Intermittent Pattern of Produced Particles in Pb-Pb Collisions at 158 A GeV

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Abstract—*Non-statistical fluctuations in the multiplicities of charged particles and photons and the total transverse energy in 158 A GeV Pb+Pb collisions are studied for a wide range of centralities. The centrality dependence of the charged particle multiplicity fluctuations in the measured data has been found to agree reasonably well with those obtained from a participant model. The motivation for studying relativistic heavy ion collisions is to gain understanding of equation of state of nuclear, hadronic and partonic matter commonly referred to as nuclear matter. Such a situation is quite suitable for the formation of a deconfined state of matter known as hot Quark-Gluon Plasma (QGP) which subsequently cools and expands. In this process the energy density becomes low enough so as a phase transition Quark-Gluon Plasma (QGP) to hadrons state occurs.*

1. INTRODUCTION

Investigation of phase transitions is a conventional study in statistical physical described by Ginzburg- Landau Model. In analogy the same is extended to the study of multiparticle production in high energy collisions the understanding of which involves study of intermittency (fluctuations) and their behaviour with respect to Quark-Gluon Plasma and first/second order phase transitions are understood accordingly. The motivation for studying relativistic heavy ion collisions is to gain understanding of equation of state of nuclear, hadronic and partonic matter commonly referred to as nuclear matter. The behaviour of nuclear matter as function of temperature and density (or pressure) is governed by its equation of state. Conventional nuclear physics is concerned primarily with the lower left portion of the diagram at lower temperature and near normal nuclear matter density. Here normal nuclei exist and at low excitation a liquid-gas phase transition is expected to occur. This is the form of experimental studies using low energy heavy ions. At some what higher excitation nucleons are excited in baryonic resonances states along with accompanying particle production and hadronic resonance matter. This region is presently accessible in heavy ion studies at the AGS accelerator facility at Brookhaven National Laboratory (BNL) and the Super Proton Synchrotron (SPS) accelerator facility at CERN. There may be possibility that some part of these collisions traverse the transition region into the quark-gluon plasma region. Formation of quark-gluon plasma, a deconfined state of quarks and gluons [1-3] is presently the major focus of relativistic heavy ion experiment at higher energies. For this purpose the relativities heavy ion collider (RHIC) [4-7] and associated experiments are performed under construction at Brookhaven for operation in 1999 and operation with heavy ion is also being planned for the Large Hadron Collider in 2005. As seen in WA98 experiment, the anticipated temperature and density trajectories at Relativistic Heavy Ion Collider (LHC heavy ions) are expected to lie close to that of the early universe while those at the AGS and SPS occur at higher baryon densities. Quark-hadron phase transition is predicted to have occurred at around ten micro seconds after the Big Bang when the universe was at a temperature of approximately 150-200 MeV. This is the same transition as that from hadronic matter to Quark-Gluon Plasma (QGP), but in the reverse direction by cooling from a higher temperature. The region of high baryon densities and very low temperature is important for various aspects of steller evolution. The nuclear matter equation of state governs star collapse and supernova expansion dynamics. The theory which at present is believed to the best description of strong forces is quantum chromodynamics (QCD) [8-10].

2. MATHEMATICAL FORMULATION

Consider a small cell in phase space with size δ. Here δ is an interval of a one-dimensional variable such as rapidity δη or that of three- dimensional space. In Ginzburg- Landau description [11-15] of phase transitions, the factorial moments F_q are given by

$$F_q(\delta) = z^{-1} \int D_\phi \, \phi^{2q} \, \delta^q \exp(- F[\phi]) \qquad (1)$$

Where Z is partition function, F [ϕ] is the free energy function of the system in the cell δm and ϕ described the probability that the system is in a pure state [ϕ] . In the general theory of phase transition.

$$F[\phi]= \delta[a(T - T_c)[\phi]^2 + b[\phi]^4 + c[\phi]^6] \qquad (2)$$

a, c > o and a, b and c are assumed to be constants or depend weakly on temperature. The order parameter $x = [\phi]^2$ corresponding to the local minimum of free energy for

