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Multiplicity distributions of shower particles and target fragments in ^{7}Li–Em collisions at 3 A GeV/c

N N ABD ALLAH[1], FU-HU LIU[2,*], E A SULTAN[1] and M HASSAN[1]
[1]Physics Department, Faculty of Science, Sohag University, Sohag, Egypt
[2]Institute of Theoretical Physics, Shanxi University, Taiyuan, Shanxi 030006, China
*Corresponding author. E-mail: fuhuliu@163.com; fuhuliu@sxu.edu.cn

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Abstract. Multiplicity distributions of shower particles and target fragments in ^{7}Li–Em (emulsion) collisions at 3 A GeV/c are experimentally studied. In the framework of the multisource thermal model, the multicomponent Erlang distribution is used to describe the experimental multiplicity distributions of shower particles, grey fragments, black fragments, and heavily ionized fragments. The correlations between these multiplicities are experimentally reported. With the increase of impacting centrality (or the target fragment multiplicity), a saturation phenomenon for shower particle multiplicity is observed in the experiment.

Keywords. ^{7}Li–Em collisions; multiplicity distribution; multiplicity correlation.

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1. Introduction

High-energy collision is an important research field in modern physics. In high-energy accelerator experiment, an incident projectile nucleus collides with a target nucleus. This results in the production of a number of final-state relativistic particles and nuclear fragments are produced in the collisions. In collider experiment which has a higher colliding energy, both incident nuclei collide with each other. More final-state relativistic particles are produced, but the number of nuclear fragments is not always more because of the limiting fragmentation phenomenon of the nucleus.

There is no doubt that the collider experiment has many advantages in the study of relativistic particle production, which is related to the formation of quark-gluon plasma (QGP). For the study of nuclear fragmentation, the accelerator experiment with the fixed target has more advantages. The emulsion experiment, which has an important role in the history of high-energy and nuclear physics, has special advantages due to its high resolving power in space. By counting the track number, the emulsion experiment can accurately give the multiplicity distributions of shower particles and nuclear fragments.

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Many models such as the statistical multifragmentation model [1], the expanding and emitting source model [2] or the expanding-evaporating source model [3], the relativistic or ultrarelativistic quantum molecular dynamics model [4–7], the dual parton model [8,9], the equivalent quark-gluon string model [10], the hadron resonance gas model [11,12], the nonequilibrium-statistical relativistic diffusion model [13], etc. have been proposed in the field of high-energy collisions. In a workshop [14] held a few years ago at CERN Theory Institute, more models have reported their predictions on the collision programme at the LHC energies. Most of the mentioned models are microcosmic models which are based on quantum chromodynamics (QCD) and concern the system evolvement and dynamical process. Some of them are thermal and statistical models which focus on the global properties of interacting system and final-state products.

Recently, in the framework of multisource thermal model (previously the multisource ideal gas model) [15,16], we have proposed a multicomponent Erlang distribution which describes the probability distributions of different quantities [17–19]. These quantities include multiplicity, transverse momentum, transverse energy, etc. The multicomponent Erlang distribution is a common law in high-energy collisions. To test this distribution further, we need more data. In this paper, we performed a ^{7}Li-induced emulsion experiment at Dubna energy to obtain different types of multiplicity distributions. The multicomponent Erlang distribution is then used to describe the multiplicity distributions of shower particles, grey fragments, black fragments, and heavily ionized fragments produced in ^{7}Li–Em (emulsion) collisions at 3 A GeV/c. Meanwhile, the correlations between different multiplicities are experimentally reported.

