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Relativistic Ion-Ion Collisions

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I. INTRODUCTION

The field of highly relativistic ion-ion collisions has attracted increasing interest in the past few years, with the focal point being the possible observation of deconfined hadronic matter — "quark-gluon plasma." I personally was drawn into this field via the enthusiasms of, among others, T. D. Lee, Bill Willis, and Larry McLerran. But my interest thus far has been "part-time." Therefore I am hard put to provide the kind of overview of the field that is implied by the title of this talk. The field is moving rapidly, and I am not doing very well in keeping up to date. I probably will omit important contributions and apologize in advance to their originators.

I will first briefly discuss the space-time evolution of relativistic nucleus-nucleus collisions, and use this as a setting for raising other issues. A major one is whether the concepts used for ion-ion collisions are also applicable to nucleon-nucleon collisions, and the second section is devoted to this question. The final section outlines a long list of issues needing further study — much of which may well be already well under way.

II. SPACE-TIME EVOLUTION

It seems clear that, unlike the case of hadron-hadron collisions, a space-time description of a nucleus-nucleus collision process is a mandatory supplement to the conventional momentum-space description. At high energies, two distinct regions of the momentum-space of produced particles exist — the projectile fragmentation regions and the central region. The space-time dynamics and evolution of the system of produced particles is distinctly different in these two regions as well. Both have been described in detail recently, and here we shall only sketch the main points.

A. Central rapidity region

The central rapidity region is, roughly speaking, defined by the statement that a given value of rapidity y is in the central region if, in the reference frame for which a produced particle of that rapidity y emerges at 90°, both incident nuclear projectiles are Lorentz-contracted to thicknesses $\lesssim 10^{-13}$cm. Under these circumstances we may expect the geometry of particle-production, to a fair approximation, to be independent of the detailed choice of the rapidity y, because the initial-state geometry in the various frames is very similar, differing essentially only in the momentum density residing in the incident nuclear pancakes. This picture is supported somewhat by the existence of a "central rapidity plateau" in particle production properties in pp and p-nucleus collisions at sufficiently high energies.

This approximate invariance suggests a simplifying starting hypothesis of an exact invariance of production properties with respect to boosts connecting two values of rapidity of y and y', provided both y and y' lie in the central region. Further simplification occurs if one also assumes, for infinite-radius nuclei (or for sufficiently short times after impact of the pancakes), that the production of secondary quanta in the primary collision does not depend upon the transverse coordinates. These symmetries in initial conditions imply that the produced system of quanta should also obey these invariance conditions – in particular (again for infinite nuclei).

i) The net mean transverse momentum of the produced system vanishes.

ii) The net mean longitudinal momentum of the system produced in the impact plane – i.e. the midplane between the receding excited nuclear pancakes – vanishes.

iii) At time t after the collision an element of the produced system a longitudinal distance z from the midplane moves with mean velocity $v=\frac{z}{t}$; i.e. the produced system expands homogeneously.

These properties of the produced system should (given the simplifying initial assumption) be quite independent of dynamical details such as whether quark gluon plasma is formed, whether it is in equilibrium, etc. Thus the basic space-time geometry for the evolution of the system may survive considerable variations of scenarios for the dynamic evolution.

Nuclei are not infinite — alas, they may not even be "large enough" — and the existence of the edges of the pancake introduce complications in the description of transverse motion. Causality suggests that, at time t after impact and in the central collision plane, the produced system at distances greater than ct the from the edge will behave in a way appropriate for infinite nuclei. Indeed, if somehow an equilibrated plasma is produced, the relevant transverse distance is probably lessened to $c_s t$ where c_s $(\sim c/\sqrt{3}??)$ is the ~~second~~ sound velocity in the fluid. Again, Lorentz-boost invariance of this picture determines the location of this inward propagating "information-front" or "rarefaction-front" at all longitudinal distances z. At transverse distances larger than the distance charaterizing this front, we may anticipate outward flow and rather fast expansion of the produced system, because there is the opportunity for expansion in all three degrees of freedom. In any case, the boost symmetry implies that it is sufficient to study the evolution of the system at the midplane, where the mean longitudinal velocity vanishes.

Implicit in the above discussion is the assumption that the baryon number contained in the incident pancakes (in central region reference frames) is found, after impact, in emergent pancakes of thickness less than 10^{-13}cm. This is supported to some extent by data on α-α collisions at the ISR and nucleon-nucleus collisions at accelerators as well as from cosmic rays. However this important point needs more study — especially since it is rather basic to the space-time picture we use. We shall come back to this question when discussing fragmentation regions.

