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NUCLEAR PHYSICS

Event-to-Event Fluctuation Analysis for Pions and Protons at SPS Energy

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Abstract This study reports a detailed analysis of spatial fluctuations as well as event-to-event fluctuations of compound hadrons (pions + protons) produced in ^{32}S–AgBr interactions at 200 AGeV with a new technique known as *erraticity analysis*. This analysis is done for both emission-angle and azimuthal-angle phase spaces using gap-moment method. The study provides a strong evidence of erratic behavior of compound hadrons in ultra-relativistic nuclear collisions.

Keywords Erratic behavior · Fluctuations · Gaps and compound hadrons

1 Introduction

In multiparticle production process, the density of emitted particle spectra fluctuates from phase-space bin to bin for each interaction. The density likewise fluctuates from one event to another, a variation that is called event-space fluctuation. The scaled factorial moments (SFMs) introduced by Bialas and Peschanski [1] are capable of detecting and characterizing non-statistical density fluctuations in the final-state phase-space particle distribution. The analyses based on SFMs have been extensively and successfully applied in many high-energy experiments [2–8], and efforts have been made to interpret these fluctuations as phase transitions, production of shock waves and related phenomena, or simple cascading effects [9–13]. The factorial moments can delete the dynamical part of the spatial fluctuation; moreover, when averaged over a large sample of events, they may lose information on the variation of such spatial fluctuations from event to event. For example, the creation of an exotic state such as a quark–gluon plasma (QGP) may result in large spatial fluctuations in the density distribution of final-state hadrons. This may happen in only a few of the events, not over the entire event sample under consideration. In the process of averaging, information on such large fluctuations may be smoothed out. Hwa and Zhang [14] proposed another method named erraticity which simultaneously takes care of spatial and event-space fluctuations.

Two different approaches describe these fluctuations: one follows the moment of the SFM distribution from event to event, a method based on bin multiplicities [15–17]. The other is the gap-moment approach, based on the gaps between the neighboring particles [14]. In case of low multiplicity events, the former one is unsuitable to measure dynamical fluctuations for erraticity analysis [18]. For low event multiplicity (n) and high number of bins (M) the ratio n/M is very small and only a few events will contribute to the SFM, which in turn makes the description of the spatial pattern events uncertain [18].

The data in the present analysis is a combination of fast-target recoil protons and pions produced in high-energy interactions. We will use the expression *compound hadron* to refer to this combination, a set of grey and shower tracks, in nuclear-emulsion terminology [19]. The shower tracks are mainly pions. Just after the pions are produced, few target recoil protons in the 30 to 400 MeV energy range come out of

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the interacting region, which manifest themselves as grey particles in emulsion media [19].

The gap-moment erraticity analysis has been applied to several high-energy hadronic and nuclear interactions [20–22]. Although the analysis is centered on the produced pions, medium-energy (30–400 MeV) knocked out protons, which manifest themselves as grey particles in nuclear emulsion, also play an important role [23–27]. It is generally believed that the grey particles carry relevant information about the hadronization mechanism, since the time scale for their emission is comparable to the time scale for the production of shower particles. The grey particles are therefore expected to remember part of the reaction history. One may consider pions and medium-energy protons on equal footing, without distinction, and call them compound hadrons [28].

Accordingly, one can combine the number of grey (n_g) and shower (n_s) particles per event in a collision into a new parameter, the *compound multiplicity* $n_c=n_g+n_s$, which is expected to play an important role in understanding the reaction dynamics in high-energy nuclear interactions. Nonetheless, no erraticity analysis has so far been performed with compound hadrons. The objectives of the present work are (1) to comprehensively investigate the erraticity characteristics of compound hadrons produced in ^{32}S beam at incident energy 200 AGeV for both cosθ and ϕ spaces and (2) to compare the results of ^{32}S–AgBr interactions at 200 AGeV for compound hadrons with the results obtained earlier from the analysis of the hadrons produced by the same interactions [21].

