Physics International 1 (2): 95-101, 2010
ISSN 1948-9803

Two Source Emission Behavior of Helium Projectile Fragments in ^{84}Kr Interactions at Around 1 GeV per nucleon

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Abstract: Problem statement: The emission of helium projectile fragments has been studied in ^{84}Kr interactions with nuclei of the nuclear emulsion detector at relativistic energies below 2 GeV per nucleon. **Approach:** The angular distribution of helium projectile fragments in terms of transverse momentum could not be explained by a straight and clean-cut collision geometry hypothesis of Participant-Spectator (PS) Model. **Results:** Therefore, it has been assumed that helium projectile fragments were produced from two separate sources that belong to the projectile spectator region differing drastically in their temperatures. It has also been clearly observed that the emissions of helium projectile fragments were from two different sources. The contribution of helium projectile fragments from contact layer or hot source was few percent of the total emission of helium projectile fragments. **Conclusion:** Most of the helium projectile fragments were emitted from the cold source.

Key words: Helium projectile fragment, nucleus-nucleus collisions, multiplicity and transverse momentum

INTRODUCTION

Nuclear fragmentation is an important experimental phenomenon in nucleus-nucleus collisions at relativistic high energy (Jilany, 2004; Andronic *et al*., 2005). Large numbers of models (Joseph *et al*., 1989; Abdel-Aziz, 2008; Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009; EL-Daiem, 2010) have been introduced in the investigation of projectile fragmentation in the nucleus-nucleus interactions at very high energies but at just relativistic kinetic energy, only a few models have been found suitable (Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009). The emission characteristics of helium projectile fragments have been studied in several experiments (Jilany, 2004; Andronic *et al*., 2005; Abdelsalam *et al*., 2005) and the general consensus was they are coming out from the projectile spectator part in the context of a PS model (Joseph *et al*., 1989; Abdel-Aziz, 2008).

The PS model is the simple and basic model for the study of the high energy nucleus-nucleus collisions. According to the PS model, the interacting system in high energy nucleus-nucleus collisions can be divided into three parts: Target and projectile, participant and spectators region. The overlapping part of two colliding nuclei is called the participant region and the other parts are called the target and the projectile spectators.

The straight and clean-cut collision geometry picture of PS model successfully explained lighter projectiles data but failed for high energy heavy ion interactions because experiments observed many helium projectile fragments having larger angle of emission (Joseph *et al*., 1989; Abdel-Aziz, 2008; El-Daiem, 2009). Thus, forcing us to rethink and modify this model according to the physics requirements by making use of the multiple sources idea i.e. emission of helium projectile fragments from different sources at different temperature.

In this study, we focus on projectile spectator region. We analyzed the multiplicity and transverse momentum distributions of helium projectile fragments produced in ^{84}Kr interactions with the nuclei of the Nuclear Emulsion Detector's (NED) target at around 1 GeV per nucleon kinetic energy (Bogdanov *et al*., 2005). NED has very high position and angular resolution and thus finds wide application in the investigation of nuclear fragmentation (Abdel-Waged, 1999; Yan *et al*., 2008) by serving as target for the projectile. NED provides 4π geometrical coverage, therefore, allows an exclusive type of analysis on an event-by-event basis with detailed information about the fragmentation mechanism of nucleus-nucleus interactions.

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Experimental details, required modification in PS Model and observed results, which explain data of projectile fragmentation using a two source PS Model, has been discussed in section results and discussion section.

The model: It is strongly believed that the nuclear collision geometry plays an important role in the study of particular behavior of the nucleus-nucleus collisions. According to the PS Model (Joseph *et al*., 1989; Abdel-Aziz, 2008), the overlapping part of two colliding nuclei is called participant, from where freshly produced particles occur. The remaining parts of nuclei which do not participate in the collision are called target spectator and projectile spectator. In collisions, due to the existence of relative motion between participant and spectator, friction is caused on the contact layer. The participant and spectator get the heat due to friction (Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009). It takes time for the heat to be transmitted to the rest part of spectator and give raise to temperature gradient in spectator region of projectile. The contact layer and the rest part are separated from each other because of the heat of friction and are considered as two sources to emit nuclear fragments with two different temperatures.

The contact layer portion has highest temperature after participant region. The temperature is almost constant in a layer and the thickness of layers increases with distance from contact layer as shown in Fig. 1. The fall in temperature is rapid towards the farther side of projectile spectator region. This could lead the whole spectator to a non-equilibrium state, but the contact layer and the rest part are in local equilibrium state. The change in temperature follows exponential decay nature and it could be explained from the measured charge spectrum of the projectile fragments.

