HEAVY-ION COLLISIONS AND THE NUCLEAR EQUATION OF STATE

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Abstract

The overall goal of this project is to study nucleus-nucleus collisions experimentally at intermediate and relativistic energies, with emphasis on measurement and interpretation of correlation effects that provide insight into the nuclear phase diagram and the nuclear equation of state. During the past year, the PI has been on leave at Lawrence Berkeley Lab and has worked on this research project full-time. A large fraction of the effort of the PI and graduate students has gone into preparing for experiments using the Time Projection Chamber at LBL's Bevalac accelerator; in March 1992, this device successfully took data in production mode for the first time, and the first physics analysis is now under way. The PI has carried out simulations that help to define the physics performance and engineering specifications of the recently-approved STAR detector for the Relativistic Heavy Ion Collider, and has identified a new capability of this device with the potential for being an important quark-gluon plasma signature. A Postdoctoral Fellow, jointly supported by this grant and Kent State University, has been recruited to augment these efforts. Since May 1991, 11 journal papers have been published or submitted for publication; 2 conference proceedings and 9 reports or abstracts have also been published during the past year. One paper in Phys. Rev. Lett., one in Phys. Rev. C, and one conference proceedings are based on the thesis project of one of the PI's Ph.D. students who is expected to graduate later this year. Partly in response to the impending closure of the Bevalac, the PI's group has recently joined the NA49 experiment at CERN.

1. Bevalac Streamer Chamber Analysis

Analysis of data from the Bevalac streamer chamber has accounted for about one-third of the research effort of the PI over the past several years. This activity has allowed productivity in terms of publications to be maintained while devoting effort to projects like the EOS TPC and STAR; moreover, the streamer chamber is an excellent testing-ground for at least some of the 4π physics that EOS will open up. At the time of writing, we have just completed the first physics-quality run of the EOS TPC, and so this marks the end of the streamer chamber analysis effort. The two streamer chamber analyses described in last year's report were published during the current reporting period (publications [iii] and [v], section 6.1).

Although it is not proposed to expend any further effort on streamer chamber analysis, work already "in the pipeline" will result in some streamer chamber publications during the coming year. Most notable among these is a very promising new analysis that constitutes part of the dissertation project of Jinghua Jiang, one of the two graduate students supported by this grant. The underlying idea has important implications for our understanding of the equation of state, as demonstrated by the fact that our paper has been accepted by Phys. Rev. Lett. despite being based on previously-reported decade-old streamer chamber data. Our paper points out that no previous study of the sideward flow effect has ruled out the possibility that the effect is dominated by a small number of correlated fragments in each event, as opposed to being a true collective motion to which most or all fragments contribute. We introduce two separate methods of characterizing "collectivity" — the percentage of fragments that carry a component of the collective motion. Collectivity is a new degree of freedom that is independent of the magnitude of the flow correlation (the quantity normally measured in studies of sideward flow). The scope of this initial study using a small sample of streamer chamber events is rather limited, but it opens the way for a wide-ranging systematic investigation of the collectivity of the sideward flow phenomenon using the EOS TPC. The preprint of our paper is included in the Appendix.

2. The EOS Time Projection Chamber

Since June 1990, Kent State graduate student Yiping Shao has been resident continuously at LBL to work on EOS; in June 1991, student Alan Scott also took up residence at LBL to work full-time on EOS. Also in June 1991, the PI's one-year leave at LBL began, with EOS as a major focus of effort.

FIG. 1

2.1 The EOS Pad Monitor

One of the more tangible Kent State contributions to EOS during the past year has been in development of the Pad Monitor software. The original concept and program shell was initiated by LBL's Howard Wieman. Yiping Shao then took over the task of continuing the development of the code and of customizing it to the EOS environment. More than half the current ~9000-line program was written by Yiping Shao, and new features are still being implemented. (A separate offshoot of Howard Wieman's original core program was independently customized to the NA35 environment.)

