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INTERMITTENCY AND TARGET FRAGMENTS IN MUON–NUCLEUS INTERACTIONS AT (420 ± 45) GeV

DIPAK GHOSH, ARGHA DEB, SYED IMTIAZ AHMED and
PARTHASARATHI GHOSH

*Nuclear and Particle Physics Research Centre, Department of Physics,
Jadavpur University, Kolkata - 700032, India*

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This paper presents an analysis of angular distribution of target fragments in lepton nucleus interactions in terms of scaled factorial moments (SFMs) in one-dimensional space. A power-law type behaviour of normalised scaled factorial moments, popularly known as 'intermittency', is expressed with a decreasing phase space. Our data of target fragments reveal a similar type of increase in SFMs with decreasing bin width of the angular distribution in muon–nucleus interactions at (420 ± 45) GeV. The new observation contradicts the existing concept of the evaporation model that the statistical equilibrium is reached before the emission of fragmented particles from residual target nuclei at high-energy nuclear interactions.

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1. Introduction

The phenomenon of a power-law behaviour of scaled factorial moments, known as intermittency, and designed for extracting non-statistical fluctuation after eliminating the statistical part, has created a great deal of interest in recent years. This formalism was first proposed by Bialas and Peschanski in a pioneering work [1] through the analysis of the distribution of produced particles in cosmic ray events [2]. Subsequent analyses [3–9] of high-energy data of various collision processes in the available accelerator-energy range repeated the basic observations, and intermittency appears to be a general phenomenon in multiparticle production as well as target fragmentation process in high-energy interactions. Initially, when the behaviour of the scaled factorial moments appeared to be inconsistent with the standard models of particle production, the concept of self-similarity in the random cascade, or α-model [1], was introduced to explain the phenomenon. The possible existence of self similarity led to further studies [10,11] in terms of the generalised dimensions of fractal geometry [12] already discussed in other branches of physics. The fluctuation in the fragment size distribution is usually well accounted for by a similar type of scaling behaviour in the percolation model. This model is also analysed in terms of intermittency. The analyses reveal the existence of the phenomenon in the fragment size distribution [13,14]. With the aim to search for the possible existence of non statistical fluctuation, or equivalently correlations, the angular distribution of debris from the hot, residual target nuclei at high-energy interactions have been analyzed in terms of scaled factorial moments (SFMs). Analysis of target-associated particles, grey and black tracks, in emulsion experiment in high-energy interactions is scanty. The knowledge of whatever has been reported about these particles is based on hadron-emulsion interactions and heavy-ion interactions, which are believed to produce grey and black tracks of the same origin in the emulsion. The black tracks of interest are identified as target-evaporation particles in a model referred to as the 'evaporation model' [15]. In the evaporation model, the shower and grey tracks are emitted from the nucleus very soon after the instant of impact, leaving the hot residual nucleus in an excited state. Emission of black particles from this state takes place relatively slowly [16]. In order to escape from the residual nucleus, a particle must await a favourable situation. Random collisions between the nucleons within the nucleus sometimes take the particle close to the nuclear boundary, travelling in an outward direction and with a kinetic energy greater than the binding energy of the nucleus. After the evaporation of this particle, a second particle is brought to the favourable condition for evaporation and so on, until the excitation energy of the residual nucleus becomes very small. After that, the transition to the ground state is likely to be affected by the emission of γ-rays only. In the rest system of the nucleus in this model, the directions of the emission of the evaporation particles are distributed isotropically. In various experiments, however, the isotropicity has been found to be disturbed, which may be due to the loss of kinetic energy of the residual nucleus through ionization, following the impulse of collision, before the evaporation process is completed. At the late stage of the reaction, when the nuclear matter is highly excited and diffused, the particle correlations can provide direct information [17]. The evaporation model is based on the assumption that the statistical equilibrium has been established in the decaying system and that the life-time of the system is much longer than the time taken to distribute the energy among the nucleons in the nucleus. This model is not free from problems. Takibaev et al. [17] and Adamovich et al. [18], analyzing the experimental data of proton–emulsion experiments at the incident energies of 67 to 400 GeV, observed the dominance of non-statistical fluctuations over the statistical part of angular distribution of black particles. Also, in a recent study, the angular distribution of black particles from the muon–nucleus interactions could not be explained very satisfactorily by the evaporation model [19]. Earlier, no data in this respect were available in lepton–nucleus interaction. This work is the first study of the intermittency phenomena in terms of SFMs of black particles in muon–nucleus interactions.

