Event-by-event analysis of maximum pseudo-rapidity gap fluctuation in high-energy nucleus-nucleus collisions

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Abstract – A detailed study of event-by-event maximum pseudo-rapidity gap fluctuations in relativistic heavy-ion collisions in terms of the scaled variance $\omega$ has been carried out for $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions at an incident momentum of 4.5 $\text{AGeV}/c$ applying the multiplicity cut ($N_s > 10$). For all the interactions the values of scaled variance are found to be greater than zero indicating the presence of strong fluctuation of maximum pseudo-rapidity gap values in the multiparticle production process. The event-by-event fluctuations are found to decrease with the increase of average multiplicity of the interactions. Experimental analysis has been compared with the results obtained from the analysis of events simulated by the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model. The UrQMD-model–simulated values of event-by-event fluctuations of the maximum pseudo-rapidity gap are less than the corresponding experimental values.

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Introduction. – High-energy nucleus-nucleus collisions deal with the production of copious amounts of various particles and multiplicity of such particles is extremely important to investigate the detailed characteristics of the particle production process. The goal of the 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. Fluctuation measurements in heavy-ion collisions have a good chance of being the signals of the QGP formation. The study and analysis of fluctuations are an essential method to characterize a physical system. Fluctuations of different observables of the final-state particles act as a probe to study the phase transition [1–4]. Fluctuation in particle multiplicity and momentum distribution has been found to be very useful to explore the thermalization and statistical behaviour of the produced particles [5–9]. Multiplicity fluctuation can tell us whether a global thermalization has been achieved [10]. 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. Studies of transverse energy fluctuations are very important [11,12] as energy density is directly related to the formation of QGP. Charge fluctuations [13–16] 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 a hadronic matter are clearly distinguishable. All these are interesting and deserve careful study. There has been evidence for the occurrence of multiplicity fluctuations in the pseudo-rapidity distributions [17–19]. The existence of such fluctuations would give information on the substructure in space-time of the collision region. Large fluctuations in the pseudo-rapidity window have been observed in cosmic-ray events and in hadron-hadron, nucleus-nucleus and hadron-nucleus interactions at accelerator energies [20,21]. 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 NA61/SHINE experiments using SPS energy, at RHIC and at the LHC. Although some progress has been made in understanding the fluctuation phenomena, a lot of questions remain unanswered.

Experimental details. – The present analysis is based on the interactions of $^{16}$O, $^{28}$Si and $^{32}$S projectiles at an incident momentum of 4.5 $\text{AGeV}/c$ with AgBr as
target present in nuclear emulsion. The data were obtained by exposing the stacks of NIKFI-BR2 emulsion pellicles of dimension $20 \text{cm} \times 10 \text{cm} \times 600 \mu\text{m}$ horizontally to $4.5 \text{AGeV}/c$ $^{16}\text{O}$, $^{28}\text{Si}$ and $^{32}\text{S}$ projectile beams at Dubna Synchrophasotron [22]. According to the terminology of nuclear emulsion, particles emitted from an interaction can be classified into four categories, namely the shower particles, the grey particles, the black particles and the projectile fragments [23]. The black and grey tracks together in an event are known as heavy tracks and are denoted by $N_h$. Shower particles are mostly pions (about more than 90%) with a small percentage of kaons and hyperons (less than 10%). Details about the black, grey, shower particles and projectile fragments can be found from our earlier publications [22,24,25]. The nuclear emulsion medium consists of variety of nuclei like H, C, N, O, Ag and Br. The number of H, C, N, O, Ag and Br atoms per c.c. in our emulsion plate has been given in table 1. In the emulsion experiment, it is very difficult to measure the charges of the fragments emitted from the target and hence exact identification of the target is not possible. However, we can divide the major constituent elements present in the emulsion into three broad target groups namely hydrogen (H), light nuclei (CNO) and heavy nuclei (AgBr) on the basis of the number of heavy (black + grey) tracks as discussed in [22,24,25].

According to the selection criteria discussed in [22,24,25], we have selected 1057 events of $^{16}\text{O}$-AgBr, 514 events of $^{28}\text{Si}$-AgBr and 434 events of $^{32}\text{S}$-AgBr interactions for the present analysis. We have performed our analysis on shower particles. Average multiplicities of shower tracks of each interaction have been calculated and presented in table 2. We have also calculated the statistical error associated with the average multiplicities of the shower tracks for our experimental events. The errors quoted in table 2 are a subjective estimate based on the sample standard deviation [24].