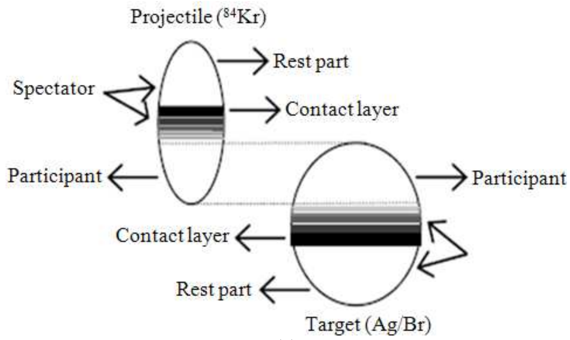
Let n_c and n_o denote the multiplicities of helium projectile fragments emitted from contact layers closer to the participant region and the rest part of the projectile spectator, respectively. It is also possible for heavy projectile clusters gets excited and decays into few helium projectile fragments in a very short time and the distance travelled before decay is close to the vertex of the event. The multiplicity of helium projectile fragments measured in the final state of interaction is denoted by n_α. The relationship between the mean multiplicities is given by:

$$< n_c > = k < n_\alpha > \quad (1)$$

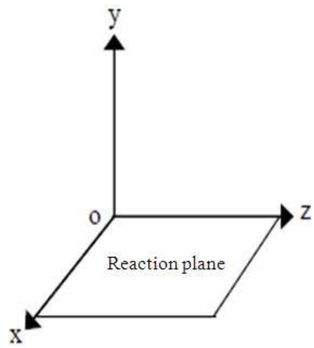
and:

$$< n_o > = (1-k) < n_\alpha > \quad (2)$$

where, k is an extra parameter.



(a)



(b)

Fig. 1: (a) Schematic overview of the contact layer and the other part of the projectile and target spectators across the incoming direction of the projectile. Different dark strips are representing different temperature regions of the projectile spectator. The projectile is approaching toward the target and target is at rest. Here we are considering only two basic regions of the projectile spectator i.e., contact layer very close to the participant region and rest of the spectator part just for the convenience in calculation. Schematic diagram of the coordinate system of interaction geometry in the laboratory frame has been shown along with reaction plane of the interaction in Fig. b.

Let $P_c(n_c)$, $P_o(n_o)$ be the probability for the contact layer and rest part of spectator to emit n_c, n_o fragments respectively. $P_c(n_c)$, $P_o(n_o)$ from are then given by:

$$P_c(n_c) = \frac{1}{< n_c >} \exp\left(\frac{-n_c}{< n_c >}\right) / \left[1 - \exp\left(\frac{-n_{cm}}{< n_c >}\right)\right] \quad (3)$$

and:

$$P_c(n_o) = \frac{1}{< n_o >} \exp\left(\frac{-n_o}{< n_o >}\right) / \left[1 - \exp\left(\frac{-n_{om}}{< n_o >}\right)\right] \quad (4)$$

where, n_{cm} and n_{om} are the maximum values of n_c and n_o, respectively.

The probability $P(n_\alpha)$ for the spectator to emit n_α fragments depends only on the sum of n_c and n_o (Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009). That is:

$$P(n_\alpha) = \int_0^{n_\alpha} P_c(n_c) P_0(n_\alpha - n_c) dn_c \quad (5)$$

On substituting (3) and (4) in (5), we get:

$$P(n_\alpha) = \frac{1}{(<n_c><n_o>)} \int_0^{n_\alpha} \exp\left(\frac{-n_c}{<n_c>}\right) \exp\left\{-\frac{(n_\alpha - n_c)}{<n_o>}\right\} dn_c$$
$$/ \left[1-\exp\left(\frac{-2n_{cm}}{<n_\alpha>}\right)\right]\left[1-\exp\left(\frac{-2n_{om}}{<n_\alpha>}\right)\right] \quad (6)$$
$$= \frac{4n_\alpha}{<n_\alpha>^2} \frac{\exp\left(\frac{-2n_\alpha}{<n_\alpha>}\right)}{\left\{\left[1-\exp\left(\frac{-2n_{cm}}{<n_\alpha>}\right)\right]\left[1-\exp\left(\frac{-2n_{om}}{<n_\alpha>}\right)\right]\right\}}$$

