Multiplicity fluctuation analysis of target residues in nucleus-emulsion collisions at a few hundred MeV/nucleon *

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Abstract: Multiplicity fluctuation of the target evaporated fragments emitted in 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions is investigated using the scaled factorial moment method in two-dimensional normal phase space and cumulative variable space, respectively. It is found that in normal phase space the scaled factorial moment ($\ln\langle F_q\rangle$) increases linearly with the increase of the divided number of phase space ($\ln M$) for lower q-value and increases linearly with the increase of $\ln M$, and then becomes saturated or decreased for a higher q-value. In cumulative variable space $\ln\langle F_q\rangle$ decreases linearly with increase of $\ln M$. This indicates that no evidence of non-statistical multiplicity fluctuation is observed in our data sets. So, any fluctuation indicated in the results of normal variable space analysis is totally caused by the non-uniformity of the single-particle density distribution.

Key words: heavy-ion collisions, target fragmentation, non-statistical fluctuation, nuclear emulsion

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1 Introduction

Since Bialas and Peschanski [1] proposed the scaled factorial moment (SFM) method to study non-statistical fluctuation in multiparticle production, a large number of experiments have been performed to search for the power law behavior, not only for relativistic produced particles (mostly pions) but also for target fragments (target evaporated fragments and target recoiled protons) in nucleus-nucleus collisions at high energies.

Intermittency is a manifestation of the scale invariance of the physical process and the randomness of the underling scaling law, which is defined as the power law growth of SFM with decreasing phase-space interval size. The unique feature of this moment is that it can detect and characterize the non-statistical density fluctuations in particle spectra, which are intimately connected with the dynamics of particle production.

According to the participant-spectator model of the high energy nucleus-nucleus collisions, the projectile and target sweep out cylindrical cuts through each other. The overlapping region of nuclear volumes is called the participant region, where multiple production of new particles occurs and the nuclear matter breaks up into nucleons. The remaining parts of nuclei that do not participate in the disintegration process are called the spectator regions of the projectile and target nuclei. In a central collision the projectile drills a cylindrical hole through the target nucleus, striking every nucleon in its path. Some of the struck nucleons will penetrate into the spectator part whereas some will escape through the hole. It is assumed that effectively only those nucleons that originate from the surface region of the cylinder penetrate into the spectator and that these nucleons move away from the center of the hole. In a peripheral or semi-central collision only a part of the cylindrical hole is developed. Here, the probability that a struck target nucleon will disappear without penetrating into the spectator increases with the decrease of the collision centrality. During this colliding process a fraction of the available energy is transferred to the spectator parts of colliding nuclei, leaving those nuclear remnants in an excited state. After this stage, the de-excitation of the nuclear remnants takes place and the target and projectile fragments are formed. In general, this reaction mechanism is also reasonable for the intermediate and high energy (a few hundreds MeV/u), but the production of new particles in the participant region is highly suppressed

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because of the limited reaction energy. When compared to high energy nucleus-nucleus collisions, the target recoiled fragments (nucleons knocked out by intranuclear cascade processes) and target evaporated fragments (nucleons and light fragments evaporated from the excited target spectator) decreased at intermediate and high energy nucleus-nucleus collisions.

In high energy nucleus-nucleus collisions, target fragmentation may also carry information about the colliding mechanism. The non-statistical fluctuations of the emission of target evaporated fragments in nucleus-nucleus collisions at high energies have been investigated not only in one-dimensional phase-space [2–7] but also in two-dimensional phase-space [8–11]. The evidence of non-statistical fluctuation of target evaporated fragments is obtained in most of these investigation, but in some of these studies [2, 4, 11] the saturation effect is observed in the dependence of the power law growth of the SFM and decreasing phase-space interval size. These effects indicate that there is not a non-statistical fluctuation in the emission of target evaporated fragments. So, the study of non-statistical fluctuation of target evaporated fragments in high energy nucleus-nucleus collisions is not conclusive. For target fragmentation at intermediate and high energy nucleus-nucleus collisions, little attention has been paid to the evaporated fragment multiplicity distribution and multiplicity fluctuation.

In this paper, the non-statistical fluctuations of target evaporated fragments produced in 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions are studied in two-dimensional phase space using not only normal variables $\cos\theta$ and ϕ but also cumulative variables $X_{\cos\theta}$ and X_{ϕ}, where θ is the emissional angle and ϕ is the azimuthal angle of the target evaporated fragment in the laboratory system. We want to test that the result of the non-statistical target evaporated fragment multiplicity fluctuation obtained in high energy nucleus-nucleus collisions is still reasonable at intermediate and high energies.

