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INTERMITTENCY ANALYSIS OF MULTIPION PRODUCTION PROCESS IN RELATIVISTIC NUCLEAR COLLISIONS – EVIDENCE OF NON-THERMAL PHASE TRANSITION

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With the help of the scaled factorial moment method, we have studied the interaction of ^{24}Mg-AgBr at the energy $4.5\,A\,$GeV. The whole process involves determination of the intermittency index (α_q), which ultimately measures the variable λ_q ($\lambda_q = (\alpha_q + 1)/q$). The occurrence of a minimum in the variation of λ_q as a function of q suggests a non-thermal phase transition and different regime of particle production during the hadronisation process.

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1. *Introduction*

The introduction of the idea about the intermittent pattern of particle production helps us to understand the statistical significance of usual events [1 − 3] having sharp spikes (large concentration of particles) in pseudorapidity spectra. The particle density fluctuation in variable phase-space domains enlightened us about the underlying dynamics of multihadron production process. The concept of intermittency was introduced by Bialas and Peschanski in analogy to turbulence theory in fluid dynamics. To learn more about the intermittency, as suggested by the pioneers, a method is used which involves statistical counting variables called scaled factorial moment F_q. The definition of scaled factorial moment is obtained from the turbulence theory [4] where it gives a measure of the amount of intermittency in a turbulent system. The pioneers suggested that the factorial moment F_q has a growth following a power law with decreasing phase space interval size and this feature signals the onset of intermittency in the context of 'high energy interactions'. This scaled factorial moment method has the feature that it can measure the non-statistical fluctuations avoiding the statistical noise.

Many more data analyses under different conditions are needed using reactants of diverse nature, covering the full extent of energy. In most of the earlier works on intermittency, best linear fits were drawn in the total bin range from some pre-conceived ideas. Actually, the plots are not perfectly linear in the whole bin range, rather nice linear behaviour is apparent in selective bin ranges. So it would be better to investigate intermittency in those bin ranges. Present work shows an increasing interest on the study of intermittency taking several bin ranges rather than a single range.

Intemittency is reasonably believed to have some connection with the phenomenon of phase transitions [5,6]. But experimentally it has not been proved yet that there is a phase transition or similar phenomenon in multiparticle production. It is convenent and better to find a suitable observable which can be measured experimentally and can probe information about a phase transition (thermal or non-thermal). It has been assumed that a self-similar cascade of multiple system is not consistent with the creation of particle during one phase, but instead requires a non-thermal phase transition [7]. We can study the non-thermal phase transition with the help of the parameter $\lambda_q = (\alpha_q + 1)/q$, where α_q is the intermittency index. The indication that such a non-thermal phase transiton may occur is that the function λ_q has a minimum value at $q = q_c$. Among the two different regions $q < q_c$ and $q > q_c$, numerous small fluctuations dominate the region $q < q_c$, but in the region $q > q_c$, dominance of small number of very large fluctuations occur. There is a co-existence of the 'liquid' phase of the many small fluctuations and the 'dust' phase of a few grains of very high density, depending on whether we probe the system by a moment of the order $q < q_c$ or $q > q_c$, respectively. The growing interesting new areas await to be thoroughly explored. This work is devoted to the study of the power-law singularities and the possible signature of phase transition in the 4.5 A GeV ^{24}Mg-AgBr interaction data.

2. *Experimental details*

The experimental details are given below in steps. In order to probe the nonstatistical fluctuations in particle production process and related phase transition we precisely study the interactions initiated by ^{24}Mg-AgBr at 4.5 A GeV. The data set used in this present analysis were obtained by irradiationg of G5 nuclear emulsion plates by an ^{24}Mg beam with incident energy 4.5 A GeV at JIRN Dubna.

The scanning of the plates is carried out with the help of a high-resolution Leitz metalloplan microscope and an online computer system. The scanning is done using objective 10× in conjunction with a 25× ocular. To increase the scanning efficiency two independent observers scanned the plates independently. For measurements, a 100× oil immersion objective was used in conjunction with the 25× ocular lens.

From the scanned events, only those events were chosen which satisfy the following criteria: a) The beam track should lie within the 3° angle to the mean beam direction of the pellicle. b) The events, which are within 20 μm thickness from the top or bottom of the plate, were rejected. c) The events whose primary beam tracks were observed at a secondary track of another interaction should not be analyzed. These events were rejected labeling them as secondary interactions.

According to the emulsion technology, shower tracks are identified with ionisation below $1.4\, I_0$ where I_0 is the minimum ionisation of a singly charged particle. These shower tracks have the range > 3 mm.

