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Study of Multiplicity and Angular Distribution of Projectile Fragments in ^{24}Mg – Em Interactions at 4.5 AGeV

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Abstract. In the study of high energy nucleus-nucleus collisions, observations on projectile fragments (PFs) have considerable advantages in comparison to target fragments (TF) as PFs can be more reliably identified and easily distinguished by the detectors. In this work, the experimental results of multiplicity and angular distribution of projectile fragments emitted from the collision of ^{24}Mg beam with emulsion targets at 4.5 A GeV are reported . It is observed that the fragmentation mechanism differs considerably in smaller and larger mass systems.

***Keywords*:** Nucleus-nucleus collision; Nuclear emulsion; Projectile fragmentation; Multiplicity; Angular distribution.

1. Introduction

According to participant spectator model [1] the interacting system in high energy nucleus-nucleus collision can be divided into three parts: a target spectator, a participant and a projectile spectator. The overlapping part of the two colliding nuclei is called the participant, and the non overlapping portions of target and projectile nuclei are respectively the target and projectile spectators. The model predicts that violent nucleon-nucleon collisions take place in the participant region and weak excitation and cascade collision take place in the spectator parts. The participants produce many mesons, nucleons, photons, lepton pairs etc., and the spectators break into many nucleons and nuclei. While the produced particles from the participant portion are believed to be emitted during the early stage of A+A collision, the knocked out protons from the participant portion are supposed to be emitted at some later stage. At the last stage of the collision, the spectator portions of both the nuclei are de-excited through evaporation or/and fragmentation resulting another stage of particle emission. It is expected that a quark-gluon plasma (quark matter) [2] will be formed in the participant at very high incident energies, and a liquid-gas phase transition [3] will occur in the spectator.

In the complex scheme of high energy nucleus-nucleus collisions, projectile fragmentation, in general, is a relatively well isolated phenomenon. In projectile fragmentation process, a projectile spectator, on excitation, often splits into several pieces of intermediate mass fragments (IMFs) which span the mass-range between alpha particle and fission fragments. In a heavy ion collision the most abundant projectile fragments are considered to be the protons and helium (alpha) particles. The number of fragments or particles produced in an interaction, called the particle multiplicity is often considered to be an important parameter as such studies are expected to yield significant information about the nuclear collision dynamics [1,4]. It is also used as an important tool for understanding the multiparticle production mechanism and the nuclear fragmentation process and also for investigating the correlation between the two processes [5]. It has also been observed that the number of various charged secondaries produced in an interaction depends strongly on the system size and energy of the incident nuclei [6-9]. The fragmentation parameters of relativistic heavy ion nuclei provide vital information for the solution of many problems in Astrophysics, Radiation Physics and associated applications [10]. Projectile fragmentation at high energies has proven to be a powerful tool in the production and study of new exotic nuclei [11]. It also gives an idea about the energy-momentum transferred to the participant part of the colliding nuclei [12-21].

In general, the constituents of the spectator part of the projectile as well as the spectator part of the target can be well separated at energies like this work. But the experimental work on high energy A+A collisions carried out with electronic detectors to study PFs have limited coverage in the pseudo rapidity range. Nuclear emulsion, on the other hand provides best spatial resolution than any other detector used in experimental high energy physics. Moreover it has the advantage of detecting charged secondaries that might have been emitted even in the extreme forward direction (0˚ acceptance). Because of these features of emulsion it has been found extremely useful to study the spatial distribution of those charged particles such as PFs that are emitted in the extreme forward angle. Besides particle multiplicity, studies on the angular distributions of projectile and target fragments are also important to understand the various collective effects such as side splash, bounce-off effect, transverse flow, etc [22-26].

In this work therefore, an attempt has been made to study the multiplicity and angular distribution of various projectile fragments emitted from ^{24}Mg-Em interactions at 4.5 AGeV.

