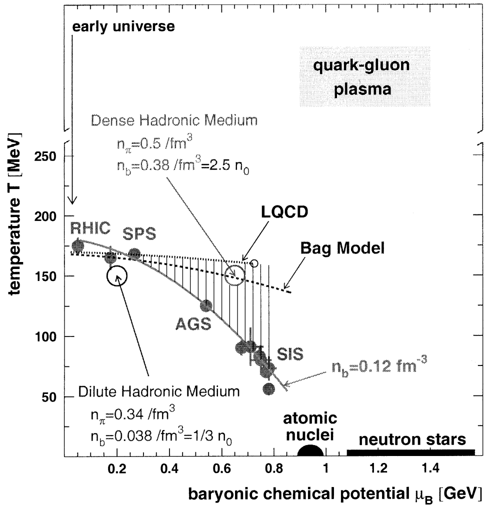

Fig. 8. Phase diagram for parton–hadron transition, as estimated from data at different energies, including the recent results from RHIC [14].

5. Charge fluctuations

It was recently suggested [24] that measurements of charge fluctuations can be used to distinguish the hadron gas in equilibrium from the quark–gluon plasma. The argument, presented by V. Koch, concerns the quantity

$$D = 4\frac{\langle \delta Q^2 \rangle}{\langle N_{\rm ch} \rangle}\,, \tag{2}$$

which should be equal to 4 in the pion gas (after appropriate corrections for resonance production are taken into account $D \approx 3$), and to 1 in the quark–gluon plasma.

This large difference is mostly a consequence of the fact that charges of quarks are much smaller than those of hadrons. To see that, consider a system of several particle species (labeled by i) with charges q_i and multiplicities n_i. Since

$$Q = \sum_i q_i n_i \quad \rightarrow \quad \langle Q \rangle = \sum_i q_i \langle n_i \rangle \tag{3}$$

we obtain

$$\begin{aligned} \langle \delta Q^2 \rangle &\equiv \langle Q^2 \rangle - \langle Q \rangle^2 \\ &= \sum_i (q_i)^2 \langle n_i \rangle + \sum_{i,k} c_{ik}^{(2)} \langle n_i \rangle \, \langle n_k \rangle q_i q_k \,, \end{aligned} \tag{4}$$

where $c_{ik}^{(2)}$ are the normalized two-particle correlation functions.

If particles are weakly correlated, the second term in (4) is small and we have

$$\langle \delta Q^2 \rangle = \sum_i (q_i)^2 \langle n_i \rangle \, . \tag{5}$$

For the pion gas this means

$$\langle \delta Q^2 \rangle = \langle n_+ \rangle + \langle n_- \rangle = \langle N_{\rm ch} \rangle \, , \tag{6}$$

and thus

$$D = 4 \, . \tag{7}$$

For a quark–gluon system, in the simplest case when abundances of all quarks are identical, we have

$$\langle \delta Q^2 \rangle = \frac{5}{18} \langle N_{\rm q} \rangle \, , \tag{8}$$

where $\langle N_{\rm q} \rangle$ is the total number of quarks and antiquarks (gluons, of course, do not contribute).

To estimate D, it is now necessary to estimate $\langle N_{\rm ch} \rangle$. The argument presented in [24] is based on consideration of entropy. Entropy is rather large for QGP (gluons provide the major contribution) and the result (confirmed by the lattice estimates) is $\langle N_{\rm ch} \rangle \approx \langle N_{\rm q} \rangle$, so that, finally, one obtains $D \approx 1$.

The preliminary data from CERES, NA49 and STAR [25] experiments reported at this meeting [1] indicate that the measured value of D is close to that predicted for hadron gas and differs markedly from that expected for QGP, *i.e.* for a weakly correlated quark–gluon system. No quark–gluon plasma in sight!

This result is, of course, very important and thus one must carefully check if the conditions necessary for the validity of the argument of Ref. [24] are indeed satisfied. The main objection may be the flow of the charge through the boundary of the region in which the measurement is performed [26]. Since the measurements are given for fairly small rapidity intervals, this is a serious problem which can only be resolved by a careful study of the dependence of D on the size of the interval. I hope that such measurements are possible at RHIC and will soon be available.

6. Quark coalescence scenario

The results reported in the previous section, if confirmed, indicate that the observed entropy of the system is much smaller than that of the quark–gluon plasma. Since, however, it is difficult to accept that the observed hadrons were produced directly, without an intermediate "partonic" phase, one should ask the question what could be the nature of this intermediate system in order to account for the present data on charge fluctuations.

One obvious way to reduce the entropy of a system of partons is to reduce the number of gluons (which carry most of the entropy). This can be realized if the system is dominated by the *constituent* quarks and antiquarks: the gluonic degrees of freedom are then "frozen" (gluons are contained in the constituent quarks) and thus do not contribute to entropy. For such a system one can estimate the number of charged hadrons as

$$\langle N_{\rm ch}\rangle \approx \frac{2}{3}\langle N_h\rangle \approx \frac{1}{3}\langle N_{\rm q}\rangle \tag{9}$$

and thus $D \approx 10/3$, a value not far from that obtained for pion gas (7). One may thus conclude that the existing data are not incompatible with the idea that the intermediate partonic system resembles a gas of constituent quarks and antiquarks. This supports the picture of the coalescence model, formulated some time ago [27, 28] and supported already by the data on particle ratios [29].