The emission angle ($\theta$) was measured with respect to the direction of the incident beam for each track by taking readings of the coordinates of the interaction point $(X_0, Y_0, Z_0)$, coordinates $(X_1, Y_1, Z_1)$ at the end of the each secondary track and coordinates $(X_i, Y_i, Z_i)$ of a point on the incident beam. In the case of shower particle multiplicity distribution the, phase space variable used is pseudo-rapidity $\eta$. The relation $\eta = -\ln \tan \frac{\theta}{2}$ relates the variable $\eta$ with the emission angle $\theta$.

**Goal of the present study.** – In the recent years studies of event-by-event fluctuations have gained immense popularity among the scientists. The study of event-by-event fluctuations in high-energy heavy-ion collisions may provide us with more information about the multiparticle production dynamics [26–34]. 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. It is believed that a detailed study of each event produced in high-energy nucleus-nucleus collision, may reveal new phenomena occurred in some rare events for which favourable conditions may have been created. High-energy nucleus-nucleus collisions produce a large number of particles. The study of a single event with large statistics can reveal very different physics than the analysis of averages over a large statistical ensemble. Event-by-event fluctuations may provide us information about the heat capacity [33,35–37], possible equilibration of the system [38–46] or about the phase transition [37,47]. An important characteristic of multi-particle production that deserves special attention is the maximum pseudo-rapidity gap. The maximum pseudo-rapidity gap ($\Delta \eta_{\text{max}}$) in an event has been defined as the difference of maximum and minimum pseudo-rapidity values of the two shower particles produced in an event. From the maximum pseudo-rapidity gap values one can get information about the particle production process. Diffractive processes are expected to contribute mainly due to the larger values of pseudo-rapidity gaps [48]. The study of event-by-event fluctuations of the maximum pseudo-rapidity gap is expected to be an important parameter to explore the dynamics of multiparticle production process. Maximum pseudo-rapidity gap values are also important to study long-range correlations suppressing the contributions from resonance and mini-jets [49]. So far investigations of fluctuations of pseudo-rapidity gaps have been carried out by different groups [40–53] to extract the dynamical signal of the particle production process. None so far have studied the event-by-event fluctuations of maximum pseudo-rapidity gap ($\Delta \eta_{\text{max}}$). This study may also be a potential source of information towards the hidden dynamics of the particle production process.

Our aim in this paper is to carry out a detailed analysis of the event-by-event fluctuations of the maximum pseudo-rapidity gap in terms of the scaled variance $\omega$ for $^{16}\text{O}$-AgBr, $^{28}\text{Si}$-AgBr and $^{32}\text{S}$-AgBr interactions at an incident momentum of $4.5 \text{AGeV}/c$. Experimental analysis has been compared with the results obtained from the analysis of events simulated by the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model.

**Analysis and results.** – Before going into the details of our analysis it will be convenient for the readers to

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**Table 1:** The number of H, C, N, O, Ag and Br atoms per c.c. in NIKFI-BR2 emulsion plate.

| Element | No. of atoms ($\times 10^{22} \text{cm}^{-3}$) |
|---------|----------------------------------|
| H       | 2.930                            |
| C       | 1.390                            |
| N       | 1.390                            |
| O       | 2.930                            |
| Ag      | 1.020                            |
| Br      | 1.020                            |
Table 2: The average multiplicities of the shower particles for all the interactions in the case of the experimental and UrQMD data for the full sample of events and events having $N_s > 10$.

| Interactions          | Experimental (full sample) | UrQMD (full sample) | Experimental events having $N_s > 10$ | UrQMD events having $N_s > 10$ |
|-----------------------|-----------------------------|---------------------|---------------------------------------|----------------------------------|
| $^{16}$O-AgBr         | 18.05 ± 0.22                | 17.79 ± 0.21        | 21.59 ± 0.22                          | 18.96 ± 0.21                     |
| $^{28}$Si-AgBr        | 23.62 ± 0.21                | 27.55 ± 0.22        | 27.44 ± 0.21                          | 27.71 ± 0.22                     |
| $^{32}$S-AgBr         | 28.04 ± 0.14                | 30.84 ± 0.17        | 31.32 ± 0.24                          | 30.90 ± 0.17                     |

Fig. 1: (a) Multiplicity distribution of shower particles for the experimental and UrQMD events for $^{16}$O-AgBr interactions. (b) Multiplicity distribution of shower particles for the experimental and UrQMD events for $^{28}$Si-AgBr interactions. (c) Multiplicity distribution of shower particles for the experimental and UrQMD events for $^{32}$S-AgBr interactions.

have a look into the multiplicity distribution and pseudo-rapidity distribution of the data sample. It should be mentioned here that in an earlier paper [54] we have presented an extensive analysis of multiplicity distribution of shower particles for $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions at an incident momentum of 4.5 AGeV/c. Figures 1(a)–(c) represent the multiplicity distribution of shower particles for $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions at an incident momentum of 4.5 AGeV/c. Figures 2(a)–(c) represent the pseudo-rapidity distribution of shower particles of the concerned data set.