The spatial angle of emission (θ) of each shower track around the beam axis is calculated by noting the space coordinates of the interaction center (x_0, y_0, z_0), one point on the incident beam track and one point on the respective secondary track, and by applying simple coordinate geometry. For this analysis, we have used the variable pseudorapidity (η) which is defined as $\eta = -\ln\tan(\theta/2)$. The uncertainty in the determination of η has been estimated to be equal to 0.1 units. The average multiplicity of produced particles of the sample is 9.6 ± 0.47.

It is essential to mention here some experimental biases, which may affect the experimental results. Factorial moments can be reduced by limited two track resolution, the track loss etc. As mentioned earlier, high spatial resolution of nuclear emulsion makes it suitable for this kind of analysis. Moments can be overestimated by counting electrons as hadrons. Special care has been taken to avoid such contamination.

3. *Method of study*

Here we adopt the scaled factorial moment method. The numbers of produced particles are finite at available projectile energies. Hence, the statistical fluctuation is much more pronounced and the standard moment fails to reveal the dynamical fluctuation of particle density distribution due to this statistical fluctuation. The scaled factorial moment method is free from hazards of statistical noise pollution.

The single particle density distibution is pseudorapidity space is non-flat. In order to reduce the effects of non-flat distribution $\rho(\eta)$, one can use a new variable $x(\eta)$ which can be defined by

$$x(\eta) = \frac{\int\limits_{\eta_1}^{\eta} \rho(\eta)\mathrm{d}\eta}{\int\limits_{\eta_1}^{\eta_2} \rho(\eta)\mathrm{d}\eta}, \tag{1}$$

where η_1 and η_2 are the extreme points in the distribution $\rho(\eta)$ between which $x(\eta)$ is uniformly distributed from 0 to 1. Now consider a certain interval in transformed pseudorapidity space, defined as $\Delta x = x_{\max} - x_{\min}$. The considered region is divided into M bins of equal size of width $\delta x = \Delta x/M$. For definiteness, δx is supposed to be an interval in transformed rapidity, but the method generalises to an arbitrary phase space variable. The normalized scaled factorial of order q is defined as [8]

$$\langle F_q \rangle = \langle M^{q-1} \sum_{m}^{M} \frac{k_m(k_m-1)\dots(k_m-q+1)}{\langle N^q \rangle} \rangle, \tag{2}$$

where k_m is the number of particles in the $m^{\rm th}$ bin ($m = 1, 2, \dots, M$), $\langle N \rangle$ is the average number of charged secondaries in the considered phase space interval and angular brackets denotes the average over the whole sample of events, while q is the order of the moment which can assume any positive value starting from 2.

If the non-statistical fluctuations are self-similar in nature, in the limit of small bin size, the factorial moment obeys the relation

$$\langle F_q \rangle \propto M^{\alpha_q}. \tag{3}$$

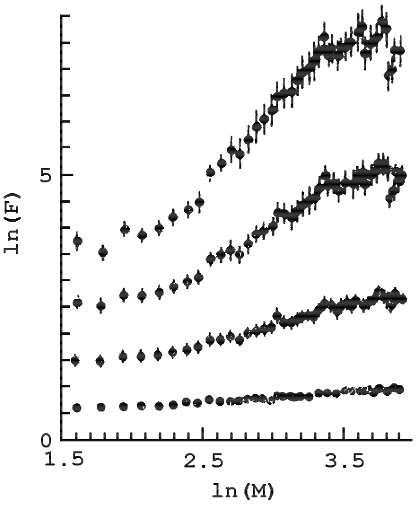
From Eq. (3) we get

$$\ln\langle F_q \rangle = \alpha_q \ln M + C\,. \tag{4}$$

In analogy with the turbulent fluid dynamics, one may call this property the 'intermittency' where α_q measures the strength of intermittency and is called the intermittency exponent.