2. Experimental details

Nuclear emulsion pellicles of the type NIKFI-BR-2 and dimensions 20×10×0.06cm^3 were irradiated parallel to their lengths by a 4.5 A GeV ^{24}Mg beam from the JINR synchrophasotron at Dubna. These pellicles were line scanned and tracks were analyzed under high magnification (2000X-oil immersion objective) with an Olympus BH-2 optical microscope fitted with an attachment for measuring the X, Y, Z co-ordinates of different points on various tracks. The tracks of the different secondary charged particles were classified according to the standard emulsion terminology based upon their ionization as described in Ref. [10]. The fragments which are emitted at a narrow forward angle of $\leq 0.2/P_{beam} = 3^o$, where P_{beam} is the beam momentum in A GeV/c, are considered to be as projectile fragments. The charge of various projectile fragments were identified by a number of methods such as grain or blob density, gap-length coefficient, lecunarity and opacity [11], δ-ray density and relative track width measurement[12]. Grain or blob density methods have been adopted for estimation of the charge of PF's having charge $Z \leq 4$.To determine the charge of the PF's within the range Z = 5 to Z = 9, the gap length coefficient method has been adopted, because it is one of the most accurate methods within this range. The charges of the PF's lying within the range Z = 10 to Z = 19 is estimated by the δ-rays density measurement. Relative track width measurements have been adopted to estimate the charge of PF's having Z > 19. Out of a total of 1390 scanned events of ^{24}Mg-Em, 585 minimum bias nuclear reaction events were finally selected for the present investigation.

3. Results and Discussion

3.1. Multiplicity Distribution

3.1.1.Dependence of mean multiplicity on A_P

The mean multiplicity of all the projectile fragments for the entire data sample of present investigation on ^{24}Mg -Em interactions at 4.5 AGeV is found to be 2.76 ± 0.37. The mean multiplicities of projectile fragments with $Z_{PF} = 1$, $Z_{PF} = 2$ and $Z_{PF} \geq 3$ are found to be 1.57 ± 0.01, 0.89 ± 0.09 and 0.47 ± 0.11 respectively.

Table 1 presents the mean multiplicities of different charged projectile fragments for the present work and compares the results with the results of other workers. It can be readily seen from this table that at about same energy the multiplicity of various charged projectile fragments increases with increase of size of the projectile.

Table (1). The average multiplicities of the different charged projectile fragments in ^{22}Ne, ^{24}Mg and ^{28}Si beams with the interaction of emulsion at 3.7 AGeV and 4.5 AGeV.

Fragments charge Z	Projectile nucleus	Mean multiplicity	Reference
	^{22}Ne	1.36±0.02	[27]
1	^{24}Mg	1.61±0.04	[6]
	^{24}Mg (4.5 AGeV)	1.57±0.01	[PW]
	^{28}Si	1.53±0.05	[28]
	^{22}Ne	0.82±0.02	[27]
2	^{24}Mg	0.86±0.03	[6]
	^{24}Mg (4.5 AGeV)	0.89±0.09	[PW]
	^{28}Si	1.06±0.03	[28]
	^{22}Ne	0.48±0.01	[27]
≥3	^{24}Mg	0.49±0.03	[6]
	^{24}Mg (4.5 AGeV)	0.47±0.11	[PW]
	^{28}Si	0.49±0.02	[28]

As the mean multiplicities of various charged projectile fragments are found to vary with the mass (size) of the incident nucleus, the mean multiplicities of the various charged projectile fragments are therefore plotted as a function of projectile mass number A_P, in Fig.1. The mean multiplicities of projectile fragments having Z_{PF} = 1, Z_{PF} = 2 and $Z_{PF} \geq 3$ are denoted by $\langle N_p \rangle$, $\langle N_{\square} \rangle$ and $\langle N_f \rangle$ respectively.