2. *Method of analysis*

For any fluctuation in the distribution of produced particles or target fragments, we use the term intermittency, and it can be defined in terms of SFMs. In the $\cos\theta$ space, for each event we calculate SFMs in the following way

$$F_q = \frac{1}{M}\sum_{j=1}^{M}\frac{M^q n_j(n_j-1)\dots(n_j-q+1)}{<n>^q}\,, \tag{1}$$

where M is the number of bins within the full $\cos\theta$ range divided by $\Delta\cos\theta$, n_j is the number of black tracks in the j^{th} bin with j running from 1 to M, $<n>$ is the average number of black tracks in the sample within $\Delta\cos\theta$, q is a positive integer which indicates the order of the moment. For given q and M values, F_q are calculated for all events and averaged over to obtain $<F_q>$. For the non-flat angular distribution, the correction factor R_q is given by

$$R_q = \frac{1}{M}\sum_{j=1}^{M}\frac{M^q <n_j>^q}{<n>^q}\,. \tag{2}$$

This formula is used to obtain the corrected or reduced scaled factorial moments (RSFMs) which are given by

$$<F_{qR}> = \frac{<F_q>}{R_q}\,. \tag{3}$$

This expression is more appropriate for the analysis of intermittency. In the case of a flat distribution, R_q's are equal to unity.

The intermittency exponents α_q are related to the anomalous fractal dimension, d_q, as follows

$$d_q = \frac{\alpha_q}{q-1}\,, \tag{4}$$

and

$$d_q = 1 - D_q\,, \tag{5}$$

where D_q is called the generalised fractal dimension.

3. *Experimental details*

The study of intermittency and of target fragments is performed with the application of the emulsion technique because of its high spatial resolution.

3.1. Exposure

In this emulsion experiment, we have exposed stacks of G5 nuclear emulsion plates to the main muon beam at (420 ± 45) GeV in Fermilab [20]. The emulsions were allowed to warm to room temperature for 4 hours before the exposure.

Two boxes with emulsions were levelled to about ± 2 mrad. The beam intensity at the emulsions was monitored with a scintillator telescope with a circular aperture of 1.25 cm. The telescope consisted of a counter with a 1.25 cm diam. hole in anticoincidence with two counters 2.5 cm × 2.5 cm. The density of the integrated exposure was 0.98×10^6 muons/sq.cm at the centre, tapering off quadratically to 0.60×10^6 muons/sq.cm at 5 cm from the centre (the edge of the emulsion sheets). The beam was deliberately defocussed with quadrupoles to get a fairly even density on all parts of the emulsion.

3.2. Scanning and measurement

The scanning of the events was done with the help of a high-resolution Leitz Metalloplan microscope with an on-line computer system, using objectives 10× in conjuction with a 10× ocular lens. The scanning was done by independent observers to increase the scanning efficiency, which turns out to be 98%.

Criteria for selecting the events were:

(i) The events within 20 μm thickness from the top or bottom surface of the plates were not analysed.

(ii) The track direction did not exceed 3° from the mean beam direction in the pellicle.

All tracks are classified as usual:

(a) The target fragments with ionization greater than $1.4 I_0$ (I_0 is the plateau ionization) produced either black or grey tracks. The black tracks with the range of less than 3 mm represent target-evaporated (light nuclei evaporated from the target) singly or multiply charged particles with $\beta < 0.3$.

(b) The grey tracks with a range ≥ 3 mm and having velocity $0.7 \geq \beta \geq 0.3$ are mainly images of target recoil protons of the energy up to 400 MeV.

(c) The relativistic shower tracks with ionization less than $1.4 I_0$ are mainly produced by pions and are not generally confined within the emulsion pellicle. They are believed to carry important information about the nuclear reaction dynamics. The spatial angle of emission (θ), in the laboratory frame, of all black tracks, is measured by taking the space coordinates (x, y, z) of a point on the track, another point on the incident beam and at the production point. The readings were taken using oil-immersion microscope (100× objective in conjunction with a 10× ocular lens). The detailed data for each event were obtained. The emulsion technique possesses the highest spatial resolution and is, thus, most effective in studying correlation and also in uor study of intermittency phenomenon.

