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THEORETICAL INTERPRETATION OF HIGH-ENERGY NUCLEAR COLLISIONS

Progress Report

for period January 1, 1988 - July 31, 1990

George Fai
Kent State University

August 1990

Prepared for the U.S. Department of Energy

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In the following, I briefly summarize the research results and progress under this project in the time period January 1, 1988 – July 31, 1990. Published and unpublished research in this time period focused on aspects of nuclear disassembly, nuclear dynamics, and subnucleonic degrees of freedom in model field theories.

To put the progress report in perspective, I wish to emphasize that the goal for heavy ion research, at least to my mind, is a microscopic, dynamical understanding of nuclear collisions. However, a reasonably complete dynamical theory is, despite much recent progress, still in the future. This is no surprise in view of the complexity of the system. It is precisely this complexity that makes statistical approaches useful. Even with well-developed dynamical models, a statistical calculation can be utilized to describe the final stages of a collision. Statistical concepts continue to be important in idealized situations, like infinite nuclear matter under extreme conditions. For example, the concept of the nuclear equation of state acquires its full meaning in such situations. The division of models into dynamical and statistical is, in fact, fairly arbitrary, and will be adopted here only for historical reasons.

In my own research, following the pioneers of the field,[1, 2, 3, 4] I have spent a large effort in the area of statistical models (e.g.[5, 6, 7, 8, 9, 10]). As detailed below, I continue to be interested in fundamental aspects and applications of statistical ideas to nuclear collisions. In addition, I started to investigate more dynamical questions. Furthermore, as a new element of my research program, I began inquiries at the level of subnucleonic degrees of freedom, the next level of our understanding.

1 Nuclear Disassembly Theory

Recently, I undertook a review of nuclear disassembly theory, to discuss the progress made in the last couple of years.[11] The latest developments include the use of molecular dynamics models to study fragmentation processes,[12] and attempts to incorporate fragmentation in one-body dynamical models.[13] In the statistical sector, the transition-state treatment of fission has been generalized to the case of multifragmentation.[14] In addition to reviewing some of these developments, I outline a classification of models based on the Liouville equation, and consider the coupling of dynamical and statistical aspects of nuclear disassembly.[15] The

review can be looked upon as a tool for orientation in this rapidly developing field.

A recurring issue in statistical descriptions of nuclear disassembly is whether the partition function of the dilute but hot source can indeed be factorized into contributions from individual prefragments. This can be achieved if the system is assumed to consist only of distinguishable, noninteracting clusters. (An excited cluster, or *prefragment* can be regarded as a metastable generalization of the concept of an ordinary atomic nucleus). In a somewhat limited context, the question was therefore traditionally referred to as 'including interactions in statistical models.' One obvious departure from the simple noninteracting situation is provided by the presence of the vapor of free nucleons, in which the prefragments are embedded. It has in fact been shown, that a consistent treatment of the prefragments can only be achieved if a nucleon vapor is included in the calculation.[16, 17] I addressed this aspect of the question in the framework of a long-term collaboration with Jørgen Randrup of the Lawrence Berkeley Laboratory.[18] We propose a specific factorization of the total partition function to delineate the prefragments relative to the nucleon vapor. The total partition function of the entire system is of course invariant to this prescription, but fragment yields turn out to be sensitive to it. Our prescription leads to a mass-dependent generalization of the concept of the limiting nuclear temperature.[19] Other aspects of the question of the separation of the partition function remain of interest.

After the completion of my review, a fresh look at the general question of fragmentation was published by A. Mekjian.[20] In a Comment submitted to Physical Review Letters, I address certain aspects of Mekjian's model with A.J. Cole.[21] We elaborate on Mekjian's ideas with the specific application to nuclear disassembly in mind. In particular, we show that proper inclusion of the mass conservation constraint in the formalism destroys the simple hyperbolic behavior of the fragment yields as a function of mass number. We apply a suitably generalized version of the model to projectile fragmentation data. Our work shows that it is possible to go further than the original model in the interpretation of nuclear disassembly data, albeit at some loss of the initial simplicity.

2 Phenomenology of Nuclear Collisions

Parallel to more fundamental questions, the principal investigator's research includes a substantial amount of work directly related to data obtained in high-energy nuclear collisions. A healthy interaction with the data and with experimentalists at Kent and elsewhere is viewed as very beneficial to the program. For example, this commitment led to the Comment mentioned above.[21] This kind of research can be best characterized as nuclear phenomenology.

I addressed the question of the entropy extracted from fragment yields at around 100 MeV/nucleon beam energy with L.P. Csernai and G.D. Westfall.[22] This work can be considered an extension of a calculation carried out earlier at higher energies.[8] The lower energy range is of special interest at several laboratories, e.g. at the National Superconducting Cyclotron Laboratory of Michigan State University (MSU). In fact, the experimentalist in the collaboration, G.D. Westfall, provided us with detailed, good quality data obtained at MSU on light-particle and complex-fragment yields from Ar+Ca at three different beam energies. A possible interpretation of the data assigns a somewhat higher value of the entropy/nucleon to the lightest particles than to complex fragments. This can be a consequence of the presence of two midrapidity sources of different character in the collision. We suggest further experimental tests which may help in identifying the nature of these sources.