2 Experimental Details

The data set for our analysis was obtained by exposing G5 nuclear-emulsion plates to a ^{32}S beam at 200-AGeV incident energy at CERN SPS. The details of scanning and measurement have been described in our previous publication [29]. For this study, we have taken 140 events of ^{32}S–AgBr interactions at 200 AGeV. According to nuclear-emulsion terminology, grey and shower tracks are identified by the following characteristics:

1. Tracks with greater than 3-mm range and ionization within the $1.4I_0<I<6I_0$ range are grey tracks, I_0 being the minimum ionization produced by a singly charged particle. The minimum ionization I_0 is related to the grain density, about 14–15 grains per 100 μm in this investigation.
2. Shower tracks are formed by relativistic particles with ionization $I<1.4I_0$, which are not generally confined to the emulsion pellicle.

The data we used is a combination of grey and shower tracks.

For each track, to determine the emission (θ) and azimuthal (ϕ) angles relative to the beam direction, we read the coordinates of the interaction point (X_0, Y_0, Z_0), the coordinates (X_1, Y_1, Z_1) of a point on each secondary track, and the coordinates (X_i, Y_i, Z_i) of a point on the incident beam and used basic coordinate geometry. The emulsion technique possesses very high spatial resolution, which makes it a very effective detector of the erratic behavior of the gaps between the neighboring particles in multiparticle production.

3 Method of Study

The non-uniformity of particle spectra influences the scaling behavior of factorial moments. Bialas and Gazdzicki [30] proposed a method to construct a set of variables that drastically reduce the distortion of intermittency due to the non-uniform single-particle density distribution ρ(z) [31]. They define a new, scaled variable X_z related to the single-particle density distribution ρ(z) by the equality [30–32]

$$X_z = \int_{z_{\min}}^{z} \rho(z')\partial z' \Big/ \int_{z_{\min}}^{Z_{\max}} \rho(z')\partial z' \qquad (1)$$

where $z_{\min}$ and $z_{\max}$ are the two extreme points of the distribution, and z represents the cosθ and ϕ phase-space variable. The variable X_z is uniformly distributed between 0 and 1.

One can consider an event with n particles, labeled by $i=1,2,.......n$, located in X_z space at X_i, ordered from the left to the right. The distances between neighboring particles are given by

$$x_i = X_{i+1} - X_i, \ ....(i = 0, 1, ...n,) \qquad (2)$$

$X_0=0$ and $X_{n+1}=1$ being the boundaries of the X_z space.

Every event e is thus characterized by a set S_e of $n+1$ numbers: $S_e=\{x_i|i=0,.....n\}$, which clearly satisfy

$$\sum_{i=0}^{n} x_i = 1, \qquad (3)$$

and these numbers are referred as “gaps”. To study the fluctuation of S_e from event to event, the moment of x_i for each event is defined as

$$\Gamma_q = \frac{1}{n+1}\sum_{i=0}^{n} x_i^q, \qquad (4)$$

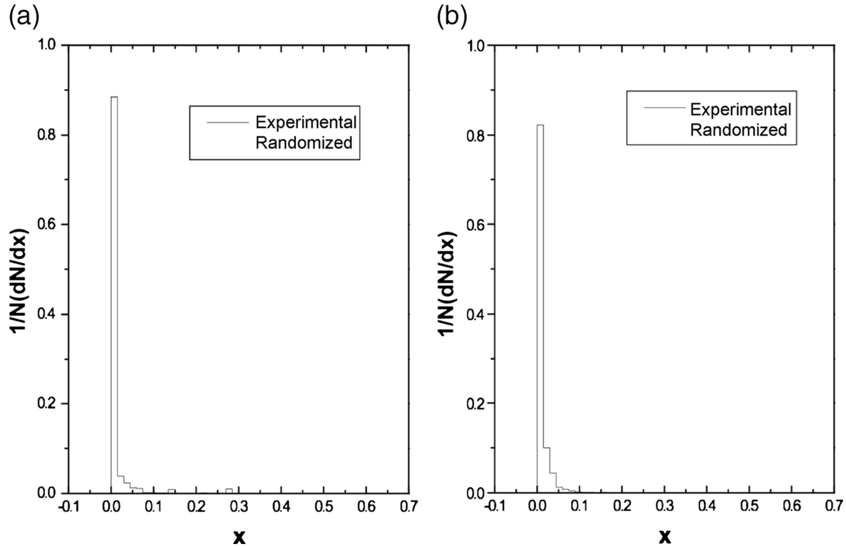

Fig. 1 Gap distribution (x_i=X_{i+1} −X_i) for ^{32}S–AgBr interactions at 200 AGeV in **a** emission-angle (cosθ) phase space and **b** azimuthal-angle (ϕ) phase space

where q is the order for spatial fluctuation. Since x_i<1, the Γ_q are usually <<1.

