Multihadron production in high-energy interactions and intermittency

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Nonstatistical multiplicity fluctuations in narrow pseudorapidity intervals have been studied in the pionization process of π^--Ag/Br and p-Ag/Br interaction data at 350 GeV/c and 400 GeV/c, respectively, in terms of scaled factorial moments. An intermittent pattern of fluctuations is evident for pionization processes in both cases. An investigation of anomalous fractal dimensions suggests a cascading mechanism for the multihadron production process. A further analysis of the data in terms of a scaling law for a different order of the moments has been done. The results support the proposed scaling behavior. We have also probed the emission process of the medium energy target-fragmented protons with the same tool. Interestingly, this study reveals similar behavior.

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I. INTRODUCTION

Among the various approaches proposed for studying nonstatistical fluctuations in the rapidity (pseudorapidity) distribution of charged secondaries, produced in high-energy interactions, the "intermittency," which involves computing scaled factorial moments in the limit of small phase-space intervals, has developed a spur of interest in recent years. The technique was introduced by Bialas and Peschanski in a pioneering work [1]. Intermittency is a general mechanism which can generate strong local fluctuations in a large uniform statistical system. The underlying physical reason is the self-similarity of the system over a range of the scales. In high-energy physics, the power law dependence of the scaled factorial moments on the width of the phase space interval characterizes the intermittent behavior. The most notable feature of this technique is that the statistical noise, which always masks the dynamical fluctuations, can be eliminated by this method. So far, this method has been experimentally applied to cosmic ray events [2] and accelerator data on hadron-hadron [3,4], hadron-nucleus [5,6] nucleus-nucleus [5,7–11], e^+-e^- [12–15] and μ-p [16] interactions at relativistic energies. In all of these experiments the intermittency effect has been observed, indicating nonstatistical fluctuations in the pionization process. The dynamical origin of such a self-similarity property is still ambiguous. There are only some speculative propositions such as the formation of quark-gluon plasma (QGP) [17] internuclear cascading or the formation of jets and minijets [18] which could be the source of such nonstatistical fluctuations. At this stage, more data on different reactants, covering the full gamut of energy, are required so that comparative studies of different aspects of such fluctuations can provide insight into the underlying mechanism.

Moreover, so far the bulk of the intermittency study is based on pionization data. Should we also probe the fragmentation process with the same tool? Only recently, people have started investigating the intermittent pattern of fluctuation in nuclear multifragmentation processes at low energies [19].

In this paper we present our enhanced data set of 350 GeV/c π^--Ag/Br interactions along with 400 GeV/c p-Ag/Br data in the light of intermittent behavior. Section II provides the experimental details. In Sec. III the self-similarity of the pionization process has been investigated and, for a comparative study of the characteristics of intermittency we have used other intermittency data from our recent investigation. Section IV deals with a scaling law, proposed by Seibert [30]. Section V is devoted to the study of power law singularities of the fragmentation process and, utilizing the facility of identification offered by the nuclear emulsion technology, we have chosen only the medium energy target-fragmented protons, known as grey particles, for the analysis.

II. EXPERIMENTAL DETAIL

The data were taken from a stack of G5 emulsion plates exposed to 350 GeV/c π^- beams at CERN and 400 GeV/c proton beams at Fermilab. These data were used in our previous analyses [20,21], although as mentioned earlier, in the present paper the sample size is richer in statistics for both cases. The emulsion plates of thickness 600 μm were area scanned with the help of a semiautomatic scanning system with a Leitz Metalloplan microscope using an objective of magnification 10× and ocular lenses of 25× magnification. The scanning efficiency was greater than 90% in either case. The criteria for selecting the events were made according to the following: (i) The beam track must be at an angle less than 3° to the mean beam direction in the pellicle; (ii) interactions should not be within 20 μm from the top or bottom surface of the pellicle; (iii) selection of the primary interactions as made by following the incident beam track in the backward direction. With the above selection criteria, a sample of 802 and 652 events were chosen for π^- and proton-initiated interactions, respectively. Here the nuclear emulsion served the purpose of a target as well as a detector. All the charged secondaries of these events were classified according to nuclear emulsion terminology in the following way.

(i) Black tracks are produced by the particles having a range less than 3 mm and an ionization greater than $6I_0$ where I_0 is the minimum ionization. The value of minimum ionization (I_0) is about 14–15 grains per 100 μm.