The Pad Monitor program runs on SUN SPARCstations and functions as a powerful and intuitive tool for examining all formats of TPC data on-line (or can operate on a disk file) with a much shorter time-lag than the normal analysis chain. During running of the experiment, it has served as our primary means for monitoring the performance of the TPC. It also proved very useful during testing of the read-out electronics. All user commands are input using the mouse, and most of the information is presented in one composite display window, as shown in Fig 1. The main pad plane display can operate on the maximum or the mean or the r.m.s. amplitude for all time-buckets collected on that pad; if the selected parameter exceeds a threshold set by the cursor of the "# pads vs amplitude" window, the pad is displayed in red. The "data" pop-up window allows two events from the same source or from different sources to be loaded simultaneously, and the pad display can operate on the amplitude difference between the two events. This feature is useful for testing pedestal subtraction. Other options include projecting all time-buckets onto the pad plane, or selecting a time-slice. Two individual pad signals can be examined in greater detail through the amplitude versus time spectra shown in the upper part of the display. These spectra have mouse-controlled zoom features, and the color-matched message boxes on the lower left of the display provide additional diagnostic information for the selected pads.

2.2 Particle Identification

Another area of responsibility for our group has been software for particle identification. The two upper panels of Fig. 2 show truncated mean dE/dx versus rigidity for fragments from collisions of Ne + NaF and Ca + Ca, and the lower panels separately show the identified protons and deuterons for the Ca + Ca data. We are already close to having an automated procedure for maintaining calibration of the particle identification in the face of drifting gas gain and changes in operating conditions from run to run, and for at least some of the data from our recent run,

FIG. 2: The two upper panels show mean truncated dE/dx versus rigidity for fragments from collisions of Ne + NaF and Ca + Ca; the lower panels show the identified protons and deuterons for the Ca + Ca data.

we have achieved the full dE/dx resolution expected on the basis of scaling the final performance of other TPCs.

2.3 Plans for Experimental Running

The Kent State beam-time proposal, one of three approved by the PAC in 1990, focused on two aspects of the study of the equation of state at lower Bevalac energies: first, the flow correlations at 200 or 250 MeV/nucleon — low enough so that fragments heavier than ${}^4\text{He}$ are produced in significant numbers in the participant region, and the hydrogen and helium isotopes can be separated with optimum efficiency; second, the energy dependence of the global event characteristics going even lower in beam energy, with emphasis on combinations like Au + Au at 100 and 150 MeV/nucleon, which are out of reach of the MSU cyclotrons. Because of the impending termination of the Bevalac research program within less than a year from now, we have deferred the second of these two goals. This decision was taken in light of the unique physics opportunities at the higher Bevalac energies, and the probable need to experiment with optimizing detector performance at and below 150 MeV/nucleon. On the other hand, as a result of our recent progress in interpretation of high-order correlations and collectivity (see section 1 and the Appendix), prospects for new and exciting physics associated with the first goal have improved. We plan to devote 100+ hours of beam time to this part of the program even in the more pessimistic scenario for the future of the Bevalac.

3. The STAR Detector

Activity in support of STAR has increased significantly during the past 12 months, despite the fact that the PI's streamer chamber effort began to wind-down only during the latter part of the reporting period. This increase has been helped by the fact that the PI has had no teaching or university service duties, and has just been further augmented by the recent hiring of Dr. Marvin Justice as a postdoc, supported jointly by this grant and by Kent State University. Marvin Justice is a UC Berkeley graduate whose thesis experiment, under the direction of Luciano Moretto, involved measurement of Coulomb fragmentation of uranium projectiles at the Bevalac. He also contributed to several other projects, including experiments at the Bevalac's JANUS spectrometer and a muon-catalyzed fusion experiment at PSI in Switzerland.

3.1 K_S^0 Interferometry

One of the PI's contributions to STAR during the past year has been in developing the idea of K_{short}^0 interferometry, and in carrying out simulations that demonstrate the feasibility and

unique advantages of such measurements using a combination of information from the STAR TPC and the Silicon Vertex Tracker. One of the main virtues of interferometry measurements at RHIC will be the possibility to observe a lengthening of the source lifetime, attributable to specific heat effects in a plasma model. Kaons offer significant advantages over pions for this purpose; resonances mimic a plasma by increasing the apparent size and lifetime of the source, and this distortion is less severe for kaons. However, Coulomb repulsion is much stronger for kaons, and so neutral kaons offer the best of both worlds. In addition, neutral kaons are immune to 2-track resolution effects that result in serious distortion of charged-particle interferometry measurements when source sizes are large. Further details and references can be found in STAR Note #47, included in the Appendix to this report.

