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MULTIPLICITY DISTRIBUTION OF PROJECTILE FRAGMENTS IN Au–Em COLLISIONS AT 10.7*A* GEV

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Multiplicity distributions of projectile fragments emitted in gold-emulsion (Au–Em) collisions at 10.7*A* GeV are reported. The projectile lithium and heavier fragments show an exponential multiplicity distribution. The projectile helium and hydrogen fragments show a single peak and a two-peak multiplicity distributions, respectively. These distributions are studied using a two-phase model.

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In nucleus–nucleus collisions at high energies, many particles are produced and many fragments are present in the final-state. These phenomena are called the multiparticle production and multifragment emission, respectively. It is expected that the multiparticle production is related to the formation of a hot fireball in violent interacting system, and the multifragment emission is mainly related to the liquid-gas phase transition in hot nucleus.

The liquid-gas phase transition in hot nucleus was predicted theoretically many years ago [1,2]. Some experimental work (*e.g.* Refs. [3–5]) were performed to search for the phase transition. A few related signals were suggested in the literature [6–10]. For example, the negative heat capacity signal [6–8], the fossil signal of spinodal decomposition [9], and the bimodality signal of the biggest fragment [10], *etc.* It is expected that if the liquid-gas phase transition happens in hot nucleus, many light fragments such as hydrogen fragments are emitted in the final-state. One thus has to search for events with high multiplicities of hydrogen fragments to identify the liquid-gas phase transition.

As a search for the identification of these processes, in this paper, we report new experimental results on multiplicity distributions of projectile fragments emitted in Au–Em collisions at 10.7A GeV. Events with high multiplicities of hydrogen fragments are found to have a high probability.

The nuclear emulsion stacks used in the present experiment were exposed to a gold beam at the AGS of Brookhaven National Laboratory. The beam energy is 10.7A GeV. The emulsion type is Russian NIKFI-BR2 and the pellicle size is 10 cm × 10 cm × 600 μm. In nuclear emulsion experiments [11], the final state products are divided generally into three groups: projectile fragments, target fragments, and shower particles. The projectile fragments are in a forward cone and have a consistent track grain density over a range of roughly 2 cm. The forward cone is defined by the Fermi momentum (0.2 GeV/c per nucleon) over beam momentum (in GeV/c per nucleon). The charges of light and heavy fragments are determined by the grain and δ-ray densities, respectively. The data studied in the present work consist of 653 random nuclear reaction events.

Figs. 1(a)–1(d) show respectively the multiplicity distributions of projectile lithium, beryllium, boron, and carbon fragments emitted in Au–Em collisions. The closed circles represent the experimental data and the error bars give the statistical errors. The calculated curve are discussed below. One can see that the four distributions in Fig. 1 have a similar shape.

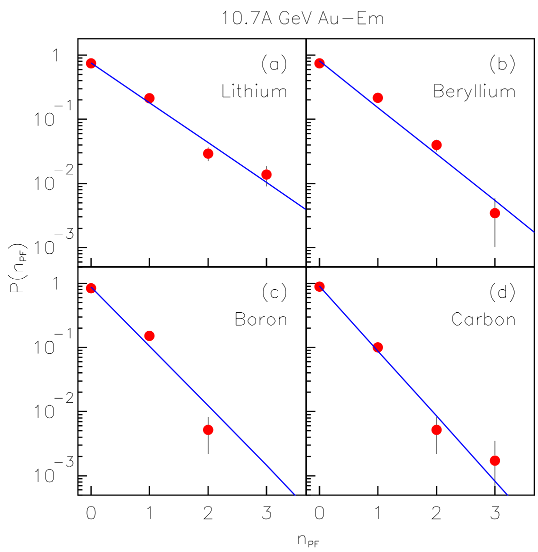

Fig. 1. Multiplicity distribution of projectile lithium, beryllium, boron, and carbon fragments emitted in Au–Em collisions at 10.7A GeV. The closed circles represent the experimental data. The curves are the results of our model.