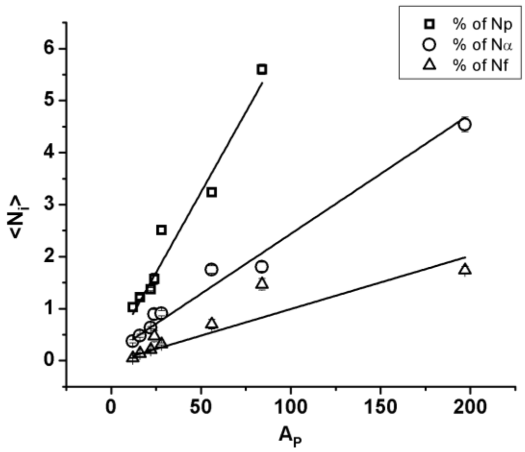

Fig.(1). The mean multiplicity of PFs $\langle N_i \rangle$ as a function of the projectile mass number A_p in the interactions of various projectile with Em nuclei

The straight lines shown in the figure are the best fitted lines for the experimental data points with R^2 values equal to 0.986, 0.969 and 0.994 for the variations of $\langle N_p \rangle$, $\langle N_{\square} \rangle$ and $\langle N_f \rangle$ respectively. It could be readily seen from this plot that the correlation between the yield of $\langle N_{\square} \rangle$ and $\langle N_f \rangle$ with A_P is weaker than that of $\langle N_p \rangle$, thereby indicating a stronger dependence of the mean multiplicity of the singly charged projectile fragments on the projectile mass. This observation supports the result obtained by S. Fakhraddin and M. A. Rahim [29] for the interactions of different projectiles with emulsion at 4.1-4.5 AGeV. Such observations have also been supported by M.A. Jilany [6] for the studies on ^{24}Mg-AgBr interactions at 3.7A GeV and for ^{16}O-AgBr interactions at 3.7A GeV by C-R. Meng et al. [30].

The increase in the mean multiplicity of $Z_{PF} = 2$ with the increase of projectile mass may be due to the fact that in case of a large projectile, on the average a large portion of the incident nucleus remains outside the overlapping region resulting a large projectile spectator to disintegrate.

3.1.2. Multiplicity distribution of projectile fragments

The multiplicity distribution of various projectile fragments emitted from ^{24}Mg-Em interactions at 4.5 AGeV is shown in Fig. 2. The black line is the fitted curve of the distribution with a Poisson function. The calculated standard deviation of the distribution is found to be 1.30 ± 0.46.

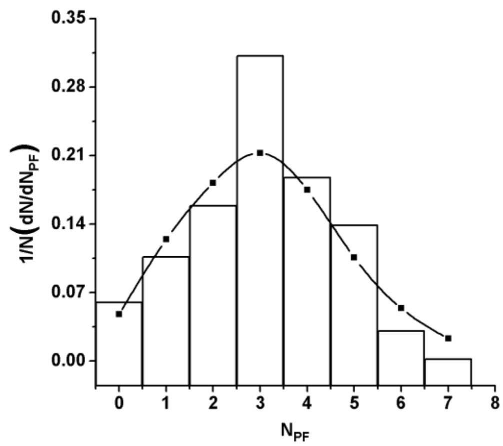

Fig. (2). Variation of normalized multiplicity of projectile fragments for Mg-Em interactions at 4.5 AGeV.

The width of the distribution at half maximum is 3.5 ± 0.30 with the tail extending up to 7. The figure indicates that most of the events in the data sample have 3 to 4 projectile fragments. On the other hand, the results obtained by Jain et al. [31] in case of ^{238}U-Em interactions at 0.96 AGeV showed that most of the events have multiplicity equal to 9. In comparison to present results on ^{24}Mg-Em interaction, the distribution of ^{84}Kr-AgBr [32], ^{238}U-Em interactions has longer tail and a larger width. This is probably due to the fact that a heavier beam breaks up into a large number of fragments with various charges resulting in increased multiplicity of projectile fragments.