(ii) Grey tracks are produced by particles having ranges greater than 3 mm and ionization values in between $1.41I_0$ and $6I_0$.

(iii) Relativistic particles with an ionization less than $1.4I_0$ formed the shower tracks which were not generally confined to the emulsion pellicle.

The sum of the number of black tracks (n_b) and grey tracks (n_g) are defined as heavy tracks (N_h), $N_h = n_b + n_g$. To ensure the target as Ag/Br, events having $N_h < 8$ were not included. To measure the emission angles of the particles we took readings of the space coordinates (x,y,z) of the production point, a point on the incident beam and a point on each of the tracks, using an oil immersion objective of magnification 100× and occular lenses of 25× magnification. The uncertainty in the angular measurement has been estimated to be 0.1 mrad. Such high spatial resolution makes the emulsion a suitable detector for this kind of fluctuation study in finer phase-space intervals. It should be mentioned here that protons, in the energy range 30–400 MeV, constitute more than 90% of the grey prongs. Moreover, as a confirmatory test, we have followed all the tracks up to their end point, but none of them showed any sign of decay or interaction.

III. SCALED FACTORIAL MOMENT ANALYSIS

A. The methodology

The normalized average inclusive scaled factorial moment $\langle F_i \rangle$ of order i is defined for a data sample as [2]

$$\langle F_i \rangle = \left\langle M^{i-1} \sum_{m=1}^{M} n_m(n_m-1)\cdots(n_m-i+1)/\langle n \rangle^i \right\rangle , \tag{3.1}$$

where M is the number of $\delta\eta$ bins into which the total available η length $\Delta\eta$ has been divided. n_m is the number of charged secondaries falling within the mth bin (m running from 1 to M) and $\langle n \rangle$ is the average multiplicity of the charged secondaries for a specific reaction within the considered phase-space region. Here angular brackets denote averaging over the total number of events N in a data sample. The factorial moments satisfy the normalization property

$$\langle F_1 \rangle = 1 \quad \text{for all } M .$$

This is the so-called horizontal averaging, where one calculates the moments for each event and then averages over all the events. Fialkowski et al. [22] showed that horizontal averaging should be followed by a correction for the nonuniformity of the single particle distribution over the considered range of the phase-space variable. The correction factor is given by

$$R_i = \frac{1}{M} \sum_{m=1}^{M} M^i \langle n_m \rangle^i / \langle n \rangle^i . \tag{3.2}$$

Now the corrected or reduced scaled factorial moments can be obtained by dividing the scaled factorial moments by the factor R_i:

$$\langle F_i \rangle^{\text{corr}} = \langle F_i \rangle / R_i . \tag{3.3}$$

Obviously R_i reduces to unity for a flat distribution.

If only statistical fluctuations are present in the pseudorapidity distribution, there is no dependence of $\langle F_i \rangle^{\text{corr}}$ on $\delta\eta$ so long as $\delta\eta$ remains small compared to the accessible pseudorapidity length over which the semi-inclusive η distribution changes slowly but significantly. If instead, there is any variation in the values of $\langle F_i \rangle^{\text{corr}}$ with $\delta\eta$, it has been speculated that there should be some physical origin of the fluctuations. The results, already available from different high-energy interactions, show a power law increase in the size of the fluctuations with decreasing $\delta\eta$:

$$\langle F_i \rangle^{\text{corr}} = [\Delta\eta/\delta\eta]^{\alpha_i} \tag{3.4}$$

or a linear relation such as

$$\ln\langle F_i \rangle^{\text{corr}} = \alpha_i(-\ln\delta\eta) + \beta_i . \tag{3.5}$$

Any parametrization for such a relation between $\ln\langle F_i \rangle^{\text{corr}}$ and $-\ln\delta\eta$ in terms of α_i and β_i is valid until the choice of $\delta\eta$ does not exceed the lower limit of accuracy in the measurement of θ. It is worthwhile to mention at this stage that not only η or the rapidity can be used as a basic variable to locate the position of a charged secondary within phase space, but any variable for which the distribution follows a slow and regular change can be used for this purpose.

