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DILEPTON PRODUCTION AS A SIGNATURE OF COLLECTIVE EFFECTS IN HEAVY ION COLLISIONS AT HIGH ENERGIES[1]

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Data on dilepton production in heavy ion collisions bring information about the intermediate stages of the time evolution of the collision. We describe the ways in which the data can be organised in order to tell whether some collective effects played an important role in the space-time evolution of the collision or whether the collision of heavy ions is just a simple incoherent sum of individually evolving nucleon-nucleon collisions

1.Introduction

During the past decade a large collection of data on various features of heavy ion collisions at high energies has been accumulated. These data contain among others: distributions of total transverse energy, strangeness production, HBT correlation's, J/ψ suppression, $\Phi/(\rho+\omega)$ production, dilepton production, correlation's between final state particles, transverse momentum and single particle rapidity spectra.

The results obtained were compared with a large number of theoretical models with a varying degree of sophistication. Originally it has been hoped that some feature of data would clearly show convincing evidence that a new type of matter, Quark-Gluon Plasma (QGP), was produced. It has turned out however that most of

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isolated features of data can be interpreted within the framework of different scenarios and that with the presently available data it is rather difficult to find a clear cut information on what type of matter is present at various stages of the collisions. The way to the answer of this fundamental question will be longer than expected. The answer could come either from a more complex analysis of the currently available data or from the new data, either those obtained at the CERN SPS with Pb-Pb collisions or in dedicated experiments at higher energies.

The first data on total transverse energy spectra, could be interpreted, see e. g. [1] as resulting from an incoherent sum of nucleon-nucleon collisions. Later studies, based on data with higher statistics has shown that some admixture of cascading is required in this simple model. These data may well admit also the interpretation in which collective states are present at the intermediate stages and the total transverse energy spectra just reflect the initial entropy production which is due to incoherent nucleon-nucleon production.

After this experience it is reasonable, when trying to understand what a given piece of data is telling us, to ask very simple questions: does this particular piece of data demonstrates convincingly the presence of collective effects in heavy ion collisions or: could one explain the data just by adding some cascading (some additional interactions) to the model of the sum of incoherent nucleon-nucleon collisions. Such an attitude might appear as overly conservative and the presence of collective effects can be taken as granted. One could argue as follows. The data on J/ψ suppresion whether interpreted as caused by J/ψ dissolution by QGP, as originally suggested [2] or as due to J/ψ disintegration by the hadron gas [3] are anyway an evidence for the presence of a rather dense matter at the intermediate stage of the collision. At such high densities the matter cannot evolve as it would evolve in the case of a sum of incoherent nucleon-nucleon collisions. Although this way of reasoning is highly plausible, it is not waterproof and since the true nature of the intermediate state is unknown (apart of the fact of the high density) one would prefer to have this "collectivisation" confirmed by other, easier interpretabble data.

In a similar way one can discuss the results on the increased strangeness production, on the $\Phi/(\rho+\omega)$ ratio and on single particle spectra.

The most transparent process providing information on intermediate stages of heavy ion collisions is the dilepton production. In principle this process brings a direct, although time - integrated evidence about the intermediate stages. This type of data can therefore confirm in a most direct way the "collective" properties of the intermediate system, resulting in the longer time-scale of heavy ion collision as compared to an incoherent sum of nucleon-nucleon collisions. Another confirmation of this longer life-time of the system can come from studies of HBT correlation's.

It would be certainly disappointing to learn that some types of data, like J/ψ suppression require the presence of strong "collective effects" whereas the most transparent window on heavy ion collisions, namely dilepton production, does not require them.

The purpose of the present paper is to show how one can organise the data on dilepton production in heavy ion collisions so that the presence of the "collective effects" would become easily visible.

The paper is organised as follows. In the next Section the model used is briefly described and some results of calculations presented. The emphasis is put at qualitative features of the model and results of calculations. Section 3 contains comments and conclusions.

2. Dilepton spectra as a source of information on the intermediate stages of heavy ion collisions

In calculations of dimuon production we have used the model of Kajantie and Ruuskanen [4]. Although the model is rather specific the qualitative features of results are to some extent independent of the assumptions made.