In the case of k = 0.5 and the maximum multiplicity of helium projectile fragments $n_{\alpha max} \approx 2n_{cm} \approx 2n_{om}$, then:

$$P(n_\alpha) \approx \frac{4n_\alpha}{<n_\alpha>^2} \exp\left(\frac{-2n_\alpha}{<n_\alpha>}\right) / \left[1-\exp\left(\frac{-n_{\alpha max}}{<n_\alpha>}\right)\right]^2 \quad (7)$$

Especially for a maximum number of helium projectile fragments ($n_{\alpha max}$) values, Eq. 7 becomes:

$$P(n_\alpha) \approx \frac{4n_\alpha}{<n_\alpha>^2} \exp\left(\frac{-2n_\alpha}{<n_\alpha>}\right) \quad (8)$$

The helium projectile fragments emission from each source is assumed to be isotropic (Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009) in the source rest frame. Let z denote the direction of the incident projectile and xoz plane be the reaction plane. The three components of helium projectile fragments momentum (p_{xyz}) in the source rest frame are assumed to have Gaussian distributions (Joseph *et al*., 1989; Abdel-Aziz, 2008) with the same width σ_p. Therefore, we have:

$$P_{px,y,z}(p_{x,y,z}) = \frac{1}{(2\pi\sigma_p)^{1/2}} \exp\left(\frac{-p_{x,y,z}^2}{2\sigma_p^2}\right) \quad (9)$$

Then, the transverse momentum:

$$p_T = (p_x^2 + p_y^2)^{1/2} \quad (10)$$

Has Rayleigh scattering distribution as:

$$P_{pt}(p_T) = \frac{p_T}{\sigma_p^2} \exp\left(\frac{-p_T^2}{2\sigma_p^2}\right) \quad (11)$$

Considering the two-source emission of helium projectile fragments, the final-state transverse momentum (p_T) distribution should be the sum of two Rayleigh scattering distributions, i.e., active sources are represented by each distribution:

$$P_{pT}(p_T) = \left(\frac{A_H p_T}{\sigma_H^2}\right) \exp\left(\frac{-p_T^2}{2\sigma_H^2}\right) + \left(\frac{A_L p_T}{\sigma_L^2}\right) \exp\left(\frac{-p_T^2}{2\sigma_L^2}\right) \quad (12)$$

where, σ_H and σ_L are the p_T distribution widths of helium projectile fragments emitted from the sources of high and low temperatures, respectively. A_H and A_L denotes the number of helium projectile fragments contribution from the two sources where temperature of the sources are considered as high and low, respectively.

MATERIALS AND METHODS

The experiment was performed in a stack of NIKFI BR-2 NED having 600 μm thickness exposed by a beam of ^{84}Kr nuclei at around 1 A GeV (Chernov *et al*., 1984; Ahamad and Hasan, 1992; Krasnov *et al*., 1996) at GSI Darmstadt, Germany. The measurements and analysis are done at Banaras Hindu University by scanning the NED volume, having dimension 9.8×9.8×0.06 cm, with the help of Olympus BH-2 transmitted light-binocular microscope under 100X oil immersion objective and 15X eyepieces. There are two standard methods for scanning of NED. A total of 600 inelastic interactions of ^{84}Kr nuclei have been picked up. Charge and angle of the projectile fragment for these events were measured. The charge estimation was performed with the accuracy of a unit charge by making use of Grain, blob and hole density and delta ray counting methods. The angle measurement carried out by a small but very effective device called "Gonio-meter" having a least count better than a quarter of a degree.

RESULTS

In the Nuclear Emulsion Detector (NED) based experiment, it is not possible to make direct momentum measurement of charge particles. However, the transverse momentum can indirectly be calculated by using the fact that the projectile fragments have nearly the same momentum per nucleon as that of the projectile in case of fixed target experiment (Chernov *et al*., 1984; Ahamad and Hasan, 1992; Krasnov *et al*., 1996), because when a projectile nucleus with relativistic energies collides with a target nucleus the projectile fragments emitted retain more or less the same momentum per nucleon as of the projectile nucleon. So, if p_o is the momentum of the incident projectile, the transverse momentum of the fragment of charge Z can be calculated by using the following relation:

$$p_T = A_F p_o \, \text{Sin}\theta \qquad (13)$$

Where:

A_F = the mass number of the fragments and
θ = the emission angle of the fragments with respect to the projectile direction.

Therefore, the pseudo-transverse momentum can be obtained from the measurement of the emission angles.

