ON EVENT-BY-EVENT PSEUDORAPIDITY FLUCTUATIONS IN RELATIVISTIC NUCLEAR INTERACTIONS*

M. Mohisin Khan†, Danish F. Meer

Department of Applied Physics, ZHCET, Aligarh Muslim University
Aligarh, India

Tahir Hussain

Applied Sciences and Humanities Section, University Polytechnic
Aligarh Muslim University, Aligarh, India

Nazeer Ahmad

Department of Physics, Aligarh Muslim University, Aligarh, India

(Received June 30, 2020; accepted January 20, 2021)

Present study is an attempt to have a detailed look into event-by-event (e-by-e) pseudorapidity fluctuations of the relativistic charged particles produced in ^{28}Si–nucleus interactions at incident momenta 4.5 A and 14.5 A GeV/c. The method used in the present study makes use of a kinematic variable which is derived in terms of the average pseudorapidity and the total number of particles produced in a single event. The multiplicity and pseudorapidity dependence of these fluctuations have also been studied. The results obtained for the experimental data are compared with a HIJING simulation.

DOI:10.5506/APhysPolB.52.53

1. Introduction

Relativistic nuclear collisions are the most fascinating and important means to produce matter under extreme conditions of temperature and density. The key point to study and understand the behavior of this produced matter is the copious production of secondary particles in these collisions.

* Funded by SCOAP[3] under Creative Commons License, CC-BY 4.0.

† mohsinkhan.ph@amu.ac.in

The global observable such as multiplicity and pseudorapidity of produced particles play an important role in understanding the particle-production process in the relativistic hadron–hadron, hadron–nucleus and nucleus– nucleus collisions. The current interest in such studies is mainly to understand the characteristics of quark–gluon plasma (QGP) and the scenario of phase transition from QGP to the normal hadronic phase. Fluctuations in the values of global observable have always been considered as one of the possible signature of QGP formation [1]. Various nearly conclusive studies [2–5] regarding QGP formation and its signatures have been made using the data on three experimental energy regime from the SPS, RHIC and LHC.

As the matter produced in high-energy heavy-ion collisions is a short-live state and the hadronization after the collisions is very fast, one has to rely on the observations made on the characteristics of the produced particles. The study of the particles coming out of the interaction region may provide important information regarding the underlying dynamics of collision process and the multi-particle production. Fluctuations in general and the e-by-e fluctuations of observable in particular are envisaged to give vital information about the phase transition [5–9]. The process of thermalization along with the statistical behavior of the produced particles can be understood by studying the fluctuation in particle multiplicity and momentum distribution [10–15]. Reference [6] stressed that the charge fluctuations may be an evidence of QGP formation. Many such studies about the fluctuations have been carried out. However, critical point of QGP phase transition can be well studied using the concept of e-by-e fluctuations because in this case the fluctuations are predicted to be large enough [14–17]. A study of each event produced in relativistic nuclear collision may reveal new physical phenomena occurring in some rare events for which conditions might have been created in these collisions. Nuclear collisions at high energies produce a large number of particles, the analysis of single event with large multiplicity can shed light on some different physics than the study of averages over a large events. Predictions have been made about the occurrence of critical density fluctuations in the vicinity of the phase transition and its manifestation as e-by-e fluctuation of different physical observable [18]. The e-by-e analysis may offer a possibility of observing a phase transition directly if the particle emitting source is a hydro-chemical composition. The NA49 Collaboration [10] observed the fluctuations of transverse momentum and kaons-to-pions ratio in central Pb–Pb collisions at 158 A GeV. Bialas and Koch [9] and Belkacem *et al.* [19] reported that the moments of e-by-e fluctuations are very nearly related to the correlation function. The ALICE Collaboration [20] has measured the e-by-e fluctuation in mean transverse momentum in p–p and Pb–Pb collisions at the LHC. A number of papers are available in literature on the e-by-e fluctuation analysis of different observables but very

few papers are there on e-by-e pseudorapidity fluctuations. The first such a study was carried out by the KLM Collaboration for 158 A GeV Pb–AgBr interactions [21]. Recently Bhattacharya *et al.* [18] and Gopa Bhoumic *et al.* [22] have carried out the e-by-e pseudorapidity fluctuations analyses on various emulsions data having different projectiles and targets at 4.1 A GeV, 4.5 A GeV, 60 A GeV and 200 A GeV.

In the present study we have carried out the e-by-e fluctuations analysis for the data at 4.5 A and 14.5 A GeV ^{28}Si–AgBr interactions for the experimental and HIJING simulated data.

The following sections of this paper are devoted to the details of the data, analysis methods, results and discussion and the observations made on the basis of obtained results.