What kind of dynamics can be expected? The initial energy deposited in the central plane by the colliding nuclear pancakes can be estimated conservatively in the following way.

Assume each transverse element of the pancakes of size d_o ($\sim$0.3-1$_f$) acts, because of causality, independently of the others. Further, assume that the energy deposited in the central plane is the same as one finds in nucleon-nucleon (or nucleon-nucleus) collisions. This must be a conservative assumption, because collective effects of different nucleons with the same impact parameter — and thus "on top of each other" in the pancakes — have been neglected. Even so, most estimates using this line of argument give an initial energy density of more than 1GeV/fm^3, sufficient in principle to create quark-gluon plasma just above the presumed phase-transition temperature of $\sim$200GeV. [Ordinary nuclear matter has an energy density $\sim$100MeV/fm^3.]

However, it is not clear which dynamical degrees of freedom are most relevant in describing the energy transport. The temperature scale is rather low to trust a description based on an ideal gas of quark and gluon partons. The energy density is clearly too high for a description in terms of a fluid of hadrons. It is also quite plausible that the gluon degrees of freedom dominate the transfer of energy from projectiles into central-plane energy density. And the mechanism might require use of nonperturbative concepts such as "bag" or "string." But despite these grave uncertainties in mechanism, naive estimates of mean free paths and equilibration times encourage the belief that after a short time ($ct \lesssim 10^{-13}$cm?) thermal equilibrium is established in the central plane — except of course near the periphery. In my view, rational consideration of alternatives involves so much uncertainty that it makes sense to assume as a working hypothesis the establisment of thermal equilibrium and follow as well as possible the consequences. Uncertainties do remain, but they are reduced by an order of magnitude.

If local thermal equilibrium is established, then the same considerations (short mean free path) which implied thermalization suggest the applicability of ideal relativistic hydrodynamics, i.e. negligible viscosity and heat conduction. This means that there exists a conserved local energy-momentum tensor

$$T_{\mu\nu} = (\varepsilon+p)u_\mu u_\nu - p g_{\mu\nu}$$

with the energy density ε and pressure p related by an equation of state. Solution of the conservation law

$$\partial_\mu T^{\mu\nu}=0$$

leads, under the symmetry assumptions described above, to an energy density which is a function of proper time $\tau=(t^2-z^2)^{1/2}$ only, and satisfies

$$\frac{d\varepsilon}{d\tau} = - \frac{\varepsilon+p}{\tau}.$$

For an ideal fluid

$$\varepsilon = 3p$$

and $\varepsilon \sim \tau^{-4/3}$, while in a naive calculation of the pre-equilibrium phase, $\varepsilon \sim \tau^{-1}$.

In ideal hydrodynamics there exists a conserved local entropy current. The entropy density

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If entropy-conservation is valid (or even approximately so), the final entropy, which is directly measured in terms of the number of produced pions, provides a direct measure of the initial conditions of the system, including initial temperature. Thus simple multiplicity measurements may provide basic information on the early conditions of the collision.

While the fluid expands longitudinally, there will be of course transverse motion as well, along the lines already described. The inward-moving "information front" will, according to hydrodynamic causality, propagate inward at the sound velocity $(d\varepsilon/dp)^{-1/2}$. The fluid beyond this "rarefaction front" moves outward rapidly. This has been calculated for the case of an ideal fluid.

What about the equation of state? In general, we may write, for pressure as function of temperature,

$$p = \frac{\pi^2}{90} n(T) T^4$$

where ignorance is buried in the function n(T). However in the limit of large T we expect ideal quark-gluon plasma, while at small T we essentially know the system becomes an ideal pion gas. Hence

$$n(T) = \begin{cases} 42\pm 6 & t >> t_c \\ 3 & t << t_c \end{cases}$$

The critical temperature is estimated from theory as well as from common sense to be $T_c \sim 200$MeV. Provided $t^{\mu}_{\mu} \geq 0$, n(t) is a monotone function of T. Lattice Monte-Carlo calculations indicate that the jump occurs abruptly with, most likely, occurrence of a single first-order phase transition. The effects of such a phase transition on the evolution of the collision products is of great interest and importance and at present under active study. It is, however, beyond the scope of this discussion.

