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PROSPECTS FOR PRODUCTION AND DETECTION OF A QUARK-GLUON PLASMA

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1. PROSPECTS

In all probability, this is the last Quark Matter Conference where theoretical speculations will dominate the scene. In a few months time, the first ion beam runs will begin at the Brookhaven AGS and the CERN SPS. By the summer of 1987, we should have the first solid data on ultra-relativistic nucleus-nucleus collisions and we should begin to narrow down the wide uncertainties underlying all past and present considerations on the search for the quark-gluon plasma (QGP). The organizers of Quark Matter '86 asked me to open the meeting with a discussion of the prospects for production and detection of the QGP. My evaluation is that these prospects are quite uncertain, in fact as uncertain as two or three years ago, despite the appearance of numerous theoretical papers in the meantime. The merit and interest of these papers is to explore the consequences of more diversified, often less simplistic assumptions for the QGP problems. By lack of guidance from experimental data, they nevertheless share with their predecessors the unavoidable character of exploratory calculations and their conclusions are frequently at variance with each other.

As the "hour of truth" approaches, what can we expect from the first generation of experiments? My answer is in two points:

- (i) We expect to obtain for the first time the type of systematic and comprehensive experimental information which is so badly needed to make theory more reliable and to guide further experiments. By their number and sophistication, the experiments to be run in 1986-87 should already provide a vast amount of systematic information. To analyze and interpret it will be a time-consuming and tedious activity, all the more so that

most results will have little glamour. This is nevertheless the most urgent task, also for the theorists.

- (ii) With lots of luck we may find in 1986-87 first indications of anomalous phenomena. With even more luck, several anomalies may emerge. If they are real (see below), and if they can convincingly be interpreted in a unified way as manifestations of QGP production, this unified interpretation of several anomalies will provide the first basis for a serious claim that the QGP has been discovered. Of course, one may also find anomalies which do not fit with the predictions on QGP. Such surprises would also be very welcome and could even be more instructive.

In the preceding considerations, the notion of anomalous phenomena is of central importance and should be clarified. For this purpose it is useful to remember the experimental discovery of the high p_T collisions (p_T = transverse momentum) a little more than ten years ago. This new particle production phenomenon, which had been predicted by QCD, manifested itself through anomalies in the p_T distribution (abnormally high tail) of the secondaries and in their azimuthal correlations (back to back jets). The identification and interpretation of the high p_T phenomena at the CERN ISR and the Fermilab accelerator turned out to be quite difficult. In contrast, their more recent manifestation at the higher energies of the CERN $p\bar{p}$ collider stands out impressively above the "normal" background, showing very directly quantitative agreement with perturbative QCD.

With this example in mind, we can clarify as follows the notion of anomalous phenomenon. At a purely empirical level, it manifests itself by deviations from a smooth extrapolation of data regarded to be normal, under the essential condition that these deviations are not explainable by statistical fluctuations. An anomalous phenomenon can also be recognized as a deviation from expectations based on successful theoretical models, if the deviation is such that it cannot be accounted for within a reasonable margin of flexibility of the models.

This raises the question of available models for the description of "normal" ultra-relativistic nucleus-nucleus collisions. The dual parton model and more recently the Lund model have been extended to hadron-nucleus and nucleus-nucleus collisions, and other "event generators" are being developed. Since systematic data will soon be available to guide this work, one can be confident that in a few years' time we shall have realistic model descriptions for the bulk of normal phenomena. What is unlikely, however, is that theorists could already predict quantitatively the properties of nucleus-nucleus collisions from those of nucleon-nucleon collisions. The modifications caused by the

nuclear environment are very subtle and are still poorly understood, especially for the tails of distributions.

