PHYSICS OF HEAVY IONS COLLISIONS: THE SUMMARY OF MORIOND-97

E.V. SHURYAK
Department of Physics
SUNY at Stony Brook, Stony Brook, NY11790, USA

Abstract

CERN dilepton experiments have provided the most exciting data. Strong enhancement at low masses observed by CERES and HELIOS3 indicate strong modification in the vector channel in matter compared to vacuum properties. NA50 data on \( J/\psi \) suppression in PbPb collisions show surprising deviation from the previous trend. The question is whether it is the expected early-time signal of QGP, or due to late-time hadronic interactions. Theoretical and experimental suggestions have been made to resolve this issue. BNL and SPS experiments have also provided rather complete data with heavy beams (Au and Pb, respectively). Very strong collective flow effects have been observed at both energies, which allow for the first time to restrict the EOS of the hadronic matter. Several observables (flow, Coulomb effects and HBT) suggest rather long evolution of systems created in heavy ion collisions and very low freeze-out densities relative to previous studies. Theory of jet stopping in QGP is becoming quantitative.
1 Introduction

At this meeting the heavy ion physics was represented much more than at any previous Morionds, but it is still a minority and therefore it is probably necessary to start this general talk by reminding why these experiments are done. Many high energy physicists, proud of their accurate studies of hard processes and (truly impressive!) agreement with the perturbative QCD, are asking if one really needs to find a quark-gluon plasma (QGP). My answer to that is that studies of the QCD phase transition is only partly related to matter properties at very high T. A very significant part of the motivation is a desire to understand how and why the ordinary hadrons “melt”, and especially how the ground state (the “QCD vacuum”) can be rearranged under these conditions. It is widely believed that it helps to understand hadronic and vacuum structure of QCD (and maybe non-perturbative phenomena in gauge theories in general). To my mind these topics are the very core of the scientific challenge which makes QCD interesting: but (very characteristically for these days) it was never even touched in the high energy part of the meeting.

To explain what I mean, let me use a very elementary example. The pressure of the QGP is \( p = O(T^4) - B \), where the first (simple) term represent perturbative quarks and gluons, while the second (non-trivial) bag term\(^1\) represents a price for suppressing non-perturbative vacuum fluctuations in QGP. Now recall textbook “vacuum engineering” experiment with Magdeburg semi-spheres: after one pumps the air out of them, one need a very large force to separate them. Indeed, in the equation above the first quark-gluon thermal term is simply the analog of horses, working against the vacuum pressure and making expansion possible. Their strong compensation (or “softness” of EOS in the phase transition region) is what we seem to observe now.

At this time it is really a pleasure to summarize the heavy ion part of the conference: there are so many excited new observations. Very different explanations of what they mean have been put forward, making discussion extremely interesting. Clearly it was a very busy meeting, and too many interesting talks I am not able even to mention, keeping to few main subjects.

\(^1\)One should not confuse the value of this B with the much smaller one found in the fit to the MIT bag model.
Fortunately, some topics had been summarized elsewhere. For example, theory of the two-particle interferometry (HBT) was nicely covered in \[1\] and experiment in \[2, 3\]. Recent progress in understanding of the microscopic mechanism of the chiral phase transition was covered in my original talk, and I would not comment on it here.

## 2 Dileptons and photons

Already at QM93, the HELIOS3 experiment has reported very interesting data, and in \[4\] it was emphasized that those significantly exceed expectations from “basic conventional sources”, the pion annihilation in the hadronic phase and \(\bar{q}q \rightarrow e^+e^-\) in QGP. Later CERES experiment (for current status see \[4\]) has observed even more dramatic excess of dileptons at \(M_{e^+e^-} \approx 400 - 600\,\text{MeV}\). Since dileptons are “penetrating probes”, the excess production happens early in the collision, and the issue of rescattering (which is so painful to settle for \(J/\psi\)) does not arise here.

Multiple attempts by theorists to explain it were discussed in some details at this meeting \[4\]. In short, all attempts to use other “conventional sources” has basically failed \[4\]. A list of “unconventional” explanations include: (i) dropping \(m_\rho\) due to chiral phase transition \[4\]; (ii) increasing width of \(\rho\) due to interaction with baryons \[11\]; (iii) pion occupation numbers at low momenta are very high \[9\]; (iv) dropping \(m_{\eta'}\) \[8\]. Let me comment on them subsequently.

