THEORETICAL INTERPRETATION OF HIGH-ENERGY NUCLEAR COLLISIONS

Progress Report

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Abstract

Nuclear collisions are interpreted theoretically. The nuclear equation of state is studied in a wide energy range. Subnucleonic degrees of freedom are invoked at high energy densities and at short length-scales. Questions of dynamical collision simulations are investigated. Direct support is provided for experiment in the form of collaborative projects. The major objective of this nuclear theory program is a better understanding of the properties of strongly interacting matter on the nuclear energy scale, as manifested in high-energy heavy-ion collisions.

This progress report is a brief summary of the research results and progress in the time period July 1, 1991 - June 30, 1992. Furthermore, in the second part of the report, I will outline some research topics of new and continuing interest to review ongoing and proposed projects for the next budget period.

The results of the research activities of the principal investigator and his postdoctoral associate during the time period indicated have been partly published. Four further papers are accepted for publication. Several contributions to the proceedings of scientific meetings are also in press, in connection with the corresponding presentations at these meetings. Other manuscripts have just been submitted for publication.

1 Results

The quark-gluon substructure of nuclear matter and nuclei is emerging as a central question of nuclear physics. This substructure can hopefully be revealed in the laboratory by studying energetic nuclear collisions. Accordingly, the principal investigator continues to be active in both (i) the theoretical modeling of subnucleonic degrees of freedom, and (ii) the phenomenology of nuclear collisions. Reaction mechanisms, dynamical simulations and fragmentation need to be better understood at all energies to have a chance of success in identifying interesting phenomena. Advances in the field are produced by the interaction between experiment and theory. Providing direct support for experiment therefore remains a high priority of this program.

In the following, I list publications in the reporting period in the categories of journal articles, contributions, and abstracts. Next, I briefly comment on those areas where, in my judgement, important new developments have occurred since the submission of my previous progress report (July 1991).

Refereed Journals:

1. 'Pion Yields and Pion Spectra from Nuclear Collisions,' A.F. Barghouty, G. Fai, and D. Keane, Nucl. Phys. A535, 715 (1991).
2. 'High-Order Collective Flow Correlations in Heavy-Ion Collisions,' J. Jiang, D. Beavis, S.V. Chu, G. Fai, S.Y. Fung, Y.Z. Yiang, D. Keane, Q.J. Liu, Y.M. Liu, Y. Shao, M. Vient, and S. Wang, Phys. Rev. Lett. 68, 2739 (1992).
3. 'Nuclear Equation of State with Momentum-Dependent Interactions,' L.P. Csernai, G. Fai, C. Gale, and E. Osnes, Phys. Rev. C in press, preprint KSUCNR-008-91 (December 1991).
4. 'Measuring the QCD Transition Temperature with Dileptons in Ultra-Relativistic Nuclear Collisions,' D. Seibert, V.K. Mishra, and G. Fai, Phys. Rev. C in press, preprint KSUCNR-002-92 (February 1992).
5. 'Momentum-Dependent Interactions and the Nuclear Equation of State,' V.K. Mishra and G. Fai, Revista Mexicana de Fisica, in press, preprint KSUCNR-018-91 (December 1991).
6. 'Nonlocal Field-Theory Model for Nuclear Matter,' V.K. Mishra, G. Fai, P.C. Tandy, and M.R. Frank, Phys. Rev. C accepted, preprint KSUCNR-006-92 (March 1992).
7. 'How to Measure the QCD Transition Temperature,' D. Seibert, Phys. Rev. Lett. 68 1476 (1992).
8. 'Robustness of Covariance Matrix Techniques,' D. Seibert, submitted for publication, preprint KSUCNR-014-91 (November 1991).
9. 'High-Energy Photons as a Thermometer for Ultra-Relativistic Nuclear Collisions,' D. Seibert, submitted for publication, preprint KSUCNR-004-92 (February 1992).

10. 'Measuring Velocity Ratios with Correlation Functions,' submitted for publication, D. Seibert, K. Haglin and C. Gale, preprint KSUCNR-005-92 (March 1992).