2. Experimental materials

A few stacks of NIKFI-BR2 emulsion plates were exposed at the Dubna Synchrophasotron, Russia. Depending on the track properties [20–22], we divide the final-state products, except for projectile fragments, in an event into four groups: shower particles, grey fragments (particles), black fragments (particles), and heavily ionized fragments (particles). Generally, the shower particles are the relativistic singly charged particles with a velocity greater than $0.7c$ and a track grain density less than $1.4I_0$, where c is the speed of light in vacuum and I_0 is the minimum grain density. The grey fragments are the target fragments which are mainly produced by the cascade collision processes in target nucleus, and the track grain density is in the range of $1.4I_0$ to $10I_0$ and the residual range is greater than 3 mm. The black fragments are the target fragments which are mainly produced by the evaporation processes in target nucleus, and the track grain density is greater than $10I_0$ and the residual range is less than 3 mm. Both the grey and black fragments correspond to heavily ionized tracks and are together called the heavily ionized fragments [20–22].

By using the scan method along the tracks, a total of 1000 minimum-bias events are obtained. In these events, we have measured the numbers (multiplicities) of different kinds of particles and fragments one by one. The multiplicities of shower particles, grey fragments, black fragments, and heavily ionized fragments are denoted by n_{s}, n_{g}, n_{b}, and n_{h}, respectively. Obviously, $n_{\mathrm{h}} = n_{\mathrm{g}} + n_{\mathrm{b}}$.

3. The model

We have used a multisource thermal model [15–18] which was proposed and developed recently. According to the model, many emission sources are assumed to form in intermediate and high-energy nucleus–nucleus collisions. Each source is assumed to emit the produced particles or nuclear fragments. In multiplicity distribution, the multisource thermal model results in a multicomponent Erlang distribution which describes different kinds of particles and fragments [17–19].

According to the model [17,18], we divide the considered event sample into l groups (or subsamples) depending on different impact parameters (participant nucleon numbers) or different reaction mechanisms such as evaporation, absorbtion, spallation, multifragmentation, etc. There are m_j sources in the jth group. Each source is assumed to contribute an exponential form to the multiplicity distribution. The multiplicity (n_{ij}) distribution contributed by the ith source in the jth group is

$$P_{ij}(n_{ij}) = \frac{1}{\langle n_{ij}\rangle}\exp\left(-\frac{n_{ij}}{\langle n_{ij}\rangle}\right), \tag{1}$$

where $\langle n_{ij}\rangle$ is the mean multiplicity contributed by the ith source in the jth group and is not related to i. The multiplicity distribution contributed by the jth group is an Erlang distribution

$$P_j(n_x) = \frac{n_x^{m_j-1}}{(m_j-1)!\langle n_{ij}\rangle}\exp\left(-\frac{n_x}{\langle n_{ij}\rangle}\right) \tag{2}$$

which is the folding result of m_j exponential functions and $n_x = \sum_{i=1}^{m_j} n_{ij}$. In eq. (2), x denotes s, g, b, and h for shower, grey, black, and heavily ionized particles or fragments, respectively. The multiplicity distribution obtained in the final state is the weighed sum of l group contributions. We have

$$P(n_x) = \frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}n_x} = \sum_{j=1}^{l} k_j P_j(n_x), \tag{3}$$

where N and k_j denote the particle or fragment number and weight factor respectively [17,18].

In the Monte Carlo method, let R_{ij} denote random numbers in [0,1]. Equations (1) and (2) lead to

$$n_{ij} = -\langle n_{ij}\rangle \ln R_{ij} \tag{4}$$

and

$$n_x = -\sum_{i=1}^{m_j} \langle n_{ij}\rangle \ln R_{ij}. \tag{5}$$

The multiplicity distribution is finally obtained by a statistical method according to different k_j [17,18].

4. Comparisons

Figure 1 shows the multiplicity distributions of (a) shower particles, (b) grey fragments, (c) black fragments, and (d) heavily ionized fragments in ^{7}Li–Em collisions at 3 A GeV/c. The histograms and curves are our experimental data and modelling results respectively. The experimental mean multiplicities are 3.91 ± 0.08, 3.15 ± 0.09, 5.89 ± 0.14, and 9.04 ± 0.20, respectively. In the calculation, we have used a two-component Erlang distribution. The parameter values and the corresponding χ^2 per degree of freedom (χ^2/dof) are given in table 1. The last two or three data in high multiplicity region are not included for calculating the values of χ^2/dof, because of their low statistics. One can see that the model approximately describes the experimental data.