Li-Ko-Brown has developed the well known idea of “dropping rho mass” into a detailed cascade model, explaining in details both all CERES and HELIOS3 data with one set of parameters. Many people have also tried to check this idea, (including both Redlich and myself \[10\]), with the conclusion that this idea may indeed explain the observed mass spectrum. In order to test it further, one may increase the resolution of CERES and check how many \(\rho\) remains in the peak, on the top of the un-shifted \(\omega\). A less trivial test \[10\]: if \(m_\rho(T)\) is dropping, that of its axial partner \(m_{A_1}\) should follow.\(^3\)

As shown in \[10\], \(a_1 \rightarrow \pi e^+e^-\) decay populate low mass region and may

\(^2\)In fact, I have never before seen that rather involved calculations by several groups agree so well, not only in the shape of spectra of \(M_{e^+e^-}\) but also in absolute normalization.

\(^3\)Strict relation between the two were made e.g. in the contexts of Weinberg-type sum rules \[12\]. Those demand that both states become identical at \(T_c\).
become comparable or exceeding the background, if this mass is decreasing enough.

The explanation (ii) [11] does not relate the low-mass enhancement with chiral restoration, but simply with the non-zero density of baryons. As also commented by Redlich, this idea has not yet developed into quite realistic model, and many questions about space-time evolution and baryon composition remains. Nevertheless, their estimates suggest that at relevant conditions the rho width is becoming large, even comparable to its mass. If so, one may argue that $\rho$ simply “melts”, it is no longer a well-defined resonance and its relevance may therefore be questioned. However if one uses simple “duality” between very wide rho and $\bar qq$ continuum, it is impossible to explain the data. What is needed here is some new dynamical correlation in the vector channel, which is absent in vacuum but appears in matter. The instanton-antiinstanton molecules (discussed in my talk) provide exactly that, a new attractive interaction close to the chiral restoration transition. However whether it is sufficiently strong to explain these data remains to be seen.

In any case, one should test experimentally whether the dilepton excess is indeed proportional to the baryon density, either by running at low energy at CERN, or by waiting till HADES data.

(iii) The observed low-$p_t$ excess of pions (over thermal spectra) can indeed dramatically increase the low-mass dilepton yield. However (see my original talk), development of the non-zero pion chemical potential is the late-time effect, which may hardly affect the early-stage dilepton production.

(iv) It seems indeed very possible that $m_{\eta'}(T)$ should drop more than any other mass. But in order to account for CERES excess one should increase yield of “escaping $\eta'$” by too huge a factor. It contradicts to observed $\eta$ yield, so this idea does not work.

The data from photon experiment WA98 [13] on $\pi^0$ spectrum of transverse momenta is now reaching above $p_t = 3 GeV$. It is probably the first data set to enter the “hard scattering” domain in heavy ion collisions. The data on another penetrating probe, direct photons, still remain the upper bound.

---

\(^4\)Significant vertex corrections due to modified rho, discussed by Redlich, is related to the same problem.
3 J/ψ suppression

Very impressive PbPb data from NA50 have been presented here [14], and then discussed extensively by many theorists.

Basically there are two alternatives: (i) the “early scenario” [15] which blames destruction of J/ψ on QGP; and (ii) the “late scenario” [16] which relates the difference between S and Pb data on much larger number of final state collisions in the latter case.

If the J/ψ absorption cross section on mesons is of the order of 1-3 mb, it was demonstrated [16] that one can fit the data. But is this number really true? It was noticed long ago that the world of heavy and light quark hadrons does not speak much to each other\footnote{For those who want an impressive experimental example: the rate of \(\psi' \rightarrow \psi \pi \pi\) decay is about thousand times less than \(\rho' \rightarrow \rho \pi \pi\).}. Theoretical explanation of this fact is that the former exist due to confinement and Coulomb-type color exchange, while the latter are mostly bound by forces responsible for chiral breaking (instantons\footnote{Although the latter effects are stronger and much better understood by theorists, they are also much less known.}).

Two experiments can significantly clarify the situation: (i) To run PbPb collisions at somewhat lower energy. If the early scenario is right and the energy behavior has a sharp threshold, one should be able to see it. (ii) To perform the inverse kinematics experiment, Pb on p, and see what happens with J/ψ at rest in matter.