We shall not describe here the details of the model since these can be found in Refs. [4,5] and limit ourselves only to basic features. In this model it is assumed that the matter produced in a heavy ion collision is thermalized within $t_i = 1$ fm/c. The phase of the matter at this time depends on the temperature reached which in turn depends on the geometry of the collision and on the position in the plane transverse to the collision axis. If the temperature is higher than T_c - the temperature of the phase transition between the pion gas and the QGP, the system in a given position starts in the QGP stage. For temperature T_c the system starts in the mixed phase - consisting partly of QGP and partly of pion gas. The ratio of both parts is given by the initial entropy density. For temperatures below T_c the system starts in the pion gas phase.

The phase diagram is sketched in Fig.1. If the systems starts at $T_i > T_c$ it expands and cools down moving to the left along the curve in Fig.1. Reaching T_c the system turns to the mixed phase and moves down along the $T = T_c$ part of the curve in Fig.1. During the expansion the energy density ε, decreases and when ε becomes equal to ε_h the mixed phase turns to the pion gas which expands further reaching T_{dec} when the pion gas turns to free particles observed in the final state. For illustration we show in Fig.2 the initial temperature distribution in central collisions of O-O, Cu-Cu, and Pb-Pb. Note that in Pb-Pb in a large fraction of the transverse plane the QGP is formed, in the Cu-Cu case the QGP fraction is relatively smaller and in the O-O collision mixed phase is formed in the central region. Longitudinal expansions follows the Bjorken hydro-dynamics [6] and the transverse expansion is neglected.

During the QGP stage dileptons are produced by the annihilation of a quark and an antiquark

$$Q + \overline{Q} \to \mu^+\mu^- . \tag{1}$$

In the pion gas phase the dominant mechanism is the $\pi^+\pi^-$ annihilation proceeding via the ρ-meson according to

$$\pi^+ = \pi^- \to \rho \to \mu^+\mu^- \tag{2}$$

In the mixed phase dileptons are produced by processes in Eqs.(1) and (2) with weights given by volumes occupied by the two phases.

Apart of dileptons produced during the evolution of the collision there are also dileptons due to the Drell-Yan mechanism. This is the hard process occurring at the very beginning of the collision. Dileptons are produced by annihilation of a quark present in one of the colliding ions with an antiquark present in the other ion or vice

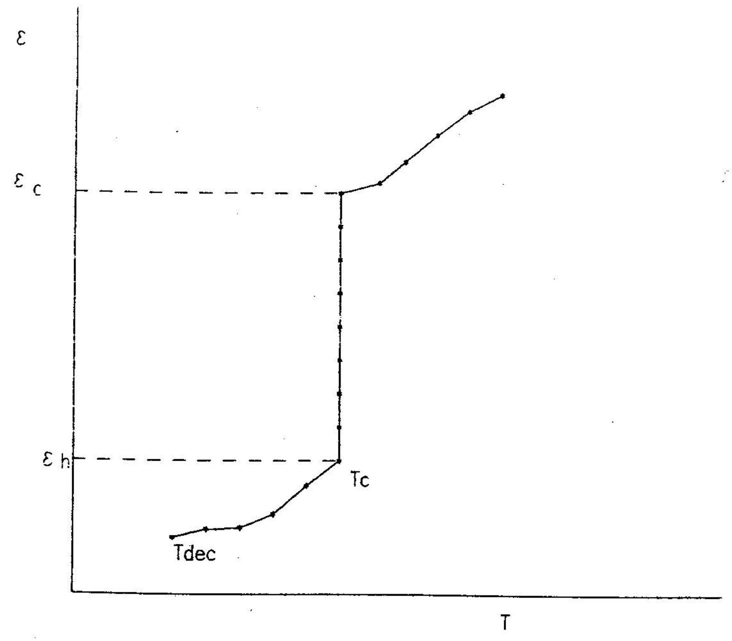

Fig.1 Energy density ε as a function of temperature T of the system consisting of pion gas and QGP. T_c- temperature of the phase transition, T_{dec}- temperature of the decay of pion gas to free pions.

versa. The Drell-Yan contribution is calculated along the standard lines, with Duke and Owens [7] distribution functions for quarks and antiquarks in nucleons in colliding ions. Contributions of various processes to the total dilepton yield for the case of the central Cu-Cu collisions are shown in Fig.3. One can see that the Drell-Yan contribution which is proportional to the number of nucleon-nucleon collisions dominates for dilepton masses above 2 GeV/c^2. Other contributions in contradistinction to the Drell-Yan process are not proportional to the number of nucleon-nucleon collisions, but their number depends on the whole history of the expanding matter, important factor being times the system spends in the three phases (QCP, mixed, hadrons).