We notice that there are two groups of events in the experiment. The contributions of the two groups are almost the same ($k_1 \approx k_2 = 0.50 \pm 0.10$). The first group corresponds to the light target nuclei (HCNO) and the peripheral collisions of the projectile with heavy target nuclei (AgBr) and the second group corresponds to AgBr. The mean multiplicities obtained from table 1 are 3.75, 3.28, 6.29, and 9.66, respectively, which are approximately the same as the experimental results.

The correlations between different multiplicities are given in figure 2. From figures 2a–2f, the correlations are $\langle n_{\rm s}\rangle - n_{\rm g}$, $\langle n_{\rm s}\rangle - n_{\rm b}$, $\langle n_{\rm s}\rangle - n_{\rm h}$, $\langle n_{\rm g}\rangle - n_{\rm b}$, $\langle n_{\rm g}\rangle - n_{\rm h}$, and $\langle n_{\rm b}\rangle - n_{\rm h}$, respectively, where $\langle n_x\rangle$ denotes the average of n_x. The points are our experimental data. We regret that the model cannot give the correlations. Instead, we show linear fitted results for most of the data. The lines in the figure are the fitted results except for a few data around letter A in some panels and can be given by $\langle n_{\rm s}\rangle = 0.37n_{\rm g} + 2.69$, $\langle n_{\rm s}\rangle = 0.20n_{\rm b} + 2.88$, $\langle n_{\rm s}\rangle = 0.22n_{\rm h} + 1.95$, $\langle n_{\rm g}\rangle = 0.37n_{\rm b} + 0.93$, $\langle n_{\rm g}\rangle = 0.35n_{\rm h}$, and $\langle n_{\rm b}\rangle = 0.63n_{\rm h}$, respectively.

From figure 2 we see that $\langle n_{\rm s}\rangle$ increases with the increase in $n_{\rm g}$, $n_{\rm b}$, and $n_{\rm h}$ and then drops at high multiplicity. The behaviour of $\langle n_{\rm s}\rangle$ at high multiplicity reflects a saturation phenomenon accompanying light projectile nucleus at a few GeV/nucleon due to the stopping power of the target nucleus. The saturation value reflects the maximum $n_{\rm s}$ at the mentioned energy. As a measurement of impacting centrality, the events with high $n_{\rm h}$ are regarded as central or nearly central events. As $n_{\rm b}$ increases, $\langle n_{\rm g}\rangle$ increases and it drops at high multiplicity. Because $\langle n_{\rm g}\rangle$ drops only two points and the errors are large, we cannot conclude saturation phenomenon for $\langle n_{\rm g}\rangle$ also. From figures 2e and 2d we see that $\langle n_{\rm g}\rangle$ and $\langle n_{\rm b}\rangle$ increase with the increase of $n_{\rm h}$. We have not observed saturation phenomenon for $\langle n_{\rm b}\rangle$ because the target spectator has enough size to evaporate black fragments in collisions induced by light projectile at a few GeV/nucleon. The saturation phenomenon for $\langle n_{\rm b}\rangle$ observed in collisions induced by heavy projectile at a few GeV/nucleon or higher energy [23] is typically caused by the limited target spectator to evaporate high $n_{\rm b}$. The saturation phenomenon for $\langle n_{\rm b}\rangle$ observed in collisions induced by light projectile at higher energy [24] is also caused by the limited target spectator due to which more particles take part in cascade collisions in target spectator leading to a small amount of residual nucleons.