The issue of J/ψ \(p_t\) distribution was discussed by R.Vogt. Her calculations are based on the initial-state re-scattering of an incoming gluon in nuclei. The prediction is that additional transverse momentum is\footnote{Experimentally the constant \(\lambda^2_\psi\) is smaller than \(\lambda^2_\Upsilon\): why this is so was discussed in [17].} \(<p^2_t> - <p^2_{tNN}} = \lambda^2_\psi (\bar{n} - 1)\), where \(\bar{n}\) is the total number of nucleons on the way. It works for pA and SA reactions: if it would be confirmed in PbPb as well, it would indeed mean that at least elastic scattering of J/ψ on mesons is small (with obvious limits on absorption from optical theorem). The opposite alternative is strong hadronic rescattering: in this case J/ψ (or some fraction of them) would tend to be “thermalized”, as other hadrons.

The final point I would like to make deals with \(\psi'/J/\psi\) ratio. Centrality dependence in PbPb of this ratio suggests that it is no more decreasing. Can
it be that we have hit the bottom, all initial \(\psi'\) are suppressed and all the observed \(\psi'\) are actually coming from an excitation of the \(J/\psi\) itself? See discussion of how this excitation may happen in [13].

4 Hadronic observables

For long time the major question was whether heavy ion collisions really produce a “hadronic matter”, a reasonably well thermalized one. Studies of particle composition have indeed shown that (apart of rare species like multistrange ones) it agrees with the thermal model well enough. The extracted “chemical freeze-out” parameters at AGS and SPS [19] both happen to be very close to the expected line of the QCD phase transition.

The next logical question is whether this matter is in a state of “collective motion”, so that (at least at sufficient late stages) one can use simple hydrodynamical language to describe it. With the arrival of Au-beam data at BNL and Pb-beam ones at CERN, we can definitely answer “yes” to this question. In fact, hydro motion is so complicated that it became necessary to divide it into 4 categories now: (i) the longitudinal motion; (ii) radial (axially symmetric) one; (iii) dipole and (iv) quadrupole (or “elliptic”) one in polar angle.

The longitudinal motion is usually related to (somewhat vague) issue known as “stopping”. One way to address it is to ask whether matter elements with different rapidities have all the same or different composition. For light ions the answer definitely is negative: near the beam rapidity the baryon/meson ratio is much larger than at midrapidity. For heavy ion data this ratio is rather constant. I think the question is not yet quite answered though, and better data on other secondaries such as \(K,d\) etc are needed to decide how collective the longitudinal motion really is.

In contrast to the longitudinal flow, a radial one is very well documented. The transverse mass slope is measured for \(\pi^+, \pi^0, \pi^-, K^+, K^0, K^-, p, \bar{p}, \Lambda, d\), it is independent on particle charge but consistently increasing with the particle mass.\(^8\) This agrees well with the theoretical ideas suggesting “dropping masses” and large cross sections, at least for \(\sigma\) exchanges.

\(^9\) It is implied that the thermal motion (depending on the particle mass and thus different for different secondaries) is deconvoluted from the distribution.
ticle mass, indicated a common flow\textsuperscript{10}. The effect is increasing strongly with $A$, and is confined to central rapidities. There seem to be little difference between the radial flow at AGS and SPS.

Quantitative study of all these data are only started, but it is already clear that they allow to address the fundamental question about the Equation of State (EOS) of hot/dense hadronic matter. Significant part of my original talk is dealing with new development along this line, a model for AGS/SPS energy domain, called \textit{Hydro-Kinetic Model}, HKM. The main conclusion coming from this (still unfinished work) is that at AGS the “standard” EOS (the resonance gas plus the QGP) is too soft, while for SPS data (especially the NA44 and NA49 ones on the slopes of $m_t$ distributions) it actually does a good job\textsuperscript{11}. The no-phase-transition scenario with the resonance gas only produce too much flow, and therefore should be considered experimentally excluded.

A dipole component of the flow (in the collision plane) was found at AGS but not so far at SPS: however the quadrupole one was recently detected at both energies. As it was originally emphasized in \cite{20}, the latter one is especially sensitive to EOS, and its further studies are clearly of great interest.

The latest stage of the collision is known as a “thermal” freeze-out: after that even elastic re-scattering of secondaries are frozen. Although this issue is related with “known physics” at the most dilute stage, this issue continue to be a matter of on-going debates. In particular, Gaardhoje (NA44) has argued that their data are best fitted with some universal freeze-out temperature $T_f = 140\,MeV$, which would mean that the interaction stops very soon after passing the phase transition line into the hadronic phase. However, a number of arguments suggest that in PbPb collisions the system actually is large enough to cool further, to $T_f = 110 - 120\,MeV$.