It is obvious from Eqs. (3) and (4) that Γ_0=1 and $\Gamma_1 = \frac{1}{n+1}$.

At higher q, the Γ_q are progressively smaller, but they are increasingly more dominated by the largest x_i components in S_e, i. e., by the largest gaps. The moment Γ_q fluctuates from event to event, and this fluctuation can then be quantified by the erraticity measure

$$s_q = -< \Gamma_q \ln \Gamma_q > \quad (5)$$

where < > stands for average over all events.

The moment Γ_q does not filter out statistical fluctuations. However, one can estimate how much s_q stands out above the statistical fluctuation by first calculating

$$s_q^{st} = -< \Gamma_q^{st} \ln \Gamma_q^{st} > \quad (6)$$

where Γ_q^{st} is the moment for statistically distributed gaps, i.e., for the gap distribution that results when all n particles in an event are distributed randomly in X_z space.

We then compute for the ratio

$$S_q = s_q / s_q^{st}. \quad (7)$$

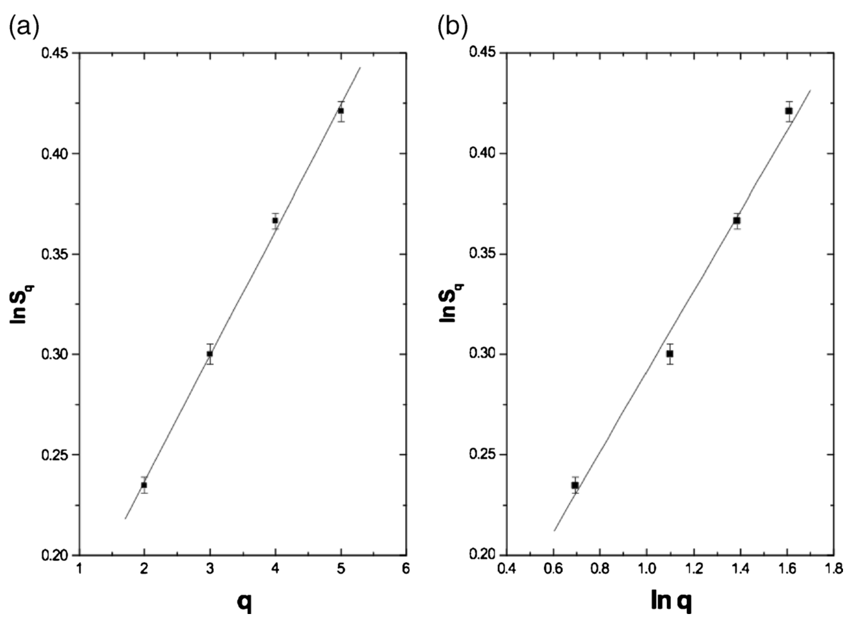

Fig. 2 **a** Logarithmic erraticiy measure ln S_q as a function of q and **b** ln S_q as a function of ln q for ^{32}S–AgBr interactions at 200 AGeV in emission-angle (cosθ) space

