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ORIGINAL PAPER

Characteristics of compound multiplicity in $^{84}Kr_{36}$ with various light and heavy targets at 1 GeV per nucleon

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Abstract: Interactions of $^{84}Kr_{36}$ having kinetic energy around 1 GeV per nucleon with NIKFI BR-2 nuclear emulsion detector's target reveal some of the important features of compound multiplicity. Present article shows that width of compound multiplicity distributions and value of mean compound multiplicity have linear relationship with mass number of the projectile colliding system.

Keywords: Nuclear emulsion detector; Compound multiplicity

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1. Introduction

The investigation of final state particles produced through nucleon–nucleus or nucleus–nucleus interactions at high energy is lately becoming an active research area. The nuclear emulsion detector (NED) is one of the oldest detector technology and has been in use from the birth of experimental nuclear and astroparticle physics. The interaction of nucleus (such as $^{84}Kr_{36}$) with NED's target at relativistic energy reveals the picture of nucleus–nucleus collisions. Recoil target nucleons are emitted shortly after the passage of leading hadrons. Therefore, it is worth studying the compound multiplicity of recoil target nucleon and freshly produced particles (mainly pions) during interactions as it contains important information about the interaction. The number of target's recoil nucleon and produced charged particles have been taken together and termed as compound multiplicity. Most of the experiments on high energy collisions have been carried out to investigate characteristics of newly created particles which are mostly pion meson and Kaons (shower; N_s). The study of characteristic of grey particles (grey; N_g) produced in such collision has also increased due to the fact that their emission takes place on the time scale of same order ($\sim 10^{-22}$ s) as that of shower particles. Hence, they are expected to keep some memory of the reaction history [1]. Furthermore, grey particle may also be taken as a good measure of the number of encounters made by impinging hadrons inside the struck nucleus [2, 3]. In order to refine the models for multiparticle production in hadron-nucleus and nucleus–nucleus collisions, a new variable termed as compound multiplicity ($N_c = N_g + N_s$), has been introduced by Jurak and Linscheid [3]. The interesting characteristics of grey and shower particles, taken together per interaction, have been investigated by several workers [2–8]. Relativistic high energy interactions of various heavy ions (projectile) with emulsion have been studied [9–12]. Therefore, it is interesting to study the use of compound multiplicity of grey and shower particles. Present work is mainly devoted to discussion of experimental data of compound multiplicity distribution and their characteristic with respect to other emitting particles in inelastic collision of $^{84}Kr_{36}$ with the nuclei of NED at $\sim$1 GeV per nucleon.

2. Experimental details

NEDs are composed of silver halide crystals immersed in a gelatin matrix [2, 13–18] consisting mostly of hydrogen, carbon, nitrogen, oxygen, silver and bromine. A small percentage of sulfur and iodine are also present. In present

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experiment, we have employed a stack of high sensitive NIKFI BR-2 NEDs of dimensions 9.8 × 9.8 × 0.06 cm^3, exposed horizontally to $^{84}Kr_{36}$ ion at kinetic energy of ~1 GeV per nucleon. The exposure has been performed at Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany. Interactions have been found by along-the-track scanning technique by using an oil immersion objective of 100× magnification. The beam tracks have been picked up at a distance of 5 mm from the edge of the plate and carefully followed until they either interacted with NED nuclei or escaped from any surface of the emulsion. A total of 700 inelastic events produced in ^{84}Kr–emulsion interactions have been located. All charged secondary particles emitted or produced in an interaction are classified in accordance with their ionization, range and velocity, as shown below [13–18].

2.1. Shower tracks (N_s)

These are freshly created charged particles with normalized grain density or ionization $g^* < 1.4$ (g^* is the normalized grain density). These particles have relative velocity $(\beta) > 0.7$. In case of a proton, kinetic energy (E_p) should be more than 400 MeV. They are mostly fast pions with a small admixture of Kaons and released protons from the projectile which have undergone an interaction.

2.2. Grey tracks (N_g)

Particles having ionization in the interval $1.4 < g^* < 6.0$ and range $L > 3$ mm are defined as grey. This particle has relative velocity (β) in between $0.3 < \beta < 0.7$. They are generally knocked out protons (NED can not detect neutral particle) of targets having kinetic energy in between $30 < E_p < 400$ MeV. They are also admixture of deuterons, tritons and some slow mesons.