In another project focused on fragment yields,[23] we examine (with A.R. DeAngelis and A.Z. Mekjian) the role of the Coulomb interaction in shaping the yield ratios. We find that the yields are strongly temperature dependent, and that conservation of baryon number and charge, as well as the intrinsic excitation energy of fragments are the key ingredients determining this dependence. We do not find it necessary to include the Coulomb energy in order to produce a minimum in the yields. This is particularly interesting in the light of repeated claims[24, 25] that the Coulomb energy is solely responsible for the minimum. At the same time, we demonstrate that the total energy of the system is a delicate balance of large contributions of opposite signs, where each term is playing an important role.

Emulsion data were used for nuclear phenomenology in investigations of high-multiplicity ^{16}O induced reactions.[26] I am pleased with my participation in this largely experimental effort. The work includes a careful reconstruction and analysis of the complete events by the

experimentalists in the collaboration. Several models are then applied to these data with the parameters adjusted to give the best possible agreement. This procedure reveals a transition from fusion-like events at the lowest energies (≈ 20 MeV/nucleon) to events which more or less conform to the participant-spectator expectations at energies above ≈ 50 MeV/nucleon. Since several models are compared, this project can be viewed as a continuation of my efforts[10] to study the relationship between different models.

3 Dynamics of Nuclear Collisions

While statistical calculations, in addition to equation-of-state studies, can be used mainly to establish a reference background, dynamical models of nuclear collisions are expected to give a full picture of the time evolution of these collisions.

In the area of macroscopic dynamics, connected to microscopic degrees of freedom as well as to the equation of state, we examine with Y. Shao and D. Keane the spectator downshift observed in a wide range of experiments. Initial results of this project, which will be part of Mr. Shao's Ph. D. dissertation, will be reported at the Fall Meeting of the Division of Nuclear Physics of the American Physical Society. Since the printed version is not available at the time of this writing, the abstract submitted is reproduced below:

Spectator Recoil and the Nuclear Matter Equation of State.
Y. SHAO, G. FAI, AND D. KEANE, Kent State University—Attempts to extract the equation of state of nuclear matter from nuclear collision data typically rely on complicated measurements and sophisticated models.¹ In contrast, we investigate the sensitivity of a simple particle-inclusive observable, the momentum downshift of spectator fragments, to the equation of state in the framework of a geometrical model. For simplicity, we assume the momentum-independent parametrization of the nuclear mean field.² We study the propagation of the equation-of-state information from the participant region to the spectators via the nuclear mean field. The spectator downshift is connected to the *bounce-off* phenomenon.³ The model can be extended to accommodate more complicated (momentum-dependent) potentials. Results will be compared to available data.

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¹H. Stöcker and W. Greiner, Phys. Rep. 137, 77 (1986).

²G. F. Bertsch and S. Das Gupta, Phys. Rep. 160, 189 (1988).

³H. Å. Gustafsson *et al.*, Phys. Rev. Lett. 52, 1590 (1984).

Considerable progress has been made recently in microscopic dynamics.[27, 28, 29, 30, 13, 12] Numerical calculations based on the Boltzmann-equation are required to pay more and more attention to the collision integral, with the in-medium cross sections as a crucial ingredient.[31, 32] Recently, I participated in two studies relevant to this problem.

The mean free path of protons was calculated in cold nuclear matter and in finite nuclei using a version of the Skyrme two-body interaction.[33] The calculation was carried out via the Green's function approach, based on the equivalence of the single-particle optical potential to the self-energy of the Green's function. In this approximation, the calculation is essentially analytical at zero temperature. We establish the connection to finite nuclei with the help of the local density approximation. Reasonable agreement is obtained with available data. The resulting long mean-free path (on the order of 5 fm for a proton of 50 – 150 MeV energy) means strongly reduced in-medium cross sections for a ≈ 100 MeV nucleon in subsaturation nuclear matter at low temperature.

First results of the other study relevant to the question of in-medium effects in Boltzmann-equation based simulations will be reported at the Fall Meeting of the Division of Nuclear Physics of the American Physical Society. The abstract is reproduced below:

Experimental Constraints on In-Medium Effects in VUU.*

J. JIANG, J. COGAR, G. FAI, AND D. KEANE, Kent State U.;
C. HARTNACK and H. STÖCKER, U. of Frankfurt—The interpretation of many heavy-ion experiments, and particularly the inference of properties of the nuclear equation of state, relies heavily on comparisons with nuclear transport theories such as the Vlasov-Uehling-Uhlenbeck (VUU) model.¹ Such models are based on assumptions about the modification of free nucleon-nucleon scattering cross sections in the nuclear medium. These assumptions have been tested through comparisons of VUU predictions with inclusive fragment momentum spectra for collisions of C, Ne, Ar and La projectiles at bombarding energies between 0.4 and 2.1 GeV/nucleon.² Good agreement is found within experimental uncertainties, although these uncertainties are generally too large to adequately constrain the models. *Supported by US DOE Grants DE-FG02-86ER40251 and DE-FG02-89ER40531 and by NSF Grant INT-8813351

¹H. Kruse, B.V. Jacak and H. Stöcker, Phys. Rev. Lett. 54, 289 (1985).