2. Experimental details of the data

The present analysis has been carried out on the experimental and simulated data. For the experimental data, two random samples consisting of 555 events of 14.5 A GeV/c ^{28}Si–nucleus interactions and 530 events of 4.5 A GeV/c ^{28}Si–nucleus interactions with $N_s \geq 10$ have been used, where N_s represents the number of charged particles produced in an event with relative velocity ($\beta = v/c > 0.7$). The emission angles of the relativistic charged particles were measured and their pseudo rapidities ($\eta = -\ln(\tan(\theta/2))$ are determined. All other details about the data may be found elsewhere [23, 24]. Furthermore, for comparing the experimental results with the corresponding values obtained for the events generated by the Monte Carlo code HIJING-1.33 [25] event generator, a similar sample of events was simulated.

3. Method of analysis

Gaździcki and Mrówczyński [7] proposed an excellent method to measure the fluctuations of any global kinematic variable. It is worth mentioning that the second moment of distributions of global kinematic variables (multiplicity, rapidity, transverse momentum *etc.*) for individual events or all the events taken together may shed light on the extent of thermalization and randomization feature of high-energy nuclear collisions. The basic idea used in this method is the fact that the correlated production of particles in each elementary interaction leads to large e-by-e fluctuations and these fluctuations in high-energy nuclear collisions are believed to originate due to trivial variation in impact parameter of the interaction. It may also be aroused due to some statistical reasons or due to some dynamical reason of the underlying processes prevailing at the instant of the collisions. The method proposed here [7] automatically filters the trivial contributions and provides a way to determine the remaining part contributing to the fluctuations. For

this, a variable Φ which is believed to be a measure of fluctuation is defined, whose non-zero values point towards the correlation and fluctuation and a vanishing value of Φ points towards the independent particle emission (random emission) from a single source. The detailed procedure of calculating this variable is described below.

As the global kinematic variable used in the present analysis to study the e-by-e fluctuation is the pseudorapidity, η, of the emitted particles, we first define a single-particle variable z in terms of η as

$$z = \eta - \bar{\eta}\,, \tag{1}$$

where $\bar{\eta}$ represents the mean value of single-particle inclusive pseudorapidity distribution that can be expressed as

$$\bar{\eta} = \frac{1}{N_{\text{total}}} \sum_{m=1}^{N_{\text{evt}}} \sum_{i=1}^{N_m} \eta_m\,, \tag{2}$$

where N_m is the multiplicity of m^{th} event. The second summation over i in the above equation runs over all the particles produced in the m^{th} event, and the first summation is performed over all the events N_{evt} in the sample. N_{total} in the denominator is the total number of particles produced in all the events. Further, a multi-particle analogue of z, Z_k, is defined as

$$Z_k = \sum_{i=1}^{N_k} \eta_i - \bar{\eta}\,. \tag{3}$$

Finally, the measure of fluctuation parameter, Φ, is defined as

$$\Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N_{\text{total}} \rangle}} - \sqrt{\bar{z}^2}\,, \tag{4}$$

where the $\langle Z^2 \rangle$ and $\langle N_{\text{total}} \rangle$ represent the event averaged of the variables therein, and the $\sqrt{\bar{z}^2}$ is the square root value of the second moment of inclusive z distribution. As stated [7], Φ vanishes when there is no correlation among the produced particles and its non-vanishing values are a measure of correlations and fluctuation present in the system. This method has been extensively used with success to analyze many experimental data [18, 21] and to verify various aspects theoretically [26, 27]. In the present analysis, we have attempted to study the e-by-e fluctuation in 4.5 A and 14.5 A GeV/c ^{28}Si–nucleus interactions.

4. Results and discussion

First of all, the values of Φ are calculated for different groups of events selected on the basis of the average multiplicity of the relativistic charged particles, $\langle N_s \rangle$. This calculation has been made for both the experimental and simulated data. These values along with statistical errors are tabulated in Table I. The different groups are selected in such a way to ensure that the average multiplicity of the group is greater than the average multiplicity of the sample of the data. In the table tabulated are the values of Φ and

TABLE I

Calculated values of Φ for different multiplicity classes for the experimental and HIJING simulated data.