4. Analysis of data and discussion

To analyze and to derive the factorial moments, intervals of width $\Delta\eta = 10$ around the peak of the η distribution have been chosen and then we perform flat distribution on the chosen interval. The transformed chosen interval has been divided into 5 to 50 subintervals ($M = 5$ to 50). For each interval, normalized scaled factorial moments of the order 2 to 5 are calculated from Eq. (2). Figure 1 shows the nature of the variation of the normalized factorial moments of order 2 to 5 with logarithm of number of bins M. This plot does not show perfectly linear behaviour in the whole bin range ($M = 5$ to 50). So, next we divide the full bin range into parts to probe whether linear behaviour is prominent in different sub-intervals of M. Figure 2 ($5 \le M \le 15$), Fig. 3 ($15 \le M \le 30$), Fig. 4 ($5 \le M \le 25$), Fig. 5 ($25 \le M \le 40$) and Fig. 6 ($10 \le M \le 25$) depict the variations of the factorial moments with $\ln M$ in selected intervals. The figures give a clear picture of intermittent behaviour of particle production. The intermittency exponents α_q are evaluated by performing best fits according to Eq. (5). Table 1 shows the intermittency exponents α_q in different phase space intervals. Error bars have been drawn in the graphs, which are actually the statistical errors, calculated from the standard deviations of the event-wise factorial moments.



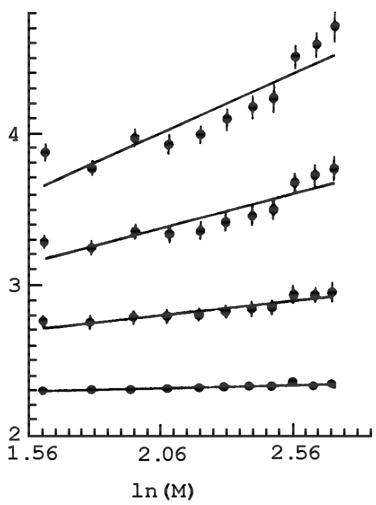
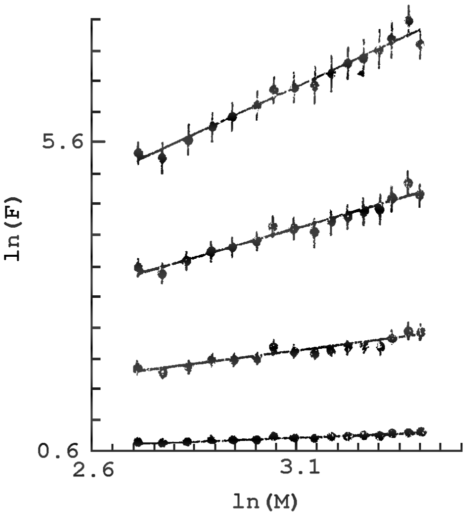


Fig. 1 (left). Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $5 \le M \le 50$.

Fig. 2. Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $5 \le M \le 15$.



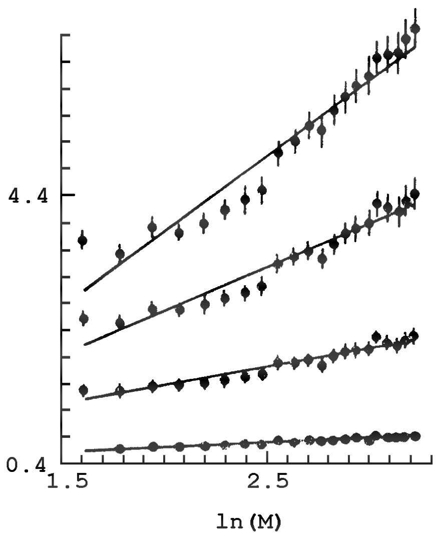


Fig. 3 (left). Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $15 \le M \le 30$.

Fig. 4. Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $5 \le M \le 25$.