2 Experimental details

Four stacks of nuclear emulsion made by the Institute of Modern Physics, Shanxi Normal University, China, were used in the present investigation. The emulsion stacks were exposed horizontally at HIMAC, NIRS, Japan. The beams were 290 MeV/u ^{12}C, 400 MeV/u ^{12}C, 400 MeV/u ^{20}Ne and 500 MeV/u ^{56}Fe, respectively, and the flux was 3000 ions/cm^2. BA2000 and XSJ-2 microscopes with 100× oil immersion objective and 10× ocular lenses were used to scan the plates. The tracks were picked up at a distance of 5 mm from the edge of the plates and they were carefully followed until they either interacted with emulsion nuclei or escaped from the plates. Interactions which were within 30 μm from the top or bottom surface of the emulsion plates were not considered for final analysis. All of the primary tracks were followed back to ensure that the events chosen did not include interactions from the secondary tracks of other interactions. When they were observed to do so, the corresponding events were removed from the sample.

In each interaction all of the secondaries were recorded, which include shower particle, target recoiled proton (grey track particle), target evaporated fragment (black track particle), and projectile fragments. According to the emulsion terminology [12], the particles emitted from high energy nucleus-emulsion interactions are classified as follows.

(a) Black particles ($N_{\rm b}$). These are target fragments with ionization $I>9I_0$, I_0 being the minimum ionization of a single charged particles. The range of black particle in nuclear emulsion is $R<3$ mm, velocity is $v<0.3c$, and energy is $E<26$ MeV.

(b) Grey particles ($N_{\rm g}$). These are mostly recoil protons in the kinetic energy range $26\leqslant E\leqslant 375$ MeV, and a few kaons of kinetic energies $20\leqslant E\leqslant 198$ MeV and pions with kinetic energies $12\leqslant E\leqslant 56$ MeV. They have ionization $1.4I_0\leqslant I\leqslant 9I_0$. Their ranges in emulsion are greater than 3 mm and they have velocities within $0.3c\leqslant v\leqslant 0.7c$.

The grey and black particles together are called heavy ionizing particles ($N_{\rm h}$).

(c) Shower particles ($N_{\rm s}$). These are produced by single-charged relativistic particles having velocity $v\geqslant 0.7c$. Most of them belong to pions contaminated with small proportions of fast protons and K mesons. It should be mentioned that for nucleus-emulsion interactions at a few hundred MeV/u, most of the shower particles are projectile protons not pions.

(d) The projectile fragments ($N_{\rm f}$) are a different class of tracks with constant ionization, long range, and a small emission angle.

To ensure that the targets in nuclear emulsion are silver or bromine nuclei, we have chosen only those events with at least eight heavy ionizing track particles ($N_{\rm h}\geqslant 8$).

3 Analysis methods

The non-statistical multiplicity fluctuation analysis is performed in a two-dimensional phase space. The phase space is divided equally in both directions, assuming that it is isotropic in nature. We denote the two phase space variables as x_1 and x_2, the horizontal SFM of order q is then defined as [1]

$$F_{qi}(\delta x_1\delta x_2)=M^{q-1}\sum_{m=1}^{M}\frac{n_{mi}(n_{mi}-1)\cdots(n_{mi}-q+1)}{n_i(n_i-1)\cdots(n_i-q+1)}, \quad (1)$$

where $\delta x_1 \delta x_2$ is the size of a two-dimensional cell, n_{mi} is the multiplicity in the mth cell of the ith event, n_i is the multiplicity of the ith event, and M is the number of two-dimensional cells into which the considered phase space has been divided. Then, the averaged horizontal SFM becomes

$$\langle F_{\mathrm{q}}(\delta x_1 \delta x_2)\rangle = \frac{1}{N_{\mathrm{ev}}}\sum_{i=1}^{N_{\mathrm{ev}}} F_{qi}(\delta x_1 \delta x_2). \tag{2}$$

A non-statistical multiplicity fluctuation would manifest itself as a power-law scaling of $\langle F_q \rangle$ with the cell size of the form

$$\langle F_q(\delta x_1 \delta x_2)\rangle \propto (\delta x_1 \delta x_2)^{-a_q} \quad \text{as } \delta x_1 \delta x_2 \to 0 \tag{3}$$

or a linear relation

$$\ln\langle F_q \rangle = -a_q \ln(\delta x_1 \delta x_2) + b_q = a_q \ln M + c_q. \tag{4}$$

The invariant quantity of the scaling $a_q > 0$ is called the intermittency exponent and it is a measure of the fluctuation strength.