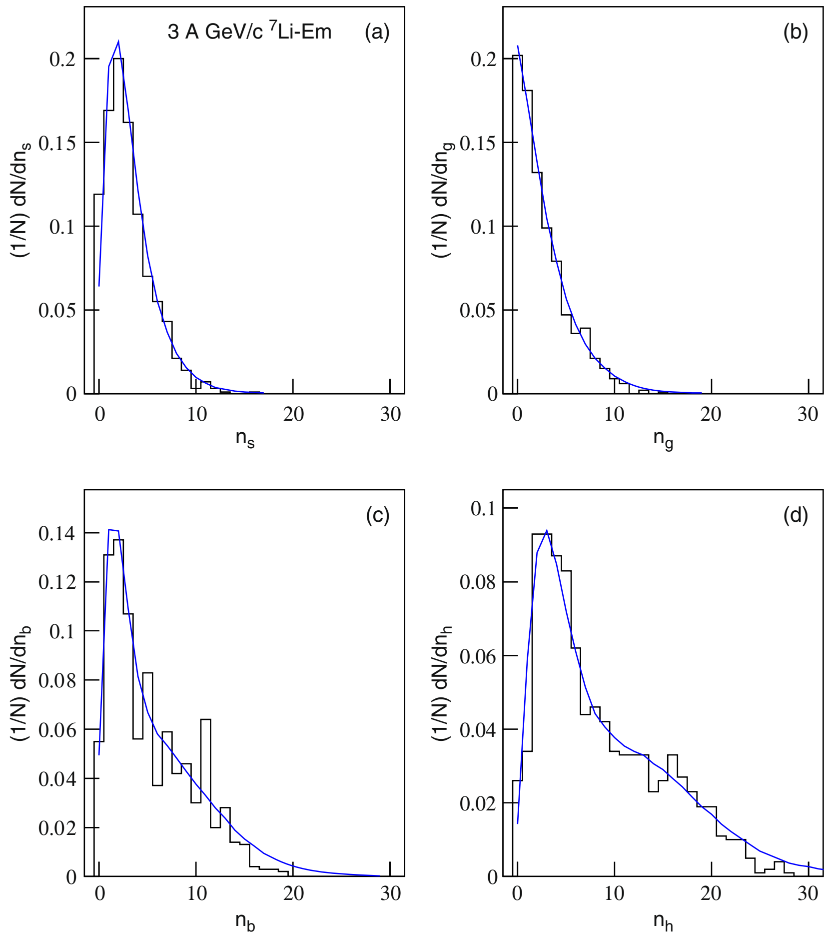

Figure 1. Multiplicity distributions of (**a**) shower particles, (**b**) grey fragments, (**c**) black fragments, and (**d**) heavily ionized fragments produced in ^{3}Li–Em collisions at 3 A GeV/c. The histograms and curves are our experimental data and modelling results respectively.

Table 1. Parameter values and the corresponding χ^2/dof for the curves in figure 1.

Figure	$\langle n_{i1} \rangle$	m_1	k_1	$\langle n_{i2} \rangle$	m_2	χ^2/dof
1a	0.9	3	0.50	1.6	3	0.578
1b	1.6	1	0.40	2.2	2	0.467
1c	0.9	3	0.48	2.4	4	1.040
1d	1.6	3	0.55	2.6	6	0.789