3.2 dE/dx Resolution of the STAR TPC

Another recent project has been simulation of the dE/dx performance of the STAR TPC. This work is a natural outgrowth from similar work done for EOS, and like the K_S^0 simulation, is a prerequisite for defining detector specifications needed for the Conceptual Design Report. Fig. 3 shows the expected distributions of mean truncated dE/dx versus momentum for Si + Si collisions; the performance for Au + Au is currently worse, but has been improving steadily as the tracking software is adjusted and improved. Fig. 3 indicates that the expected flux of electrons (from π^0 s and direct γ s) is low enough that there is little motivation for further improving dE/dx resolution for the purpose of separating electrons from pions and kaons. Likewise, the spectra of pions, kaons and protons are such that relatively few particles populate momenta in the region of the relativistic rise, where improved dE/dx resolution might otherwise have some utility. These considerations have an impact on engineering specifications such as anode wire tolerances which determine the uniformity of the gas gain.

3.3 Plans for Coming Year

Looking ahead to the coming year, our group has undertaken to develop an integrated monitor and control system for the STAR TPC anode voltage supplies. This will probably use as a foundation the SUN SPARCstation software that Yiping Shao is currently writing for EOS as a replacement for the passive terminal control feature of the LeCroy 1440 HV chassis. A powerful and flexible user interface can be implemented using the SPARCstation, and it permits keeping records of the monitored parameters. A major shortcoming of the 1440 is the fact that it cannot monitor currents at the nanoamp level, as typically drawn by a group of TPC anode wires. We will build an external nA current monitor for several hundred channels and integrate its output

FIG. 3: Expected distribution of dE/dx vs. momentum for Si + Si collisions in the STAR TPC.

into the monitor/control software. The nA current monitoring and logging function is needed for at least a limited number of channels on a short timescale, to facilitate testing of TPC endcap prototypes. The hardware construction phase of this project will begin at Kent this fall, after the PI has returned from the current one-year leave at LBL.

The new generation of tracking detectors planned for experiments at RHIC are faced with the formidable task of pattern recognition and tracking in a very high multiplicity environment. Marvin Justice has chosen to work on innovative approaches to the tracking problem, such as the "elastic" algorithm advocated by Miklos Gyulassy. He plans to evaluate and improve the new algorithms in the realistic environment of the EOS TPC data as well as using STAR simulations.

4. The NA49 Experiment

The impending shutdown of Nuclear Science research at the Bevalac has far-reaching implications for the research plan laid out in last year's proposal, and prompted the PI's decision (made within the past few weeks) to join the NA49 Pb beam experiment at CERN. NA49 is an obvious bridge between EOS and STAR in terms of both timing and physics. The most compelling consideration in this decision, aside from the intrinsic scientific importance of NA49, is that as the PI's current graduate students finish-up (Jinghua Jiang this year, Yiping Shao probably in 1993, and Alan Scott in '93 or '94), there would be no experimental dissertation project available for new students for several years without such an intermediate-term project. Another consideration was that Art Poskanzer invited our group to join NA49 at this time, prompted by a recommendation from the DOE that he should recruit additional university groups from the US. This recommendation from DOE is interpreted as a signal that the resources needed to take on this new commitment are available.

During the past year, about two-thirds of the PI's research effort has been devoted to EOS and STAR, about 20% to streamer chamber analysis, and the remainder to other projects, notably the neutron flow experiment at the Bevalac, E848H (see section 5). Now that streamer chamber analysis and E848H running are no longer a factor, this part of the effort can be redirected to NA49. On the other hand, after returning to teaching and service duties in the fall, and factoring-in the new workload associated with the HV control and monitoring project (section 3), a dilution of effort seems inevitable without at least a modest increase in manpower at Kent. The scenario being proposed is to share 50% of the effort of a new postdoc with Prof. Mark Manley. Mark Manley's experimental work is mainly in the area of electron scattering and is funded by NSF; he needs a 0.5 FTE postdoc to work on Bates and CEBAF-related hardware

development, and his half of the support for FY 92/93 is available. The plan is to recruit a hardware-oriented person, possibly from a heavy ion background but maybe from another subfield of nuclear or high energy physics, and for this new postdoc to begin contributing to the PI's program by taking responsibility for much of the work on the HV project. Although this HV project is primarily motivated by the needs of STAR, it is sufficiently generic to benefit NA49 also; moreover, this scenario would allow the PI to devote more time to NA49.

