Chapter 9
Hadronic Matter: The Moscow Perspective

Igor Dremin

Abstract I describe studies done by the theory group of Lebedev Physical Institute in Moscow and point out the cross-influence of some of our work with that of Rolf Hagedorn, and show how this research continued and evolved up to the present.

9.1 The Beginning

Cosmic Rays and Landau

High energy hadron interactions were always one of the main topics of research at the Moscow Lebedev Physical Institute. On the experimental side, cosmic ray studies which started already in the 1930s were quite successful. The interest in high energy studies further increased after construction of first accelerator at the Institute with active participation of V.I. Veksler who soon proposed the autofocusing concept (1944) and moved to Dubna with many collaborators to realize his visions and build accelerators.

In parallel, theoretical work became more intense. Many researchers became excited seeing L.D. Landau paper on the hydrodynamic model of hadron interactions in 1953 [1]. Landau used to say that the work on it was the most hard, and time-consuming compared to all other of his papers. Actually, it was the first one which contained the detailed calculations ascribing the macroscopic features to the microscopic objects along the line of thought initiated by E. Fermi in 1950. At that time, in my 3rd graduate year, I devoted several days to studying Landau's paper in the Moscow Polytechnic library.

Landau's approach was widely discussed by theorists at LPI. Hydrodynamic equations were further analyzed by E.L. Feinberg, D.S. Chernavsky and G.A. Milekhin. They published a series of papers on this topic in the 1950s. This

I. Dremin (✉)
Lebedev Physical Institute, Moscow 119991, Russia

National Research Nuclear University "MEPhI", Moscow 115409, Russia

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work appeared in Russian journals and is unfamiliar to Western scientists. The activity was strongly slowed down after the tragic death of Milekhin. At the same time, some experimentalists (e.g., G.T. Zatsepin) in our Institute dealing with high energy particles in cosmic rays insisted—mainly based on intuition—that beside drastic central collisions, as we call them nowadays, they observed another class of interesting events which cannot be described by the hydrodynamic approach.

Multiperipheral Collisions

I was impressed by these statements and at the very end of 1958 calculated first the one-pion exchange graph of peripheral truly inelastic collisions where both colliding hadrons get excited and produce new particles. This was just at the time when experimental data from the newly constructed Dubna accelerator about inelastic collisions at the laboratory energy 9 BeV (now GeV) became available and were argued about even though not yet published.

Many leading Russian theorists were gathered at our department by I.E. Tamm for a discussion of experimental results and their description by our model. The publication with D.S. Chernavsky appeared in JETP January 1960 [2] issue and initiated a large series of papers on peripheral and multiperipheral models.

The early contributions of D. Amati et al. reviewed in [3] were especially important. However, they got the total cross section decreasing with energy increase. To improve their model we proposed that heavier blobs (which we called fireballs and later—clusters) should be created at each vertex, for a review see [4]. At that time such guesses originated from cosmic ray observations, especially those presented by M. Miesowich from Krakow.

In our model, the cluster decay was treated by statistical laws, and that appealed to R. Hagedorn. I do not remember exactly when I first visited CERN, there were so many visits since then. Surely, it was very soon after Hagedorn published his study of particle production. After my CERN seminar and several discussions at the theory department, Hagedorn invited me to his home and we spent a wonderful long evening chatting on many topics including science, literature, theater, politics, and surely, he proudly showed me his horses!

In my conversations with him I gained the feeling that he was very glad to get support from our group and to be able to discuss with all those who could understand his ideas. His work was at the time still little appreciated. This was also true at the CERN Theory Division.

Nowadays, the concept of clusters could be somewhat related to jets numerously created at the LHC. The cluster concept is revived also by studies of *AA* collisions at RHIC. As we say in Russia "Horses run along the rings" and "People come to use old galoshes sometimes!"

9.2 Hot Hadron Matter

Photons and Leptons

E.L. Feinberg actively promoted the statistical and hydrodynamical concepts and at the 1970 Kiev conference he first proposed [5] the photon and dilepton signatures (the so-called direct photons and dileptons) of the early stage of the quark-gluon matter (see his summary of 1976 [6]). Namely, these particles could escape from hadronic medium being in comparison almost non-interacting and, therefore, provide important information about its properties.