2.3. Black tracks (N_b)

Particles having range $L < 3$ mm from interaction vertex (from which they originated) and $g^* > 6.0$ are termed as Black tracks (N_b). This corresponds to a relative velocity $(\beta) < 0.3$ and a proton with kinetic energy $(E_p) < 30$ MeV. Most of these are produced due to evaporation of residual target nucleus.

In present analysis, out of 700, 570 events have fulfilled the above required criteria (N_s, N_g and N_b) for further investigation. The number of heavily ionizing charged particles ($N_h = N_b + N_g$) depends upon target breakup. The peaks in N_h distribution have strong correlation with the classes of emulsion target. Three very distinct regions can be seen from N_h distribution and each region belongs to a known target as shown earlier [16]. Therefore, we have used such distribution to fix criteria for target separation.

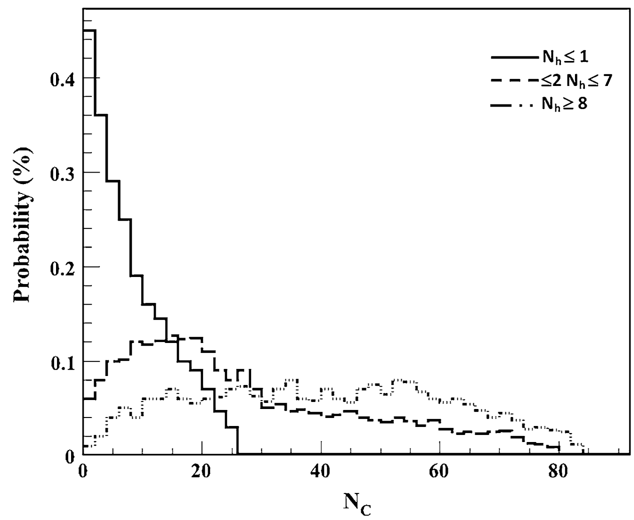

Fig. 1 Compound multiplicity distributions for different emulsion target groups in $^{84}Kr_{36}$ with nuclear emulsion collisions at ~1 GeV per nucleon

Table 1 The value of mean compound multiplicity $\langle N_c \rangle$, dispersion D (N_C) and ratio $\langle N_c \rangle / D$ (N_C) in $^{84}Kr_{36}$ interactions

Target group	$\langle N_c \rangle$	D (N_c)	$\langle N_c \rangle / D$ (N_c)
H	7.56 ± 0.12	4.47 ± 0.32	1.69 ± 0.37
CNO	14.93 ± 0.15	10.66 ± 0.28	1.40 ± 0.53
Emulsion	47.04 ± 0.27	27.19 ± 0.40	1.73 ± 0.67
Ag/Br	53.27 ± 0.31	20.10 ± 0.79	2.65 ± 0.39

Table 2 A compilation of compound multiplicity for different projectile induced emulsion reactions

Projectile	$\langle N_c \rangle$	References
^{1}H	4.44 ± 0.66	[22]
^{2}H	5.42 ± 0.09	[23]
^{4}He	8.60 ± 0.22	[24]
^{22}Ne	16.67 ± 0.64	[7]
^{16}O	18.10 ± 0.85	[25]
^{24}Mg	23.63 ± 0.48	[4]
^{56}Fe	38.61 ± 1.16	[19, 20]
^{84}Kr	47.04 ± 2.27	Present work

2.4. Ag/Br target events

$N_h \geq 8$ and at least one track with $R < 10$ μm is present in an event. This class of target is known to have cleanest interaction and high statistics are known as Ag/Br target events.