B. Results and discussions

Scaled factorial moments of orders 2, 3, and 4 have been calculated for $\Delta\eta = 4$ using Eq. (3.1) for π^--Ag/Br interactions at 350 GeV/c along with proton-Ag/Br interactions at 400 GeV/c. Moments have been corrected for the curvature in the single particle distribution with the help of Eqs. (3.2) and (3.3). Figures 1 and 2 represent the variation in the value of $\ln\langle F_i \rangle^{\text{corr}}$ with $-\ln\delta\eta$ for π^- and proton interactions, respectively. The error bars shown in the figures are nothing but the standard statistical errors. The figures clearly suggest intermittent behavior of particle production in π^--Ag/Br as well as in p-Ag/Br interactions. To ensure that the observed behavior is not a manifestation of mere statistics alone, we have distributed $\sum n_m$ particles of each event randomly throughout the considered η interval and then factorial

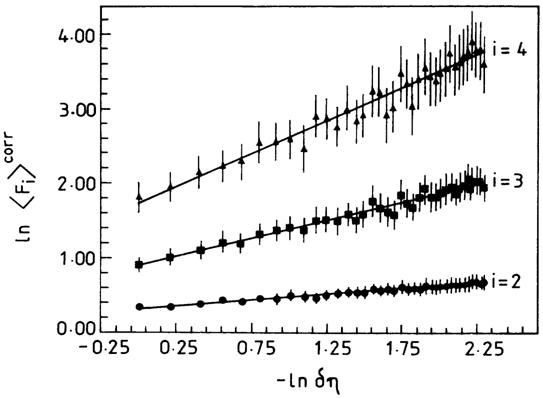

FIG. 1. Plot of $\ln\langle F_i\rangle^{\text{corr}}$ vs $=-\ln\delta\eta$ for π^--Ag/Br interaction at 350 GeV/c.

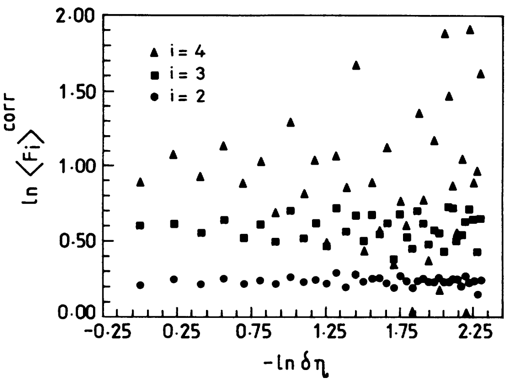

FIG. 3. Plot showing $\ln\langle F_i\rangle^{\text{corr}}$ vs $-\ln\delta\eta$ for Monte Carlo simulated events (pions) for π^--Ag/Br interactions.

moments are calculated following the usual procedure. Figure 3 depicts the calculated moments as a function of bin width for 350 GeV/c data. Nonintermittent behavior is very much evident which confirms that the experimental data analysis reveals the true dynamical signal. The 400 GeV/c proton-Ag/Br data also show similar behavior. The intermittency parameters α_i are obtained by performing best fits according to Eq. (3.5). The fitted values are presented in Table I. For comparative knowledge about the characteristics of the intermittency exponents, we have extracted the values of α_i for ^{24}Mg-Ag/Br interactions at 4.5A GeV/c and ^{16}O-Ag/Br interactions at 2.1A GeV from our recent investigation [7] on A-A interactions. These parameter values are also shown in Table I. It is observed that the slope parameter α_i increases with the order of moment for any type of interaction and both for hadron-nucleus and nucleus-nucleus interaction α_i decreases as the projectile energy is increased for any order of moment. This is consistent with earlier observations [5,9].

The intermittency exponents α_i determined from the experiments are related to the anomalous fractal dimensions d_i of the distribution [23] by the relation [24,25]

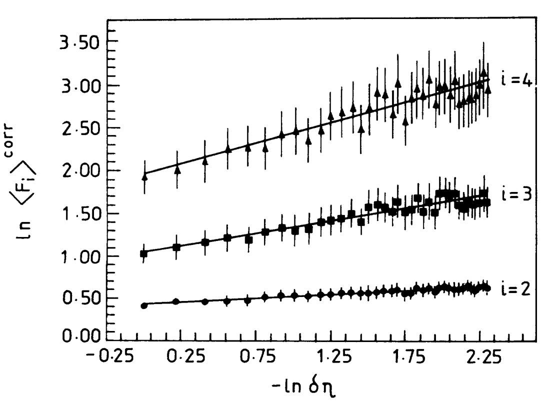

FIG. 2. Plot of $\ln\langle F_i\rangle^{\text{corr}}$ vs $-\ln\delta\eta$ for p-Ag/Br interaction at 400 GeV/c.

$$d_i=\alpha_i/(i-1)\ . \tag{3.6}$$

Recently Bialas and Hwa [26] pointed out that the study of the dependence of d_i on i can reveal interesting results. It was suggested by several authors [27] that there are two natural scenarios which can explain the intermittent behavior in the particle production process.