Published Contributions:

11. 'Hadron-Quark Phase Transition with a Momentum-Dependent Yukawa Interaction for Hadrons,' L.P. Csernai, G. Fai, C. Gale, Gy. Kluge, V.K. Mishra, and E. Osnes, **Proceedings of the Workshop on Relativistic Heavy Ion Physics at Present and Future Accelerators**, Budapest, Hungary, June 1991 (CRIP, 1991; T. Csörgö, S. Hegyi, B. Lukács, and J. Zimányi, eds.), p. 124.
12. 'Studying Ultra-Relativistic Nuclear Collisions with Dileptons and Photons,' D. Seibert, **Proceedings of the 8th Winter Workshop on Nuclear Dynamics**, Jackson Hole, Wyoming, January 1992 (World Scientific, 1992; W. Bauer and B. Back, eds.), in press, preprint KSUCNR-003-92 (February 1992).
13. 'Rapidity Correlations in Ultra-Relativistic Nuclear Collisions,' D. Seibert, **Proceedings of Quark Matter '91**, Gatlinburg, Tennessee, November 1991 (Nucl. Phys. A; T.C. Awes, F.E. Obenshain, F. Plasil, M.R. Strayer and C.Y. Wong, eds.), in press, preprint KSUCNR-012-91 (November 1991).

Abstracts:

14. 'A Thermometer for the QCD Transition Temperature,' D. Seibert, V.K. Mishra, and G. Fai, **Proceedings of the 1992 International Nuclear Physics Conference**, July 26 - August 1, 1992, Wiesbaden, Germany
15. 'Lagrangian Model of the Pauli Potential,' J.J. Neumann and G. Fai, **Bull. Am. Phys. Soc.** 37, 931 (1992).
16. 'Relativistic Hartree Approximation in QHD with Sideways Form Factors,' V.K. Mishra, P.C. Tandy, and G. Fai, **Bull. Am. Phys. Soc.** 37, 1040 (1992).

The first item of the above list represents work carried out in the previous budget period and is discussed in my July '91 progress report. It is included here with the full bibliographic information for completeness.

Interpretation of data at BEVALAC energies

The observation of nuclear matter flow (the collective sideways deflection of the reaction products) is frequently hailed as the most important result of the experimental program at the BEVALAC. Nevertheless, previous studies of this effect have not ruled out the possibility that the flow effect is dominated by a small number of correlated fragments in each event, as opposed to being a collective motion to which most or all fragments contribute. In a recent Phys. Rev. Letter (item 2), we use 4π data from the BEVALAC streamer chamber to study azimuthal correlations for fragment pairs and higher-order multiplets. Based on a simulation we infer that more than 70% of the forward-going fragments from collisions of Ar on Pb at 0.4 GeV/nucleon carry a component of the collective motion. The simulation we utilize is the *FREESCO* code developed earlier by the principal investigator and J. Randrup of the Lawrence Berkeley Laboratory. The work reported on in item 2 was carried out in collaboration with experimentalists, in particular with D. Keane, the other DoE funded faculty member at KSU. The crew included several graduate students, among them Y. Shao, who is coadvised by D. Keane and the principal investigator.

The flow of nuclear matter is intimately related to its equation of state (EOS). The incompressibility of nuclear matter is frequently taken to be the most important indicator of the static properties of nuclear matter. This EOS information is extracted from BEVALAC and other collision data via dynamical simulations using effective interactions as input. There is a qualitative change in the results when a momentum dependence is allowed in the effective interaction. With an eye on interpreting BEVALAC data, we have studied the equilibrium properties of momentum-dependent interactions. Progress in this area will be described next.

Momentum-dependent interactions

Momentum-dependent mean fields play an increasing role in the description of nuclear collisions at BEVALAC energies. The momentum dependence has important implications on the EOS. In addition, in a momentum-dependent mean field, the momentum distribution of nucleons at finite temperature is more complicated than a simple Maxwellian. This may change production cross sections of recent interest. We have studied (items 3, 5 and 11) the equilibrium properties of nuclear matter with a momentum-dependent effective interaction, referred

to as MDYI, in the Boltzmann approximation. We have shown that the zero-temperature optical potential obtained from the MDYI describes data satisfactorily up to energies on the GeV/nucleon scale. We have demonstrated that the momentum dependence can effectively stiffen nuclear matter while the usual incompressibility parameter remains relatively low. The conditions for equilibrium with a quark phase described by a bag-model equation of state have been investigated. We found that the momentum dependence of the hadronic mean field acts to decrease the temperature of the phase transition at a given (nonzero) baryon density.