One such indication in fact was included in Gaardhoje’s talk: it is recent analysis \cite{21} of the Coulomb effects seen in $\pi^+/\pi^-$ ratio at small $p_t$. The second one follows from HBT radii (see talks by Foka and Wiedemann).

\textsuperscript{10}Studies of the question inside the event generators such as RQMD lead to the same conclusion.

\textsuperscript{11}Cascade event generators (such as Venus,RQMD,ARC etc) also have their own EOS as well. For example, Venus and RQMD also are rather “soft” at the early stages: although they have no QCD phase transition, their longitudinally stretched strings do not lead to the transverse pressure.
Two more arguments were presented in my talk: one is direct application of kinetics of the freeze-out, another is related with a very strong A-dependence of radial flow. I have argued that “extra push” in PbPb case may only come from the latest hadronic stage of the evolution.

5 Jet energy losses in matter and Landau-Pomeranchuck-Migdal effect

These issues were the subject of several theoretical talks. Shulga reviewed the situation in QED, pointing out that recent SLAC experiments have confirmed not only the original LPM predictions but also a thin-target predictions made by him and collaborators.

Baier has described some theoretical problems with “hard loop re-summation”, which appears in higher order processes in QGP with photon and dilepton emission. He then go on to describe what is known as BDMPS mechanism [22] of the energy loss calculation, the QCD analog of LPM effect. He has explained that there is a very significant difference between QCD and QED: it is gluons which mostly experience rescatterings and therefore a color charge is constantly “undressing” in matter. As a result, the conventional idea of dE/dx does not hold and the energy loss is proportional to the second power of distance L traveled in matter: for estimates one can use

$$-\Delta E_g = (10 - 20)(L/10\text{fm})^2$$

B.Zakharov (using a different formalism) has studied how the effective power of L changes from 2 to 1 for thin targets.

This large energy loss of jets is very important because it supports the idea of very rapid thermalization of QGP at RHIC/LHC. It can be directly observed by looking at jet shape (see talk by S.Gupta). Another important consequence is that charmed quarks emitted early in hard processes got “stuck” in matter: this basically kills the correlated charm background to the dilepton signal at RHIC [23].

References

[1] H.Heiselberg and U.A.Wiedemann, this proceedings.
[2] Y.Foka (NA49), this proceedings.
[3] J. Gaardhoje (NA44), this proceedings.
[4] A.Pfeiffer (CERES), this proceedings.
[5] L. Xiong and E. Shuryak, Phys. Let. B333(1994)316.
[6] K.Redlich, this proceedings.
[7] G.Q. Li, C.M. Ko, and G.E. Brown. Phys. Rev. Lett., 75:4007, 1995.
M.Hofman et al. Nucl. Phys., A556:15c, 1994.
[8] J. Kapusta, D. Kharzeev, and L. McLerran. Phys. Rev., D53:5028, 1996.
Zheng Huang, Xin-Nian Wang. Phys.Rev., D53:5034-5041,1996.
[9] B. Kaempfer, P. Koch, and O.P. Pavlenko. Phys. Rev., C49:1132, 1994.
[10] C.M. Hung and E. Shuryak. Dilepton production in heavy ion collisions, SUNY-NTG, 1996.
[11] R. Rapp, G. Chanfray and J. Wambach, Phys.Rev.Lett.76:368-371,1996.
[12] J. Kapusta and E. V. Shuryak. Phys. Rev., D49:4694, 1994.
[13] T.Peitzmann, WA98, this proceedings.
[14] F.Fleuret (NA50),this proceedings.
[15] J.P.Blaizot,this proceedings.
[16] N.Armesto, R.Vogt and W.Cassing,this proceedings.
[17] S. Peigne, this proceedings.
[18] H. Sorge, E. Shuryak,I. Zahed, Why is the $\Psi'/\Psi$ ratio in nucleus-nucleus collisions no longer decreasing? Stony Brook preprint 1997.
[19] P. Braun-Munzinger and J. Stachel, Nucl.Phys.A606:320-328,1996.
[20] J.Y. Ollitrault Nucl. Phys. A590 (1995) 561c-564c.
[21] H.W.Barz, J.P.Bondorf, J.J.Gaardhoje and H.Heiselberg, Colomb effects in heavy ion collisions (discussed in Gaardhoje’s talk).

[22] R. Baier, Yu.L. Dokshitser, A.H. Mueller, S. Peigne, D. Schiff. Nucl.Phys.B484:265-282,1997.

[23] E.Shuryak,Phys.Rev.C55, (1997) 961.