1. Second-order phase transition [17,28,29]

At the critical point the correlation length diverges and the system becomes scale invariant. If there is no long-range correlation we then expect that all anomalous fractal dimensions are equal to each other; i.e., the system is a simple fractal as demonstrated explicitly for the Ising model [28] and for Feynmann-Wilson fluid [29]. The value of d_i can be related to a critical exponent for the phase transition.

2. Self-similar cascade [1,18]

In this case anomalous fractal dimensions are sensitive to the detail of the vertex describing the cascade and there is no reason to expect d_i to be independent of i in general [1]. Thus the measurements of the i dependence of d_i can give an indication which one of the two scenarios is at work.

In Fig. 4 the anomalous fractal dimensions (d_i) are plotted against the order i for each type of interaction. One sees that for any order the value of d_i is different for different classes of interaction, but for all the cases d_i increases with the increase of i, disfavoring the origin of any exotic phenomenon. So the behavior of the anomalous fractal dimension suggests, as far as our data are concerned, a cascading mechanism for pionization.

IV. SCALING OF SCALED FACTORIAL MOMENTS

A theory-independent method for the separation of higher-order effects from two-particle correlations was proposed by Seibert [30] which relates all moments of a distribution to second order (in the small fluctuation limit) with a scaling law indicating that the different moments are not independent. The scaling law is indepen-

TABLE I. Values of intermittency exponent α_i for π^--Ag/Br, p-Ag/Br, ^{16}O-Ag/Br, and ^{24}Mg-Ag/Br interaction data.

Data	Energy/ momentum	Intermittency exponent α_i $i=2$	$i=3$	$i=4$
π^-	350 GeV/c	0.16±0.02	0.49±0.06	0.89±0.12
p	400 GeV/c	0.10±0.01	0.29±0.05	0.47±0.07
^{16}O	2.1 GeV/N	0.09±0.01	0.37±0.04	0.83±0.09
^{24}Mg	4.5 GeV/c N	0.048±0.007	0.14±0.02	0.38±0.05

dent of the source of correlation and was derived for the inclusive scaled factorial moments and the scaled multiplicity moments. The higher-order moments relate to the second order by the relation,

$$F_i^{\text{incl}}=1+\frac{i(i-1)}{2}(F_2^{\text{incl}}-1)$$

or (4.1)

$$(F_i^{\text{incl}}-1)/i(i-1)=(F_2^{\text{incl}}-1)/2 .$$

Thus the entire functional form of the ith-order inclusive scaled factorial moments F_i^{incl} is determined by the second-order moment F_2^{incl}.

The inclusive scaled factorial moments can be expressed as the product of multiplicity and scaled factorial moments, giving

$$F_i^{\text{incl}}(\delta\eta,\Delta\eta)=\frac{\langle N(N-1)(N-i+1)\rangle}{\langle N\rangle^i}F_i(\delta\eta,\Delta\eta)$$

where N is the number of particles in a rapidity window of width $\Delta\eta$. In terms of the scaled multiplicity moments and scaled factorial moments, the above equation can be written in the form [30]

$$F_i^{\text{incl}}(\delta\eta,\Delta\eta)=\left[C_i-\frac{i(i-1)}{2\langle N\rangle}C_{i-1}+O(\langle N\rangle^{-2})\right]\times F_i(\delta\eta,\Delta\eta) , \quad (4.2)$$

where $C_i=\langle N^i\rangle/\langle N\rangle^i$ is scaled multiplicity moment.

It was shown in Ref. [30] that the scaled multiplicity moments C can be expanded in powers of (C_2-1) by considering the deviation from the mean multiplicity as an expansion parameter, the lowest-order truncation of which gives the scaling law of the form (4.1), when fluctuations are small. On the other hand, the scaled factorial moments F_i obey the same scaling law which was derived by calculating the scaled factorial moments from an independent-cluster model assuming boost invariance of the cluster rapidity distribution [31]. This scaling law is model independent and holds for all values of $\delta\eta$ and $\Delta\eta$. Combining these two scaling laws along with expression (4.2), it has been inferred that the same scaling law also holds for the inclusive scaled factorial moments in the small fluctuation limit.