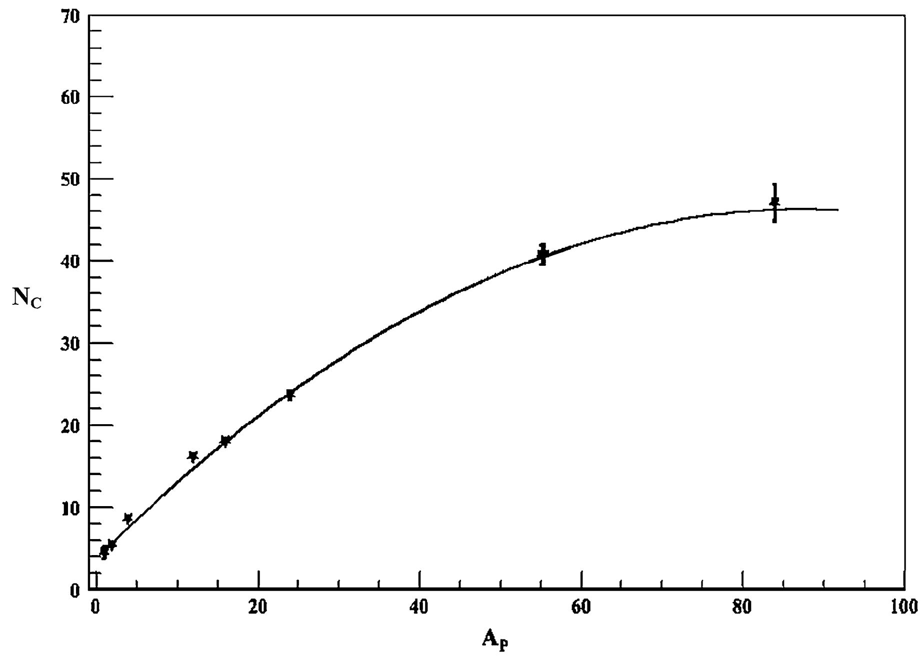

Fig. 2 Dependence of $\langle N_c \rangle$ on the mass number (A_p) of different projectiles in nucleus–nucleus collisions

2.5. CNO target events

$1 < N_h < 8$ and no tracks with $R < 10$ μm are present in an event. This class always contains very clean interaction of CNO target.

2.6. *H* target events

$N_h \leq 1$ and no tracks with $R < 10$ μm are present in an event. This class includes all $^{84}Kr_{36} + H$ interactions & also some of the peripheral interactions with CNO and also very peripheral interactions with Ag/Br targets.

In previous work [16], we have shown the percentage variation of target interactions with respect to projectile mass number for fixed target emulsion experiments. We obtained 13.4, 39.0 and 47.6 % of interactions with *H*, CNO and Ag/Br targets, respectively.

3. Results and discussion

Figure 1 represents compound multiplicity distributions for $^{84}Kr_{36}$ interactions with different target groups of NED such as *H*, CNO and Ag/Br, selected on the basis of heavily ionizing charged particle (N_h). Figure 1 reveals that multiplicity distributions become wider with increasing target size. The average value of compound multiplicity $\langle N_c \rangle$, its dispersion $D\ (N_c) = \sqrt{\langle N_c^2 \rangle - \langle N_c \rangle^2}$ and the ratio $\langle N_c \rangle / D\ (N_c)$ are represented in Table 1, while Table 2 summarizes compound multiplicity of different projectiles [7, 19–25].

Figure 2 shows the dependence of average compound multiplicity $\langle N_c \rangle$ on mass number of beam nucleus (A_p). It may be observed from Fig. 2 that $\langle N_c \rangle$ increases rapidly with increasing mass of the incident beam. The points represent experimental data while continuous line is result of fitting by the relation $\langle N_c \rangle = KA_p^{\alpha}$. The fitting parameters are $k = 3.57 \pm 0.48$ and $\alpha = 0.47 \pm 0.05$. The corresponding fitting parameters for ^{24}Mg, ^{12}C and ^{84}Kr are $k = 4.40 \pm 0.43$ and $\alpha = 0.44 \pm 0.03$ at 4.5 A GeV [21], $k = 3.25 \pm 0.12$ and $\alpha = 0.40 \pm 0.36$ at 3.7 A GeV [6] and $k = 2.64 \pm 0.66$ and $\alpha = 0.47 \pm 0.07$ at 1.7 A GeV [2], respectively. Thus our results are consistent with other reported works.