As we are dealing with interactions at 4.5 AGeV/c, problems may be caused by lower-multiplicity events. To avoid this for the present analysis we have selected those events which have the number of shower particles ($N_s$) greater than 10. The average multiplicity of those events having number of shower tracks greater than 10 ($N_s > 10$) have been presented in table 2. In order to calculate the event-by-event fluctuations of the maximum pseudo-rapidity gap ($\Delta \eta_{\text{max}}$) in $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions at 4.5 AGeV/c, we have calculated the maximum pseudo-rapidity gap for each event of each interaction. The quantification of event-by-event fluctuations of the maximum pseudo-rapidity gap has been performed with a variable $\omega$, called the scaled variance such that $\omega = \frac{\langle \Delta \eta_{\text{max}}^2 \rangle - \langle \Delta \eta_{\text{max}} \rangle^2}{\langle \Delta \eta_{\text{max}} \rangle}$. Event-by-event fluctuation of the maximum pseudo-rapidity gap signifies the correlated production of shower particles. We have calculated the value of the scaled variance $\omega$ and presented the calculated values in table 3. Errors associated with the maximum pseudo-rapidity gap fluctuation value are the statistical errors. The statistical error of the scaled variance has been calculated following [55,56]. If the scaled variance $\omega = \frac{\langle \Delta \eta_{\text{max}}^2 \rangle - \langle \Delta \eta_{\text{max}} \rangle^2}{\langle \Delta \eta_{\text{max}} \rangle}$, the statistical error of $\omega$ is given by $\sigma(\omega) = \sqrt{\text{Var}(\omega)}$. In our study, calculating the variance of $\frac{\langle \Delta \eta_{\text{max}}^2 \rangle - \langle \Delta \eta_{\text{max}} \rangle^2}{\langle \Delta \eta_{\text{max}} \rangle}$ as described in [56], we have estimated the statistical errors associated with our variable.

From table 3 it may be pointed out that the values of the scaled variance indicating event-by-event fluctuations of the maximum pseudo-rapidity gap are found to be
greater than zero indicating the presence of strong fluctuation of the maximum pseudo-rapidity gap values in the multiparticle production process. From table 2 and table 3 it can be easily seen that the values of the event-by-event fluctuations of the maximum pseudo-rapidity gap decrease with the increase of the average multiplicity \( \langle N_s \rangle \) of the interactions. The variation of the variable \( \omega \) with the average multiplicity of interactions \( \langle N_s \rangle \) has been presented in fig. 3 for all the interactions.

The experimental results have been compared with those obtained by analyzing events generated by the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model. The UrQMD model is a hadronic transport model based on the covariant propagation of all the hadrons on the classical trajectories in combination with stochastic binary scattering, color string formation and resonance decay. This model can be used in the entire available range of energies from the Bevalac region to RHIC to simulate the nucleus-nucleus collisions. For more details about this model, readers may refer to [57,58]. We have generated a large sample of events using the UrQMD code (UrQMD 3.3p1) for \(^{16}\text{O}-\text{AgBr}\), \(^{28}\text{Si}-\text{AgBr}\) and \(^{32}\text{S}-\text{AgBr}\) interactions in the pseudo-rapidity phase space [25]. The multiplicity distribution and pseudo-rapidity distribution of the UrQMD-model–generated data sample have been presented in figs. 1(a)–(c) and 2(a)–(c), respectively, along with the experimental multiplicity and pseudo-rapidity distribution. From figs. 2(a)–(c) it may be seen that the peaks of the pseudo-rapidity distribution of the experimental data do not coincide with that of the UrQMD simulated data. In the nuclear emulsion track detector one cannot determine the centrality of collisions. While simulating the emulsion data by the UrQMD model...
as we do not know the range of centrality, we give a different impact parameter range in the input file of the UrQMD data and test which one comes closer with respect to the average multiplicity and the rapidity distribution. In our case we have chosen $b_{\text{max}} = 6$ and $b_{\text{min}} = 0$ to get the required data. Different other combinations of $b_{\text{max}}$ and $b_{\text{min}}$ were also tried but this value of $b_{\text{max}}$ and $b_{\text{min}}$ gives the simulated data with comparable average multiplicity and rapidity distribution. If we can determine the centrality range of the experimental data we can match the rapidity distribution of the simulated data with the experimental one exactly.