The multiplicity distribution of projectile helium fragments is shown in Fig. 2. The closed circles represent the experimental data and the error bars give the statistical errors. The calculated curves and open circles will be discussed later. One can see that a clear difference exists between the multiplicity distribution of projectile helium and that of heavier fragments. There is a peak appearing in the multiplicity distribution of projectile helium fragments.

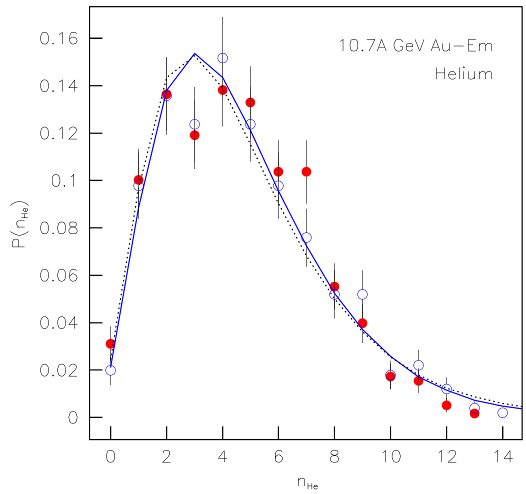

Fig. 2. Multiplicity distribution of projectile helium fragments emitted in Au–Em collisions at $10.7A$ GeV. The closed circles represent the experimental data. The calculated curves and open circles are obtained using the model described in the text.

Fig. 3 presents the multiplicity distribution of projectile hydrogen fragments. The closed circles represent the experimental data and the error bars give the statistical errors. Once more the observed distribution is totally different from those of helium and heavier fragments. There are two peaks appearing in the multiplicity distribution of projectile hydrogen fragments.

To explain the experimental result, a two-source model which was suggested in our previous work [12–15] is used. The model based on the participant–spectator model [16–18] describes the multiplicity and angular distributions of projectile fragments emitted in nucleus–nucleus collisions at high energies.

According to the participant–spectator model [16–18], the overlapping part of the projectile and target nuclei is called the participant. The parts outside the overlapping region are called the spectators. In the framework of our two-source model [12–15] the spectator includes a hot component originating from the contact layer with the participant. The other part of

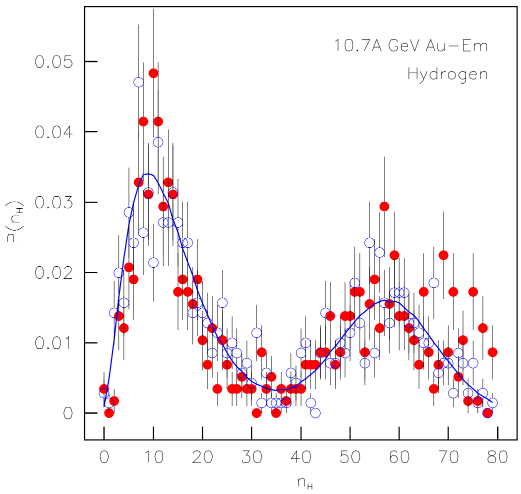

Fig. 3. As for Fig. 2, but showing the multiplicity distribution of projectile hydrogen fragments.

the spectator constitutes a colder source. The hot spectator source has a high temperature and a small size. Its decay leads only to light fragments. In contrast, the cold spectator source has a lower temperature and a larger size. It emits light fragments and few heavy fragments. Meanwhile, some light fragments come from the participant as leading particles. Thus light fragments such as hydrogen and helium fragments are produced by three emission sources, *i.e.* the hot spectator source, cold spectator source, and participant. On the other hand, lithium and heavier fragments are expected to come mainly from only one emission source, *i.e.* the cold spectator source. The biggest fragment is usually regarded as the residual one in hot nuclear fragmentation [19].

In the description of the experimental data, according to our two-source model [12] and the three-fireball model [20], each source is assumed to contribute an exponential multiplicity distribution. For emission from a single source as for lithium and heavier fragments, using the Monte Carlo method, the multiplicity is expected to be described by a relation of the form

$$n_{\rm PF} = -\langle n_{\rm PF}^{\rm c}\rangle \ln R_1 \,, \tag{1}$$

where $\langle n_{\rm PF}^{\rm c}\rangle$ is the mean multiplicity contributed by the cold spectator source and R_1 is an random variable in $[0, 1]$ range. The upper letter "c" denotes the cold source.