In order to test the two source fragment emission, we compared the sum of two Rayleigh scattering distributions of the transverse momentum with the observed data for ^{84}Kr projectile with different kinetic energies. The multiplicity distribution of helium projectile fragments emitted in ^{84}Kr at the energies (0.50-0.08), (0.80-0.50) and (0.95-0.80) A GeV (Bogdanov *et al*., 2005; Chernov *et al*., 1984; Ahamad and Hasan, 1992; Krasnov *et al*., 1996) was evaluated and are compared with 1.7 A GeV and 1.5 A GeV (Bogdanov *et al*., 2005) is shown in Fig. 2. The Gaussian function fitting's parameters for the distributions are tabulated in Table 1.

The transverse momentum distributions of helium projectile fragments at energies (0.80-0.50) and (0.95-0.80) A GeV was evaluated and are compared with 1.7 A GeV and 1.5 A GeV (Bogdanov *et al*., 2005) are shown in Fig. 3. The tail portion of the p_T distribution has an extra shape with peak around 480 MeV/c and less than 5% of total helium projectile fragments are contributing towards the peak.

The transverse momentum distribution of helium projectile fragments has been plotted for the above mentioned energies in Fig. 4a-d respectively. Solid curve is the sum of two Rayleigh scattering distribution function as described in Eq. 12 are superimposed.

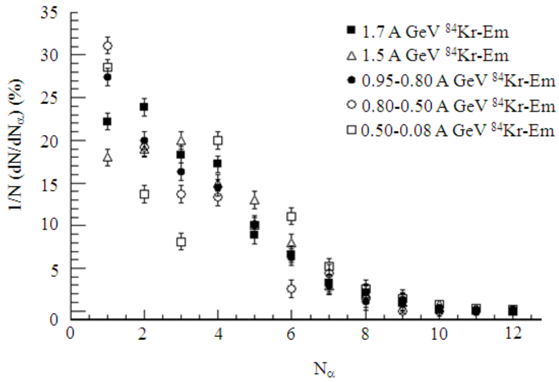


Fig. 2: Multiplicity distribution of helium projectile fragment emitted in ^{84}Kr nuclei interactions with emulsion target nuclei at different energy

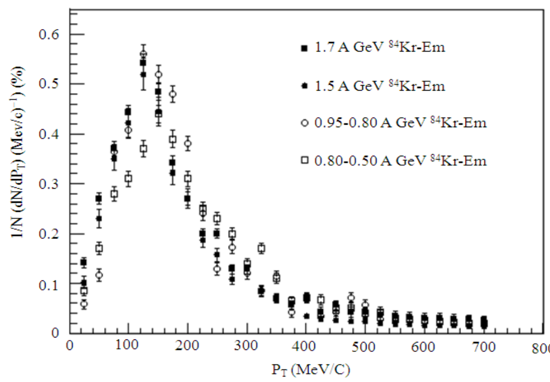


Fig. 3: Transverse momentum distribution of helium projectile fragments emitted in ^{84}Kr nuclei interactions with emulsion target nuclei at different kinetic energies

Table 1: Multiplicity distribution of helium projectile fragment has been fitted with the Gaussian function and the fitting parameters values are tabulated in this table

Projectile	Energy (A GeV)	Constant	Mean	Sigma
^{84}Kr	1.7	23.00±0.67	1.49±0.28	2.79±0.22
^{84}Kr	1.5	27.34±0.39	1.30±0.94	2.64±0.39
^{84}Kr	0.95-0.80	22.79±0.56	1.37±0.85	2.77±0.55
^{84}Kr	0.80-0.50	21.95±0.92	1.38±0.16	2.97±0.39
^{84}Kr	0.50-0.08	19.84±0.58	2.29±0.19	2.68±0.18

Table 2: Rayleigh scattering function's fitting parameters for the concept of two sources of helium projectile fragments emission during nucleus-nucleus interactions at high energy. Rayleigh scattering function was fitted on the observed data of the transverse momentum distribution of ^{84}Kr interactions with target nuclei at different kinetic energies ranging from around 2-0.5 GeV per nucleon

Projectile	Energy (A GeV)	A_H	A_L	σ_H (MeV/c)	T_H (MeV)	σ_L (MeV/c)	T_L (MeV)
^{84}Kr	1.7	0.5	0.5	175	32.64	96	9.82
^{84}Kr	1.5	0.5	0.5	172	31.53	95	9.62
^{84}Kr	0.95-0.80	0.5	0.5	170	30.80	93	9.22
^{84}Kr	0.80-0.50	0.5	0.5	169	30.44	92	9.02