One obvious project for the PI is to investigate the feasibility of K_S^0 interferometry in the NA49 environment. Although the detected K_S^0 multiplicity will at best be much lower than at STAR, collisions at the SPS explore a more baryon-rich region than at RHIC, and this increases the chances for detecting an entirely new component of interference, having a connection with "strangeness distillation" effects (see STAR note #47 in the appendix, and references therein).

5. Other Activities

5.1 The Neutron Flow Experiment E848H

During July and August 1991, Prof. Dick Madey's neutron flow experiment E848H had its second major run (the first was in 1988). After a number of overnight tests, the experiment took data in the uninterrupted "block running" mode for more than three weeks, using Au, La and Nb beams at a variety of bombarding energies. In the 1988 run, we could record only the time-of-flight information in the case of most of the 184 elements of the plastic wall that serves to tag the orientation of the reaction plane for each event. A major improvement in the recent run was the added capability to record pulse height information for the entire wall; as documented in the PI's 1988 proposal, this reduces dispersion in the determination of the reaction plane.

It was necessary to dismantle the E848H setup after the 1988 run. Since then, the HISS cave has been lengthened by about 25 feet in order to accomodate the E848H detectors with minimal disruption to (and from) the main part of the HISS facility, including the EOS TPC. A new dedicated E848H electronics house has also been provided. The VME data acquisition system used during the 1988 run was no longer available, and instead we used a system developed by Bill Rathbun for use at the 88-inch cyclotron at LBL. As a result of all these changes, a major effort was needed to prepare for the 1991 run, and the PI and all three students worked full time on these preparations during the month preceding the run. This experience was especially valuable for Jinghua Jiang, whose research to date (e.g., publications [i] and [vii]) has focused on analysis of data from older experimental runs in which she did not participate.

5.2 Collaboration with Harbin

The collaboration with the group of Prof. Yiming Li of the Harbin Institute of Technology, China, has continued to be very productive; two studies resulting directly from this collaboration that were described in last year's report, and were in the draft phase at that time, are now published (publications [iii] and [iv]). About half our collaborative work has taken the form of theoretical studies relating to the HBT effect, e.g., publications [iv] and [viii] (the latter explores the effect that triplet and higher-order HBT interference has on the interpretation of conventional pair HBT analyses, a question that has always been ignored in the past). We plan to continue this line of investigation in the future, with emphasis on understanding higher order HBT interference, a topic that is of increasing relevance and importance as the multiplicities of produced particles becomes higher. Prof. Shan Wang of Harbin is scheduled to visit Kent for about 8 months beginning this fall, and this visit will facilitate plans for the Harbin group to diversify into new areas of experimental analysis such as the EOS TPC and/or E848H.

6. Publications for 12-Month Period Ending April 1992

This section lists all work coauthored by the PI having a publication date within the 12-month interval since last year's report; in the case of journal publications, papers in press or submitted for publication are also listed. The abstracts for the published journal papers are reproduced in the Appendix, along with the full preprint for [vii]. An unpublished STAR report is also included in the Appendix.