The single-particle density distribution in two-dimensional space (emission angle space and azimuthal angle space) is non-flat. As the shape of this distribution influences the scaling behavior of the SFMs. Bialas and Gazdzicki [13] introduced "cumulative" variable, which drastically reduced the distortion of intermittency due to non-uniformity of single-particle density distribution. Following Bialas and Gazdzicki [13], the cumulative variable $X(x)$ is related to the single-particle density distribution $\rho(x)$ through

$$X(x) = \int_{x_1}^{x} \rho(x')\mathrm{d}x' \Big/ \int_{x_1}^{x_2} \rho(x')\mathrm{d}x', \tag{5}$$

where x_1 and x_2 are two extreme points of the distribution $\rho(x)$. The variable $X(x)$ varies between 0.0 and 1.0, with $\rho(X(x))$ kept almost constant. The values of x_1 and x_2 are -1 and 1 in $\cos\theta$-space, 0 and 2π in azimuthal angle space, respectively.

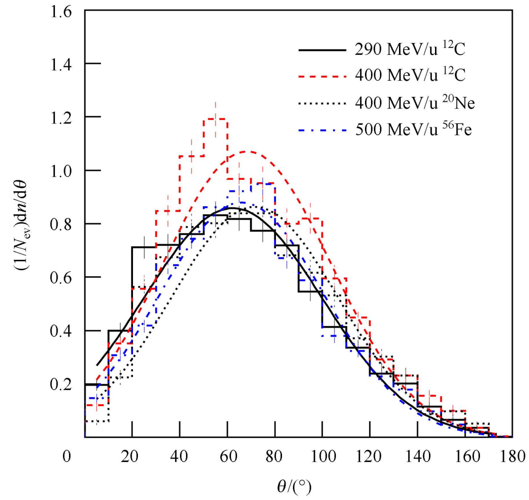

Fig. 1. (color online) Emission angle distribution of target residues, the smooth curve is fitted by a Gaussian distribution.

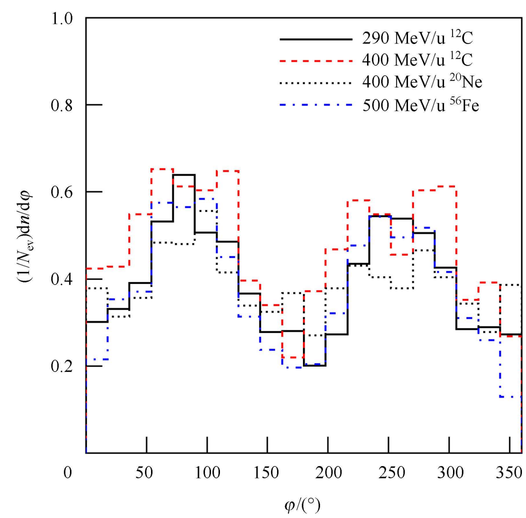

Fig. 2. (color online) Azimuthal angle distribution of target residues.

4 Results and discussion

Figures 1 and 2 show the emission angle and azimuthal angle distributions of the target evaporated fragments that are emitted from 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions. It is found that the angular distributions are not uniformly in whole phase space. The emission angle distribution is fitted by a Gaussian distribution, which is plotted in a smooth curve. The azimuthal angle distribution are symmetric around $\phi = 180$ degrees.

Figure 3 shows the dependence of $\ln\langle F_q \rangle$ on $\ln M$ for target evaporated fragments emitted from 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions in normal variable space. It can be seen that for lower order q the $\ln\langle F_q \rangle$ increases linearly as $\ln M$ increases, but for higher order q the $\ln\langle F_q \rangle$ increases linearly with an increase of $\ln M$ and then becomes saturated or decreases. So, we cannot get clear evidence of non-statistical multiplicity fluctuation from the results of Fig. 3.