7. Searching for a phase transition

Antoniou presented an interesting proposition of the Athens group [31, 32] to search for the tricritical point in the confinement–deconfinement transition. The idea is to select the events where the net baryon number distribution is quasi-independent of rapidity and then look for a signal of intermittency in the distribution of pion pairs close to the 2π threshold. The argument is based on the observation that the net baryon number can be taken as an order parameter which, at the transition, must take a specific value (related to the critical density) [31]. Furthermore, the analysis performed in [32] has shown that although the intermittency signal expected for σ mesons is practically washed out in the pion spectrum, it can be recovered when the two-pion spectra are investigated. It may be interesting to check these ideas against the forthcoming data.

8. Comments

Let me finish by emphasizing again the main problems, as I see them, with which we were confronted at this meeting.

(i) I think we all agree that the main goal of the research in high-energy heavy ion collisions is to obtain an understanding of the emerging high density system and its evolution. As we are still rather far from achieving this, various concepts are possible and should be tried. I feel, however, that this does not allow one to ignore information from experiment and from theory which has been already accumulated. For example, it does not seem reasonable to assume that hadrons are created instantly during the collision and thus to consider only the so-called hadron gas phase as an alternative to the quark–gluon plasma phase we are searching for[3]. Actually the task is much more subtle: how to confront (and distinguish experimentally from each other) various possible intermediate states.

(ii) We have seen during this meeting that the nucleon–nucleon and nucleon–nucleus data behave, in some aspects, similarly to those obtained in nucleus–nucleus collisions. This implies that in the search for new phenomena, a simple comparison of NN, NA and AA data is not enough. This remark only emphasizes the observation made in *(i)*: apparently, we need much more subtle methods to understand the early stages of the collision.

(iii) We have learned that the performance of the microscopic MC codes is rather poor. The natural conclusion may be that more work is needed to tune them better to the data. I feel, however, that this is not a correct route, that to achieve a detailed description of such a complicated phenomenon as a central collision of two heavy ions, starting from a "microscopic" description is an almost hopeless task. This is even more so, if one realizes that the microscopic parameters are poorly known and, consequently, the number of (almost arbitrary) input information often largely exceeds the output of the program.

It seems to me that, in this situation, it is much more important to identify first the relevant variables which determine the behavior of the system. It was thus encouraging to see that some simple parametri-

[3] From all we know about the high-energy collisions, emerging final hadrons are preceded by an intermediate state formed of more elementary objects. There is a rather strong evidence that this happens in hadron–nucleus collisions (as shown by measurements of absorption of hadrons created in nuclear matter [33]) and thus it seems rather eccentric to think that it does not happen in collisions of heavy ions.

zations in terms of the number of wounded nucleons and the number of collisions can capture certain essential features of the data. More work along these lines should be strongly encouraged, I think.

(iv) The excellent agreement of the thermal model with the data is not really understood and still represents a good question to theorists. Since the thermal model works also for NN collisions and even for e^+e^- annihilation [30], it is by no means clear how the thermalization is achieved. An even greater challenge is presented by the observed universality of the freeze-out energy density [17]. No convincing interpretation of these observations is in sight.

(v) The energy independence of the measured HBT parameters remains at present, for me, the most important challenge in modeling the phenomena associated with heavy ion collisions. It is well known, of course, that (for several reasons) the HBT parameters do not give a direct information about the size of the system. Therefore, the existing data do not *contradict* our general ideas about the mechanism of the collision. Nevertheless, it seems hard to believe that the energy independence in such broad range is the result of an *accidental* cancellation.

(vi) Recent measurements of charge fluctuations indicate that the possibility of an intermediate system in the form of a gas of constituent quarks and antiquarks should be considered as a serious alternative, as it is also supported by the data on particle ratios. In this context, theoretical investigations in the nature of the constituent quarks and their interactions would be most welcome.

(vii) I strongly feel that the CERES data send us an important message which is only partly understood. As explained in the point *(i)* above, the description in terms of hadron gas with standard or modified properties cannot be accepted without reservations. In view of the comment *(vi)* it may be interesting to estimate *quantitatively* the dilepton production from the gas of constituent quarks and antiquarks.

I would like to thank M. Jeżabek and B. Wosiek for inviting me to the meeting. Discussions with the participants of the conference are highly appreciated, although they were too numerous to list them here. Special thanks are due, however, to V. Koch for discussions on the subject of charge fluctuations.

This investigation was supported in part by the Subsydium of the Foundation for Polish Science NP 1/99 and by the Polish State Committee for Scientific Research (KBN) grant No. 2 P03B 09322.

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