Different dependence on the number of nucleon-nucleon collisions of various contributions can be used in order to see the "collective effects".

At dilepton masses above $M_0 \sim 3\text{GeV/c}^2$ the Drell-Yan mechanism dominates. The dilepton production in the region $M > M_0$ divided by $N_{AB}(b)$ (the number of nucleon-nucleon collisions for the interaction of heavy ions A and B at the impact parameter b gives collision independent cross-section corresponding to nucleon-nucleon collision. Let us denote this quantity explicitly as

$$\frac{\mathrm{d}\sigma_{nn}^{(AB,b)}}{\mathrm{d}M\mathrm{d}y} \equiv \frac{1}{N(AB,b)} \frac{\mathrm{d}\sigma^{AB}}{\mathrm{d}M\mathrm{d}y} \tag{3}$$

Here M is the dilepton mass and y the dilepton rapidity, and $N(AB,b)$ denotes the

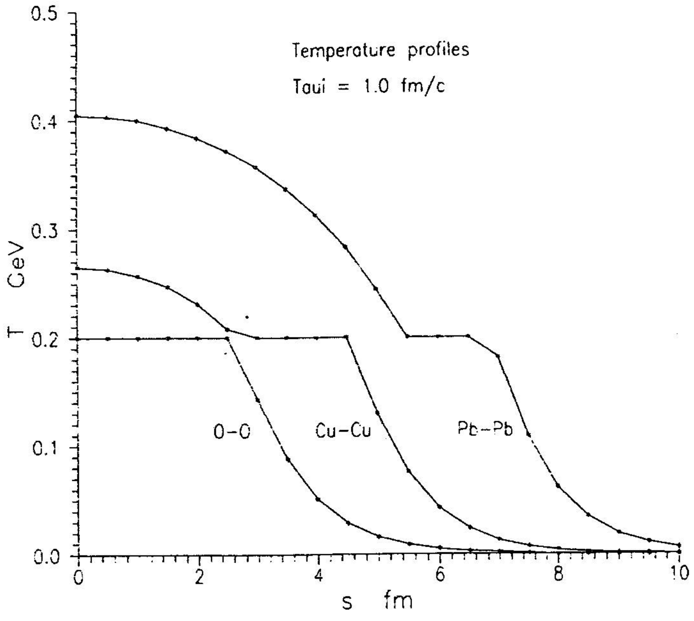

Fig.2 Temperature profiles for central ^{16}O + ^{16}O or ^{63}Cu + ^{63}Cu and ^{207}Pb + ^{207}Pb collisions at the time of thermalization t_i =1 fm/c. The temperature is plotted vs. the distance in the transverse plane from the common centre of colliding nuclei.

number of nucleon-nucleon collisions in the A+B interaction at impact parameter b. Note that b or the whole $N(AB,b)$ can be determined from the total transverse energy production in a particular heavy ion collision.

The left hand side in the Eq.(3) is independent of A, B and b for $M > M_0$ where Drell-Yan contribution dominates, but it is not independent of A, B and b in the region of lower dilepton masses dominated by the production from thermal sources (QGP, mixed phase and hadron gas). For larger A and B (heavier ions) and smaller b (more central collisions) the left hand side in Eq.(3) will be larger reflecting longer space-time evolution and higher temperatures.

The experimentally accessible quantity is therefore the ratio

$$r(AB,b,A'B',b',M,y) = \frac{\mathrm{d}\sigma_{nn}^{(AB,b)}/\mathrm{d}M\mathrm{d}y}{\mathrm{d}\sigma_{nn}^{(A'B',b')}/\mathrm{d}M\mathrm{d}y} \frac{N(A'B',b')}{N(AB,b)} \tag{4}$$

which is by construction approaching one for $M > M_0$. The ratio can be studied in a multitude of ways. The simplest two probably are:

(i) Take $A = B$, $A' = B'$, $b = 0$. This corresponds to central collisions of the same nuclei as, say ^{16}O + ^{16}O or ^{63}Cu + ^{63}Cu or ^{207}Pb + ^{207}Pb. For heavier nuclei the ratio will rise faster with decreasing M.