Interactions	Multiplicity selection	Experimental		HIJING	
		$\langle N_s \rangle$	Φ	$\langle N_s \rangle$	Φ
4.5 A GeV/c ^{28}Si–nucleus	$N_s \geq 10$	15.33	5.402 ± 0.073	17.85	4.491 ± 0.088
	$N_s \geq 20$	31.54	5.010 ± 0.071	33.55	3.923 ± 0.080
	$N_s \geq 30$	42.14	4.410 ± 0.082	39.74	3.108 ± 0.082
	$N_s \geq 40$	52.76	4.106 ± 0.088	51.23	2.213 ± 0.089
	$N_s \geq 50$	64.75	3.710 ± 0.069	63.25	1.984 ± 0.094
14.5 A GeV/c ^{28}Si–nucleus	$N_s \geq 10$	24.98	5.281 ± 0.074	19.71	3.874 ± 0.089
	$N_s \geq 20$	33.99	5.010 ± 0.077	36.25	3.093 ± 0.101
	$N_s \geq 30$	47.99	4.740 ± 0.088	43.55	2.823 ± 0.113
	$N_s \geq 40$	51.86	3.901 ± 0.097	50.55	2.123 ± 0.134
	$N_s \geq 50$	64.66	2.558 ± 1.066	61.58	1.674 ± 0.149

the averaged multiplicity of relativistic charged particles, $\langle N_s \rangle$, for various multiplicity classes for the experimental and simulated events. It is observed from the table that the values of Φ are non-zero for all the multiplicity classes considered in the present study and this observation is the same for both the experimental and simulated data at the two incident energies for ^{28}Si–nucleus interactions. These non-zero values of Φ support the occurrence of dynamical fluctuations in the η-variable and the presence of correlation during particle production process in high-energy nucleus–nucleus collisions. It is also observed from the table that the Φ, which is considered to be the strength of correlation and fluctuation, shows a decreasing trend with increasing $\langle N_s \rangle$. This dependence on $\langle N_s \rangle$ is shown in Fig. 1. The errors shown in Fig. 1 are the statistical ones. It is clear from Fig. 1 that the e-by-e η fluctuation tends to decrease with increasing mean multiplicity of the produced relativistic charged particles. This may be due to the fact that the contribution to particle production would have taken place by several independent sources. These contributions might be masking the correlated

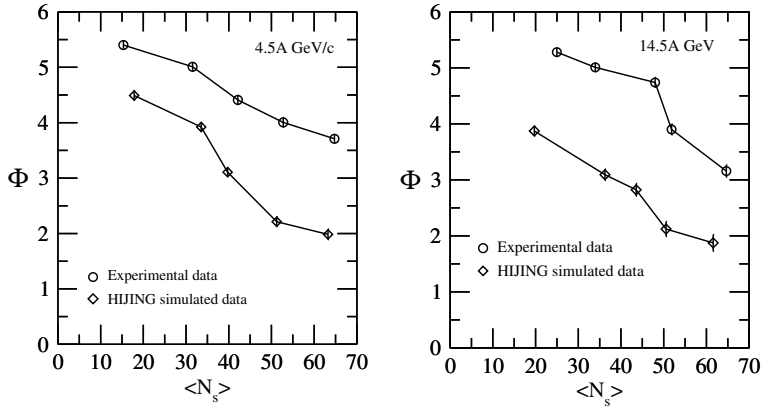


Fig. 1. Variation of Φ with $\langle N_{\mathrm{s}} \rangle$ for the experimental and simulated data on ^{28}Si–nucleus interactions.

production. One can argue that there are identical sources which are producing low-multiplicity events which is resulting in the low-Φ values. It means that when source fluctuation tends to vanish, pseudorapidity fluctuation increases. This observed trend of variation of Φ with the average multiplicity at high energies is in agreement with observations made by other studies in high-energy regime [18, 20, 21]. To compare the experimental results with HIJING simulation, samples of events are generated with statistics approximately 10 times that of the experimental statistics. It is clear from Fig. 1 that the Φ values obtained for HIJING data are lower than its values for the experimental data at both the energies but the trend of variation of Φ with $\langle N_{\mathrm{s}} \rangle$ is almost the same for both experimental and simulated data.

Another interesting aspect of the e-by-e pseudorapidity fluctuation or the fluctuation of any global observable describing high-energy nuclear collision data is to see its dependence on phase-space region, which in this study is the pseudorapidity space itself. For this, the values of Φ are determined for various pseudorapidity intervals, $\Delta\eta = \eta_2 - \eta_1$, where η_1 and η_2 are the lower and upper limit of a chosen η-window. In the present study, the chosen $\Delta\eta$ are 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0 for both the data sets. The calculated values of Φ corresponding to these pseudorapidity regions are listed in Table II. It is observed from Table II that as we widened the pseudorapidity space, we noticed larger e-by-e fluctuations. The values of Φ first increase with increasing $\Delta\eta$ and then tend to saturate for much larger $\Delta\eta$. This behavior is observed at both the energies considered in this analysis. This might be due to the dominating long-range correlations as compared to short-range correlations as we explore a larger rapidity space. Based on phenomenological evidence, it has been argued that particle production in high-energy hadron–hadron and nucleus–nucleus collisions have been carry-

TABLE II

Calculated values of Φ in different pseudorapidity windows for the experimental and HIJING simulated data.

