Chapter 28

Hot Quark Plasma in ISR Nuclear Collisions: January 1981

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Abstract In 1980/81 the ISR community of Physicists at CERN was preparing for a heavy ion experimental program. My lecture was moved-up from a later AA-meeting after another speaker bowed-out from the α -meeting. Before describing my presentation, I provide a few circumstantial details of potential interest.

An Invitation to ISR-discussion meeting at CERN read: Discussion Meeting
 $\alpha\alpha$ and αp Interactions
ISR Amphitheatre
Thursday, 22 January 1981
14:00 hours

The purpose of this meeting is to review and discuss present information about $\alpha\alpha$ and αp interactions following the analysis of the data collected during the runs of July 1980. Whilst this meeting will focus on low $p_{\perp}$ physics another meeting, scheduled for 19 February, will discuss large $p_{\perp}$ results.

Introductory talks will be given by¹:

D. Lloyd-Owen (R210) on elastic scattering
T.J.M. Symons (R418) on elastic scattering
S. Frankel (R807) on inelastic interactions
R. Szwed (R418) on inelastic interactions at low $p_{\perp}$
and
J. Rafelski (Frankfurt) who will review theoretical models²

This announcement is sent to contact persons only. Please post or circulate it. For questions or comments, please contact M. Albrow (5924) or M. Jacob (2414).

¹The Numeral in parentheses indicates the ISR experiment reference.

²I was invited as replacement for L. Bertocchi (CTP Trieste).

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Each introductory talk is scheduled to last about 30 min with ample time for discussion. The meeting is expected to be over by 18:00 and will include a coffee break.

Shortly after my lecture, I found in my CERN mailbox a note from Maurice Jacob : *Thank you for your beautiful talk. I think the meeting was quite lively and it was good to give the field momentum.*

I do hope that you can leave me something for the proceedings. At least your μ/T figure with an extensive caption and an explanation of the LBL/ISR behaviors is almost a must. Can you leave me at least that before you depart.

I left a handwritten response before departing in early morning: *This is for the ISR meeting on 22 January, 1981; consult R. Hagedorn (2138) for unreadable words and insertion of formulas.* I never saw the ISR report, the following transcript is from my own correspondence records.

Write-up for the ISR-report:

Hot Quark Plasma in ISR Nuclear Collisions

As nucleons consist of three quarks trapped in their perturbative vacuum domain, there is a non-vanishing probability that in high energy heavy nuclear collisions sufficient temperatures and compressions will be reached to form a quark gluon plasma. The experiments currently in progress at LBL, Dubna and ISR may be capable of producing this new form of matter.

The thermodynamic properties of a hadronic fireball created in such collisions are best characterized by the following three parameters: Volume V , Temperature T and the baryon chemical potential μ that controls the baryon density in the fireball. In the Fig. 28.1 a summary of the current qualitative knowledge about hadronic matter is described. Further details can be found in [1, 2].

For relatively small temperatures, i.e. $50 < T < T_0$, hadronic matter will consist of individual hadrons, mesons for small μ and also nucleons brought into the reaction for $\mu \sim 500$ MeV. This part of the phase diagram is shown dashed in Fig. 28.1. For $\mu \rightarrow 1$ GeV and $T \rightarrow 0$ we enter the dark-shaded domain of normal nuclear matter where effects other than those of interest here are relevant.

The phase transition from the hadronic gas to the quark-gluon plasma occurs when the number of hadrons at a given temperature and chemical potential is so large that their energy density corresponds to $4\mathcal{B}$, the value known from the quark bag models. $\mathcal{B}$ is the energy density of the perturbative vacuum as compared with the “true” vacuum state of QCD. At the same time $P_{\text{vac}} = -\mathcal{B}$ is the pressure exercised by the true vacuum on the surface of the perturbative vacuum, balanced by the pressure of the quark-gluon plasma at the phase transition line where the total pressure of hadronic matter in comparison is small.