(ii) This corresponds more to the situation of a single experiment. Take $A = A'$ and $B = B'$ but consider different impact parameters: $b = 0$ corresponding to central

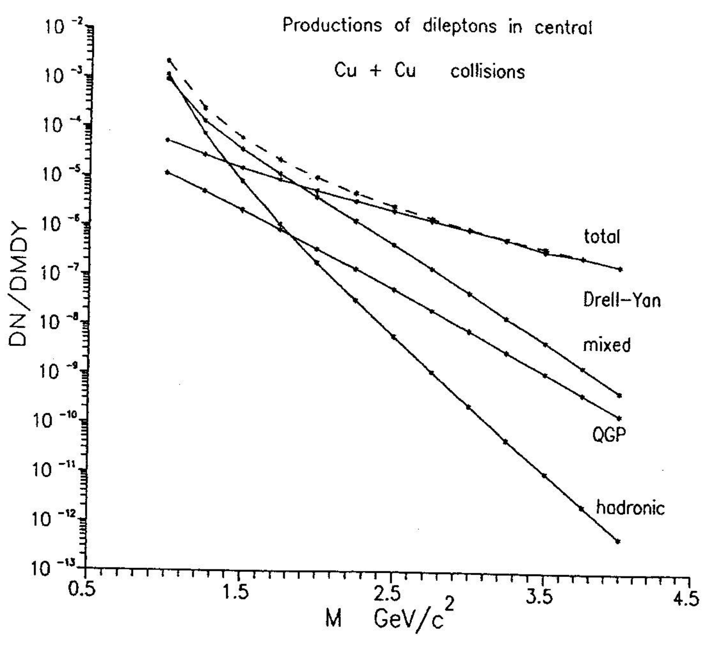

Fig.3 Contributions of Drell-Yan process, QGP, mixed phase and hadron gas stage to the total production of dileptons in the central ^{63}Cu -^{63}Cu collision. The sum of all the four contributions is labelled as "total".

collisions, b only somewhat smaller than the sum $r_A + r_B$ of the radii of colliding nuclei, corresponding to peripheral collisions and finally $b \approx (r_A + r_B)/2$ which is typical for the plateau region of the total transverse energy distributions. The ratio in Eq.(4) will grow faster with decreasing M for central than e.g. for peripheral collisions.

As an example we show in Fig.4 ratios for peripheral, plateau and central S+W collisions. The magnitude of ratios makes them accessible from already available data obtained in studies at the CERN SPS.

Of course, the ratios would be larger for heavier ions, like for Pb-Pb collisions. It is to be noted also that the ratios would further grow with dilepton masses decreasing below 1 GeV/c^2 and there is no reason why not to study the ratio in this region. The interpretation is however a bit more difficult here, because of the Landau-Pomeranchuk effects [9] suppressing the low mass dilepton production.

3. Comments and conclusions

The picture we have used above somehow overestimate the production of dileptons during the thermal phases. This is due to two factors. First the transverse expansion of the thermalized system is neglected in this model, what overestimates the time of the longitudinal expansion of the system, thereby enhancing the dilepton production.

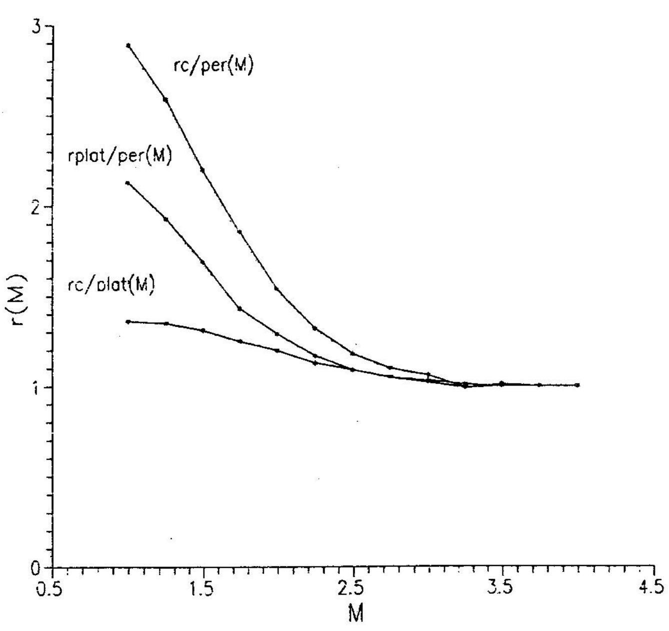

Fig.4 The ratio r_{centr}/r_{periph} (etc) in Eq.(4) calculated for central, plateau and peripheral S + W collisions for the same target projectile combination.

