RELATIVISTIC HEAVY ION COLLISIONS AND PARTICLE PHYSICS

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In recent years, there has been interest in the study of relativistic heavy ion collisions as a window to new phenomena*, particularly the study of possible new phases of hadronic matter — a quark-gluon plasma filling a volume of fm^3 is one example. On the experimental side, only fragmentary hints of interesting features exist, such as signs of coherence in photon yields from α-α collisions at the ISR, the "anomalons" seen in Bevalac, and other experiments. On the theoretical side, lattice gauge theory calculations in QCD (without fermions) show fairly reliably the existence of a phase transition from confined to unconfined gluons at a temperature of about 200 MeV. Estimates of the effects of fermions indicate that there might also be a phase transition in nuclear matter from confined hadrons to a quark-gluon plasma at a similar temperature (or equivalently, at energy densities of 2-3 GeV/fm^3).

Certainly, from the point of view of fundamental physics, the establishment of such a phase transition, and the study of the properties of quarks and gluons in the excited phase, are of great importance. QCD is a highly nonlinear theory. Many interesting peculiarities could occur. Study of collective aspects (beyond individual hadrons) can be expected to throw new and different lights on QCD, even though, in principle, no really new degrees of freedom are involved.

The rub comes when one considers the feasibility of achieving such a new state of matter, and ascertaining that one has done so. The conditions of thermal excitation necessary to cause the phase transition will soon be known to adequate theoretical accuracy. But it is not known whether a collision between relativistic ions can cause this transition. The basic difficulty is that heavy nuclei are quite transparent to very high energy nucleons, as is clear from the remarkably slow growth of the multiplicity of secondaries, and of the inelasticity, with increasing A. The basic reason for this phenomenon is understood: because of time dilatation, the projectile nucleon evolves into a state Ψ that differs but little from the initial states in its traversal of the target†. Ψ consists of partons that populate a broad range of rapidity. Present indications are that this parton density in the central region only has a strong A-dependence in the portions of the phase space adjoining the target fragmentation regions. If the projectile is a nucleus instead of a nucleon, the state after traversal is an incoherent set of packets Ψ_i whose space-time distribution is determined by the Lorentz-contracted projectile nucleus, and the time evolution of Ψ_i itself. The only way that a large energy density could be accumulated is from the spatial overlap of different packets. Let Ψ_1 and Ψ_2 be two packets stemming from two adjacent nucleons in the projectile that have the same impact parameter. The desired energy pile-up may occur when the leading portion of Ψ_2 catches up with the slow portion of Ψ_1. But the latter is not energetic, nor is it greatly amplified by successive collision. As a consequence, after traversal of the target the energy density of the projectile nucleus does not become very concentrated, and by symmetry, the same is true of the target.

The preceding description is appropriate to typical collision at all impact parameters, and for all rapidities except, perhaps, the central region.* It leads to the conclusion that on those rare occasions when enough energy is deposited in a region of nuclear dimension to cause a phase transition, it must be due to mechanisms that play an insignificant role in determining the average properties of collisions. In consequence, estimates of the probability that one can attain the energy accumulation needed are, by necessity, speculative. A further level of speculation is required if one also asks for collisions that lead to a plasma in thermal equilibrium, because typical collision mechanisms tend to give states whose components have large differences of rapidity. Hence, the advertised characteristic signatures for the creation of the plasma (Planck distribution of photons with $T \sim 200$ MeV, lepton pairs outside the Drell-Yan kinematic region, abnormally large K/π ratios, etc.) may not exist, even if a plasma state is formed, because it may be far from thermal and/or chemical equilibrium.

There is apparently a possibility that, in the next three or four years, ions up to atomic mass $A \approx 20$, and with energies of order 200 GeV/amu, will be available at the CERN SPS to bombard fixed heavy targets. Such experiments should provide tests of speculations concerning plasma formation in the projectile fragmentation region, though it should be noted that these projectiles may still be too light. The prospects are sufficiently exciting to warrant pursuit of this goal as a first step before consideration of the heavy ion option at future collider.

In the meantime, theoretical work aimed at more realistic calculations of the dynamics of heavy ion collisions should continue†.

Questions to which one hopes to have more detailed answers include:

*A week-long Workshop on the Physics of Relativistic Heavy Ions was held in May 1982 in Bielefeld, West Germany. The reader should refer to the Proceedings for reviews and references.

†The finally observed multi-hadron state only comes into being at large distances from the target.

*There are recent speculations by J. D. Bjorken (unpublished), based on Landau's hydrodynamic model, that a plasma in thermal equilibrium could be formed in the central region.

†The intriguing results observed in emulsions at the Bevalac [E. M. Friedlander, Phys. Rev. Letts. 45, 1084 (1980); P. L. Jain et al., ibib. 48, 305 (1982); Physics Today 35, No.4, pp.17-19 (1982)] should also be followed up on both the theoretical and experimental fronts before a massive commitment to heavy ion colliders is undertaken.

i) What is the nature of the QCD phase diagram? In particular, how is what is known about the pure gauge theory (equivalent to infinitely heavy quarks) related to the situation of interest, where the quark mass is at most as heavy as the characteristic QCD scale?

ii) How does the plasma-formation probability in various regions of longitudinal phase space depend on the c.o.m. energy of the nucleon pairs, and on the atomic numbers of the colliding nuclei;

iii) Are there signature which are insensitive to the existence of thermal and/or chemical equilibrium and how are they to be extracted from the enormously complex final states that are certain to be produced.