The average multiplicities of black, grey and shower particles in different ensembles of ^{84}Kr–nuclear emulsion interactions are presented in Table 3. For comparison, corresponding results from ^{84}Kr–nuclear emulsion collisions and ^{56}Fe–nuclear emulsion collisions at 1.7 GeV per nucleon are also tabulated in Table 3. From Table 3, it is appear that average multiplicity of black, grey and shower particles increases with the increase of target mass for both ^{84}Kr–nuclear emulsion and ^{56}Fe–nuclear emulsion interactions.

Koba–Nielsen–Olesen (KNO) scaling is a well established empirical law for multiparticle production in $p + p$ collision. KNO scaling behavior of compound multiplicity distribution is also observed in nucleus–nucleus collisions [13–18]. Figure 3 shows $\langle N_c \rangle$ (σ_n / σ_{inel}) versus $N_c / \langle N_c \rangle$ for $^{84}Kr_{36}$-emulsion interactions at 1 GeV per nucleon, where σ_n denotes the partial cross section for producing *n* charged compound particles, σ_{inel} denotes the total inelastic cross

Table 3 The percentage occurrence and average multiplicities of charged particles in different target groups of ^{84}Kr (1.7 A GeV), ^{56}Fe (1.7 A GeV) and ^{84}Kr ($\sim$1 A GeV) interactions

Beam	Type of events	%	$\langle N_b\rangle$	$\langle N_g\rangle$	$\langle N_s\rangle$	References
^{56}Fe	$N_h \leq 1$	14.33 ± 1.24	0.15 ± 0.03	0.32 ± 0.05	2.77 ± 0.20	[19, 20]
^{56}Fe	$1 < N_h < 8$	34.12 ± 1.91	1.84 ± 0.07	2.91 ± 0.13	8.03 ± 0.43	[19, 20]
^{56}Fe	$N_h \geq 8$	51.55 ± 2.35	7.38 ± 0.18	14.90 ± 0.50	19.60 ± 0.60	[19, 20]
^{56}Fe	$N_h \geq 0$	100	4.45 ± 0.14	8.71 ± 0.34	13.30 ± 0.40	[19, 20]
^{84}Kr	$N_h \leq 1$	16.67 ± 1.73	0.08 ± 0.03	0.19 ± 0.04	4.68 ± 0.79	[2]
^{84}Kr	$1 < N_h < 8$	41.76 ± 2.74	2.17 ± 0.11	1.97 ± 0.10	7.08 ± 0.48	[2]
^{84}Kr	$N_h \geq 8$	41.58 ± 2.73	10.22 ± 0.29	9.91 ± 0.44	14.69 ± 0.77	[2]
^{84}Kr	$N_h \geq 0$	100	5.17 ± 0.22	4.98 ± 0.26	9.84 ± 0.44	[2]
^{84}Kr	$N_h \leq 1$	14.76 ± 1.23	0.06 ± 0.03	0.19 ± 0.06	3.99 ± 0.69	Present work
^{84}Kr	$1 < N_h < 8$	41.85 ± 2.78	1.99 ± 0.29	1.75 ± 0.47	8.10 ± 0.90	Present work
^{84}Kr	$N_h \geq 8$	43.07 ± 1.97	10.05 ± 0.21	10.09 ± 0.38	15.09 ± 0.60	Present work
^{84}Kr	$N_h \geq 0$	100	6.25 ± 0.22	5.21 ± 0.47	8.99 ± 0.73	Present work

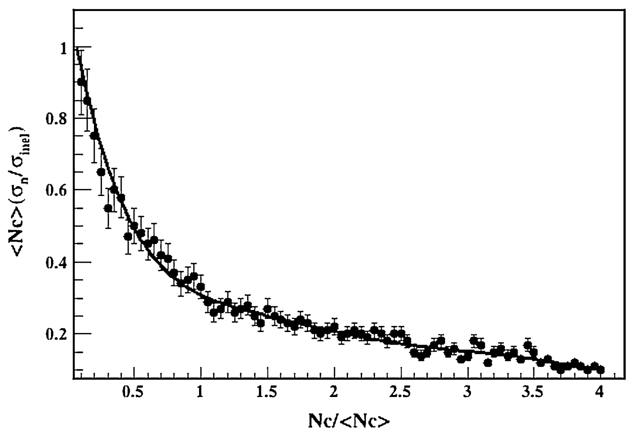

Fig. 3 $\langle N_c\rangle$ ($\sigma_n/\sigma_{\text{inel}}$) versus $N_c/\langle N_c\rangle$ for ^{84}Kr$_{36}$–nuclear emulsion interactions at 1 GeV per nucleon