Second, the structure of the hadron gas is overly simplified. In reality the hadron gas contains more types of hadrons than just pions. This enhances the entropy density between the QGP and hadron gas phases and in this way enhances also the life-time of the mixed phase. It would be possible to consider a richer structure of the hadron gas, including further stable particles and resonance's. The complication which appears lies in uncertainties of dilepton production in collisions of various types of hadrons. In the pion gas the ρ-dominance gives a simple and reasonable estimate. Recent studies [9] by Gale, Kapusta, Lichard and Seibert has however shown that even for more complicated compositions of the hadron gas one can obtain reasonably accurate estimates of the dilepton production from the thermalized system.

In our opinion it would be very desirable to study experimentally the ratio in Eq.(4) in a systematic way by measuring first the collisions of light ions, determining from that the dilepton production in an average nucleon-nucleon collision and than putting $A' = B' = 1$ in Eq.(4) with $b' = 0$. The ratio could then be studied as a function of A, B and b. In this way one would receive experimental tests of models of dilepton production in heavy ion collisions.

Putting $y = 0$ the ratio in the Eq.(4) becomes

$$r = \frac{\mathrm{d}\sigma^{(AB,b)}}{\mathrm{d}M} \frac{1}{N(AB,b)\frac{\mathrm{d}\sigma^{nn}}{\mathrm{d}M}} \tag{5}$$

where $\mathrm{d}\sigma^{nn}/\mathrm{d}M$ is the dilepton production cross-section for nucleon-nucleon collision.

Measuring both cross-sections in the Eq.(5) in the same experimental set-up would decrease the systematic errors. In the same experimental study one should also observe the total transverse energy produced, determining thus the relationship between $N(AB,b)$ and the total transverse energy ET per rapidity unit.

References

[1] J.Ftáčnik, K.Kajantie, N.Pišútová, J.Pišút: *Phys.Lett. B* **188** (1987), 279;

[2] T.Matsui, H.Satz: *Phys.Lett. B* **179** (1986), 416;

[3] J.Ftáčnik et al: *Phys.Lett. B* **207** (1988), 194; S.Gavin et al: *Phys.Lett. B* **207** (1988), 257; R.Vogt et al: *Phys.Lett. B* **207** (1988), 263;

[4] K.Kajantie, P.V.Ruuskanen:*Production of Thermal Dileptons in High Energy Nucleus-Nucleus Collisions*, Helsinki preprint, HU-TFT-87-7, Match 1989

[5] J.Masarik, N.Pišútová, J.Pišút: *Z. Phys. C* **59** (1993), 295;

[6] J.D.Bjorken: *Phys.Rev. D* **27** (1983), 1409;

[7] D.W.Duke, J.F.Owens: *Phys.Rev. D* **30** (1984), 49;

[8] J.Cleymans, V.V.Goloviznin, K.Redlich: *Influence of the Landau-Pomeranchuk effect on Lepton-Pair Production in a Hadronic Gas.* Bielefeld preprint BI-TP 92/29, 1992; J.Cleymans, V.V.Goloviznin, K.Redlich: *Virtual Photon Bremsstrahlung in Quark-Gluon Plasma*, Bielefeld preprint, BI-TP 92/35, 1992;

[9] C.Gale, P.Lichard: *Lepton Pairs from Thermal Mesons*, McGill University preprint, McGill/93-8 and TPI-MIN-93/19-T; J.Kapusta, P.Lichard, D.Seibert: *Phys.Rev. D* **44** (1991), 2774; P.Lichard: *Three-Pion Reactions in Dilepton Production from Hadron Gas*, Minnesota preprint, TPI-MINN-92/5-T (rev.)