Following the above selection procedure, we have chosen 353 events in our sample plate of muon–nucleus interactions.

4. *Results and discussion*

The variation of RSFMs with $\mathrm{d}\cos\theta = \Delta\cos\theta/M$, the width of the distribution variable, was studied for $q = 2, 3$ and 4 and for M ranging up to 20 in the case of black tracks in muon–nucleus interaction. The increase of F_q with decreasing bin width for $q = 2, 3$ and 4 is evident from the plots of $\ln < F_q >$ vs $-\ln \mathrm{d}\cos\theta$ in Fig. 1. The best fits satisfy the power law $\ln < F_q >= (\mathrm{d}\cos\theta/\Delta\cos\theta)_q^{-\alpha}$, where values of α_qs are also included in Fig. 1.

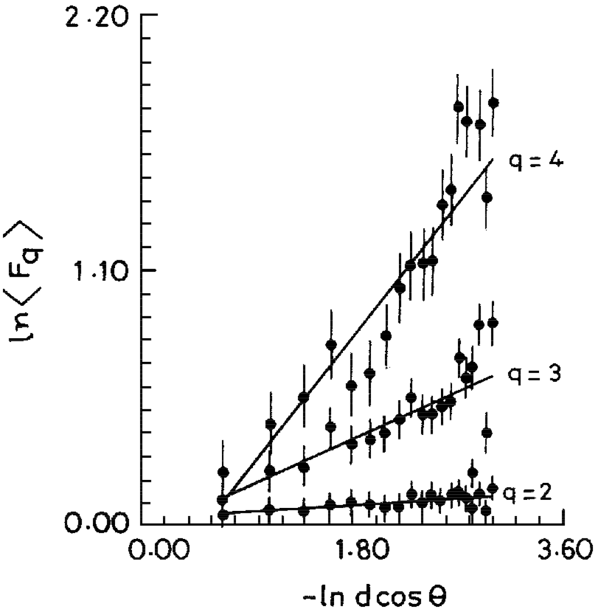

Fig. 1. Plot of $\ln < Fq >$ *vs.* $-\ln(\mathrm{d}\cos\theta))$, *which indicates intermittency in the black-particles emission in muon–nucleus interactions at* (420 ± 45) GeV.

From Fig. 1, it is seen that the best fit for $q = 2$ shows a good agreement with the experimental data, while for $q = 3$ and $q = 4$, there are some apparent deviations from point to point. Figure 1 clearly suggest intermittent behaviour of target fragment in muon nucleus interactions. The errors of α_q shown in Fig. 1 represent the standard deviations over all events and bins used. Errors of α_q have been obtained through the fitting procedure. These are not the correct estimations of errors. Although different approaches for error calculations are prescribed [6,7,21], none of them give the correct estimations of errors. For a given order, the values of the moments for different values of $\mathrm{d}\cos\theta$-bin are correlated. Different orders of moment for the same $\mathrm{d}\cos\theta$ are also correlated. To minimize likely errors in angle measurement, cross checking by several people was performed. The observed increase of the higher-order factorial moments is largely due to F_2, i.e., due to the dynamical two-particle (fragment) correlations, while the observed increase in SFMs with decreasing bin size clearly contradicts the evaporation model. This model is based on the assumption of black particle emission from a state of statistical equilibrium of nucleons in the residual target nucleus also in the case of leptonic interaction. Figure 1 shows a linear behaviour in $\cos\theta$ phase space for $q = 2, 3, 4$. To cross-check our observations, a similar SFMs analysis was performed on a data sample, with the same number of Monte-Carlo generated random events, achieving an angular distribution identical to that obtained from the experimental data. The plots of $\ln < F_q >$ vs $-\ln(\mathrm{d}\cos\theta)$, for this case, are given in Fig. 2. This figure represents the invariance of SFMs with bin size, which is expected from the data in the absence of dynamical phenomena. A comparison of plots of $\ln < F_q >$ vs $-\ln(\mathrm{d}\cos\theta)$ in Fig. 1 with that of Fig. 2 thus confirms the presence