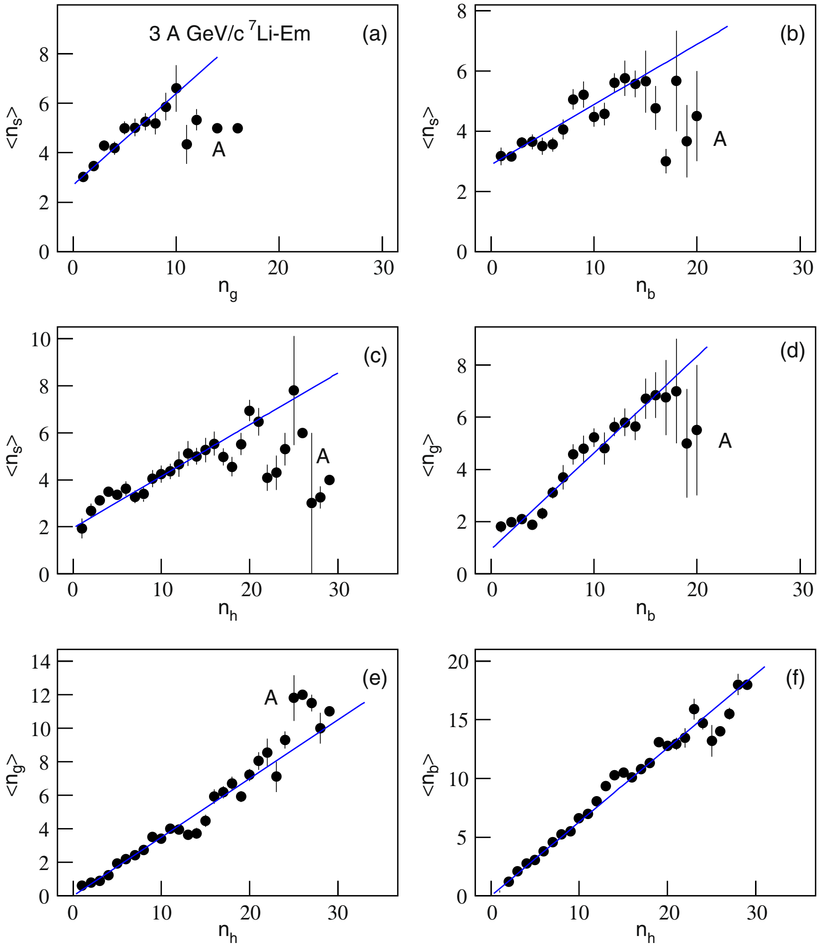

Figure 2. Correlations between (**a**) $\langle n_{\rm s}\rangle - n_{\rm g}$, (**b**) $\langle n_{\rm s}\rangle - n_{\rm b}$, (**c**) $\langle n_{\rm s}\rangle - n_{\rm h}$, (**d**) $\langle n_{\rm g}\rangle - n_{\rm b}$, (**e**) $\langle n_{\rm g}\rangle - n_{\rm h}$, and (**f**) $\langle n_{\rm b}\rangle - n_{\rm h}$ in ^{3}Li–Em collisions at 3 A GeV/c. The points are our experimental data and the lines are the fitted results except for the data around letter A in some panels.

5. Conclusion

We have reported experimentally the distributions of different multiplicities and the correlations between different multiplicities in ^{7}Li–Em collisions at 3 A GeV/c. The multiplicity distributions have been analysed by the multicomponent Erlang distribution and the multiplicity correlations have been analysed by an experiential fit method.

The multiplicity distributions of shower particles and grey fragments are in a narrow range, and appear to be relatively smooth curves. The multiplicity distributions of black fragments and heavily ionized fragments are in a wide range, and appear with relatively large fluctuations in a few bins due to the low statistics. A two-component Erlang distribution with approximately equal weight for each component describes the distributions of the four types of multiplicities.

In the correlations, the behaviour of shower particle multiplicity may reflect a saturation phenomenon accompanying light projectile nucleus at a few GeV/nucleon due to the stopping power of the target nucleus. We have not observed a saturation phenomenon in grey and black fragment multiplicities because the target has enough size to support cascade collisions and evaporation processes.

The saturation phenomenon for black fragment multiplicity observed in collisions induced by heavy projectile at a few GeV/nucleon or higher energy [23] is caused by the limited target spectator. Similar phenomenon observed in light projectile-induced collisions at higher energy [24] is also caused by the limited target spectator in which a small amount of target nucleons remained after the cascade collisions of particles which are produced more.

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