This scaling law for inclusive scaled factorial moments is the lowest-order truncation of the expansion in powers of (F_2-1) which was developed by Carruthers and Sarcevic [32]. From now on we will write F_i to indicate inclusive scaled factorial moments as in Sec. III. Instead of expanding (F_i-1) as a function of (F_2-1), $\ln F_i$ can also be expanded as a function of $\ln F_2$, giving (taking up to the first-order approximation) the scaling law for $\ln F_i$ as

$$\ln F_i/i(i-1)=\ln F_2/2 . \quad (4.3)$$

This scaling law is obeyed by almost any valid correlation function in the small fluctuation limit, as the derivation of the law rests only on the fact that the correlation function can be expanded in a power series about the

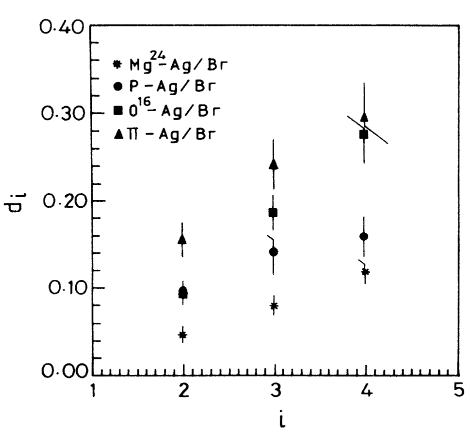

FIG. 4. Variation of anomalous fractal dimension (d_i) with order i for the pionization process.

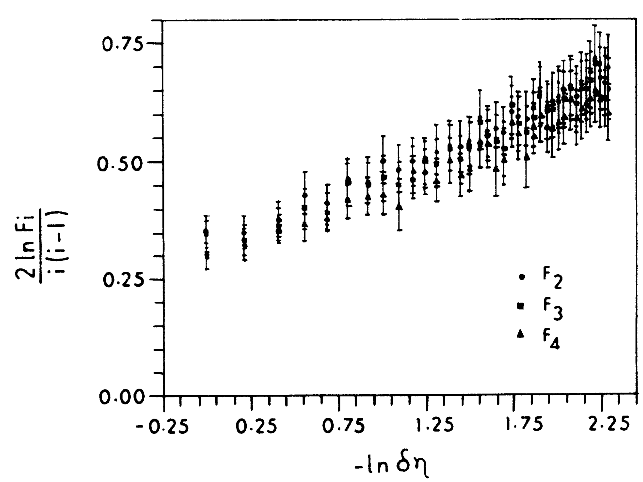

FIG. 5. Plot of $2\ln\langle F_i\rangle^{\text{corr}}/i(i-1)$ vs $-\ln\delta\eta$ for π^--induced interaction at 350 GeV/c.

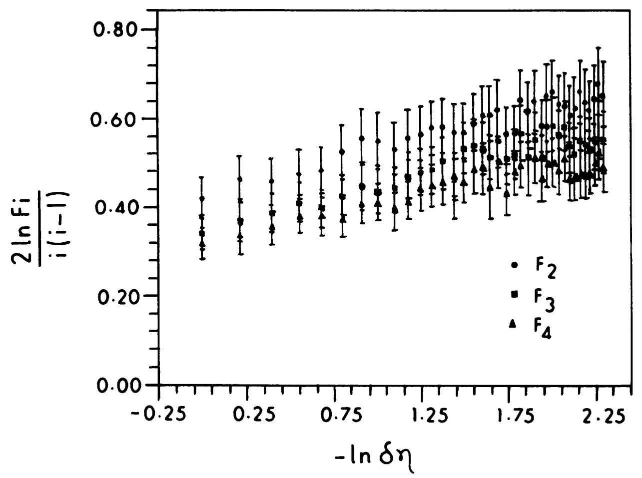

FIG. 6. Plot of $2\ln\langle F_i\rangle^{\rm corr}/i(i-1)$ vs $-\ln\delta\eta$ for p-induced interaction at 400 GeV/c.