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different cases. For x = 0, it is the quark phase and x> 0 corresponds to the hadron phase. For b $\geq$ 0, the order parameter varies smoothly as a function of temperature and vanishes at T= T_c and above. Thus the system undergoes second order phase transition. For b< o, there exists a temperature T = $T_c + b^2/4ac$ at which the free energy has two minima at x_1 = 0 and x_2 = |b|/2c> 0, both with F=0. For T lower slightly than T_c the order parameter turns suddenly from x_1 = 0 to x_2> 0 thus the system exhibits first order phase transition. Defining

$$H_q(v) = \int_0^\infty dy\, y^q \exp(-y^2 + uv^2y + vy^2) \qquad (3)$$

Where u = - a (T – T_c) /b^2, v = - ($b/c^{2/3}$)$\delta^{1/3}$

Thus v > 0 corresponds to first order phase transition and v < 0 corresponds to a second order phase transition. With this definition, the Scaled Factorial Moments

$$F_q(\delta) = \frac{f_q(\delta)}{[f_1(\delta)]^q} \qquad (4)$$

Scaled Factorial Moments can be expressed as a function.

$$lnF_q = (q-1)\ln\left(\frac{H_0}{H_1}\right) + \ln\left(\frac{H_0}{H_1}\right) \quad (5)$$

The Scaled Factorial Moments F_q were first proposed to eliminate the statistical fluctuations. From the above relations, one can calculate the Scaled Factorial Moments as a function of resolution δ. To show the dependence of InF_q on v analytically, one can expand H_q in powers of v and get

$$H_q(v) = \sum_{k=0}^{\infty} a_{q,k} v^k \qquad (6)$$

$$a_{q,k} = \frac{1}{3}\sum_{m,n>0}^{2m+n=k} \frac{u^m}{m!n!}\,\Gamma\left(\frac{m+2n+q+1}{3}\right) \qquad (7)$$

It may be seen $b_{q,o}$ and $b_{q,1}$ are parameter u independent but bq,k for K> 1 depend on parameter u. The values of bq,0, bq,1 and bq,2 for q = 2,3 and 4 are listed in Table1. In Table1, the values of bq,2 depend on parameter u and are obtained when the parameter u is chosen to be 1.0 for illustration.

One can rewrite InF_q as functions of X = ± $\delta^{1/3}$ in which + and – correspond to the cases of v>0 and v<0 respectively. One can discover the difference immediately in the behaviour of InF_q as a function of X for first order and second order phase transitions. Thus in Ginzburg-Landau description of phase transition, the coefficients of X obtained from the polynomial fit of InF_q according to this model should agree with $b_{q,1}$ upto a factor |b|/$c^{2/3}$ if the system undergoes a first order phase transition (i.e. v > 0). On the contrary if the system undergoes second order phase transition, the coefficients of X fitted should be with opposite sign to $b_{q,1}$ while the constant term should be equal to $b_{q,0}$. One sees that the relative sign of the coefficients of X obtained from fitting to those from theoretical calculation can be regarded as a definite criterion of the order of phase transition. This variation of In <F_q> are studied as a function of X = $\delta^{1/3}$.

TABLE 1:The values bq, 0, bq, 1 and bq, 2 for q = 2, 3 and 4

bq,k	2	3	4
bq,0	0.379	1.641	2.047
bq,1	1.763	-0.485	0.021
bq,2	-1.117	-0.911	-2.030

$$\ln F_q = \sum_{k=0}^{\infty} C_{q,k} X^k \qquad (8)$$

Where $C_{q,k} = b_{q,k}(\pm b/c^{2/3})^k$

The data is fit to a polynomial of degree at least two. The sign of coefficient of X will then speak about the order of phase transition in the Pb-Pb collisions.

3. WA98 EXPERIMENT

A high granularity Preshower Photon Multiplicity (PWD) Detector as a part of CERN International hybrid experiment WA98 collaboration is mainly used for these studies.