We have also calculated the average multiplicities of the shower tracks for all the three interactions in the case of the UrQMD data sample. Average multiplicities of the shower tracks in the case of the UrQMD data sample have been presented in table 2 along with the average multiplicity values of shower particles in the case of the experimental events. Errors associated with the average multiplicity of the UrQMD data sample are also statistical errors calculated in the same way as done in the case of the experimental data. The analysis of event-by-event maximum pseudo-rapidity gap fluctuations has been repeated with the UrQMD simulated events with the multiplicity cut ($N_s > 10$). The average multiplicity of all the interactions for the UrQMD events after applying the multiplicity cut ($N_s > 10$) has also been presented in table 2. The errors shown in table 2 are statistical errors. The calculated values of the scaled variance signifying event-by-event fluctuations for the UrQMD simulated events have been presented in table 3 for $^{16}$O-AgBr, $^{28}$Si-AgBr, $^{32}$S-AgBr interactions. From table 3 it may be seen that the UrQMD model simulated values of event-by-event fluctuations of the maximum pseudo-rapidity gap are less than the corresponding experimental values. So the UrQMD model reflects weaker dynamical fluctuations in comparison to the experimental data. From the table it can also be seen that for the UrQMD events, the event-by-event fluctuations of the maximum pseudo-rapidity gap decreases with the increase of the average multiplicity of the interactions. The variation of the variable $\omega$ with the average multiplicity of the interactions has been presented in fig. 3 in the case of the UrQMD-simulated events along with the experimental events.

Before we conclude, let us discuss the effect of systematic uncertainties on our analysis. In the nuclear emulsion detector, sources of systematic uncertainties are the scanning procedure, fading of tracks and the presence of background contaminations. It has been discussed in our earlier papers that the total contribution of systematic errors coming out from the scanning procedure, fading of tracks, and presence of background contaminations is around (1–2)% [59,60]. It has been pointed out earlier that the shower particles are mostly pions (more than 90%) with a small proportion (less than 10%) of kaons and hyperons among them. The presence of K-mesons, hyperons and any other mesons among the pions are treated as contaminations. As the nuclear emulsion track detector cannot distinguish between pions and other mesons or hyperons, one possible source of systematic uncertainty is the presence of such contaminations among the shower particles. We have calculated the maximum systematic uncertainty while dealing with shower particles for $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions in [60]. The contribution to the systematic errors due to the presence of other mesons and hyperons with the pions in the shower particles has been calculated [60]. The total contributions of systematic errors in our analysis for $^{16}$O-AgBr, $^{28}$Si-AgBr and $^{32}$S-AgBr interactions at an incident momentum of 4.5 AGeV/c are 9.60%, 10.22% and 10.56%, respectively.

**Conclusions.** – The study of event-by-event maximum pseudo-rapidity gap fluctuations in terms of the scaled variance $\omega$ has been carried out for $^{16}$O-AgBr, $^{28}$Si-AgBr, $^{32}$S-AgBr interactions at an incident momentum of 4.5 AGeV/c applying the multiplicity cut ($N_s > 10$). For all the interactions event-by-event maximum pseudo-rapidity gap fluctuations are found to be greater than zero indicating the presence of strong correlations in the multiparticle production process. The event-by-event fluctuations of the maximum pseudo-rapidity gap are found to decrease with the increase of the average multiplicity of the interaction. Experimental analysis has been compared with the results obtained from the analysis of events simulated by the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model. The UrQMD-predicted values of event-by-event maximum pseudo-rapidity gap fluctuations decrease with the increase of the average multiplicity of the interactions. However, the UrQMD model predicts weaker fluctuations in comparison to the experimental analysis.

This is the first ever report of event-by-event analysis of maximum pseudo-rapidity gap fluctuations in high-energy nucleus-nucleus collisions at a few AGeV/c. It may be interesting to apply this technique to RHIC BES I and II data, data of the NA61/SHINE Collaboration and data of LHC in the future.

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