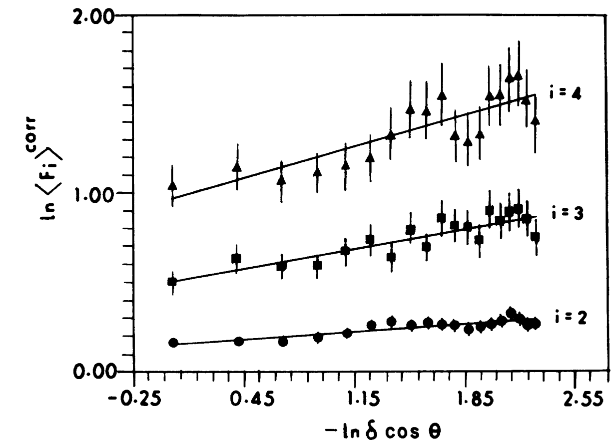

FIG. 8. Plot of $\ln\langle F_i\rangle^{\rm corr}$ vs $-\ln\delta\cos\theta$ for medium energy protons emitted in p^--Ag/Br interactions at 400 GeV/c.

mean value of some quantity.

So far this scaling law has been verified by the data of π-p and k-p collisions at 250 GeV [31] and O-emulsion interactions at 200 GeV/N [30]. Here we check the validity of the scaling law with our hadron-nucleus data of π^-Ag/Br interactions at 350 GeV/c and p-Ag/Br interactions at 400 GeV/c for the inclusive scaled factorial moments (corrected). For this purpose we have calculated the values of $2\ln\langle F_i\rangle^{\rm corr}/i(i-1)$ using the values of $\ln\langle F_i\rangle^{\rm corr}$ obtained in Sec. III. Figures 5 and 6 show the plot of $2\ln\langle F_i\rangle^{\rm corr}/i(i-1)$ against $-\ln\delta\eta$ ($i=2$, 3, and 4) for π^- and proton data, respectively. The figures speak in favor of the scaling law. Though our data, with the others, show the scaling behavior, it is too early yet to conclude the universality of the scaling law. However, this scaling law of Seibert is interesting and needs further verification using different projectiles of various energies.

V. INTERMITTENCY STUDY OF TARGET-FRAGMENTED MEDIUM ENERGY PROTONS

So far we have been discussing the intermittent behavior and its characteristics in the context of the pionization process. In this section attention will be focused on the target-fragmented medium energy protons. These protons are strongly correlated with the produced particles [33] and so far as the time scale of emission is concerned, they are as prompt as the produced particles [34]. So it would not be unjustified to think that, being target fragments, they are also carriers of pionization information and thus their study acquires an extra importance.

The usual variable pseudorapidity is not appropriate for studying these medium energy protons due to heavier mass and lesser energy, and so like the other workers, we have used $\cos\theta$ (θ is the emission angle) as the basic variable.

To measure the dynamical fluctuation associated with the emission of the protons in π^--Ag/Br and p-Ag/Br interactions at 350 GeV/c and 400 GeV/c, respectively, scaled factorial moments up to fourth order have been evaluated for $M=2$ to 20. Here the full phase-space interval ($\cos\theta$ from -1 to $+1$) has been considered as the investigation zone. The nonuniformity of the distribution of the variable used is taken care of by introducing the correction factor. The bin size $\delta\cos\theta$ dependence of the average corrected moments $\langle F_i\rangle^{\rm corr}$ is depicted in Figs. 7 and 8 for π^- and proton-induced interactions, respective-

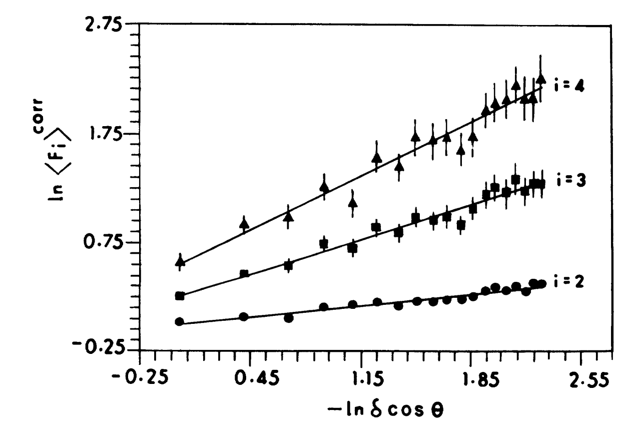

FIG. 7. Plot of $\ln\langle F_i\rangle^{\rm corr}$ vs $-\ln\delta\cos\theta$ for medium energy protons emitted in π^--Ag/Br interaction at 350 GeV/c.