6.1 Papers in Refereed Journals

- [i] J. Jiang, D. Keane, J. Cogar, G. Fai, S. Hayashi, C. Hartnack and H. Stöcker,
"Nuclear Transport Models Can Reproduce Charged-Particle-Inclusive Measurements But Are Not Strongly Constrained By Them",
Phys. Rev. C **43**, 2353 (1991).
- [ii] Abdulnasser F. Barchouty, George Fai, and Declan Keane,
"Pion Yields and Pion Spectra from Nuclear Collisions",
Nucl. Phys. A **535**, 715 (1991).
- [iii] S. Wang, Y.Z. Jiang, Y.M. Liu, D. Keane, D. Beavis, S.Y. Chu, S.Y. Fung, M. Vient, C. Hartnack, and H. Stöcker,
"Measurement of Collective Flow in Heavy Ion Collisions Using Particle-Pair Correlations",
Phys. Rev. C **44**, 1091 (1991).
- [iv] Y.Z. Jiang, L. Huo, Y.M. Liu, S. Wang, D. Keane, S.Y. Chu, and S.Y. Fung,
"Spatial Information on the Pion-Emitting Source from Pion Interferometry",
Phys. Rev. C **44**, 1957 (1991).
- [v] D. Beavis, R. Bock, R. Brockmann, P. Danielewicz, S.Y. Fung, J.W. Harris, D. Keane, Y.M. Liu, G. Odyniec, R.E. Renfordt, A. Sandoval, D. Schall, R. Stock, H. Ströbele, M.A. Vient,
"Collective Motion in Ar+Pb Collisions at Beam Energies between 400 and 1800 MeV/nucleon",
Phys. Rev. C **45**, 299 (1992).
- [vi] W.B. Christie, W.F.J. Mueller, D.L. Olson, T.J.M. Symons, H.H. Wieman, D. Beavis, F.P. Brady, J. Romero, C.E. Tull, T. Abbott, S.Y. Fung, D. Keane, and Y. Liu,
"Pion Correlations in 1.8 A GeV Ar on KCl and on La and 1.2 A GeV Xe on La",
Phys. Rev. C **45** (in press).
- [vii] J. Jiang, D. Beavis, S.Y. Chu, G. Fai, S.Y. Fung, Y.Z. Jiang, D. Keane, Q.J. Liu, Y.M. Liu, Y. Shao, M. Vient, and S. Wang,
"High-order Collective Flow Correlations in Heavy-Ion Collisions",
Phys. Rev. Lett. **68** (in press).
- [viii] W.N. Zhang, Y.Z. Jiang, S. Wang, Y.M. Liu, D. Keane, J. Jiang, Y. Shao, S.Y. Fung, and S.Y. Chu,
"Multi-pion Correlations in Two-pion Interferometry",
High Ener. & Nucl. Phys. **16** (in press).
- [ix] Q.J. Liu, Y.Z. Jiang, S. Wang, Y.M. Liu, D. Keane, S.Y. Fung, and S.Y. Chu,
"Multi-particle Azimuthal Correlations and the Nuclear Equation of State",
submitted to High Ener. & Nucl. Phys.

- [x] L. Huo, Y.Z. Jiang, S. Wang, Y.M. Liu, D. Keane, S.Y. Fung, and S.Y. Chu,
"Spatial Parameter from Two-pion Interferometry",
 submitted to High Ener. & Nucl. Phys.
- [xi] A.R. Baldwin, R. Madey, W.-M. Zhang, B.D. Anderson, D. Keane, J. Varga, J.W. Watson, G.D. Westfall, K. Frankel, and C. Gale
"Inclusive Neutron Cross Sections from Ne-Pb Collisions at 790 MeV/nucleon",
 submitted to Phys. Rev. C

6.2 Conference Proceedings

- [a] D. Keane, J. Jiang, Y.Z. Jiang, Q.J. Liu, Y.M. Liu, S. Wang, S.Y. Chu, and S.Y. Fung,
"Multi-Particle Correlations and the Nuclear Equation of State",
 Proc. of the 4th Conf. on Intersections between Particle and Nuclear Physics, Tucson, Arizona, 1991, ed. W. Van Oers, (AIP, New York, 1992), p. 829.
- [b] R. Madey, T. Eden, W.M. Zhang, B.D. Anderson, A.R. Baldwin, D. Keane, D.M. Manley, J.W. Watson, S. Kowalski, W. Bertozzi, G. Dodson, K. Dow, M. Farkhondeh, W. Korsch, D. Tieger, W. Turchinets, L. Weinstein, T. Reichelt, J.M. Finn, K. Beard, P. Markowitz, P. Rutt, R. Lourie, D. Barkhuff, S. Van Verst, C.C. Chang, J.J. Kelly, T. Payerle, J. Cameron, B. Ni, M. Spraker, J. Mougey, P. Ulmer, R. Whitney, B. Flanders, P. Pella, C. Hyde-Wright, and W.-D. Jiang,
"Status of Bates Experiment 85-05: The Electric Form Factor of the Neutron from the $d(e, e'n)p$ Reaction",
 Proc. of the 4th Conf. on Intersections between Particle and Nuclear Physics, Tucson, Arizona, 1991, ed. W. Van Oers, (AIP, New York, 1992), p. 954.