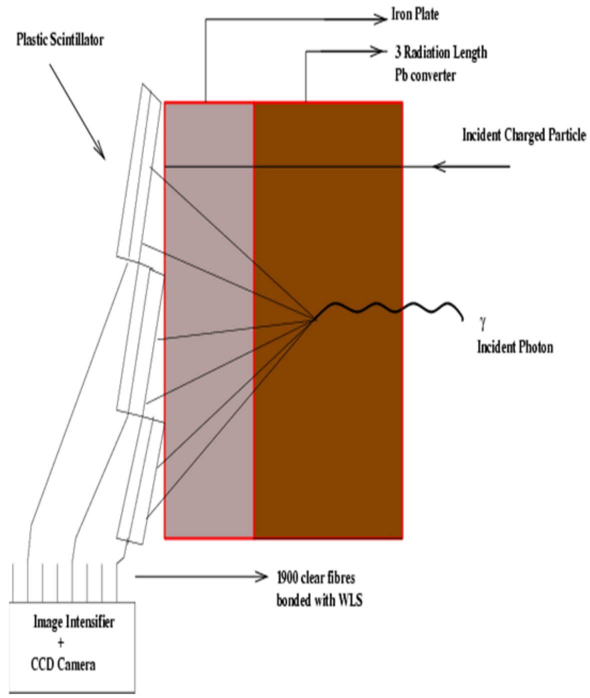

Fig. 1: Principle of Photon Multiplicity Detector

The sophisticated online nuclear detector PMD uses scintillating plastics as the radiation sensitive material and lead sheets of three radiation length as the converter for the development of the electromagnetic shower [16]. The readout signal after pedestal correction is subjected to cluster algorithm to count for gamma-like clusters. The output of experiments is the photon multiplicity with pseudorapidity coverage 2.5 ≤η≤ 4.2 of which 3.2 ≤η≤ 4.0 has full azimuthal angular configurations. The detector has been designed, fabricated and assembled in India and installed at European Nuclear Research Centre (CERN) as a part of WA98 collaboration. The phenomenological models on nuclear collisions are discussed. The theoretical predictions from Quantum chromodynamics for the onset of deconfined state of nuclear matter (QGP). The results from the analysis of data on photon multiplicities distributions of Pb+Pb collisions at 158 A GeV beam energy are discussed below.

Table 2: Experimental data of WA98 experiment.

Data sets	Type	ET (GeV)	No. of events
Cent-I	Most central	> 347.6	79005
Cent-II	Central	225.5-298.6	55656
Cent-III	Peripheral	89.9-124.3	18748

4. DETAILS OF CALCULATIONS

The analysis is made on central collisions only which are characterized by E_T cut of 348.8 GeV. From the sample of the interactions, we have collected 27063 central events. The quality of the events is tested for various plots like η-distribution and ϕ-distribution which are in line with the published results. For this purpose the VENUS 4.12 and GEANT (GWA98) package is used and the number of central collisions simulated was about 15342.The data is analysed in restricted pseudorapidity window $3.2 \leq \eta \leq 4.0$ with full azimuthal coverage. The distribution of particles in bins of different size (δη=0.1) from a given pseudorapidity. Window width (δη=0.8) is studied. The bin width of δη=0.1 is chosen constrained by resolution limits of experimental setup. In order to interpret the results of experimental distributions, simulation studies for an identical experimental set up was made. These events were also subjected to all the procedures laid down for the experimental data. A relative comparison of the above studies was made for the relevant parameters and attempt has been made to understand the mechanism of the particle production and the observation of the fluctuations in the photon multiplicities in Pb-Pb collisions at 158 A GeV.

Table 3: The values of coefficients of A, B and C obtained from horizontal scaled factorial moment corrected for Experiment central data (polynomial fit).

bq,k	2	3	4
bq,0	0.032±0.02	0.055±0.04	0.237±0.06
bq,1	0.044±0.09	0.075±0.14	0.543±0.01
bq,2	0.038±0.09	0.058±0.14	0.442±0.01

Table 4: The values of coefficients of A, B and C obtained from horizontal scaled factorial moment corrected for simulated central data (polynomial fit).

bq, k	2	3	4
bq,0	0.031±0.01	0.052±0.03	0.147±0.03
bq,1	0.041±0.05	0.071±0.07	0.442±0.08
bq,2	0.035±0.06	0.056±0.08	0.352±0.07

5. SUMMARY AND CONCLUSION

To understand the nature of phase transitions in the description of Ginzburg-Landau Model, the Scaled Factorial Moments are utilized. Large multiplicity fluctuations exist with hadronisation process in phase transitions. The study of multiplicity fluctuations of hadrons in final state enables one to find some new quantities to reflect the features of different kinds of phase transitions. The characteristics of Scaled Factorial Moments (SFM) are investigated in the context of Ginzburg-Landau Model and the attempt is made to identify experimental signatures to specify the nature of phase transitions. The behavior of InF_q as a function of resolution enables one to determine the order of phase transitions unambiguously. The present studies have resulted in useful inferences in regard to parameters discussed above for ultra-relativistic Pb-Pb collisions at 158 A GeV. The experimental results are compared with predictions of simulation studies using Monte Carlo (MC) code, VENUS, for particle production in relativistic nucleus-nucleus collisions.

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