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Event-by-event pseudo-rapidity fluctuations in high energy nucleus–nucleus interactions

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ABSTRACT

A detailed study of event-by-event pseudo-rapidity fluctuations in relativistic heavy-ion collisions in terms of the Φ measure and its multiplicity and target dependence has been carried out for heavy (AgBr) and light (CNO) groups of targets present in the nuclear emulsion using ^{16}O (at an incident momentum of 4.5 A GeV/c), ^{22}Ne (at an incident momentum of 4.1 A GeV/c), ^{28}Si (at an incident momentum of 4.5 A GeV/c) and ^{32}S (at an incident momentum of 4.5 A GeV/c) projectiles. For all the interactions, the total ensemble of events has been divided into three overlapping multiplicity classes depending on the number of shower particles. For all the interactions and for each multiplicity class, the Φ values are found to be greater than zero indicating the presence of strong correlation in the multiparticle production at Dubna energy. The measured Φ values are found to decrease with the increase of average multiplicity for all the interactions. The Φ values for the AgBr target are found to be greater than that for the CNO target for all the projectiles. This observation indicates the presence of stronger correlation for heavier projectiles. The experimental results have been compared with the modified FRITIOF model. It has been seen that the modified FRITIOF model cannot reproduce the experimental results.

1. Introduction

The strong interaction, described by the quantum chromodynamics (QCD), may be studied under conditions of high parton density and high energy density using ultra-relativistic heavy ion collisions. The high energy density regime of QCD is sensitive to non-linear dynamics and non-perturbative effects, including parton saturation, the onset of color deconfinement and chiral symmetry restoration. Lattice QCD calculations indicate that [1] at zero net baryon density at a critical temperature of $T_c \sim 170$ MeV and energy density $\varepsilon_c \sim 1$ GeV/fm^3 a color deconfined and a chirally restored QGP phase is formed [2]. These energy densities may be attained in relativistic heavy ion collisions where it is believed that a dense system of quarks and gluons is created. The system undergoes rapid collective expansion before the patrons hadronize and eventually decouple. Goal of current heavy ion collision physics is to study the properties of the phase transition between the quark–gluon plasma (QGP) phase and the ordinary hadronic phase. In many-body systems, phase transition often causes more dramatic changes in the fluctuations of an observable than in the average of an observable. For instance, as a system goes through a phase transition, heat capacity changes abruptly whereas the energy density itself remains to be a smooth function of the temperature. Therefore, fluctuation measurements in heavy ion collisions have a good chance of being the signals of the QGP formation. Interesting fluctuation variables considered so far include multiplicity fluctuations, energy fluctuations, charge fluctuations and mean transverse momentum fluctuations. In idealized situations, these fluctuations can reveal the following properties of the underlying system: if a thermal equilibrium is reached, the multiplicity distribution is very close to a Poisson distribution. Therefore, the multiplicity fluctuation can tell us whether a global thermalization has been achieved [3]. In nucleus–nucleus collisions, transverse energy is an extensive global variable. Transverse energy is also an indicator of the energy density achieved in the collisions. Energy fluctuation is related to the specific heat. Lattice QCD calculations show that the specific heat has a sharp peak around the critical temperature. Since energy density is directly related to the formation of QGP, it is extremely important to study transverse energy fluctuations [4,5]. Non-statistical mean transverse momentum fluctuations [6] can signal the existence of the tricritical point. Charge fluctuations [7–9] are sensitive to the unit charge of the underlying system. Quarks have fractional electric and baryonic charges. Therefore, the fluctuations of those charges in a QGP and

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a hadronic matter are clearly distinguishable. All these are interesting and deserve careful study.

There has been evidence for occurrence of multiplicity fluctuations in the pseudo-rapidity distributions [10]. The existence of such fluctuations would give information on the substructure in space–time of the collision region. Large fluctuations in pseudo-rapidity window have been observed in cosmic ray events and in hadron–hadron, nucleus–nucleus and hadron–nucleus interactions at accelerator energies [11,12]. They have been interpreted in terms of several models: as a possible indication of hadronic phase transition, as Cherenkov radiation or simply originating from a cascade mechanism. The rapid development in the field of pion multiplicity fluctuations in recent years is related to the large amount of high multiplicity data from well-known heavy ion experiments at CERN-SPS and BNL-RHIC. Although some progress has been made in understanding the fluctuation phenomena, a lot of questions remain unanswered.

2. Goal of the present study

In the quest for a quark–gluon plasma, which is the ultimate goal of heavy ion studies foreseen at the RHIC and LHC colliders, great expectations are placed on an event-by-event analysis. It is believed that the characterization of each collision event, in as much detail as possible, should reveal the onset of new phenomena that may occur rarely, only in those few individual events in which favorable conditions for the formation of the QGP state have been created. However, at much lower energy, where QGP formation is not possible, event-by-event fluctuation study is still important.