3.1.3. Multiplicity distribution of Z_{PF} = 1, 2 and ≥ 3 projectile fragments

As mentioned earlier, the study of multiplicity distribution of projectile fragments is important for investigating the underlying mechanism of nuclear fragmentation [25]. Most significantly, the helium projectile fragments produced from various heavy ion beams at different energies have been studied extensively during the last one and half decade [25, 33-40]. These studies have revealed that the multiplicity distributions of alpha fragments obey a universal scaling law and that the transverse momenta distributions can be explained by two or three different emission sources at different temperatures. Present studies on ^{24}Mg-Em interactions are expected to provide some more information on the fragmentation mechanism of the projectile nucleus into helium fragments at Dubna energy.

The distributions of Z_{PF} =1, 2 and ≥ 3 projectile fragments are shown in Figs. 3 to 5 taking the total ensemble of minimum biased events. Multiplicities for projectile $N_z > 1$ with $Z_{PF} \geq 5$ were not observed, i.e. the cross-section for fragmentation of ^{24}Mg in emulsion into two pieces each of Z_{PF} = 5 or 6 is smaller than 5.8×10^{-4} of the total inelastic cross-section [41].

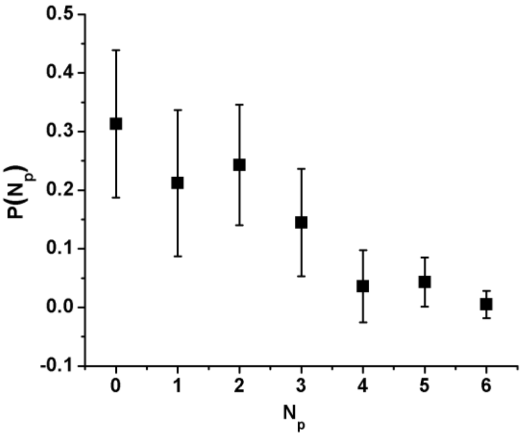

Fig. (3). Normalized multiplicity of Z_{PF} =1 projectile fragments.

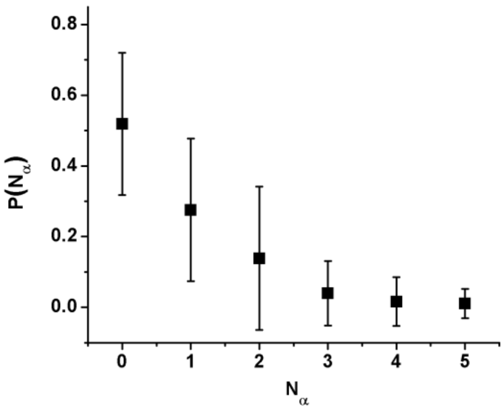

Fig. (4). Normalized multiplicity of Z_{PF} =2 projectile fragments.

It is quite evident from the Fig. 4 that, for the present study, most of the events in the data sample have no Z_{PF} = 2 projectile. The results reported by other workers on 4.5 A GeV ^{12}C, ^{16}O and ^{28}Si and 4.1 AGeV ^{22}Ne projectiles with AgBr nuclei also confirms higher yields of events with no Z_{PF} = 2 projectile fragments [29, 36,42-44]. On the other hand, the results obtained by M.L. Cherry et al. [45] on ^{197}Au-AgBr interactions at 10.7 AGeV reveal that most of the events in the data sample have four Z_{PF} = 2 projectile fragments. Thus, it appears that a larger mass of the projectile nucleus results in the emission of a larger number of Z_{PF} = 2 projectile fragments. It is therefore evident that the fragmentation mechanism differs considerably in smaller and larger mass systems.

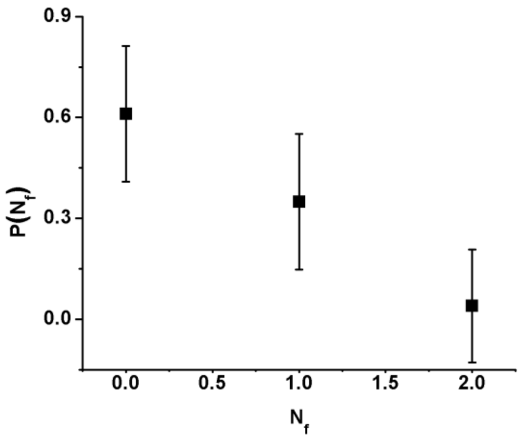

Fig. (5). Normalized multiplicity of $Z_{PF} \geq 3$ projectile fragments.