For light fragments such as hydrogen and helium fragments, we expect a multiplicity of the form

$$n_{\rm PF} = -\langle n_{\rm PF}^{\rm h}\rangle \ln R_2 - \langle n_{\rm PF}^{\rm c}\rangle \ln R_3 - \langle n_{\rm PF}^{\rm p}\rangle \ln R_4 \,, \tag{2}$$

where $\langle n^{\rm h}_{\rm PF}\rangle$ and $\langle n^{\rm p}_{\rm PF}\rangle$ are the mean multiplicities contributed by the hot spectator source and participant, respectively. R_2, R_3, and R_4 are random variables in $[0, 1]$ range. The upper letters "h" and "p" denote the hot spectator source and participant, respectively.

We expect in our measurement where the target made of an emulsion is complex to have two types of events. Some events will be associated to collisions with heavy target nuclei leading to a small spectator component and a larger participant component. These events should have relatively low spectator multiplicity and should be described by Eqs. (1) and (2). Other events will correspond to collisions with light target nuclei leading to a large enough spectator component and small participant component and as a result events of large forward multiplicity and possible contribution from a liquid-gas phase transition coming from the large enough spectator. Neglecting the small contribution from the participant, the hydrogen fragments are expected to come mainly from the spectator in its gas phase leading to a predicted multiplicity distribution of a Gaussian type with a width σ and mean value n_0, *i.e.*

$$n_{\rm H} = \sigma\sqrt{-2\ln R_5}\,\cos(2\pi R_6) + n_0\,, \tag{3}$$

where R_5 and R_6 are random variables in $[0, 1]$ range.

We choose the Gaussian multiplicity distribution to describe the decay of the spectator in its gas phase because this decay is similar to that of a fireball formed in central nucleus–nucleus collisions. The multiplicity distribution of particles produced in such a fireball obey approximately the Gaussian distribution [21]. In fact, we may regard the fireball as a multisource system. Each source is assumed to contribute an exponential multiplicity distribution. The folded result of many exponential distributions is expected to be an Erlang distribution which is similar to the Gaussian distribution.

According to the above discussion, lithium and heavier fragments should come from the cold spectator and obey Eq. (1). Helium fragments should come from the hot spectator, cold spectator, and participant and obey Eq. (2). Hydrogen fragments in events with no gas phase component should come from the hot spectator, cold spectator, and participant and similarly obey Eq. (2). In contrast, hydrogen fragments in events where spectators decay from a gas phase should obey Eq. (3). The final state distribution of multiplicities can be calculated by a statistical method.

In Fig. 1, the curves are our calculated results using Eq. (1). In the calculation, for Figs. 1(a)–1(d), the calculated curves correspond to $\langle n^{\rm c}_{\rm PF}\rangle =$ 0.70, 0.60, 0.47, and 0.43, respectively, with χ^2/degree of freedom (d.o.f.) of 0.386, 0.765, 1.384, and 0.390, respectively. One can see that Eq. (1) describes multiplicities of lithium and heavier fragments very well.

The solid curve in Fig. 2 is our calculated result using Eq. (2). In the calculation, $\langle n^{\rm h}_{\rm He}\rangle = \langle n^{\rm c}_{\rm He}\rangle = \langle n^{\rm p}_{\rm He}\rangle = 1.75$ with χ^2/dof to be 0.602. Thus the total mean multiplicity $\langle n_{\rm He}\rangle$ of helium fragments is obtained from these parameter values to be 5.25. To describe qualitatively fluctuations of the experimental data, the calculated fluctuations associated with the numbered of measured events are shown in the figure by the open circles. These open circles are obtained by Eq. (2) which is a Monte Carlo presentation of the fold of three exponential distributions. In the calculation for the open circles, 500 helium fragments are produced. One can see that Eq. (2) describes fairly well the mean trend and fluctuations of the multiplicity distribution of helium fragments.