The study of event-by-event fluctuations in high-energy heavy-ion collisions may provide us more information about the multi-particle production dynamics [13–16]. The importance of event-by-event physics is evident from the following simple analogy, originally given by Prof. A.D. Jackson [3]: Stick a sheet of paper out of the window on a rainy day. Keeping it there for a long time corresponding to averaging the paper will become uniformly wet and one would conclude that rain is a uniform mist. If, however, one keeps the sheet of paper in the rain for a few seconds only, one observes the striking droplet structure of rain. Incidentally, one has also demonstrated the liquid–gas phase transition. Analyzing many events gives good statistics and may reveal rare events as snow or hail and thus other phase transitions. The statistics of droplet sizes will also tell something about the fragmentation, surface tension, etc. By varying initial conditions as timing and orienting the paper, one can further determine the speed and direction of the raindrops. Central ultra-relativistic collisions at RHIC and LHC are expected to produce many particles, and thus present one with the remarkable opportunity to analyze, on an event-by-event basis, fluctuations in physical observables such as particle multiplicities, transverse momenta, correlations and ratios. Analysis of single events with large statistics can reveal very different physics than studying averages over a large statistical sample of events. Event-by-event analysis is potentially a powerful technique to study relativistic heavy-ion collisions, as the magnitude of fluctuations of various quantities around their mean values is controlled by the dynamics of the system. For example, as stated earlier, the energy and multiplicity fluctuations of the many body system are related to, respectively, the heat capacity of the system and compressibility. The two susceptibilities strongly depend on the state of the system and they experience dramatic changes at phase transitions. So, measuring the fluctuations we can learn about effective degrees of freedom of the system and their interactions. Event-by-event fluctuations may provide us information about the heat capacity [15,17–19], possible equilibration of the system [20–28] or about the phase transition [19,29]. The NA49 Collaboration has presented a prototypical event-by-event analysis of fluctuations in central Pb + Pb collisions at 158 GeV/n [30,31]. Bialas and Koch [32] and Belkacem et al. [33] has found that moments of event-by-event fluctuations are closely related to inclusive correlation functions.

In the vicinity of the deconfinement phase transition, critical density fluctuations have been predicted to cause non-statistical event-by-event fluctuations of experimental observables. In particular, the study of event-by-event fluctuations in the hadro-chemical composition of the particle source offers the possibility to directly observe effects of a phase transition. Depending on the nature and the order of the phase transition one expects anomalies in the energy dependence of event-by-event fluctuations. Ideally, a sudden non-monotonous change in the dynamical fluctuations measured as a function of beam energy would be a signal of the critical endpoint. The use of Hanbury-Brown–Twiss (HBT) correlations to extract the system geometry is a familiar application of event-by-event physics in nuclear collisions [34] and elsewhere, e.g., in sonoluminescence [35]. The power of this tool has been strikingly illustrated in study of interference between Bose–Einstein condensates in trapped atomic systems [36]. Fluctuations in the microwave background radiation as measured by COBE [37] restrict cosmological parameters for the single Big Bang event of our universe. M. Toscano et al. [38] have measured the velocities of the neutron stars. Their study indicates that the supernova collapse is very asymmetrical and leads to large event-by-event fluctuations in “kick” velocities during formation of neutron stars. The tools applied to study these phenomena do, however, vary in order to optimize the analysis and due to limited statistics. The COBE and the interference in Bose–Einstein condensates require study of fluctuations within a single event. The HBT studies in heavy-ion collisions and sonoluminescence require further averaging over many events in order to obtain sufficient statistics; one has not yet studied fluctuations in source radii in event-by-event basis. Anisotropic flow requires an event-plane reconstruction in each event [39] but again averaging over many events is necessary to obtain a statistically relevant measurement of the flow. However, it will be worthwhile to mention that the event-by-event fluctuation of flow is indeed possible to measure. Very recently, ATLAS Collaboration has measured [40] the distributions of event-by-event harmonic flow coefficients v_n for $n = 2$–4 in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the ATLAS detector at LHC. The event-by-event fluctuations in heavy-ion collisions (and neutron star kick velocities) go a step further by studying variations from event to event.

Intermittency [41] studies in terms of factorial moments of the pion multiplicity distribution are related to event-by-event fluctuations. One of the motivations for intermittency studies was the idea of self-similarity on small scales, an idea borrowed from chaos theories. The factorial moments of particle multiplicities did find power-law behavior when the intervals of rapidity and angles were made increasingly smaller, at least until a certain small scale. The power-law scaling in nucleus–nucleus collisions was, however, weaker than in proton–proton collisions [3]. This indicated that the stronger correlations in proton–proton collisions were mainly due to resonances, minijets and other short-range correlations, but that they were averaged out in nuclear collisions by summing over the many individual participating nucleons. The scaling was not a collective phenomenon and indications of new physics were not found [42]. Numerous papers on event-by-event fluctuation study have been published in the field of high-energy collisions, as discussed earlier, but indeed measurements concerning the pseudo-rapidity fluctuations are very rare. The KLM Collaboration studied the event-by-event pseudo-rapidity fluctuations