In a similar way, from the Fig.5 it is clear that the occurrence of $Z_{PF} \geq 3$ projectile fragments is zero in most of the events of the entire sample of data of this work. M.L. Cherry et al. [45] and P.L. Jain et al. [46] have found the mode of the multiplicity distribution of $Z_{PF} \geq 3$ projectile fragments at 1 for 10.6 AGeV ^{197}Au-AgBr and 1 AGeV ^{238}U-Em interactions, respectively. It is also interesting to note that the probability of occurrence of events having $N_f = 0$ decreases with increasing mass number of the projectile. Similar results were also reported by other workers [47-49] almost at the same incident energy. Such studies show that heavy beams rarely yield events having no heavier fragments.

Thus the probability of projectile multifragmentation (events having two or more fragments with $Z_{PF} \geq 3$) has been found to increase as we go from ^{24}Mg to ^{238}U [6, 45-49].

3.2. Angular Distribution of Projectile fragments

As mentioned earlier, projectile fragments have the momentum per nucleon almost equal to that of the parent nucleus and hence they are essentially emitted inside a narrow forward angle around the direction of the incident beam and remain relativistic. Hence unlike the target fragments, the heavy fragments of the projectile nucleus are very closely spaced having a very small angular separation. To understand thoroughly the complicated mechanism of heavy ion collision one has to take into account how the produced particles as well as the fragments of both TFs and PFs coming out of an interaction are distributed in phase space.

3.2.1. Angular distribution of Z_{PF} = 1 projectile fragments

The normalized angular distribution of the Z_{PF} = 1 projectile fragments is shown in Fig.6 and is fitted with a Gaussian function.

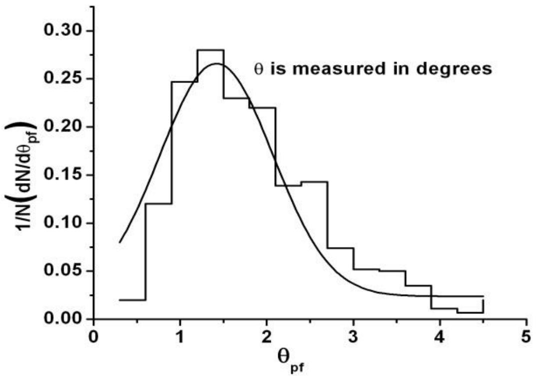

Fig. (6). Angular distribution of Z_{PF}=1.

The centre and width at half maximum of the fitted Gaussian distribution (±7 degrees) are found to be 1.41 ± 0.06 and 1.30 ± 0.16 respectively. In case of ^{28}Si-Em interactions at 4.5 AGeV [47] it was reported that most of the singly charged projectile fragments were emitted in a narrow forward cone peaking at 0.9^{o}.

3.2.2. Angular distribution of Z_{PF} = 2 projectile fragments

Fig.7 represents the angular distribution of ^{4}He projectile fragments and shows that most of the fast alpha fragments are emitted at an angle 1- 2^{o}. The peak of the fitted distribution is found to be at 1.10 ± 0.04 and the characteristic width is 0.82± 0.09.

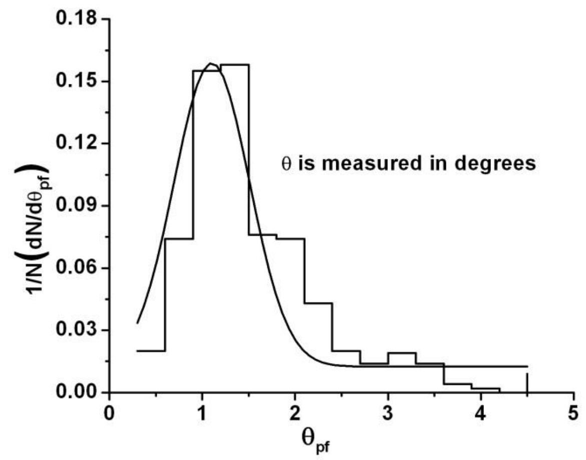

Fig. (7). Angular distribution of Z_{PF} =2.