B. <u>Fragmentation regions</u>

The space-time evolution of the nuclear projectiles per se is most clearly followed in the rest frame of one of the initial nuclei. In that frame, as the incident pancake sweeps across the stationary nucleus, we expect that each nucleon is struck and accelrated to a momentum ~0.3-1.0GeV, typical of what happens in nucleon-nucleon or nucleus-nucleon collisions. Thus just after the incident pancake has left the target, we find the baryon number compressed into a ellipsoidal region moving semi-relativistically behind the projectile pancake. The internal properties of that system are inferred by estimating the total energy of that system and its total momemntum. In the total energy-momentum budget must be included produced medium-to-large-angle pions which are trapped and presumably thermalized within the ellipsoidal volume under consideration. This has been done in some detail, and it turns out that even in its rest frame the volume containing the baryon-number is a pancake-shaped ellipsoid with an initial energy density $\gtrsim$ 1 GeV/fm^3, again high enough to produce quark plasma. In the cms frame, we may say that the initial density in rapidity of the baryon number should be quite similar to what is seen in pp collisions, but that the baryon number is presumed to be in the form of quark plasma. Because the quanta in this plasma are massless, this means that as the system evolves hydrodynamically, the baryon-number may diffuse into or toward the central region more than would be the case if it were bound in ordinary baryons. However the maximum amount of such diffusion is limited by causality:

$$|y_f - y_i| \leq \log \frac{\tau_f}{\tau_i}$$

where y_f ~~and~~ (y_i) and $\tau_f(\tau_i)$ are the final (initial) rapidities and proper times appropriate for the description of the flow. To my knowledge no detailed estimate of baryon-number diffusion, even assuming ideal longitudinal hydrodynamic flow, has yet been made.

Transverse motion is again described in a way similar to what was done in the central rapidity region. A rarefaction front moves inward from the surface at the local sound velocity, while the system exterior to the front expands outward, cooling rapidly. ~~moves inward from the surface at the local sound velocity, while the system exterior to the front expands outward, cooling rapidly.~~ Again existence of a presumed first-order phase transition needs to be taken into account, but is beyond the scope of this discussion.

C. Signatures

A major problem for future experimental programs on relativistic ion-ion collisions is how to determine what is going on. Experimental signatures are indirect and as yet not too amenable to theoretical analysis.

Much work remains to be done on signatures, and much of it will depend upon some understanding of the space-time evolution of the system as sketched above. We note some of the ideas below:

1. Increased K/π ratio (or even charm) due to high initial temperature.

2. Bulk radiation of photons or low mass dileptons from the volume of plasma. [This is <u>not</u> an easy calculation to do, because free-gas models are probably not reliable.]

3. Unusual event structure, such as lumpy distributions of multiplicity, $\langle p_\perp \rangle$, compositions, etc., with respect to rapidity or azimuth. These fluctuations would be too coarse-grained to interpret as statistical or jet-associated fluctuations, and collective mechanisms would have to be involved. These might be condensation and growth of hadronic droplets during the phase transition, or hydrodynamic instabilities such as "flares."

4. Correlation studies, especially Hanbury-Brown-Twiss $\pi^-\pi^-$ (or KK) Bose-statistics correlations, which may help to determine the size, shape and bulk motion of the produced system at the hadronization stage.

5. Study of baryon-number diffusion away from the fragmentation regions toward the central region; in the plasma phase there may be considerably more mobility than in the hadronic phase.

While these ideas (and others I am sure I have forgotten to mention) hold much promise, I suspect that if the quark-gluon plasma is produced, it will manifest itself in experimental signatures as yet unforeseen. The system is after all a complicated relativistic fluid subject to highly nonlinear quantum forces. We should not expect to anticipate everything which can happen, no more than astronomers and astrophysicists can be expected to have anticipated phenomena of the solar surface, or pulsars, or quasars. On the other hand, if very interesting and novel phenomena will be seen in ion-ion collisions, theory must develop the capability to interpret them, if not to predict them.

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III. PROTON-ANTIPROTON COLLISIONS

It is probably unrealistic to expect quark-gluon plasma to be produced in ordinary hadron-hadron collisions. in an average sp$\bar{p}$s collision the energy released isotropically into, say, 10 steradians of central detector (i.e. $\Delta y \sim 2$) is about 10 pions worth, or $\sim$4 GeV. If we distribute this uniformly into a spherical volume at the critical energy density of, say, 0.5 GeV/fm^3, the radius of the system turns out to be only 1.2fm. If plasma were produced, it would have to happen on time scales very short compared to 1 fm. This is not out of the question, but requires some optimism. During this short time scale, the longitudinal evolution in space-time might be similar to what was described above for ion-ion collisions.