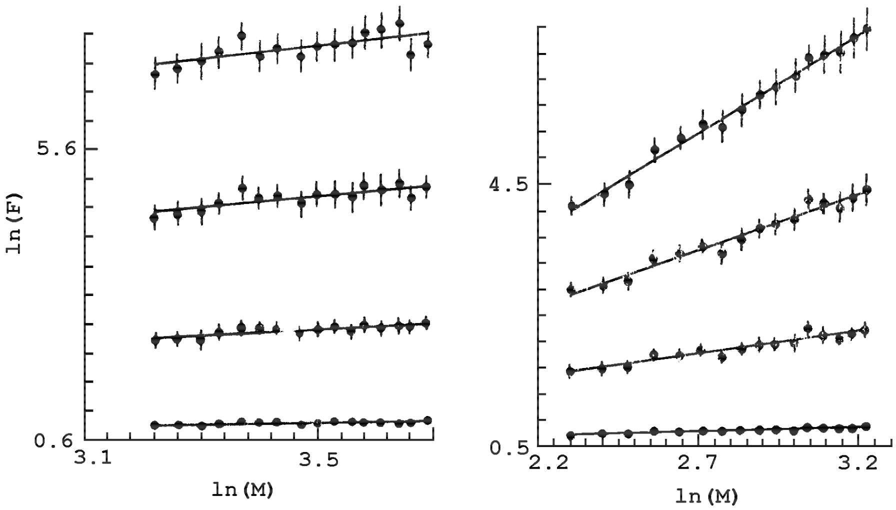


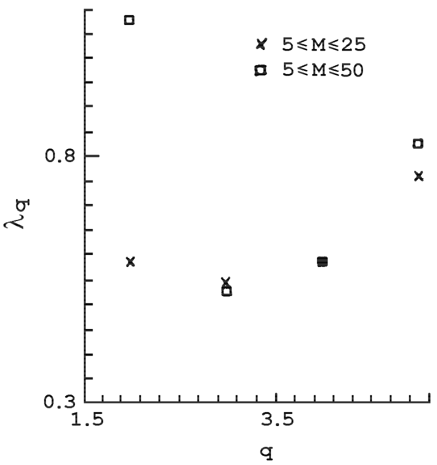
Fig. 5 (left). Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $25 \leq M \leq 40$ *.*

Fig. 6. Variation of the normalized scaled factorial moment of order 2 to 5 with logarithm of number of bin for bin region $10 \leq M \leq 25$ *.*

TABLE 1. Intermittency exponents for different bin regions.

Bin range	$q = 2$	$q = 3$	$q = 4$	$q = 5$
$5 \leq M \leq 50$	0.155 ± 0.005	0.606 ± 0.020	1.314 ± 0.050	2.752 ± 0.095
$5 \leq M \leq 15$	0.127 ± 0.015	0.430 ± 0.050	0.960 ± 0.136	1.615 ± 0.246
$15 \leq M \leq 30$	0.195 ± 0.022	0.851 ± 0.079	1.937 ± 0.113	3.094 ± 0.134
$5 \leq M \leq 25$	0.139 ± 0.008	0.547 ± 0.033	1.313 ± 0.080	2.264 ± 0.136
$10 \leq M \leq 25$	0.155 ± 0.016	0.693 ± 0.050	1.729 ± 0.078	2.991 ± 0.086
$25 \leq M \leq 40$	0.170 ± 0.038	0.558 ± 0.112	0.928 ± 0.197	1.153 ± 0.309

The plots and the table show that the intermittency exponents α_q increase sharply with the order of moment in all of the bin ranges. In the one-dimensional study, we have analyzed the scaled factorial moments in the pseudorapidity phase space intervals to search for a signal of the non-thermal phase transition. The results of our study on the variation of λ_q with q for different M intervals are shown in Figs. 7 and 8. For all regions, a certian minimum of λ_q ccurs at $q = 3$ except the region $25 \leq M \leq 40$. In this $25 \leq M \leq 40$ region, the values of λ_q's gradually descrease and no certain minimum occurs up to $q = 5$.



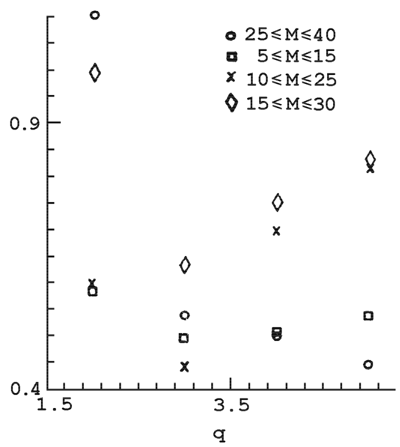


Fig. 7 (left). Variation of λ_q with q for different regions.

Fig. 8. Variation of λ_q with q for different regions.

Thus this analysis of ^{24}Mg-AgBr data at 4.5 A GeV indicates a different regime of particle production at different scales of random cascading with a non-thermal phase transition, rather than a thermal phase transition formation.

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PREKIDNA ANALIZA PROCESA TVORBE VIŠE PIONA U RELATIVISTIČKIM SUDARIMA NUKLEONA – ZNAK NETERMIČKOG FAZNOG PRIJELAZA

Primjenom metode sumjernog faktorskog momenta proučavamo međudjelovanje ^{24}Mg-AgBr na energiji 4.5 A GeV. U analizama računa se prekidni indeks (α_q) koji određuje varijablu λ_q ($\lambda_q = (\alpha_q + 1)/q$). Pojava minimuma u promjenama λ_q u ovisnosti o q ukazuje na netermički fazni prijelaz i različite uvjete tvorbe čestica u procesu hadronizacije.