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Annual Report

II. REPORT OF PAST RESEARCH

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The research program undertaken since May 1991 has been devoted entirely to the physics issues of relativistic heavy-ion collisions. Several topics have been investigated; they address the central theme from different lines of inquiry. They are described below under separate headings, starting from the one that is most exciting. The references in { } refer to the work done under this grant either published or in preprint form each with an OITS number, while those in [] are general references listed at the end of this section and the next.

A. QUARK-HADRON PHASE TRANSITION

1. Motivation and Aim

The community's aim in heavy-ion collisions is to create quark-gluon plasma. Various proposals have been made on the signatures of such a plasma. Nearly all of them probe the bulk of the plasma medium where it is hot (above T_c) or dense, e.g., dilepton, strangeness enhancement and J/ψ suppression [1]. So far none of them have been found to be clean enough to avoid the ambiguities that arise from competing processes. My approach has been to emphasize the signatures from the boundary of the plasma --- in physical space as well as in temperature and density, i.e. at phase transition (PT) into hadrons. We know that there are many examples in nature where PT leads to very noticeable phenomena, such as storm in liquid-gas transition and opalescence in binary mixtures. Those are first-order PTs; in second order we know that the fluctuations become very large at T_c . Detecting storm is surely easier than measuring the water vapor before it condenses. If we can similarly detect a distinctive signature for quark-hadron PT, then it can be inferred that a quark-gluon plasma has to exist first before hadrons are produced.

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The problem then is to identify characteristic features of hadron production through PT that are observationally different from those associated with the conventional production mechanism, such as in pp collision, without the formation first of a dense medium. The latter is not well understood despite the existence of several models that can simulate gross feature. More on that will be discussed in Sec. II-B below.

Lattice gauge calculations in QCD suggest that the confinement and chiral transitions occur at the same temperature T_c , and that for two flavors the PT is most likely second order [2]. Studying at the microscopic level reveals information on the order of the transition, the origin of the Nambu-Goldstone mode for pion production, the T dependence of the dynamical mass, etc. [3] However, it does not provide any insight into the collective behavior of the system at PT, nor suggests any distinctive features of phenomenological importance. We need a treatment at a scale slightly more macroscopic than QCD, but more refined than hydrodynamics, which is concerned only with average quantities.

Since fluctuations are large near the critical point, a sensible place to look for signatures of PT is in the properties of hadron multiplicity fluctuations. Furthermore, only when those fluctuations exhibit some universal features that are independent of the details of PT can we use them as a characteristic signature. In the past several years considerable work has been done in the area of intermittency [4, 5], where self-similarity behavior of the multiplicity fluctuations has been studied at varying scales of detection resolution. The connection between intermittency and PT has initially been only a conjecture [6]. It is only during the past several months that work done in this research grant has led to a breakthrough in the understanding of the phenomenological consequences of a quark-hadron PT [1].

2. Ginzburg-Landau Theory

The framework of our analysis is the Ginzburg-Landau (GL) theory of second-order phase transition. It is a phenomenological theory that has no derivation from a microscopic basis, although it has formal similarity to the σ model for chiral transition. The order parameter is related to the hadron density. It should be mentioned that after forty years of study of strong interaction there is still no fundamental derivation from first principles of such basic observables as average multiplicity $\langle n \rangle$ in a pp collision at high energy.

It is known that the GL theory [7] has captured the essence of the superconducting transition and the macroscopic nature of the superconducting state. In nonlinear optics the problem of photon production at the threshold of lasing can be treated as a second-order PT, and the GL theory can be used also to describe the lasing transition. Indeed, we can find analogy between the quark-hadron PT and both the superconducting and lasing transitions.

Our emphasis has been in the study of the hadron multiplicity fluctuations. One may be concerned with the reliability of the GL theory for the study of fluctuations, since in the usual statistical problems it is known that it can predict the correct critical exponents only for dimensions greater than the critical dimension, which for the Ising system is 4. However, the critical exponents for quark-hadron PT are not measurable, since there is no experimental control of temperature, and are not the quantities we aim to calculate. Our goal has been to discover universal quantities that are measurable in heavy-ion collisions on the one hand, and are independent of the details of the GL parameterization on the other --- and, of course, can serve as a distinctive signature of the PT.

In this and the preceding section on introductory remarks, I have given an extensive description of the background and central ideas of my approach, perhaps

somewhat longer than is usually called for in a proposal. However, it seems important to make clear the general direction and framework of an unconventional approach before delving into the specifics, since some of the reviewers of my previous proposal on the same subject expressed the conservative opinion based on the conventional notion that any interesting signal of a plasma must emanate from the hot medium early in its evolutionary history. My emphasis is on phase transition, and hadrons are the carriers of the signatures about that transition. There is a legitimate concern about the loss of information during the period between the formation and detection of the hadrons. Indeed, not all properties of hadron production will survive the final-stage evolution. We search for universal properties to be discussed below. Other possible complications will be examined in the years to come, as proposed in Sec. III. My bottom line is: the most copiously produced particles in relativistic heavy-ion collisions should not be ignored.