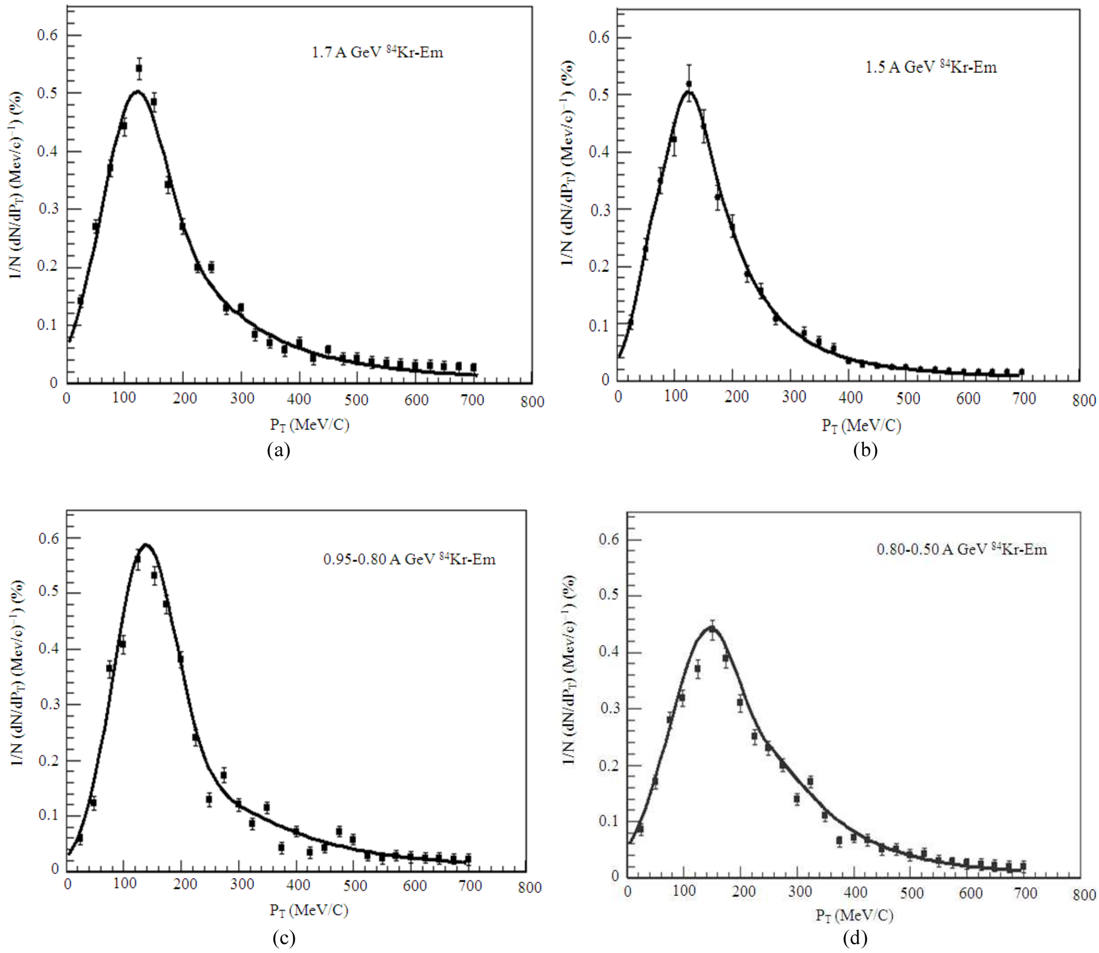


Fig. 4: Transverse momentum distribution of helium projectile fragments emitted in ^{84}Kr nuclei interactions with emulsion target nuclei at (a) 1.7 A GeV, (b) 1.5 A GeV (Bogdanov *et al*., 2005); (c) 0.95 A GeV and (d) 0.80-0.50 A GeV (Bogdanov *et al*., 2005) respectively. The closed circles are observed values and the solid curve is the calculated values of the assumption of two source of helium projectile fragments emission which is the sum of the two Rayleigh scattering distributions

In the framework of the Maxwell's ideal gas model, the corresponding temperatures of both the sources are also obtained by σ^2/m_p and tabulated in Table 2 where m_p is the mass of proton. These values are plotted in Figure 5 with respect to the projectile mass number (A_p). The best fit parameter values are 0.092±0.006 (0.166±0.049) and 1.82±0.57 (17.99±4.63) for slope and intersection, respectively for cold (hot) region. After excluding the ^{208}Pb data point the slope and constant values are 0.196±0.021 and 13.16±2.16, respectively with far better χ^2 value.