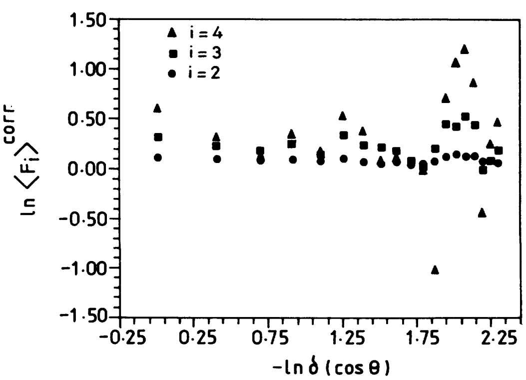

FIG. 9. Plot showing $\ln\langle F_i\rangle^{\rm corr}$ vs $-\ln\delta\eta$ for Monte Carlo simulated events (protons) for π^--Ag/Br interactions.

TABLE II. Intermittency exponent α_i for π^--Ag/Br interaction at 350 GeV/c and p-Ag/Br interaction at 400 GeV/c.

Data	Momentum (GeV/c)	α_i $i=2$	$i=3$	$i=4$
π^-	350	0.15±0.01	0.45±0.05	0.72±0.10
p	400	0.06±0.01	0.16±0.02	0.26±0.04

ly. In both cases the linear growth of the factorial moments with decreasing bin size (in logarithmic scale) manifests intermittent-type fluctuations and hence proves the self-similarity of the dynamical process leading to the emission of the protons. Here also the observed effects are subjected to statistical bias verification by the method described in Sec. III which guarantees the dynamical origin of the observed fluctuation pattern. The result of the test for π^- data is shown in Fig. 9. Intermittency exponents α_i are presented in Table II. The intermittency exponents increase with the order of moment for either of the interactions and for any order of moment the exponent value is higher for the lower-energy interaction. Both these features of the intermittency exponents are similar to what is observed for the pionization process. More interestingly, for the π^- data both processes have almost equal (within errors) intermittency exponents for any order, though the case is not so for the proton data. We have also investigated the anomalous fractal dimension as a function of order of moment so that it can be used for comparison in future analyses of medium energy proton data. Figure 10 represents the variation of d_i with i for π^--Ag/Br and p-Ag/Br interactions. It is seen that both for pion and proton interactions the d_i value is different for different orders of the moments. An increase in the value of d_i with i is observed, though the rate of growth falls as we go to higher orders.

Thus this analysis indicates self-similar proton emission in hadron-nucleus interactions for the first time and prompts one to consider seriously the emission process of the medium energy protons. Though it is difficult to explain the observed self-similarity of proton emission within the framework of the existing models, it may hint at an intranuclear cascading-type phenomenon. In this connection we may mention that the medium energy proton multiplicities are observed [35] to obey the negative binomial (NB) distribution, which is given by

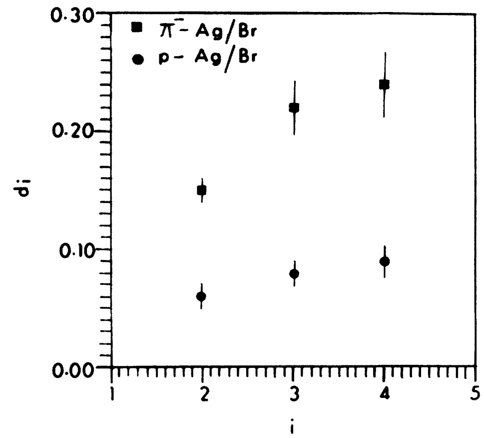

FIG. 10. Variation of anomalous fractal dimension, d_i, with order, i, for the emission process of the target-fragmented protons.

$$P(n,k,\bar{n})=\frac{k(k+1)\cdots(k+n-1)}{n!}\frac{\bar{n}^{\,n}k^k}{(\bar{n}+k)^{n+k}} .$$

The free parameters $\bar{n}$ and k are related to the average multiplicity $\langle n\rangle$ and the dispersion D of n by the relations

$$\langle n\rangle=\bar{n} \quad \text{and} \quad D^2=\bar{n}+\bar{n}^{\,2}/k .$$

The success of the NB distribution in describing the multiplicity distributions can be explained in terms of either the partial stimulated emission of bosons or the cascading nature of the process [36]. Since the first cause is not applicable for the protons, the observed validity of the NB distribution in this case seems to support the notion of a cascading-type phenomenon for the emission of the medium energy protons. However, further data analysis is of course needed to conclude anything unambiguously.