A slightly less radical approach is to first concentrate on the high-multiplicity, high-E_T, events observed at FNAL, SPS, and sp$\bar{p}$s. These events are associated with the phenomenon of KNO scaling and large multiplicity fluctuations. The observed isotropic energy deposition into 10 steradians can be as high as 50 GeV, indicating an initial energy deposition far in excess of the 1 GeV/fm^3 needed to make quark-gluon plasma. This implies that considerations of macroscopic space-time development of this initially produced system may be needed. A very simplistic picture of what may happen is that the initially very hot system essentially explodes — i.e. expands outward more or less at the velocity of light in a relatively thin shell of thickness 1-2 fm. This is a hypothesis which can be tested by carrying out 3-dimensional hydrodynamic calculations with spherical symmetry. The formalism exists,but to my knowledge no calculation relevant to these initial conditions has been carried through. However, in the limit of initial energy (contained say in a uniform volume $\gtrsim 1\ fm^3$) tending to infinity, simple solutions for the hydrodynamic flow follow from the spherical-shell geometry and the conservation laws for entropy and energy. One finds, for the ideal Stefan-Boltzmann equation of state,

$$\begin{aligned} \gamma &\sim R \\ T &\sim R^{-1} \\ \varepsilon &\sim R^{-4} \end{aligned}$$

If there is negligible entropy generation and angular inhomogeneity while passing through the phase transition region (dubious assumptions to be sure,) then

$$\begin{aligned} T &\sim \text{constant} \\ \gamma &\sim \text{constant} \\ \varepsilon &\sim R^{-2} \end{aligned}$$

during that period. Thus, since ε decreases by a factor ~10, the radius of this "fireball" can expand three fold just while passing through the hadronization transition. There can be an additional factor 2-3 expansion during the hot Stefan-Boltzmann quark-gluon phase. It follows that the radius of the sphere at which the hadrons are produced in these high-multiplicity events may indeed be very large, ~5-10 fm. Such a phenomenon might be observable via $\pi^-\pi^-$ Bose correlation studies using the Hanbury-Brown-Twiss effect.

Needless to say, these estimates are only to be considered as rough sketches of what might happen. Better estimates can and should be done.

However, the results suggest the possible importance of collective effects creating net outward flow and distortion of transverse momentum distributions as function of multiplicity. Realistic calculations are needed before serious attempts at comparison with data are made.

IV. SOME QUESTIONS

What follows is a set of questions often asked about this subject. While the questions are authoritative, the answers are not.

1. Is the space-time picture correct?

The crux issue is whether the energy flux travels in straight lines outward from the original collision point. Alternatives to this picture (valid in the old fashioned parton model, perturbative QCD branching processes, and Landau hydrodynamic model) might have large angle particles produced downstream of the collision point. But this leads to considerable awkwardness in the space-time picture, especially when viewed in other frames of reference.

2. Is ideal hydrodynamics really applicable?

As we already mentioned, it will be very hard to answer that question from theory alone. I suspect that the most viable strategy will be to assume it to be true as a working hypothesis. It may be necessary to ultimately include non-ideal hydrodynamics — i.e. effects of viscosity and heat conductivity. But theoretical uncertainty in the parameters probably implies that guidance from experiment will be required.

A full quantum-mechanical kinetic theory would of course be very welcome. But unless the parameterization is simple, it may be better to stay with the relatively simple formalism of ideal hydrodynamics.

3. How does one go about describing the passage through the first order phase transition?

This is probably the most fertile open question in the field. We may intuitively expect a mixed phase of hadronic droplets condensing in the midst of the quark-gluon plasma as the system cools. But is this true? If so, how do the droplets grow? Is there supercooling of the plasma? How much entropy production occurs? Does droplet formation and growth lead to bulk inhomogeneities in the phase space of produced hadrons — inhomogeneities which could provide good experimental signatures? How do fluctuations, e.g. "hot spots" associated with quark or gluon high-p_T jets, in the initially produced plasma influence the evolution during the phase transition. What kind of shock fronts or other discontinuities may be propagating through the system during the transition? Many of these questions are under active study now, and much more may be understood within the next year.

4. Is quark-gluon plasma really produced in high-energy, high multiplicity nucleon-nucleon collisions?

We have already expressed some views above on it. This question will be harder to answer from theory than for ion-ion collisions. It is hard to see how the issue of very rapid approach to equilibrium can be put under good theoretical control.

In this case it may be better to assume a working hypothesis that branching processes within the framework of QCD may account for KNO scaling and the phenomenology of high multiplicity, high isotropic-E_T events. If, after careful attention to the credibility and self-consistency of the QCD calculations, (including credible space-time evolution), a satisfactory accounting can be made, then that theoretical case would be easier to support than a purely statistical-hydrodynamic approach. In either case, the obstacles are great.