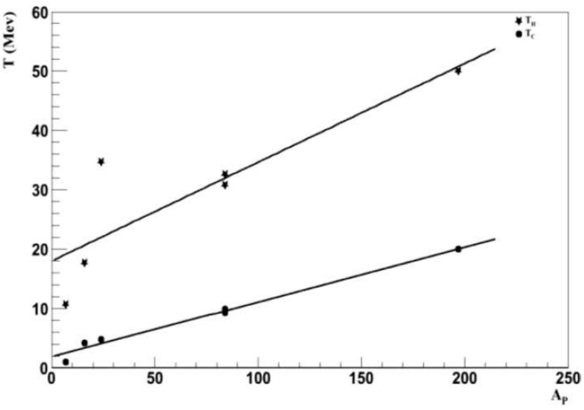


Fig. 5: Derived temperature of hot and cold regions is fitted with a best fit straight line function excluding data point of ^{208}Pb

DISCUSSION

The transverse momentum distributions of helium projectile fragments produced in the nucleus-nucleus collisions at relativistic energies was analyzed in the context of two emission source of helium projectile fragments as shown in Fig. 1. The two helium emission sources are projectile spectator's contact layer which is hot due to close contact with the participant region and the other source is the rest part of the projectile spectator which is assumed to be colder than the first source, both belong to the projectile spectator region.

The hot portion of the projectile spectator with the high excitation degree will emit lighter fragments with high momentum and momentum distribution of lighter (Z = 1 &2) fragments may tell us about their special distribution into the hot spectator region. The cold portion of the projectile spectator with low excitation degree will generally emit heavy charged fragments with low temperature but can also emit lighter charge fragments too.

It is evident from Fig. 2 and Table 1 that the fitted values of the Gaussian function for multiplicity distribution is dependent on the incident energy of the projectile and it also reflects that the maximum number of helium projectile fragments emitted in an interaction is increasing in both the cases, when projectile kinetic energy is high and low.

It can be seen from Table 2 that the values of σ_H and σ_L are decreasing with decrease in incident energies of the projectiles. It also reflects that as the kinetic energy of projectile will be less and less the hot region must be smaller and smaller i.e. the thermal equilibrium can be achieved very quickly at low kinetic energy of the projectile (Ornik *et al*., 1994; Fan and Liu, 2008; Dong-Hai *et al*., 2009). It can be seen from Fig. 5 that temperature of both the regions has strong dependence on the projectile mass number (A_p) and are independent of incident energy. It can also be seen from Fig. 5 that the hot and cold region temperature has dependence with projectile mass number i.e. size of the colliding system. Therefore it is clear that relativistic fragments produced in high energy nucleus – nucleus collisions can be regarded as the result of a two source emission.

CONCLUSION

It is very interesting to study the projectile fragmentation of heavy ions such as ^{84}Kr as some of the fragmentation characteristics does not show strong dependence on projectile kinetic energy but have strong dependence on the mass number of the projectile. The following conclusions are drawn from this experimental study.

The emission probability of single helium projectile fragment in an interaction is gradually decreasing with projectile kinetic energy that reflects the multiple helium projectile fragments have more chance of emission during interaction keeping the average helium projectile fragments value almost constant.

The transverse momentum distributions of relativistic fragments are described by two-source emission picture. The distribution of transverse momentum is the sum of two Rayleigh distributions. The helium projectile fragments belonging to hot source with high temperature are distributed in the tail portion of the transverse momentum distribution of helium projectile fragments. The number of such type of helium projectile fragments is few percent of the total helium projectile fragments. Most of the emitted projectile fragments are from cold source with low temperature. The temperature changes in this region of the projectile spectator part sharply and follow an exponential law. As the projectile kinetic energy becomes less and less the area or volume of the rest part becomes larger and larger and play an important role of heavy fragment emission.

We, thus conclude that two source model gives a reasonable description in the case of helium projectile fragments emitted in ^{84}Kr nuclei interactions with target nuclei at different kinetic energies below 2 GeV per nucleon.

ACKNOWLEDGEMENT

Researchers are thankful to the accelerator division staffs at GSI/SIS and JINR (Dubna) for exposing nuclear emulsion detector with ^{84}Kr beam and their other helps.

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