In this context it is interesting to note a recent result obtained by M.J. Tannenbaum from old ISR data of the BCMOR Collaboration¹. It concerns the distribution of neutral transverse energy E_0 measured in a part of the central rapidity region for pp and $\alpha\alpha$ collisions at c.m. nucleon-nucleon energy 31 GeV. Both distributions are extremely well represented by the very simple gamma distribution

$$\langle E_0 \rangle f(E_0) = [p^p/\Gamma(p)] z^{p-1} \exp(-pz), \quad z = E_0/\langle E_0 \rangle \quad (1)$$

with practically identical values of the parameter p , namely $p = 2.50 \pm 0.06$ for pp and $p = 2.48 \pm 0.05$ for $\alpha\alpha$, which corresponds to KNO scaling between pp and $\alpha\alpha$ collisions at the same nucleon-nucleon energy. As shown in Ref. 1, starting from the distribution (1) for pp, it is difficult to reproduce the distribution for $\alpha\alpha$ in terms of multiple nucleon-nucleon collisions. While this works reasonably well for the upper two decades or so, the multiple collision estimate falls far below the observed tail of the $\alpha\alpha$ distribution for $E_0 > 25$ GeV, which is the region of highest initial energy density and therefore of greatest interest for the search of abnormal phenomena.

It would not be surprising if simple functions like (1) would give good descriptions of many transverse energy distributions. Such simple empirical laws could become more useful for the description of normal nucleus-nucleus collisions than complicated models of multiple nucleon-nucleon collisions, and they may give useful clues for more collective theoretical approaches.

2. THERMODYNAMICS OF PLASMA AND TRANSITION

Despite the massive lattice-QCD computations performed in the last years by several groups, only modest progress has been made on the equation of state of hadronic matter and on the nature of the transition between QGP and hadron gas (HG). We shall therefore be very brief on this subject which will be discussed extensively at the meeting. While the situation for pure gauge theory (gluons only) seems to be in good shape and indicates a first-order transition, the case of QCD with light quarks continues to be inconclusive and technical difficulties remain, especially for non-vanishing chemical potential μ . The only prediction which can probably be made with some confidence is that, as one goes from QGP to HG by lowering the temperature at $\mu = 0$, the densities of energy and entropy both decrease substantially (by a factor ~ 2 or perhaps even more?) while temperature and pressure vary little (they would remain constant if the transition were of first order). Fortunately, this "large latent heat"

property, which perhaps extends to non-vanishing μ , matters more than the nature of the transition for the minute amounts of hot hadronic matter that could be produced in nucleus-nucleus collisions.

Regarding the QGP itself, it should be stressed that the popular assumption to treat it as an ideal gas of partons (gluons, quarks and antiquarks) with opposite vacuum shifts in the energy density ϵ and the pressure p is very primitive and unreliable, especially near the transition. It is true that for pure gauge theory, ϵ is close to the ideal gas value, but p is definitely smaller. No reliable information exists for QCD with light quarks. Even for temperatures far above the transition, the QGP is expected to show departures from ideal gas behaviour, a topic on which new speculations will be presented by J. Polonyi at the meeting.

3. THE QUESTION OF THERMALIZATION

Up to now, most theoretical work on QGP formation and evolution in nuclear collisions assumes local thermalization at early times. In addition, attempts have been made to apply transport theory (in the form of irreversible transport equations of Boltzmann type) to the early evolution and the thermalization of the many-parton system initially produced in the collision. It should be realized that also the application of transport theory is subject to assumptions.

Firstly, the partons are treated as real particles or quasi-particles. Of course, each incident nucleon contains a distribution of virtual partons which is described by the structure functions measured in deep inelastic lepton scattering experiments. When transport theory is applied to these partons, they are assumed to be on their mass shell, and this can only be valid after some time ($\gtrsim 1$ fm/c for soft partons in each comoving frame).

Secondly, enough randomness must be generated before the evolution of the parton system can be described by an irreversible transport equation (with entropy production) rather than by a deterministic wave equation (which would conserve entropy). While this is unlikely to happen fast in a single collision, early randomness may be contributed by the fact that in most cases one studies ensembles of collisions.