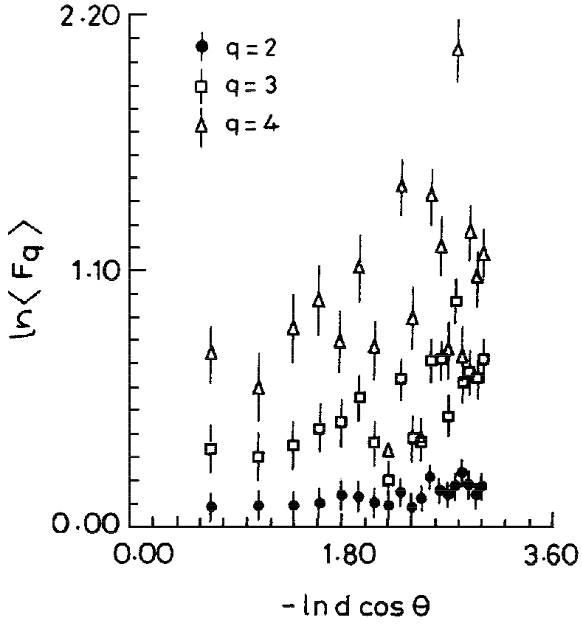

Fig. 2. Plot of $\ln < Fq >$ *vs.* $-\ln(\mathrm{d}\cos\theta)$ *for randomly-generated data of the muon–nucleus interactions at the same energy as in Fig. 1.*

TABLE 1. Values of the intermittency exponent α_q *and of the generalised fractal dimensions* D_q *for three values of* q*.*

q	α_q	D_q
2	0.0260.005	0.973
3	0.2190.006	0.890
4	0.6290.285	0.790

of non-statistical fluctuations in the emission of black particles in muon–nucleus interaction at (420 ± 45) GeV. It is true that for $q = 2$ the Monte Carlo simulated values for F_q are almost the same as the experimental values. However, for higher orders, $q = 3$ and $q = 4$, the Monte Carlo values are significantly different from the experimental values which speaks in favour of the presence of non-statistical fluctuations.

The generalised fractal dimensions, D_qs, are obtained from the values of slopes of α_q using the relations (4) and (5).

In Table 1, the values of the intermittency exponent α_q for qs of different order are given. Also, Table 1 shows that the generalised fractal dimensions decrease with the increase of q values. This is illustrated in Fig. 3.

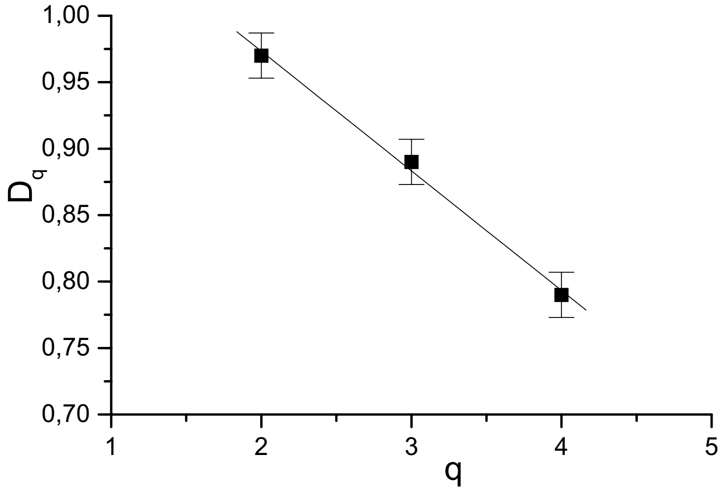

Fig. 3. Plot of D_q vs. q for muon–nucleus interactions at the same energy as in Figs. 1 and 2.

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ODSTUPANJA RASPODJELE DIJELOVA METE U SUDARIMA MIONA S JEZGRAMA NA (420 ± 45) GeV

Predstavljamo analizu kutne raspodjele dijelova mete u sudarima leptona s jezgrama pomoću sukladnih faktorijalnih momenata (SFM) u jednodimenzijskom prostoru. Sa smanjenjem faznog prostora dolazi do izražaja potencijalna ovisnost normaliziranih sukladnih faktorijalnih momenata, koja se obično naziva "odstupanjem raspodjele" (intermittency). Naši podaci za dijelove mete pokazuju slično povećanje SFM-ova kada se smanjuju intervali kutne raspodjele sudara mion–jezgra na (420 ± 45) GeV. Ova su opažnja suprotna prevladavajućoj zamisli modela isparavanja prema kojoj se statistička ravnoteža postiže prije emisije otkinutih dijelova mete u sudarima na visokim energijama.