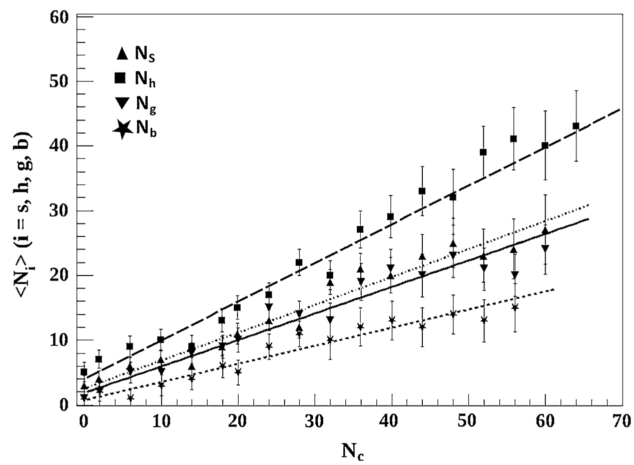

Fig. 5 Dependence of $\langle N_b\rangle$ and $\langle N_h\rangle$ on N_c for ^{84}Kr$_{36}$ with emulsion at $\sim$1 GeV per nucleon

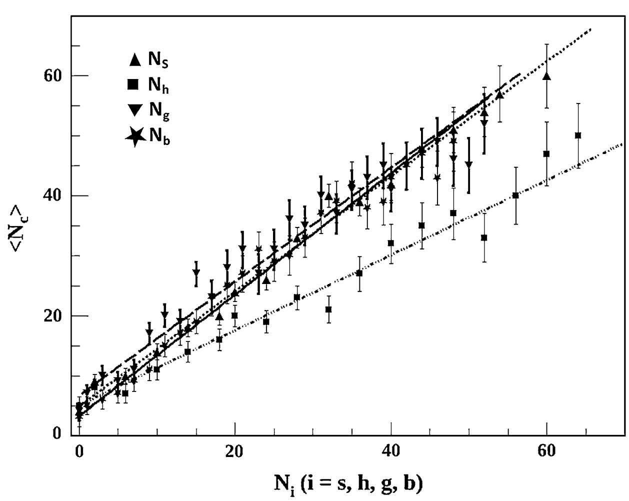

Fig. 4 Dependence of $\langle N_c\rangle$ on N$_i$ (i = s, h, g, b) for ^{84}Kr$_{36}$ with emulsion at $\sim$1 GeV per nucleon

section, and $z = N_c/\langle N_c\rangle$, respectively. From Fig. 3 it can be seen that experimental data lie on a universal curve, which can be fitted by a KNO scaling function with the form

$$\Phi(z) = \left(Az + Bz^3 + Cz^5 + Dz^7\right) e^{Ez}. \quad (1)$$

The best fitting parameters are $A = 8.34 \pm 1.28$, $B = -(1.46 \pm 2.38)$, $C = 3.99 \pm 2.76$, $D = 1.17 \pm 0.77$ and $E = -(3.41 \pm 0.88)$. The minimum fitting χ^2/DOF is 1.05, which means that experimental data can be well explained by KNO scaling law. The fitting parameter value is similar as that reported in [2] for ^{84}Kr–emulsion interaction at 1.7 GeV per nucleon. Figure 4 shows correlations between $\langle N_c\rangle$ and N_s, N_h, N_g, N_b for ^{84}Kr–emulsion collisions at around 1 GeV per nucleon. These correlations exhibit linear relationships as follows:

$$\langle N_c \rangle = (1.01 \pm 0.04)N_b + (3.28 \pm 0.67), \quad (2)$$

$$\langle N_c \rangle = (0.95 \pm 0.03)N_g + (6.70 \pm 0.66), \quad (3)$$

$$\langle N_c \rangle = (0.63 \pm 0.03)N_s + (5.07 \pm 0.77), \quad (4)$$

$$\langle N_c \rangle = (0.96 \pm 0.03)N_h + (4.87 \pm 0.69). \quad (5)$$

Figure 5 shows correlations between $\langle N_s \rangle$, $\langle N_h \rangle$, $\langle N_g \rangle$, $\langle N_b \rangle$ and N_c for ^{84}Kr–nuclear emulsion collisions at around 1 GeV per nucleon. These correlations are nicely fitted by linear relations of the form,

$$\langle N_b \rangle = (0.28 \pm 0.05)N_c + (0.72 \pm 0.07), \quad (6)$$

$$\langle N_g \rangle = (0.41 \pm 0.03)N_c + (1.85 \pm 0.76), \quad (7)$$

$$\langle N_s \rangle = (0.59 \pm 0.03)N_c + (4.21 \pm 0.77), \quad (8)$$

$$\langle N_h \rangle = (0.43 \pm 0.02)N_c + (2.58 \pm 0.69). \quad (9)$$

4. Conclusions

Present study reveals that mean compound particle multiplicity increases rapidly with the increase of projectile mass number. The multiplicity correlation between N_b, N_g, N_s, N_h, and average value of N_c exhibit linear relation. The compound multiplicity distribution is observed to obey KNO scaling law, which is independent of mass number and energy of the projectile.

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References

[1] N N Abd-Allah and M Mohery *Turk. J. Phys.* **25** 109 (2001)
[2] C Y Bai and D H Zhang *Chin. Phys.* **C 35** 349 (2011)
[3] A Jurak and A Linscheid *Acta Phys. Pol.* **B 8** 875 (1977)
[4] G Ghosh, A Mukhopadhya, A Ghosh and R Sengupta *Nucl. Phys.* **A 499** 850 (1989)
[5] T Ahmad and M Irfan *Nuovo. Cim.* **A 106** 171 (1993)
[6] M S Khan et al. *Can. J. Phys.* **75** 549 (1997)
[7] Z Abou-Moussa *Can. J. Phys.* **80** 109 (2002)
[8] D H Zhang et al. *Chin. J. Phys.* **44** 405 (2006)
[9] M Mohery and M Arafa *Inte. J. Mod. Phys.* **E 20** 1735 (2011)
[10] T Ahmad, N Ahmad, S Ahmad and M Zafar *Indian J. Pure Appl. Phys.* **48** 855 (2010)
[11] D Ghosh, A Deb, S Biswas, P Mandal and P K Haldar *Indian J. Pure Appl. Phys.* **45** 959 (2007)
[12] S Sarkar and T D Goswami *Indian J. Pure Appl. Phys.* **40** 539 (2002)
[13] M K Singh, A K Soma, R Pathak and V Singh *Indian J. Phys.* **87** 59 (2013)
[14] M K Singh, A K Soma, R Pathak and V Singh *Indian J. Phys.* **85** 1523 (2011)
[15] M K Singh, R Pathak and V Singh *J. Purv. Acad. Scie. (Phys. Scie.)* **18** 233 (2010)
[16] M K Singh, R Pathak and V Singh *Indian J. Phys.* **84** 1257 (2010)
[17] V Singh, S K Tuli, B Bhattacharjee, S Sengupta and A Mukhopadhyay *arXiv:nucl -ex/0412049v1* (2004)
[18] S A Krasnov et al. *Czec. J. Phys.* **46** 531 (1996)
[19] S A Azimov et al. *Nucl. Phys.* **A 470** 653 (1987)
[20] V E Dudkin et al. *Nucl. Phys.* **A 509** 783 (1990)
[21] A Abd El-Daiem *Phys. Int.* **1** 31 (2010)
[22] AABDDKLMTU-B Collaboration *Z. Phys.* **A 302** 133 (1981)
[23] E S Basova et al. *Z. Phys.* **A 287** 393 (1978)
[24] DGKLMTN Collaboration. *JINR Dubna Comm. P* 1-8313 (1974)
[25] V A Antonchick et al. *Sov. J. Nucl. Phys.* **39** 774 (1984)