In the calculation for the solid curve in Fig. 2, we have used the same contribution for different sources, *i.e.* $\langle n^{\rm h}_{\rm He}\rangle = \langle n^{\rm c}_{\rm He}\rangle = \langle n^{\rm p}_{\rm He}\rangle$. To reproduce the position of the peak and its width, one requires three independent components of comparably value with a total mean multiplicity of 5.25. For example, let $\langle n^{\rm h}_{\rm He}\rangle = 1.00$, $\langle n^{\rm c}_{\rm He}\rangle = 1.75$, and $\langle n^{\rm p}_{\rm He}\rangle = 2.50$, the calculated result is obtained and shown in Fig. 2 by the dotted curve with χ^2/dof to be 0.707. We would like to point out that the assignment of the mean multiplicities to hot source, cold source, and participant in Fig. 2 is arbitrary. Any permutation of the values $\langle n^{\rm h}_{\rm He}\rangle = 1.00$, $\langle n^{\rm c}_{\rm He}\rangle = 1.75$, and $\langle n^{\rm p}_{\rm He}\rangle = 2.50$ gives the same curve. In principle the data cannot answer which of the sources has the largest mean multiplicity.

Using Eqs. (2) and (3), the calculated curve of the multiplicity distribution of projectile hydrogen fragments is shown in Fig. 3. In the calculation, the probability of the spectator in its gas phase is taken to be 0.4. For the first type of events described by Eq. (2), one used $\langle n^{\rm h}_{\rm H}\rangle = \langle n^{\rm c}_{\rm H}\rangle = \langle n^{\rm p}_{\rm H}\rangle = 4.75$. This dominates the first peak in the distribution. The contribution from Eq. (3) was obtained using parameters $\sigma = 10.00$ and $n_0 = 58.00$ and describe the second peak. The value of χ^2/dof is 0.708. Thus the mean multiplicity $\langle n_{\rm H}\rangle$ of hydrogen fragments obtained from these parameter values is 31.75. The indicated fluctuations are calculated and shown in the figure by the open circles. One can see that a combination of Eqs. (2) and (3) succeeds to describe the mean trend and fluctuations of the multiplicity distribution of hydrogen fragments emitted in Au–Em collisions at $10.7A$ GeV.

In Fig. 3, the contributions of Eqs. (2) and (3) are 0.6 and 0.4, respectively. This indicates that we divided all the events into two groups: 60% with a liquid phase and 40% with a gas phase. The assumed probability 0.4 of events with a gas phase has implications on other observables besides the hydrogen multiplicity. It causes other fragments to have low multiplicity and small mean value. It is regretful that the present data cannot be clearly separated the two kinds of events in distributions of helium and heavier fragments. In addition, we do not think the events with a gas phase to stay at a purely state of gas phase. Some of them may stay at a fixed state of liquid and gas phases. The present distribution of hydrogen multiplicity cannot be separated the events with a fixed phase from those with a purely gas phase.

From the comparisons between the calculated results and the experimental data, one concludes that the model with two phases describes the multiplicity distributions of projectile fragments emitted in Au–Em collisions at $10.7A$ GeV. The events with high multiplicities of projectile hydrogen fragments have a very high probability. Perhaps, we may regard these high multiplicity events as a special type of events in which a liquid-gas phase transition had occurred.

To conclude, we have reported new experimental data of multiplicity distributions of projectile fragments emitted in Au–Em collisions at $10.7A$ GeV. For projectile lithium and heavier fragments, an exponential multiplicity distribution is observed. The projectile helium fragments shows a single peak multiplicity distribution. A two-peak structure is found in the multiplicity distribution of projectile hydrogen fragments.

The experimental data obtained in the present work are analyzed using a two-phase model. The multiplicity distributions of lithium and heavier fragments are described considering only the contribution of the cold spectator. The multiplicity distribution of helium fragments and the first peak in the two-peak distribution of hydrogen fragments are approximately described considering the contributions of the hot spectator, cold spectator, and participant. The second peak in the hydrogen distribution is described assuming the contribution of the spectator in its gas phase.

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