Final Report on Grant DE-FG02-86ER40251

Title: Theoretical Interpretation of High-Energy Nuclear Collisions

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This grant was active for 24 years, during which time I count 81 refereed publications. This translates to ≈ 3.5 publications/year on the average.

The time period of this activity witnessed a continuous re-interpretation of “high” energy in nuclear collision physics. At the inception of the grant, in 1986, high energy meant Bevalac energies (hundreds of MeV/nucleon in the center-of-mass frame), while in 2010 we think about LHC energies (TeV/nucleon) as high energies. A similar comment applies to the use of the word “relativistic”. Accordingly, the scope of work covered under grant DE-FG02-86ER40251 bridges roughly six orders of magnitude in energy.

One overarching theme in this research was the equation of state of strongly-interacting matter. Another central element of the PI’s efforts was the focus on experimental data and the connection to the experimental heavy-ion program. In the following, I will highlight some of the accomplishments from the perspective of providing useful tools for experiments, both in terms of helping data analysis and planning and designing new experiments. I will conclude this final report with a list of publications resulting from work supported by the grant. The references in the text cite the items in this list.

A prime example of these ideas at Bevalac energies was the event generator *FREESCO* (Fragmentation in an Explosion-Evaporation Statistical Code) that I wrote with J. Randrup of Lawrence Berkeley National Laboratory and that is used to this date by practitioners in the Bevalac energy range. This was one of the first event generators (maybe the first) in nuclear collision physics made available to the community via publication in Computer Physics Communications [2]. One great advantage was the speed of the code that made it possible to generate event sets comparable in size to the collected data sets. This was out of the question with other models available at the time. Based on statistical physics principles, the *FREESCO* code can be thought of as calculating phase space, replacing all transition matrix elements with unity. As a background calculation that describes the expectation in this complicated situation if nothing remarkable happens, *FREESCO* has proven its value e.g. in extracting the information on collective flow (see many experimental papers and e.g. [4]) from Bevalac data.

Another application of *FREESCO* was in designing new experiments. In a 1987 paper on optimizing experiments [7] we have compared various methods for determining the reaction plane and studied the accuracy of its extraction. The importance of reaction plane information has grown strongly since the eighties, and is recognized today for a large number of phenomena across the six orders of magnitude of energy that the field has covered since the eighties. Based on this paper [7], a Bevalac experiment focusing on measuring neutrons was proposed and carried out in the early nineties.

An important aspect of the final state in the Bevalac energy domain is the creation, in a given collision, of several nuclear fragments heavier than single protons, i.e. deuterons, alpha particles, ... up to $\approx {}^{16}\text{O}$ nuclei. In connection to this feature, the phenomenon is sometimes described as multifragmentation. In 1990 I published a review article on multifragmentation theory [15], reviewing the statistical models available at the time to describe the final states created in these heavy-ion collisions.

A statistical description typically proceeds through the partition function of the system. The partition function can be canonical, micro-canonical, or grand-canonical. Capturing different levels of conservation laws, each of these have their physical significance and associated computational challenges. The discussion, evaluation, and implementation of the differences that appeared in these papers is another topic that is still hotly debated at energies that are six orders of magnitudes higher.

The partition function contains all information on the system, including its entropy and equation of state. These quantities depend on the nucleon-nucleon interaction used. In the early nineties momentum-dependent interactions were in the center of attention. With my collaborators, I significantly contributed to the discussion on the equation of state with momentum-dependent interactions [19,22,24].

Another feature of the equation of state, the phase transition to quark-gluon matter becomes the focus of attention at higher energies. The QCD phase transition is predicted by lattice QCD, and is also addressed by field-theory models (e.g. [30]). At some level, the most important question becomes the observation of this QCD transition temperature. I proposed measuring the QCD transition temperature using resonant dileptons [21,28].

Increasing the energy through SPS to RHIC energies brings up the question of jet production. I started to address this in the early 2000-s [37], focusing my attention more and more on high transverse-momentum particle production at RHIC. These rare probes, while not as abundant as the low transverse-momentum particles forming the bulk of the final state, can be used as “probes” of the matter produced in relativistic nuclear collisions. The quenching of the jets, in particular, can be looked upon as a tomographic tool to ascertain the properties of the medium the jets propagate in. This topic is subject to intense investigation and has many open questions today, a decade later. However, the nuclear collision community is now by and large convinced that jet quenching is one of the signals of quark-gluon plasma formation. This was not always obvious. At around the turn-on of RHIC (2000) and in the first couple of years of data taking we had intense discussions about jet quenching and its meaning relative to the quark-gluon plasma. I believe that our paper on the discovery of jet quenching at RHIC and the opacity of the produced quark-gluon plasma [41] (first presented at a Quark Matter Conference) helped convince the community that a quark-gluon plasma was indeed discovered.

Another well-cited RHIC paper addressed the production of high transverse-momentum mesons in the framework of perturbative QCD [42]. This was followed up by several variations on meson production in pp, pA, and AA collisions [45,49,52]. It turns out that perturbative QCD is much less successful in the description of baryon production. This has to do with the intricacies of the factorization theorem and the amount of information we have on fragmentation functions. We called attention to the role of fragmentation functions in hard hadron production in an important letter [46].

Continuing the tradition of being useful to our experimental colleagues, in anticipation of the EBIS ion source at RHIC, we studied the advantage of U+U over Au+Au collisions at

constant beam energy [61,72]. At about the same time as preparing for future RHIC experiments, research also addressed upcoming questions related to the future LHC heavy ion program [74,75,76]. Prior to the start of nuclear collisions at LHC, these predictions serve of course as initial orientation only. I hope that my collaborators will continue discussing these issues and checking the results against LHC data when they become available.

The above is but a small sample of highlights of accomplishments in the 24 year history of the grant. It was presented from the point of view of serving experimental needs and not all areas were mentioned. Further details are available in the list of publications below.

List of Publications

1. *Angular distributions of low-energy neutrons from 390 MeV/nucleon Ne + Pb collisions*, R. Madey, J. Varga, G. Fai, A. F. Barchouty, B. D. Anderson, A. R. Baldwin, R. Cecil, J. W. Watson, and G. D. Westfall, Phys. Rev. C **34**, 1342 (1986).
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4. *A quantitative analysis of the collective outward motion of nuclear matter in central Ca + Ca and Nb + Nb collisions*, L. P. Csernai and G. Fai, Acta Physica Hungarica **62**, 355 (1987).
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8. *Minimal information and statistical descriptions of nuclear fragmentation*, G. Fai and A. Z. Mekjian, Phys. Lett. B **196**, 281 (1987).
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16. *Chiral solitons with quarks and composite mesons*, M. R. Frank, P. C. Tandy, and G. Fai, Phys. Rev. C **43**, 2808 (1991).
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19. *Nuclear equation of state with momentum-dependent interactions*, L. P. Csernai, G. Fai, C. Gale, and E. Osnes, Phys. Rev. C **46**, 736 (1992).
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