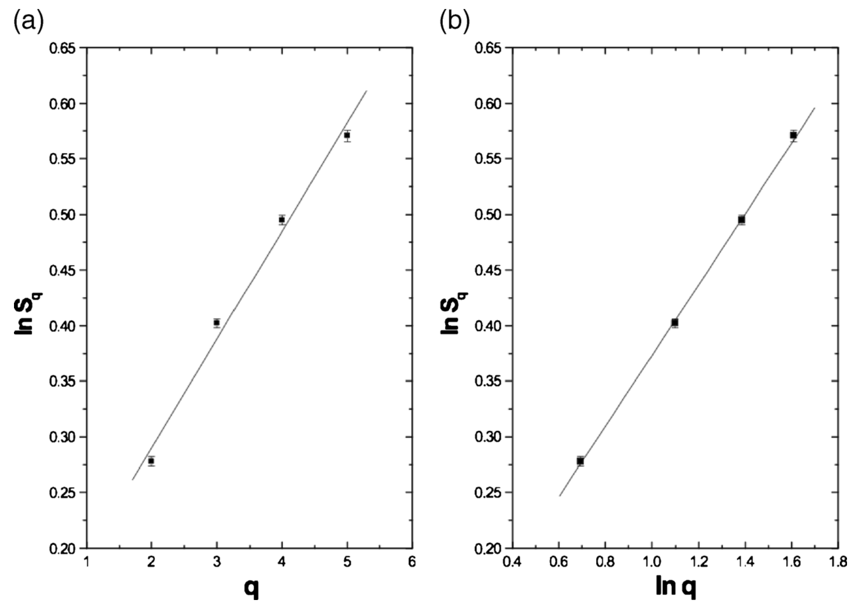

Fig. 3 **a** Logarithmic erraticiy measure ln S_q as a function of q and **b** ln S_q as a function of ln q for ^{32}S–AgBr interactions at 200 AGeV in azimuthal-angle (ϕ) space

If S_q deviates from 1, then it will be the erraticity measure of the spatial pattern.

The q dependence of S_q is obtained from the analysis of the data.

4 Results and Discussion

For the analysis, we have constructed a randomly distributed reference sample corresponding to the experimental data set of ^{32}S–AgBr interactions at 200 AGeV for the emission- and azimuthal-angle phase spaces. Figure 1a, b shows the gap distributions of experimental and random data sets, respectively, for the two aforementioned phase spaces. From Eq. (4), we have calculated the moment Γ_q for each event for both the phase spaces. For each order of spatial fluctuation q (q=2, 3,—,5), Γ_q fluctuates from event to event for both phase spaces. To capture this event-to-event fluctuation, the erraticity measure s_q has been calculated using Eq. (5). To filter out the statistical part, s_q^{st} has been calculated using the random data with the help of Eq. (6) and an entropy-like parameter S_q has been evaluated from Eq. (7).

The values of ln S_q are plotted against q in Figs. 2a and 3a, respectively, for emission-angle (cosθ) and azimuthal-angle (ϕ) spaces. It is evident from the figures that the S_q deviate from 1 significantly, and hence constitute a statistically significant measure of gap erraticity, and that ln S_q and q are linearly related. This indicates that S_q satisfies the following relationship:

$$S_q \propto e^{\alpha q} \tag{8}$$

The straight lines in Figs. 2a and 3a are linear fits of ln S_q versus q in the two phase spaces. The fit parameters are listed in Table 1. Certain studies [17, 21, 22] have observed power law behaviors of the form

$$S_q \propto q^{\beta}. \tag{9}$$

For comparison, we have also fitted our compound hadron data according to Eq. (9). Figures 2b and 3b show the results for the emission (cosθ)- and azimuthal (ϕ)-angle phase spaces, respectively. The fit parameters are also shown in Table 1. The value of β for pions produced in ^{32}S–AgBr interactions at 200 AGeV [21] in pseudo-rapidity space is also shown in Table 1. Shaoshun and Chong [22] performed an erraticity analysis of pseudo-rapidity gaps for the pp collisions at 400 GeV/c. For comparison, we have included the resulting α and β in Table 1. The table shows that α increases with projectile energy, but

Table 1 Fitting parameters from the ln S_q versus q and ln S_q versus ln q plots

Interactions	Particle type	Phase space		χ^2/NDF		χ^2/NDF
^{32}S–AgBr at 200 AGeV	Compound hadrons	cos	0.0620.002	0.37	0.1200.013	2.10
			0.0970.008	0.59	0.3180.005	0.26
	Pions	η	–	–	3.89±0.43 [21]	
pp collisions at 400 GeV/c [22]	Pions	η	0.2370.003	0.56	1.20.1	10.8

notice should be taken that the targets are different. For the same interactions (^{32}S–AgBr interactions at 200 AGeV), β changes from 3.89±0.43 for produced pions to 0.1200.013 and 0.3180.005 for compound hadrons (produced pions and protons) in cosθ- and ϕ-phase spaces, respectively.

5 Conclusions

We have performed a gap-moment compound hadron erraticity analysis for the ^{32}S–AgBr interaction data at 200 AGeV. The findings from this analysis are the following:

1. Deviations of the entropy-like parameters S_q from unity indicate that the gap erraticities in the studied multiparticle productions are statistically significant.
2. The S_q grow with the order q, which gives more weight to the largest gaps.
3. The S_q values obtained from the compound hadron fluctuations are smaller than those associated with the produced pions [21]. This indicates that the production of compound hadrons is less chaotic.

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