The results of R. Bhanja et al. [50] on ^{14}N-Em interactions at 2.1 AGeV reveal that the emission angle of most of the helium projectile fragments is 0^o . The centre and characteristic width at half maximum of the fitted distribution as reported by V. Singh [51] for 0.95 AGeV ^{84}Kr-Em interactions were found to be $1.09^o \pm 0.18^o$ and 3.73 ± 0.33^o respectively. On the other hand, for ^{28}Si-Em interactions at 4.5 AGeV [47], it was reported that most of the doubly charged projectile fragments were emitted in a narrow forward cone peaking at 0.6^o. Clearly there lies inconsistency in the result of emission angle of fast projectile fragments with $Z_{PF} = 2$ and such discrepancy may be attributed to the inaccuracy of various measuring techniques.

3.2.3. Angular distribution of $Z_{PF} \geq 3$ projectile fragments

The angular distribution of $Z_{PF} \geq 3$ projectile fragments is plotted in Fig.8 and the distribution is fitted with a Gaussian function.

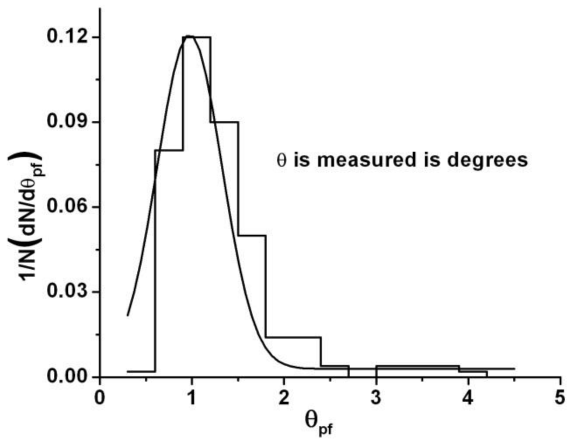

Fig. 8. Angular distribution of $Z_{PF} \geq 3$.

It is observed that most of the heavier projectile fragments are confined to a narrow forward cone 0.97° ± 0.07° and the characteristic width of the distribution at half maximum is found to be 0.70° ± 0.22°. In case of ^{84}Kr-Em interactions at 0.95 AGeV it was reported in ref. [51], that most of the heavier projectile fragments were confined to a narrow forward cone peaking at 0°, having a characteristic width at half maximum of □1°. In case of ^{28}Si-Em interactions at 4.5 AGeV [47] it was observed that most of the heavy projectile fragments were emitted in a narrow forward cone peaking at 0.2°. Table 2 shows the results of projected angular distributions of projectile fragments for various other systems.

Table. (2). Standard deviations of projected angular distributions of projectile fragments for different systems in emulsion.

Reaction Channel	Z_{PF} =1	Z_{PF} =2	$Z_{PF} \geq 3$	Energy in AGeV	Reference
^{12}C -Em	1.3±0.09	0.54±.02	0.33±0.02	4.5	52
^{24}Mg -Em	1.41±0.06	1.10±0.04	0.97±0.07	4.5	PW
^{28}Si -Em	1.26±0.106	0.77±0.024	0.29±0.03	4.5	47
^{84}Kr-Em	1.73±0.043	1.44±0.14	0.71±0.07	0.95	32

From all the above discussions it may therefore be inferred that the width of the distribution at half maximum decreases with the increase of the charge of the projectile fragments. It is further observed from these figures that with the increase of the charge of the PFs, the peaks of the fitted distributions shift towards lower $\square_{PF}$ value indicating that most of the heavier PFs are emitted at narrow forward angle than that of lighter ones.

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