Interactions	$\Delta\eta$	Φ	
		Experimental	HIJING
4.5 A GeV/c ^{28}Si–nucleus	0.5	0.199 ± 0.009	0.116 ± 0.008
	1.0	0.499 ± 0.018	0.362 ± 0.023
	1.5	1.159 ± 0.028	0.905 ± 0.082
	2.0	2.179 ± 0.041	1.937 ± 0.088
	2.5	2.890 ± 0.098	2.987 ± 0.092
	3.0	3.972 ± 0.101	3.257 ± 0.098
	4.0	4.452 ± 0.161	4.096 ± 0.117
	5.0	4.622 ± 0.201	4.362 ± 0.188
	6.0	5.027 ± 0.211	4.674 ± 0.198
14.5 A GeV/c ^{28}Si–nucleus	0.5	0.194 ± 0.006	0.102 ± 0.021
	1.0	0.387 ± 0.009	0.341 ± 0.029
	1.5	1.097 ± 0.021	0.891 ± 0.038
	2.0	2.063 ± 0.082	1.912 ± 0.043
	2.5	2.732 ± 0.111	2.889 ± 0.055
	3.0	3.817 ± 0.128	3.172 ± 0.076
	4.0	4.158 ± 0.141	3.995 ± 0.102
	5.0	4.489 ± 0.188	4.355 ± 0.111
	6.0	4.811 ± 0.214	4.788 ± 0.175

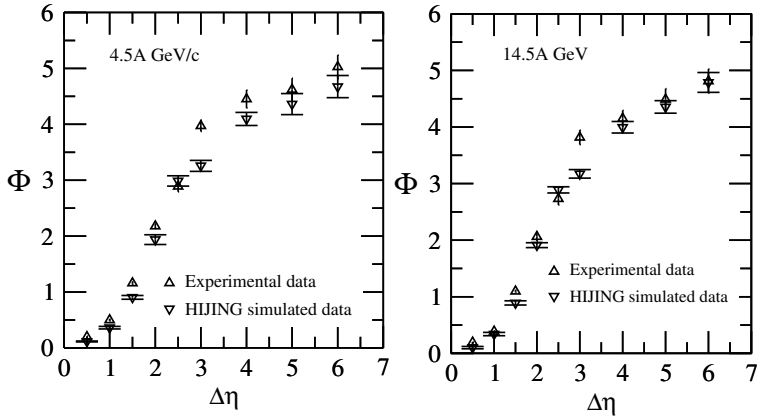


Fig. 2. Variation of Φ with $\Delta\eta$ for the experimental and simulated data on ^{28}Si–nucleus interactions.

ing the signals of both the short- and long-range correlations. The average number of produced particles virtually depends on the size of the initiating cluster, this gives rise to the long-range correlation, means the particles which are separated by relatively large η show some correlation. The values of Φ for HIJING simulated data are smaller as compared to its values for the experimental data but HIJING data too show the similar dependence of Φ on $\Delta\eta$. These observations are much more clearly depicted in Fig. 2, where we plotted Φ against $\Delta\eta$ along with statistical errors.

5. Conclusions

Event-by-event fluctuations of pseudorapidity of the relativistic charged particles produced in ^{28}Si–nucleus interactions at 4.5 A and 14.5 A GeV/c have been studied in terms of the fluctuation and correlation quantifying parameter, Φ. Analysis reveals the presence of e-by-e η fluctuations and correlation amongst the produced particles in pseudorapidity space at both the incident momentum as the non-vanishing values of Φ are obtained. It is observed that these fluctuations decrease with increasing mean multiplicities of the produced particles. This might be due to smearing out of the existing correlation as the more and more independent particle emitting sources are added up. E-by-e fluctuations are also found to depend on the pseudorapidity windows and show an increasing behavior with increasing $\Delta\eta$. Results obtained for HIJING data exhibit a similar trend as compared to the experimental data at both the energies. Correlation and fluctuation studies remain to be excellent tools to explore the behavior of the system produced in heavy-ion collisions at relativistic and ultra-relativistic energies.

Financial support from DST, Government of India is acknowledged with thanks.

REFERENCES

[1] M.A. Stephanov, K. Rajagopal, E.V. Shuryak, «Signatures of the Tricritical Point in QCD», *Phys. Rev. Lett.* **81**, 4816 (1998).