3. Scaling Exponent

We now describe only the result. The normalized factorial moments are defined as

$$F_q = \frac{\langle n(n-1)\dots(n-q+1) \rangle}{\langle n \rangle^q} \quad (1)$$

where n is the hadron multiplicity in a rapidity window of width δ , the averages being performed over many events. Intermittency refers to the power-law behavior [4].

$$F_q \sim \delta^{-\phi_q} \quad (2)$$

over a range of small δ . Phenomenological evidence for this behavior has been found in a wide variety of collision processes: e^+e^- , μp , pp , pA and AA [8]. In GL theory we found that there is no extensive region of δ in which (2) is valid. Besides, locally the value of ϕ_q depends on the parameters of the GL free energy, thus precluding any possibility of experimental verification, since those parameters are unknown.

However, we found that in the GL theory F_q satisfies very well the scaling behavior

$$F_q \propto F_2^{\beta_q} \quad (3)$$

over almost the entire range of F_2 . Furthermore, β_q does not depend upon the parameters in the theory after hadronization occurs. In that sense it is universal. What is more astounding is that β_q can be described extremely well by the formula

$$\beta_q = (q - 1)^\nu \quad (4)$$

where $\nu = 1.31$. We call ν the universal scaling exponent. Seldom have I encountered, if ever, in strong interaction physics a numerical constant that is the consequence of a theory and is directly measurable. These results have been reported in Refs. {1-3}.

The experimental results on F_q in high-energy nuclear collisions (EMU01 [9] and KLM [10]) can be cast in the form (3) and (4), and the fitted value for ν is 1.55 ± 0.12 , which is 2σ above the theoretical value. We may therefore claim that no quark-hadron PT has taken place in current experiments. If in future experiments at RHIC the value of ν comes down to 1.31, then the community should have a good reason to be excited about.

B. HADRON PRODUCTION WITHOUT PHASE TRANSITION

1. Geometrical Branching Model

If we want to identify a signal for phase transition, we ought to have a good idea of what to expect when there is no phase transition. The study of multiparticle production in pp collisions has been my interest for a long time. Over the years I have acquired considerable experience in interpreting the data and incorporating many strands of conventional wisdom into the construction of a sound model. This is inductive work, since soft production is known to be untractable in any fundamental theory.

The Geometrical Branching Model (GBM) was developed several years ago for pp collisions [11], and has since been extended to pA [12] and AA collisions [13]. Basically, it involves two parts: the geometrical aspect of hadrons that have sizes and opaqueness, and the branching aspect of the production process that is based on the stochastic behavior of partons. The former is treated in the eikonal formalism, while the later is modeled after Furry branching [14]. Many gross features of pp, pA and AA collisions have been reproduced by the GBM.

2. Event Generator for Soft Production

Without a Monte Carlo code the GBM cannot be used to simulate experimental events and check the detailed properties of the collision processes. Furthermore, the analytical description of a model is insufficient to predict the type of fluctuations that have been quantified by intermittency. The event generators of some of the familiar models (e.g., Fritiof [15] and Dual Parton Model [16]) have been shown to be inadequate in fitting the intermittency data of hadron-hadron collisions [17]. There was

therefore an urgent need to develop a Monte Carlo code for GBM not only to make it accessible to the experimentalists for simulating their collision events, but also to test the model in light of the intermittency data.

During this grant period I have worked in collaboration with J. Pan to develop the Eikonal Cascade Code (ECCO). Instead of the analytical expression for Furry branching, we could build in successive random processes at each step of the cascading. In order to get the intermittency behavior it is necessary at each such step to use a singular rapidity distribution for the daughter clusters. Beside the usual global features of multiparticle production that any viable model must have (viz., σ_T , $\sigma_{e\bar{e}}$, $\langle n \rangle$, P_n , C_q , dN/dy , $d^2N/dy_1 dy_2$, dN/dp_T) ECCO is able to fit the δ dependence of F_q in Eq. (2), thus becoming the only event generator that is currently capable of accomplishing that. This work was reported in Refs. {4,5}.

3. Intermittency in Nuclear Collisions

With the availability of ECCO for pp collisions we could extend the intermittency analysis to nuclear collisions. One complication that had to be dealt with is the treatment of subsequent interaction of the "broken" nucleons with other nucleons downstream inside the nucleus; in particular, we had to develop a modified eikonal function for the broken nucleon within the framework of ECCO, and to extend the branching mechanism to collisions involving the broken nucleons. Our simulated result agrees with the usual nuclear data on intermittency in that the effect is very weak. However, when we pushed the calculation of F_q to higher values of q , so far unattainable by current experiments, we found a dramatic increase of the intermittency index ϕ_q . This is a special feature of the nuclear problem because when many particles are produced, it is only when the multiplicity in a small bin is required to be large can one expect large fluctuation; when q is small, statistical fluctuation

dominates, resulting in small ϕ_q . We await the experimental confirmation of our prediction when better statistics can allow the data to be analyzed at higher q . This work was reported in Ref. {6}.