Many experimental papers aiming to detect such radiation and to confront its properties with theoretical prediction appeared afterwards. The theory was extended to include parton based processes and production of psions ($c\bar{c} = \Psi$) [7].

E.L. (as we called him) often corresponded with Rolf Hagedorn, and also with Peter Carruthers, discussing with them statistical and hydrodynamic approaches which were out of the mainstream of theory research at that time. One had to wait long for experimental data on AA collisions before this approach to strong interactions was recognized.

Quark-Gluon Plasma

Soon two other papers dealing with properties of hadronic matter appeared independently. The work by Kalashnikov-Klimov [8] contained QCD calculations of quark and gluon interactions in matter. At Lebedev (as LPI is often called in the West) we used to speak about the quark-gluon medium without specifying how free are quarks and gluons inside. Thus the term QGP was not widely used here. Earlier, I.Y. Pomeranchuk of ITEP used to call this yet-to-be-identified state of matter, verbatim translated, “the boiling operator liquid”.

Cherenkov Radiation

At the same time in 1979 I proposed [9] the idea about Cherenkov gluons which could produce jets (collimated groups of particles) in high energy collisions. That happened after our experimentalists showed me the emulsion plate with the newly registered cosmic ray event where distinct rings formed by secondary hadrons reminding us of the ordinary Cherenkov rings were easily seen.

That new property could also serve as a signature of the properties of the medium. In analogy to the permittivity of the ordinary medium, the term “chromo-permittivity” was coined to describe the hadronic medium containing colored quarks and gluons. Its value was directly determined by the positions of the rings. For further work of our group, and in particular, on comparison with the data of RHIC experiments I refer to papers [10, 11] where our approach has been reviewed.

Correlations and Fluctuations

Since then a lot of work was done on correlations and fluctuations of characteristic distributions of particles created from such a medium. More recently, some work on kinetic properties of the quark-gluon medium has been done as reviewed in [12]. The instabilities and time evolution of the newly created state of matter are the main topics of recent research [13].

Charm

The abundant production of charm related to hadron medium properties was noticed in cosmic rays as an effect of the long-flying cascades (for the review see [14]).

9.3 Open Questions

Another direction is represented by my recent attempts to visualize the geometric picture of hadron collisions. By comparison of ISR and LHC data it appears that protons become more dark (absorbing), and larger in size with an increase of energy. Analysis of elastic pp scattering data with use of the irrefutable unitarity condition gives rise to a speculative conclusion about very dense (absolutely black at the center) state of matter created at LHC energies in pp collisions [15]. A new critical regime of full absorption and rather wide spatial extension has perhaps been reached at the LHC. This could imply that a limiting temperature regime advocated by Hagedorn has been reached, and spatial expansion with increasing number of degrees of freedom prevails. That could correspond to the constancy of this new Hagedorn temperature.

Further implications for pA and AA collisions should be studied to learn what kind of possibly new matter is produced in these processes. Highest LHC energies can lead to new completely unexpected features also discussed in [15].

Appreciation

These remarks are in the spirit of my friends and mentors, Feinberg and Hagedorn, see Fig. 9.1, who always were looking for new frontiers and applying new methods in the area of multiparticle production. They certainly would be strongly involved in this present day research. I am very glad to join E.L., (Fig. 9.2), in toasting Hagedorn, and to pay a tribute to these two giants of science who inspired our investigations and paved the path we are walking on today.

Fig. 9.1 *Front row*: E.L. Feinberg (on *left*) with Rolf Hagedorn (*right*), June 27, 1994. In *second row* behind Feinberg: T.E.O. Ericson, and *centered* A. Martin of CERN-TH. *CREDIT: CERN Photo 1994-06-063-003*

Fig. 9.2 E.L. Feinberg (on *left*) toasts Rolf Hagedorn on occasion of his 75th Birthday. Sitting: Tania Fabergé, onlooking J. Rafelski, June 30, 1994. *CREDIT: CERN Photo 1994-06-066-015*

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