[2] M. Luzum *et al.*, «Initial state fluctuations and final state correlations in relativistic heavy-ion collisions», *J. Phys. G.* **41**, 063102 (2014).

[3] Y.Yoki *et al.*, «The order of the quantum chromodynamics transition predicted by the Standard Model of particle physics», *Nature* **443**, 675 (2006).

[4] S. Jeon *et al.*, «Detecting quark gluon plasma with charge transfer fluctuations», *Phys. Rev. C* **73**, 014905 (2006).

[5] L.F. Babichev, A.N. Khmialeuski, Proceeding of 15$^{\text{th}}$ Int. Conf.-School, September 20–23, 2010.

[6] M. Weber, «Correlations and fluctuations studied with ALICE», *J. Phys.: Conf. Ser.* **389**, 012036 (2012).

[7] M. Gaździcki, S. Mrówczyński, «A method to study "equilibration" in nucleus–nucleus collisions», *Z. Phys. C* **54**, 127 (1992).

[8] E.V. Shuryak, «Event-by-event analysis of heavy ion collisions and thermodynamical fluctuations», *Phys. Lett B* **423**, 9 (1998).

[9] A. Bialas, V. Koch, «Event-by-event fluctuations and inclusive distributions», *Phys. Lett. B* **456**, 1 (1999).

[10] H. Appelshäuser *et al.*, «Event-by-event fluctuations of average transverse momentum in central Pb+Pb collisions at 158 GeV per nucleon», *Phys. Lett. B* **459**, 679 (1999).

[11] G. Baym, H. Heisenberg, «Event-by-event fluctuations in ultrarelativistic heavy-ion collisions», *Phys. Lett. B* **469**, 7 (1999).

[12] G.V. Danilov, E.V. Shuryak, «On the Origin of the Multiplicity Fluctuations in High Energy Heavy Ion Collisions», arXiv:nucl-th/9908027.

[13] T. Anticic *et al.*, «Transverse momentum fluctuations in nuclear collisions at 158 A GeV», *Phys. Rev. C* **70**, 034902 (2004).

[14] T.K. Nayak, «Event-by-event fluctuations and the QGP phase transition», *J. Phys. G.* **32**, S187 (2006), arXiv:nucl-ex/060802.

[15] H. Heiselberg, «Event-by-event physics in relativistic heavy-ion collisions», *Phys. Rep.* **351**, 161 (2001).

[16] M. Stephanov, «QCD Phase Diagram and the Critical Point», *Prog. Theor. Phys. Suppl.* **153**, 139 (2004).

[17] M. Stephanov *et al.*, «Angular distribution and asymmetries in the decays and», *Phys. Rev. D* **61**, 114028 (2000).

[18] S. Bhattacharya *et al.*, «Event-by-event pseudo-rapidity fluctuations in high energy nucleus–nucleus interactions», *Phys. Lett. B* **726**, 194 (2013).

[19] M. Belkacem *et al.*, «Moments of event observable distributions and many-body correlations», arXiv:nucl-th/9903017.

[20] B. Abelev *et al.*, «Event-by-event mean p_{T} fluctuations in pp and Pb–Pb collisions at the LHC», *Eur. Phys. J. C* **74**, 3077 (2014).

[21] KLM Collaboration (M.L. Cherry *et al.*), «Event-by-Event Analysis of High Multiplicity Pb(158 GeV/nucleon)–Ag/Br Collisions», *Acta Phys. Pol. B* **29**, 2129 (1998).

[22] Gopa Bhoumic *et al.*, «Event-by-Event pseudorapidity fluctuation analysis: An outlook to multiplicity and phase space dependence», *Eur. Phys. J. A* **52**, 196 (2016).

[23] S. Ahmad *et al.*, «Study of Non-Statistical Fluctuations in Relativistic Nuclear Collisions», *J. Phys. Soc. Jpn.* **75**, 064604 (2006).

[24] S. Ahmad *et al.*, «Erratic Fluctuations in Rapidity Gaps in Relativistic Nucleus–Nucleus Collisions», *Acta Phys. Pol. B* **35**, 809 (2004).

[25] M. Gyulassy, X.N. Wang, «HIJING1.0: A Monte Carlo program for parton and particle production in high energy hadronic and nuclear collisions», *Comp. Phys. Commun.* **83**, 307 (1994).

[26] M. Gaździcki *et al.*, «On event-by-event fluctuations in nuclear collisions», *Eur. Phys. J. C* **6**, 365 (1999).

[27] M. Mrówczyński, «Transverse momentum and energy correlations in the equilibrium system from high-energy nuclear collisions», *Phys. Lett. B* **439**, 6 (1998).