6.3 Technical Reports & Abstracts

- [a] R. Madey, T. Eden, W.M. Zhang, B.D. Anderson, A.R. Baldwin, D. Keane, D.M. Manley, J. Schambach, J.W. Watson, S. Kowalski, M. Farkhondeh, W. Sapp, L. Weinstein, J.M. Finn, P. Markowitz, R. Pourang, P. Rutt, W. Herzog, R. W. Lourie, C.C. Chang, J.J. Kelly, B. Ni, M.C. Spraker, P. Ulmer and R. Whitney, and P.J. Pella, *"Feasibility Test of the $d(\bar{e}, e'n)p$ Reaction to Measure G_E^n "*, Bates Linear Accelerator Center Annual Scientific and Technical Report 1990, ed. W. Lobar, (1991).
- [b] W. Christie, D. Olson, T. Abbott, D. Beavis, P. Brady, S. Fung, J. Kang, D. Keane, Y. Liu, W. Mueller, J. Romero, J. Symons, C. Tull, H. Wieman, *"Pion Correlations in Relativistic Heavy Ion Collisions at the Bevalac"*, Annual Report of Nuclear Science Division, Lawrence Berkeley Laboratory, 1989-1990.
- [c] M. Elaasar, J. Schambach, R. Madey, W. Zhang, D. Keane, B.D. Anderson, A.R. Baldwin, J.W. Watson, G. Westfall, G. Krebs, and H. Wieman, *"Bevalac Experiment E848H: Neutron Triple-Differential Cross Sections from Au-Au Collisions at 400 A MeV"*, Bull. Amer. Phys. Soc. **36**, 2152 (1991).
- [d] K. Kadija, G. Paic, D. Vranic, F.P. Brady, J.E. Draper, J.L. Romero, J.B. Carroll, V. Ghazikhanian, E. Gulmez, G.J. Igo, S. Trentalange, C. Whitten Jr., M. Cherney, S. Margetis, R.E. Renfordt, D. Röhrich, R. Stock, H. Ströbele, S. Wenig, T. Hallman, L. Madansky, B. Anderson, D. Keane, R. Madey, J. Watson, F. Bieser, M.A. Bloomer, D. Cebra, W. Christie, E. Friedlander, D. Greiner, C. Gruhn, J.W. Harris, H. Huang, P. Jacobs, S. Kleinfelder, P. Lindstrom, H. Matis, C. McParland, C. Naudet, G. Odyniec, D. Olson, A.M. Poskanzer, G. Rai, J. Rasmussen, H.-G. Ritter, I. Sakrejda, J. Schambach, L.S. Schroeder, P.A. Seidl, T.J.M. Symons, S. Tonse, H. Wieman, W.K. Wilson, D.D. Carmony, Y. Choi, A. Hirsch, E. Hjort, N. Porile, R.P. Scharenberg, B. Srivastava, M.L. Tincknell, A.D. Chacon, K.L. Wolf, W. Dominik, M. Gazdzicki, W.J. Braithwaite, J.G.

- Cramer, D. Prindle, T.A. Trainor, A. Breakin, R. Chechik, Z. Fraenkel, A. Shor, and I. Taerruya, "Update to the RHIC Letter of Intent for An Experiment on Particle and Jet Production at Midrapidity, LBL-31040 (1991).
- [e] P. Markowitz, K. Beard, J.M. Finn, P.M. Rutt, B. Flanders, J. Mougey, P. Ulmer, R. Whitney, P. Pella, J. Cameron, B. Ni, M. Spraker, R. Madey, T. Eden, W.M. Zhang, B.D. Anderson, A.R. Baldwin, D. Keane, D.M. Manley, J.W. Watson, S. Kowalski, W. Bertozzi, G. Dodson, K. Dow, M. Farkhondeh, W. Korsch, D. Tieger, W. Turchinets, L. Weinstein, T. Reichelt, C.C. Chang, J.J. Kelly, T. Payerle, D. Barkhuff, R. Lourie, S. Van Verst, C. Hyde-Wright, and W.-D. Jiang, "The Magnetic Form Factor of the Neutron G_M^T using the $(e,e'n)$ Reaction: Status of Bates Experiment 85-05", *Bull. Amer. Phys. Soc.* **36**, 2729 (1991).
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