²S. Nagamiya *et al.*, Phys. Rev. C24, 971 (1981); D. Keane *et al.*, Phys. Rev. C37, 1447 (1988); S. Hayashi *et al.*, Phys. Rev. C38, 1229 (1988).

Another topic of interest is pion production, where we investigate the question whether dynamical effects are needed over and above the statistical background to understand the data. Most of the numerical work associated with this project is carried out by my former graduate student, A.F. Barghouty, who is a young assistant professor at Roanoke College. The first account of this work will be given at the Fall Meeting of the Division of Nuclear Physics of the American Physical Society. The abstract is reproduced below:

Dynamical Effects on Pions in Energetic Nuclear Collisions.*

A. F. BARGHOUTY, Roanoke College; G. FAI and D. KEANE, Kent State University—The continuing experimental interest in the properties of pions produced in high-energy nuclear collisions¹ motivated us to revisit model predictions for pion spectra, total yields and pion-charged particle multiplicity correlations. A statistical background calculation carried out with the FREESCO event generator² indicates that it is necessary to take account of dynamical effects if the experimental data are to be reproduced. The presence of nuclear matter flow is well-known from the analysis of nucleons and heavier fragments.³ Incorporating the $\Delta(1231 \text{ MeV})$ resonance gives reasonable agreement with the experimental pion yields as a function of the beam energy for different symmetric systems. We discuss the necessity of further dynamical effects in the model calculation to obtain an approximate reproduction of the pion spectra.
*Supported by US DOE Grants DE-FG02-86ER40251 and DE-FG02-89ER40531 and by NSF Grant INT-8813351

¹S. I. Chase *et al.*, Proc. Workshop on Nuclear Dynamics VI, Feb. 1990, Jackson Hole, Wyoming, ed. J. Randrup, LBL-28709, 67 (1990).

²G. Fai and J. Randrup, Comp. Phys. Comm. **42**, 385 (1986).

³H. Å. Gustafsson *et al.*, Phys. Rev. Lett. **52**, 1590 (1984).

4 Subnucleonic Degrees of Freedom

My KSU-supported research leave in the 1987/88 Academic Year provided an opportunity to begin the extension of my research program to the area of nonlinear phenomena in model field theories. With R.J. Perry and L. Wilets we studied a nontopological soliton model, the chromo-dielectric model of confinement.[34] The Lagrangian contains, in addition to the quark and gluon fields, a scalar field which provides confinement through a chromo-dielectric function. To achieve chiral invariance, the direct quark-scalar coupling is put equal to zero. The static chromo-electric gluon propagator is calculated in medium in the one-

loop approximation with a regularization for fixed quarks. Effective quark-scalar coupling emerges through the self-energy of quarks in the dielectric medium, bringing about absolute confinement in the model.

The confinement properties of the chromo-dielectric model are intimately related to the appearance of a Goldstone pion generated by chiral symmetry breaking. It is therefore of interest to apply recent developments[35, 36] in the techniques of bosonization of quark fields to the chromo-dielectric model to analyze the effective $\bar{q}q$ fluctuations with particular emphasis on the pion mode. We carried out such an analysis with P. Tandy, the other theorist at KSU and a very talented graduate student, Mr. M. Frank, and reported on our work at two meetings.[37, 38]

Usually, soliton models (including the chromo-dielectric model) postulate elementary boson fields that are used to hold the quarks together as a bound state. This does not satisfactorily describe the way a nucleon will emit or absorb bosons in order to interact with other nucleons in the nucleus. Partly with this motivation, we explore another nontopological soliton model, referred to as the global color symmetry model.[36] Here, fields with meson quantum numbers are internally generated from fluctuations above the vacuum configuration of the dynamical quark self-energy. In our study, we pay particular attention to the composite nature of the obtained meson degrees of freedom and to the resulting nonlocal vertex for coupling to quarks. Only scalar-isoscalar and pseudoscalar-isovector meson fields are retained at present. We use functional methods and bilocal field techniques and work to lowest order in loops for the retained degrees of freedom. We identify a static soliton solution from the effective action through a Legendre transformation with a chemical potential constraint that fixes the number of valence quarks and thereby induces a classical value for the mesonic fluctuation fields. The traditional dependence of the fermion sector of the action upon the chemical potential is extended to deal with the nonlocal coupling present here.

The first detailed account of this work has just been submitted for publication.[39] However, the project is far from being completed. This subject continues to be an important part of the principal investigator's current and proposed research. It is expected that our new postdoc, V. Mishra, will fully focus his efforts in this exciting area of research.

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