5. How much cms energy is required to make quark-gluon plasma in ion-ion collisions?

There is some optimism that an ion beam energy as low as 10 GeV/nucleon (in the cms) is sufficient. This is roughly what the upcoming sps fixed target program can provide. However, it will eventually be desirable to cleanly separate fragmentation-region phenomena, inasmuch as the equation of state, initial excitation, and space–time evolution can differ in substantial ways in these two phase-space regions. The fragmentation region can operationally be defined as that domain of rapidity where the net baryon-number density of produced particles is nonzero (say, where $\gtrsim$% of the final energy of produced particles (per unit rapidity) is in net baryons). These should be cleanly separated by a central region of at least two units of rapidity. Were the final baryon-number distribution ion-ion collisions identical to that in nucleon-nucleon collisions, the ISR energy scale of 30 GeV/nucleon could be sufficient. But there are at least two mechanisms which might help fill in the central region with projectile baryons. The first is any cumulative effects in even nucleon-nucleus collisions which lead to more energetic nucleons (in the nucleus rest frame) than assumed in our above discussion. The second is "backflow" of the baryon-number during the quark-plasma phase when it is easiest for the (massless) quarks to diffuse. Thus a cms beam energy of 50-100 GeV/nucleon is a prudent value. One sees that the desire for clean kinematics tends to force the cms energy sufficiently high that it should be a sure thing that quark-gluon plasma is indeed produced.

6. Can nucleon-ion collisions enhance plasma formation in hadron-hadron collisions?

Already high multiplicity, high isotropic-E_T events are observed in SPS and Fermilab fixed-target experiments. It will be interesting to study in more detail these phenomena, and in particular to learn about their A-dependence. Does the proximity of extra nuclear matter lead to higher initial temperature in the fragmentation and/or central region? Is there transport of baryon-number out of the (target) fragmentation region? There exists some data on the A-dependence of $d\sigma/dE_T$, which indicates an A^{α} dependence with $\alpha \sim 1.4-1.5$. It is not yet clear how much is a consequence of the (expected) increase of target fragments with increasing A.

7. Why is any of this interesting?

This question is serious. The phenomena are sufficiently complicated that it will be very difficult to figure out what is really going on. I think the venture of building and using a heavy-ion collider must be regarded as a calculated risk. The scientific output is not likely to look at all like what will exist in the proposals — for better or worse. But what might be the payoffs? The reader will readily agree with the author that the best answers are probably not on this list:

i. A good measurement of Λ_{qcd}. Λ_{qcd} is, for pure gluon plasma, directly proportioned to the critical temperature. We know, just from common sense, that $100 \text{ MeV} < T_c < 300 \text{ MeV}$. 100 MeV is dilute cold pion gas, well below Hagedon's temperature of 145 MeV, while the energy (and particle) density is much too high at 300 MeV for distinguishable individual hadrons to exist. Thus, if theorists can provide the constant of proportionality, the estimate $T_c = 200 \pm 100$ MeV translates into a 50% measurement of Λ — as good as anything which presently exists. And since the equation of state should be one of the easier lattice calculations to perform, and since the power of lattice calculation is sure to improve greatly with time, we should expect some accuracy in the theory. What will be needed is some evidence for the phase transition and a measurement of the critical temperature. The reward, an accurate measurement of Λ_{qcd}, cannot be called anything but fundamental physics.

ii. Liberation of fractional charge? A recurrent speculation is that, if fractionally charged hadrons do exist because of some minute flaw in an otherwise perfect confinement mechanism, a good way to liberate them is in a chaotic, hot environment of color sources and gluon fields. Far out? Yes. Impossible? Probably no.

iii. Metastable globs of quark matter? There exist conjectures that superdense quark matter of critical baryon number might be metastable, due to a balance between surfce energy and volume energy. These would most likely be emitted from fragmentation regions. Ideas like this have been entertained in attempts to explain the cosmic-ray Centauro" and "Chiron" events.

iv. Centauros and Chirons These cosmic-ray events tend to defy rational interpretations. Maybe it takes ion-ion collisions to produce the phenomenon in the laboratory. However, 50-100 GeV/nucleon may be much too low an energy.

v. Astrophysics Homogeneous longitudinal expansion of the plasma in the central rapidity region bears a great resemblance to the homogeneous isotropic expansion of quark-gluon plasma believed to occur during the first three microseconds of the Big Bang. Some people conjecture that the fluctuations which occurred during the passage through the deconfinement transition provide the seeds for density fluctuations which have grown into the galaxies. Thus the prehistory of our natural habitat may be better understood through the study of relativistic ion-ion collisions.