Another important point is the distinction to be made between collective flow and internal motion, not only after local thermalization has been reached (hydrodynamical stage), but from the beginning, more exactly from the earliest space-time hypersurface Σ_0 on which the participating partons can be treated as real (Σ_0 is presumably close to the hypersurface $t^2 - z^2 = 1 \text{ fm}^2$, with t the time and z the longitudinal space co-ordinate in, e.g., the c.m. frame, if the ultra-relativistic collision occurs at $t = z = 0$). From Σ_0 onward, it is the

internal motion of the partons, i.e., their motion relative to their local comoving frame in every space-time point, which will be the main source of irreversible behaviour and eventual thermalization, with little additional contribution from the collective flow.

For a number of years, most papers on the hydrodynamical model for ultra-relativistic nuclear collisions took the initial longitudinal collective flow into account by adopting a simple ansatz for it on Σ_0 (usually the Lorentz-boost invariant ansatz), but they neglected completely the transverse collective flow (transverse expansion). Since the basic paper of Baym et al.², it became customary to include the transverse expansion in the calculation, under the assumption that it vanishes initially, i.e., on Σ_0 .

A further step toward realism is needed, however, because there must also be some transverse collective flow from the beginning. Its inclusion in hydrodynamical calculations should be straightforward, but it of course adds more freedom in the initial conditions and therefore reduces the predictive power. Another effect of the initial transverse expansion is to decrease by an unknown amount the maximum energy density which can be assumed to be thermalized, so that the standard estimates of Ref. 3 become overestimates. Since also the entropy density estimate based on the observed multiplicity⁴ is an upper bound (due to entropy production during the expansion and at freeze out), caution is called for in using these estimates to argue for or against QGP production in particular classes of collisions.

Although the initial transverse expansion adds an additional unknown element in the discussion of ultra-relativistic nuclear collisions, it should be possible to parametrize it in simple ways by imagining space and momentum distributions for the "real" partons on Σ_0 . Given such a distribution one can work out the local comoving frames and the separation between collective flow and internal motion. Some qualitative remarks can immediately be made. If all partons originate from a small space region (as is the case in hadron-hadron collisions, and by Lorentz contraction also in ultra-relativistic hadron-nucleus collisions) and if they do not multiply rapidly by cascading or branching, they will all fly away from the small source region and this will produce much centrifugal collective flow and little chaotic internal motion. If the partons multiply by cascading, their flight directions will get partially randomized and chaotic internal motion will be increased. Furthermore, with or without cascading, central nucleus-nucleus collisions should provide a strong gain of chaotic internal motion in the transverse directions because of the larger transverse size of the source region.

4. SIGNALS FOR PLASMA FORMATION

A great deal of theoretical work has continued to appear on this topic, mainly on strangeness production, dilepton production and the $\langle p_T \rangle$ versus dn/dy correlation. Variations have been introduced in the assumptions, calculations have been improved by inclusion of additional effects, especially transverse expansion. All this has been found to modify the results considerably, and their dependence on the assumptions is often quite strong.

A striking example of this is the $\langle p_T \rangle$ versus dn/dy correlation, for which the present situation is rather confusing. Theoretical calculations of this correlation have been extended to include transverse expansion and they indicate that the effects of a phase transition are model-dependent but generally weak⁵. On the other hand, Shuryak and Zhirov returned to this problem in a very recent paper⁶ and predict strong effects due to a fast, explosion-like transition from the plasma to the hadron gas phase. I see no way to decide between the various models without input from future experiments (the JACEE data are insufficient). One important feature emerging from the recent theoretical work is that one should try to measure separately the p_T spectra of light and heavy secondaries in the hope of separating collective flow and internal motion contributions.

5. OUTLOOK

This introductory lecture should not close with concluding remarks. They belong at the end of the meeting and will be given by Gordon Baym. My aim was to attempt a critical assessment of where we stand on a few central topics of the search for the quark-gluon plasma, after years of theoretical exploration without adequate data. With the advent of systematic experimental programmes at BNL and CERN, we shall soon enter a new phase which will certainly bring new knowledge. Let us hope that it will reveal what we called anomalous phenomena (Section 1), perhaps pointing to the plasma explanation, perhaps to new surprises.

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