When the quark-gluon plasma is produced in nuclear collisions at some characteristic temperature T and chemical potential μ , it will expand against the vacuum pressure. The conservation laws of total energy and baryon number introduce two constraints between V, μ and T of the fireballs as a function of time. Assuming instantaneous thermal equilibrium, the fireballs can evolve only along the paths shown in the μ - T diagram. During this expansion, the entropy grows substantially. We note that in particular at ISR energies only the emission of particles from the

Fig. 28.1 See text; one non-explained item—a QGP fireball that equilibrates faster than it cools and expands at a prescribed energy and baryon content has $T_{\max}$ as shown on abscissa for $\alpha_s = 0.6$

fireballs that may lead to the high $p_{\perp}$ effects influence negligibly the energy and baryon number balance. The same is true for the energy of radial expansion mode.

The understanding of the quark-gluon plasma is not complete at present, but important qualitative insights can be gained by considering the effects of a Fermi-Bose gas with interaction of order α_s . Then at given collision energy at ISR, per nucleon, $\sqrt{s_{NN}}/2 \sim 15$ GeV we find a relation

$$\sqrt{s_{NN}} = 2 \frac{(\pi T)^2}{\mu} \left[f(\alpha_s) \sim 1 + \frac{N_G}{N_q} \right], \quad (28.1)$$

which describes the initial quadratic rise of μ as function of T of the ISR path shown in Fig. 28.1.

As mentioned, the pressure is small and even vanishes at the phase boundary which leads to the relation

$$T_0 \simeq \mathcal{B}^{1/4}. \quad (28.2)$$

Consequently at ISR energies the chemical potential at the phase transition, where hadronization will occur, is

$$\mu_{cr} = \frac{2\pi^2 \mathcal{B}^{1/2}}{\sqrt{s_{NN}}} \sim 20 \text{ MeV}. \quad (28.3)$$

In this number we recognize the main difference to the LBL Bevalac energies which lead to chemical potentials of the order and above 500 MeV at $T \sim (2/3)T_0$, see LBL path in [1].

When the hadronization occurs, the entropy of the fireball with $A = 4 + 4$

$$S = \ln Z + \frac{E - \mu A}{T} \quad (28.4)$$

can be well approximated for $\alpha\alpha$ ISR collisions as

$$\frac{S}{A} = \frac{\sqrt{s_{NN}}}{2T_0} \sim 100 \quad (28.5)$$

given that $T \ln Z = PV \rightarrow 0$ and $\mu \ll \sqrt{s}$. This is an extremely high entropy per participating nucleon and it requires very high particle multiplicity by use of Boltzmann's relation $S \propto \ln W$. Hence we are led to the conclusion that the production of quark-gluon plasma at ISR must be characterized by very high multiplicities. The mean transverse momenta of the hadrons produced will show the known features of pp collisions as almost all particles are made in the final stages of the fireball explosion when the transition to the hadronic gas phase occurs.

I do not doubt that important signatures of quark-gluon plasma will be found, however we expect the relative particle yields and appearance of high $p_\perp$ particles to be more valuable indicators, rather than the inclusive particle spectra. I am not yet prepared to speculate further on possible characteristic features of the quark-gluon plasma formation in $\alpha\alpha$ collisions.

Finally let us stress the similarity of the physics at LBL-Bevalac and ISR, as shown in Fig. 28.1, despite different domains explored in the μ, T diagram and different type of experiments. It could be therefore desirable to have at ISR data with heavy nuclei (as compared with α 's) at perhaps somewhat lower $\sqrt{s_{NN}}$. This would close the gap between both available experiments, at the same time allowing for higher collectivity (higher number of nucleons A) and thus a much larger probability for production of the plasma.

I would like to thank R. Hagedorn for his interest, support and stimulating discussions.

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References

1. R. Hagedorn, J. Rafelski, CERN preprints TH 2947, TH 2969 (1980); From hadron gas to quark matter I & II: in the *Proceedings of the International Symposium on Statistical Mechanics of Quarks and Hadrons*, Bielefeld, Germany, August 1980, ed. by H. Satz, (North Holland Publishing Company); see Extreme states of nuclear matter – 1980, Chapter 27 in this volume.
2. E.V. Shuryak, QCD and the Theory of Superdense Matter, Phys. Rep. **61**, 71 (1980)