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HEAVY IONS AT STEAMBOAT: SUMMARY OF PARALLEL SESSIONS

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HEAVY IONS AT STEAMBOAT: SUMMARY OF PARALLEL SESSIONS

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Earlier in this meeting we were reminded by John Kogut of the dictum, attributed to Sigmund Freud, that to understand the ordinary it is often useful to study the extremes.

It is certainly true that the interest in heavy ions at the intersection between particle and nuclear physics is motivated by the opportunity for an entirely new approach to the understanding of fundamental interactions by studying extreme states of nuclear matter. At this conference we have seen important new results on some of the central issues:

- How well can we predict the landscape of the extremes--that is, the phase structure of QCD and nuclear matter?
- Can we explore it with heavy ion collisions?
- Can we recognize the appearance of new terrain?

Our present understanding of the behavior of nuclear matter under extreme conditions is illustrated in Fig. 1 (G. Baym, Ref. 1). Here temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point ρ_{nm} at zero temperature, and this is the neighborhood explored by low energy nuclear physics. Along the density axis one finds a liquid/gas phase and, at high densities, a possible pion-condensed phase. The shaded band shows the regions of temperature and density at which QCD predicts a phase transition of nuclear matter from a system of nucleons to a deconfined plasma of quarks and gluons. The critical parameters for such a transition have been calculated from bag models.² Of more interest recently has been the success of lattice gauge simulations in which the critical behavior and limiting phases are derived from a fundamental description of finite temperature QCD.

Fig. 2 shows the result of a lattice gauge calculation³ indicating two coupled first-order phase transitions. At zero temperature quarks are confined in hadrons ($W = 0$ corresponds to infinite self-energy for a free quark) and chiral symmetry is spontaneously broken (a non-zero quark-antiquark mass term, $\langle\bar{\psi}\psi\rangle$, in the QCD Lagrangian). At a critical temperature $T_c \approx 200$ MeV both quantities undergo a discontinuous transition corresponding to the deconfinement of quarks and gluons and the restoration of chiral symmetry. Calculations of this sort, including that shown in Fig. 2, have been incomplete in that the effects of vacuum polarization (i.e., the "sea quarks") are ignored. Theorists have questioned the relevance of these so-called "quenched approximation" calculations to QCD, and it has been a widely held view that the sharp phase transition seen in Fig. 2 would be washed out in a more realistic calculation.

New results⁴ shown by John Kogut at this conference indicate that this may not be the case after all. This work, in which light dynamical fermions are included in the computer simulation through a microcanonical ensemble, finds no qualitative difference in the phase structure from that of earlier calculations. One still finds a sharp transition, with deconfinement and chiral symmetry restoration above a critical temperature whose value is similar to that obtained in the quenched approximations. This work is something of a computational tour de force (≈ 300 Cray hours), and the authors stress that some of the results from the simulation are not yet theoretically understood. Nonetheless, this is an important advance and should be a watershed for much work to follow.

The question of how the thermodynamic conditions for such a phase transition can be achieved in ultra-relativistic collisions of nuclear beams has been the topic of several presentations at this meeting. These have included elegant and ambitious designs for new accelerator facilities dedicated to this physics.⁵ The crucial question of nuclear stopping power, which governs the energy deposition in such collisions is taken up in detail by Alfred Goldhaber.⁶

From a new generation of cosmic ray experiments, we are getting a glimpse of the extraordinary final states which are the signature of high energy density in very energetic collisions of heavy nuclei. New results from the Japanese American Collaborative Emulsion Experiment (JACEE)⁷ were presented here by Y. Takahashi. This experiment flies emulsion stacks in balloons above the atmosphere. Here incident "beams" of nuclei with energies ranging up to hundreds of TeV and masses extending roughly up to iron are available for study. The detector, consisting of many layers of plastic and emulsion interleaved with plates of dense metallic absorber, measures the charge of the incident projectile nucleus and provides a nearly complete measurement of charged and neutral secondaries. The experiment has recorded ≈ 150 events in which the total incident energy exceeds 10 TeV. The projectile nuclei are typically Si, A, Ca, Fe. Of these events, seven have > 500 charged secondaries, and two have charged particle multiplicity greater than 1000. All of the high multiplicity events have calculated energy density (determined from the angular density of produced particles near 90° in the cm) in excess of 2 GeV/fm^3 : well into the range for which the deconfined plasma phase is predicted. Since the experiment makes no selection on impact parameter, it is reasonable to conclude that the high multiplicity events correspond to head-on collisions of small impact parameter, and that among such events, given the observed yield of high multiplicity final states, events of high energy density are fairly typical.

If these high energy densities can ultimately be realized in laboratory experiments, can we recognize new phenomena in the data thus obtained? Can we, for instance, establish the existence of a phase transition? Some of the results presented here are illuminating in this regard.

An experiment performed recently⁸ with internal gas jet targets in the Fermilab proton accelerator has reported evidence for the

liquid-gas phase transition indicated at low densities in Fig. 1. In a talk given here,⁹ David Boal discussed the theoretical expectations. The phase transition is expected to occur with a critical temperature in the range 16-20 MeV, at a density of about one-half that of normal nuclear matter. These conditions should be accessible in p-nucleus collisions, and an expected signature is a yield of fragment masses (A_F) proportional to

$$A_F^{-t}$$

where the exponent, t , should lie in the range 2 - 3.

The experimental data, shown in Fig. 3, have just this behavior. The measured value for the exponent is 2.6 ± 2 . This would appear to be a compelling indication for the existence of the predicted phase transition. However a phase transition is not required by the data, and the calculated curve shown in Fig. 3 includes no phase transition. One does not have an iron-clad case. This illustrates the difficulty of inferring thermodynamic properties of a complex configuration of nuclear interactions from single-particle inclusive measurements. One needs to constrain more completely the properties of individual events which go into such a distribution, and this in general implies multiparticle correlation measurements.