Figure 4 shows the dependence of $\ln\langle F_q \rangle$ on $\ln M$ for target evaporated fragments emitted from 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions in cumulative variable space. It can be seen that $\ln\langle F_q \rangle$ decreases linearly with an $\ln M$ increase, which indicates that no evidence of non-statistical multiplicity fluctuation is observed in our data sets. So, any fluctuation indicated

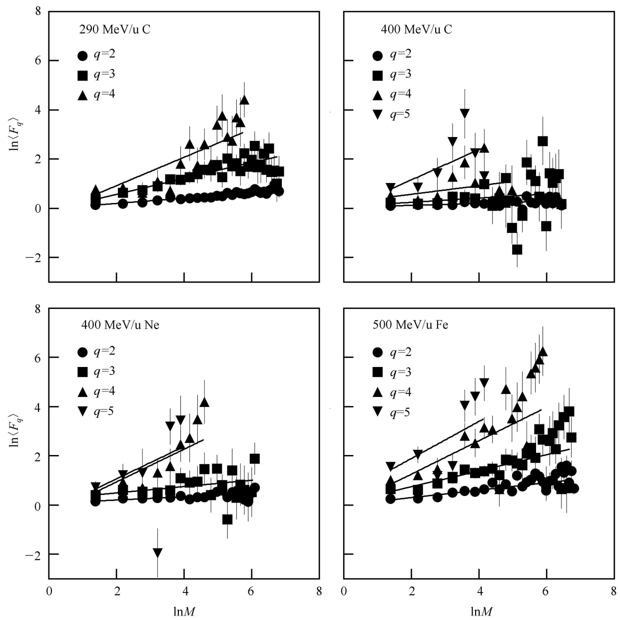

Fig. 3. Plots of $\ln\langle F_q\rangle$ against $\ln M$ in normal two-dimensional variable space.

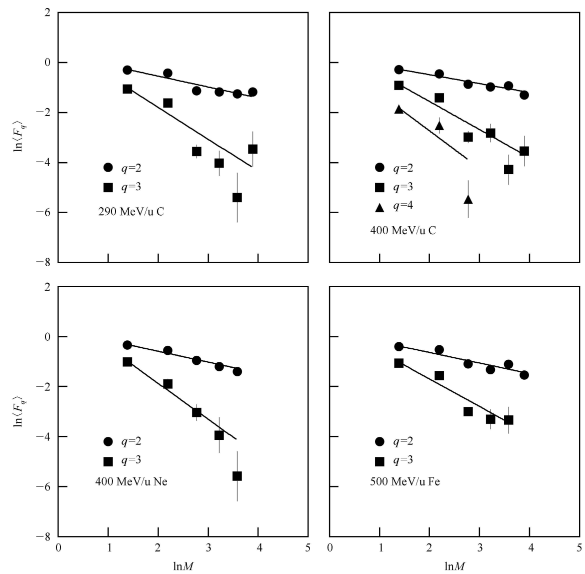

Fig. 4. Plots of $\ln\langle F_q\rangle$ against $\ln M$ in cumulative variable space.

in Fig. 3 is totally caused by the non-uniformity of the single-particle density distribution.

In intermediate and high nucleus-nucleus collisions the target fragmentation produces "grey" and "black" tracks in the nuclear emulsion. The grey tracks are formed by the fast target protons, whose energy ranges up to 400 MeV. The black tracks are images of target evaporated particles of low-energy ($E<30$ MeV) singly or multiply charged fragments. In the cascade evaporation model [12], the grey tracks are emitted from the nucleus very soon after the instant of impact, leaving the hot residual nucleus in an excited state. The emission of black particles from this state takes place relatively slowly. In the rest system of the target nucleus, the directions of the emission of evaporation particles are distributed isotropically. Non-statistical multiplicity fluctuation does not exist in the state of statistical equilibrium. We have observed this in Fig. 3 and Fig. 4.

5 Conclusions

The emission angle and azimuthal angle distributions of target evaporated fragment emitted from 290 MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions are investigated. It is found that the angular distributions are not uniformly in whole phase space. The non-statistical multiplicity fluctuation of target evaporated fragments produced in 290 A MeV/u ^{12}C-AgBr, 400 MeV/u ^{12}C-AgBr, 400 MeV/u ^{20}Ne-AgBr and 500 MeV/u ^{56}Fe-AgBr interactions are studied not only in normal variable space but also in cumulative variable space. No evidence of non-statistical fluctuation in the emission of target evaporated fragments is found in our data sets.

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