4. Intermittency in Higher Dimensions

It was pointed out by Ochs [18] that intermittency should become a much stronger effect when analyzed in 2- and 3-dimensional spaces. Subsequent data indeed confirmed that predication in both pp [19] and AA [20] collisions. We thus, extended ECCO to 3-dimensional branching with p_T being treated as conjugate to the impact parameter which, of course, fluctuates from event to event. We were able to fit the NA22 data on intermittency in all combinations of the (y, p_T, ϕ) variables. Amazingly, there is universality in the Ochs-Wosiek plot [21] for all dimensions. We went further to determine the scaling exponent in Eq. (4) and found $\nu = 1.45$ for pp collisions. The fact that it is greater than the value 1.31 predicted for PT (Sec. A-3) indicates that the fluctuation probed by $q = 2$ is weaker for pp than for AA with PT. We expect ν for AA without PT to be much greater, since ϕ_2 is extremely small. Thus our conclusion is that the smearing of multiplicity fluctuations in AA collisions without PT due to the incoherent sum of contributions from many sources weakens the intermittency at low q and makes ν large. It is distinctly different from the predictions of the GL theory, where fluctuations are strong and ν is low. This work was reported in Ref. {7}.

C. FRACTAL STRUCTURE IN MULTIPARTICLE PRODUCTION

The study of self-similarity behavior in particle production at high energies has opened up a new area of inquiry, i.e., the fractal structure of particle population in

phase space. I introduced the use of G moments to investigate the multifractality of the problem [22], and then applied them to the determination of the multifractal spectral function $f(\alpha)$ for two branching models, including the gluon model [23]. Subsequently, a number of experimental groups have used the G moments to perform multifractal analyses on their data [24-28]. One of the goals is to determine the fractal dimensions of the processes and to explore their connection with the basic dynamics.

There are, however, some problems that must be overcome. They are of two types: the finite N problem and the dip problem. The former is due to the fact that the multiplicity of any event at finite energy is finite, so one cannot subdivide the phase space indefinitely to uncover finer and finer substructure *ad infinitum*, as one does with usual fractals. The latter involves studying dips in addition to spikes in a rapidity distribution, but beyond a certain scale of resolution the dips are all empty bins which must be avoided. Mathematically, it means that one must find a way to eliminate the statistical fluctuations while allowing a unique way to continue the order of the moments to negative values.

Some progress has been made in solving the first problem, but not the second. The G_q moments have been modified to include a cut in the sum over bins to leave out $n < q$ bins. It is then shown that G_q is power-law behaved without saturation. The component corresponding to statistical fluctuation is then subtracted out, and the remaining dynamical component is used to determine the fractal dimension. The method was first tried out in collaboration with the EMC experimental group [8]. Then using ECCO to carry out our ideas, some theoretical improvement was made in understanding the connection between G_q and F_q , thereby laying the foundation for the fractal interpretation of intermittency [9,10].

The dip problem remains unsolved. It is similar to the void problem of the galactic distribution in the sky. What we need is an efficient way to quantify the structure of the dips, which should be especially important for collisional events at

RHIC where high multiplicities will make the origin of the dip structure more interesting.

D. J/ψ SUPPRESSION IN pA COLLISIONS

The initial-state interaction in pA collisions has been recognized as having an important effect on the suppression of J/ψ production [29-32]. It can broaden the transverse momenta of the gluons entering the gluon-fusion subprocesses, and it can alter the longitudinal-momentum fraction of the target gluons due to nuclear shadowing. However, there is another aspect of the initial-state interaction that has previously been overlooked. It is the depletion of gluons on the projectile side due to soft interaction upstream in the target nucleus before fusion to produce $c\bar{c}$. This depletion effect is related to, but not the same as, the multiple scattering problem of the initial gluon that results in p_T broadening. In considering multiple scattering of the partons, one should recognize that there are both gain and loss terms for both quarks and gluons and at all parts of the momentum space. Since hadrons are produced as a result of the incident proton colliding with the target nucleons upstream (even though the actual materialization of the produced hadrons may take place outside the nucleus), in the parton picture some gluons in the incident proton must have been depleted from the beam. Thus at the point of fusion to form the $c\bar{c}$ state the incident gluon distribution cannot be the same as that in the physical proton in the initial beam. It is this difference that we have studied in connection with the J/ψ suppression.

We have done the reverse. Assuming no final-state interaction (as a working hypothesis), factorizable hard subprocess, and nuclear shadowing of the target gluon distribution, we have related the projectile gluon distribution to the x_F distribution of the produced J/ψ or Υ . The data on the latter then infer the former, which is found to be approximately independent of both the collision energy and the mass of the heavy

quark states, J/ψ , ψ' , and Υ . Thus the idea of gluon depletion is supported by the existence of a universal depletion factor, which turns out to be at the 70% level. The result does not preclude further improvement due to final-state interactions, but it is sufficient to validate our assertion that the initial-state interaction considered is important. This work was reported in Ref. [11].

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