In a similar vein, both Tanaka¹⁰ and Zajc¹¹ have described results from very high energy collisions of alpha particle beams at the ISR in which apparent nuclear enhancements in the amount of energy carried by particles emitted near 90° in the c.m. can be well described by a model in which proton-proton spectra are convoluted to simulate multiple collisions in the alpha-alpha case.

The power of detailed specification of multiparticle final states is appreciated in two recent Bevalac experiments,^{12,13} where the properties of hydrodynamic flow and the compression of nuclear matter are observed in samples of events for which a large fraction of the final-state four-momentum space are determined from the directions and energies of final-state particles as indicated in Fig. 4. In collisions of heavy nuclear beams at 400 MeV/amu (the heaviest studied to date are Nb beams on a Nb target) an ellipsoidal shape is found with an axis which is not in general aligned along the beam direction. This corresponds to a fluid-like behavior of the interacting nuclear matter which cannot be the result of a simple cascade mechanism. Comparing the observed particle production with a simple model, the authors estimate that typically 10% of the kinetic energy of collision goes into compression of nuclear matter. In an analysis which is conceptually similar, though technically very different, the GSI-LBL streamer chamber group is able to extract an equation of state relating the compressional energy to the nuclear matter density during the collision.¹³ The results of this analysis are shown in Fig. 5.

The analysis of interference effects in two-particle correlations among identical particles continues to be refined as a tool for studying extent in space and time of the particle-emitting source in nuclear collisions. At the Bevalac, systematic studies

are under way^{14, 15} to carry out these measurements with very massive beams and targets, while at the ISR such measurements have been carried out for light ions at very high energies.^{11, 16}

While each of these results is an advance in its own right, the overall picture presented here is equally important for the prospects of future experiments with very high energy beams of heavy ions. It seems that one can very selectively delineate the thermodynamic environment in specific event samples, and even in single events. By such selection experiments can focus on events--possibly representing a very tiny fraction of the total cross section--in which the conditions are most favorable for the formation of new types of matter at high temperatures and densities. In these events, then, one can look for the more direct signals carried by photons, lepton pairs, jets, etc. As these direct signals were not extensively discussed at this conference, the reader is referred to the proceedings of the recent Quark Matter '83 Conference, and the Workshop on Detectors for Relativistic Nuclear Collisions, held at LBL in March, 1984, for which proceedings will be available soon.

REFERENCES

1. G. Baym, Proc. Third Int. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (T. Ludlam and H.D. Wegner, Eds.), Nucl. Phys. A418, 433 (1984).
2. See, for example, H. Satz, Phys. Rev. 88, 349 (1982).
3. J. Kogut et al., Phys. Rev. Lett. 50, 393 (1983).
4. J. Polonyi, H. Wyld, J. Kogut, J. Shigemitsu, D. Sinclair, "Finite Temperature Phase Transitions in SU(3) Lattice Gauge Theory with Dynamical Light Fermions," these proceedings.
5. Presentations by G. Young, L. Schroeder and N.P. Samios at this conference.
6. A.S. Goldhaber, "In Search of the Quark-Gluon Plasma," and "Nuclear Stopping Power," talks presented at this conference.
7. Y. Takahashi, presentations at this meeting; see also W.V. Jones, Ref. 1, P. 39.
8. A.S. Hirsch, "Fragment Production and the Liquid-Gas Phase Transition," Talk presented at this conference. See also A.S. Hirsch et al., Ref. 1, p. 267.
9. D. Boal, "Low energy phase transitions in Nuclear Matter," Talk presented at this conference.
10. M. Tanaka, "Study of the Neutral Energy Spectrum in the Central Region of $\alpha\alpha$ Interactions at $\sqrt{s} = 12.4$ GeV at the CERN ISR," Talk presented at this conference.
11. W. Zajc, "Particle Production in $\alpha\alpha$ Collisions at the CERN ISR," Talk presented at this conference.
12. H.G. Ritter, "Collective Flow and High Density Nuclear Matter," talk presented at this conference; see also H.A. Gustafsson et al., Phys. Rev. Lett. 52, 1590 (1984).
13. A. Sandoval, "Nuclear Matter Equation of State," talk presented at this conference; see also J.W. Harris and R. Stock, LBL-17054 (1984).

14. S.Y. Fung, "Source Size Measurements in High Energy Nucleus-Nucleus Collisions and First Results on Uranium in Streamer Chamber at Vevalac," talk presented at this conference.
15. K. Crowe, " $\pi\pi$ Correlation Measurements in Fe + Fe Collisions," talk presented at this conference.
16. T. Åkesson et al., Phys. Lett. 129B, 269 (1983).

FIGURE CAPTIONS

- Fig. 1. Phase diagram of nuclear matter (Ref. 1).
- Fig. 2. Predicted phase changes for SU(3) gauge theory on 4×8^3 lattice, in the quenched approximation (Ref. 3).
- Fig. 3. Fragment mass yields for proton-Krypton collisions (Ref. 9).
- Fig. 4. Illustrating the momentum-flow analysis of Ref. 12. The event shape is obtained by calculating a sphericity tensor.
- Fig. 5. Compressional energy, W , vs. nuclear density (Ref. 13). The result is obtained by comparing the configuration of final-state pions, observed in a streamer chamber, with model calculations.

Fig. 1

Fig. 2

XBL 838-3127

Fig. 3

Fig. 4

XCG 8312-4936A

Fig. 5

Fig. 6