Semiclassical dynamical simulations of nuclear collisions frequently incorporate another momentum-dependent interaction, the so-called Pauli potential. These calculations proceed through an essentially classical description, where the only quantum-mechanical effect taken into account is the identity of the nucleons. The exclusion principle is simulated by the Pauli potential, designed to keep the nucleons apart in classical phase space. With a new graduate student, Mr. J.J. Neumann, we started to look into questions related to the Pauli potential (item 15). It is important to realize that with velocity/momentum-dependent potentials the simple relation between canonical momenta and velocities is no longer valid: e.g. nucleons in a ground-state nucleus have finite momenta, but zero velocities. This leads to problems with thermodynamical quantities that are related to the kinematic (not the canonical) momenta. One hopes to cure these difficulties by treating the Pauli potential in the Lagrangian formalism. This is the approach taken in our work with Mr. Neumann. We have studied the two-body problem and demonstrated that the Fermi gas can be simulated this way; next we will move on to nuclear matter, always carefully distinguishing between canonical and kinematical quantities.

Quark-gluon plasma

A major development of this research program at Kent State University is the new focus on quark-gluon plasma (QGP) issues. Items 4, 7, 8, 9, 10, 12, 13 and 14 belong in this category. As expected and outlined in my July 1991 progress report, my new postdoctoral associate, Dr. D. Seibert is playing a key role in this initiative. Some of the above items represent independent work by Dr. Seibert, others reflect our collaboration, which started in a very promising manner and is producing its first results.

Items 7, 4, 9, 12, 13 and 14 can be considered as part of a systematic program to address the diagnostics of the QGP. The initial (and schematic) discussion was given in a Phys. Rev. Letter by Dr. Seibert (item 7), where he showed that the transverse mass distribution of lepton pairs from rho mesons is highly sensitive to the QCD transition temperature. This was followed up by including photons as diagnostic tools (items 9 and 12) and by considering more realistic collision scenarios and different assumptions about the QGP transition (items 4 and 14). Assuming that a transition takes place in the 150–200 MeV temperature range and neglecting transverse expansion, we show that the transverse energy distribution of lepton pairs under the rho peak provides a good ‘thermometer’ for the transition temperature. Photons can also be used in certain scenarios. Neglecting transverse expansion and assuming thermal and chemical equilibrium throughout the collision are the most restrictive approximations in our work carried out to date. We plan to relax these as future steps of our program.

In addition, Dr. Seibert continues to collaborate with several researchers; the results of one such collaboration are reported in item 10, which proposes a new technique for measuring the ratio of the source transverse velocity to the particle emission velocity, using split-bin correlation functions. This new technique can be used in the absence of particle identification, unlike previous techniques.

Modeling of subnucleonic degrees of freedom

Items 6 and 16 represent steps in our ongoing effort with Dr. P. Tandy, the other (NSF supported) nuclear theorist at KSU, in the theoretical modeling of nuclear matter, paying due attention to the underlying degrees of freedom. Although not immediately practically useful, these calculations are expected to be relevant to the experimental situation (in particular as encountered at CEBAF) at a later stage of their development.

We investigate nuclear matter using a relativistic Hartree approximation to a nonlocal sigma-omega model containing short distance vertex form factors to simulate the underlying QCD substructure. At the Hartree level only the nucleon momentum dependence of the distributed vertices enters, and the resulting finite nonlocal field theory model is solved with simple gaussian forms for the so-called sideways form factors. To reproduce saturated nuclear

matter the nonlocal model selects form factor ranges at the nucleon mass scale. The model produces a reduced incompressibility and an increased effective mass compared to standard point-coupling quantum hadrodynamics (Walecka model). The values obtained here are much easier to reconcile with experimental information.

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