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[1] A. Bialas and R. Peschanski, Nucl. Phys. **B273**, 703 (1986).
[2] A. Bialas and R. Peschanski, Nucl. Phys. **B308**, 857 (1988).
[3] NA22 Collaboration, I. V. Ajinenko *et al.*, Phys. Lett. B **222**, 306 (1988); **235**, 373 (1990).
[4] UA1 Collaboration, C. Albagar *et al.*, Nucl. Phys. **B345**, 1 (1990).
[5] KLM Collaboration, R. Holynski *et al.*, Phys. Rev. Lett. **62**, 733 (1989); Phys. Rev. C **40**, R2449 (1989).
[6] NA22 Collaboration, F. Botterweck *et al.*, Z. Phys. C **51**, 37 (1991).
[7] D. Ghosh, P. Ghosh, A. Deb, A. Ghosh, and J. Roy, Phys. Lett. B **272**, 5 (1990).
[8] EMU-01, M. I. Adamovich *et al.*, Phys. Rev. Lett. **65**, 412 (1990).
[9] K. Sengupta, P. L. Jain, G. Singh, and S. N. Kim, Phys. Lett. B **236**, 219 (1990).
[10] *Festschrift Leon Van Hove*, edited by A. Giovannini and W. Kittel (World Scientific, Singapore, 1990), p. 257.
[11] HELIOS Collaboration, T. Åkesson *et al.*, Phys. Lett. B **252**, 303 (1990).
[12] B. Buschbeck, P. Lipa, and R. Peschanski, Phys. Lett. B **215**, 788 (1988).

[13] TASSO Collaboration, W. Braunschweig *et al.*, Phys. Lett. B **231**, 548 (1989).
[14] CELLO Collaboration, H. J. Behrend *et al.*, in *Proceedings the XXVth International Conference on High Energy Physics,* Singapore, 1990, edited by K. K. Phua and Y. Yamaguchi (World Scientific, Singapore, 1991).
[15] DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. B **247**, 137 (1990).
[16] EM Collaboration, I. Derado, G. Jancac, N. Schnitz, and P. Stopa, Z. Phys. C **47**, 23 (1990).
[17] J. Wosik, Acta Phys. Pol. **B19**, 863 (1988).
[18] W. Ochs and J. Wosick, Phys. Lett. B **214**, 617 (1988).
[19] M. Ploszajczak and A. Tucholski, Phys. Rev. Lett. **65**, 1539 (1990).
[20] D. Ghosh *et al.*, Nuovo Cimento **105A**, 159 (1992).
[21] D. Ghosh *et al.*, Phys. Rev. D **26**, 2983 (1982).
[22] K. Fialkowski, B. Wosick, and J. Wosick, Acta Phys. Pol. **B20**, 639 (1989).
[23] G. Paladin and A. Vulpiani, Phys. Rep. **156**, 147 (1987).
[24] P. Lipa and B. Buschbeek, Phys. Lett. B **223**, 465 (1989).
[25] R. C. Hwa, Phys. Rev. D **41**, 1456 (1990).
[26] A. Bialas and R. C. Hwa, Phys. Lett. B **253**, 436 (1991).
[27] A. Bialas, in *Festschrift Leon Van Hove* [10].
[28] H. Satz, Nucl. Phys. **B326**, 613 (1989).
[29] N. G. Antoniou *et al.*, Phys. Rev. D **45**, 4034 (1992).
[30] D. Seibert, Phys. Lett. B **254**, 253 (1991).
[31] D. Seibert, Phys. Rev. D **41**, 3381 (1990).
[32] P. Carruthers and I. Sarcevic, Phys. Rev. Lett. **63**, 1562 (1989).
[33] B. Anderson *et al.*, Nucl. Phys. **B191**, 173 (1981).
[34] A. Jurak and A. Linscheid, Acta. Phys. Pol. **B66**, 875 (1977).
[35] D. Ghosh *et al.*, Report No. JU-HEP-EMU 5, 1992 (unpublished).
[36] A. Giovannini and L. Van Hove, Z. Phys. C **30**, 391 (1986).