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PSEUDORAPIDITY DISTRIBUTIONS STUDY FOR FAST TARGET PROTONS PRODUCED IN THE INTERACTIONS OF ^{84}Kr WITH EMULSION AT 1 GeV PER NUCLEON

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The study of the process of particle creation in high-energy nucleon–nucleon and nucleus–nucleus collisions heavily relies on the pseudorapidity distribution (PD) of charged particles. Several theoretical theories and concepts may frequently be tested using the multiplicity distributions (MD) and PD of final-state particles. In this work, we have utilized PD to investigate potential processes that might produce the fast target protons (FTP) released from the interactions of ^{84}Kr with emulsion at $1\,A\,$GeV. In order to examine the properties of the FTP emitted system for various targets (such as AgBr, CNO, and Em) of the nuclear emulsion detector (NED), the angular distribution (AD) and PD of the generated FTP were examined.

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1. Introduction

One of the most intriguing experimental variables to study the process of multiparticle formation in nuclear and hadronic collisions is PD. Since only one kinematic characteristic (*i.e.*, emission angle (θ) with respect to the projectile beam) needs to be measured for each particle, pseudorapidity is easier to obtain experimentally [1–3]. The collision between two nuclei can be explained by three areas according to the Participant–Spectator model (PSM). New particles, referred to as shower particles, are created in the participant region (PCR), which is the overlapping area between two colliding nuclei. Projectile spectator region (PSR) and target spectator region (TSR), which are not engaged in the collision, are the remaining components [4]. While the TSR produces target pieces such as black and grey particles, the PSR produces single-, double-, and multiple-charged particles. Target protons having a kinetic energy of $<$ 30 MeV are evaporated by the TSR.

The majority of the grey particles of interest are recoiling protons that have been expelled from the target nucleus at energies between 30 and 400 MeV. The grey particles are regarded as FTP that were created either while or soon after the leading particles passed. Studying the emission properties of FTP is particularly important since it is anticipated that they would convey the majority of the information from the initial stages of the collision [5, 6].

The AD and PD of the FTP emitted during ^{84}Kr-emulsion interactions at $1\,A\,\mathrm{GeV}$ and their dependency on various emulsion target groups have been the main focus of this work.

2. Experimental details

The NED utilized in this experiment was made available by GSI in Darmstadt, Germany. Ag, Br, O, N, C, and H are mixed with minor amounts of I and S on the NED plates. The NED was created using a ^{84}Kr projectile with $1\,A\,\mathrm{GeV}$ [7, 8]. The two most popular scanning methods, line scanning and volume scanning, were employed in this experiment to scan the event of interest using an Olympus BH-2 binocular microscope. A variety of dry and oil immersion objectives with magnifications of 10X, 20X, 40X, 60X, and 100X are among the key parts of this binocular microscope. Sandalwood oil and a 100X objective were used to keep air out of the space between the lens and emulsion plate. Line scanning requires keeping an eye on the events until they strike or leave the emulsion plate. We have employed volume scanning for low-energy events. We use volume scanning to find the event tracks and then investigate the accuracy of the occurrences. Background events need to be looked at, since they can interact anywhere on the plate. A sequence of events that were carefully monitored to ensure they truly occurred was triggered by the projectile's impact with the emulsion target [9, 10].

Following the event collection, we grouped the data using many criteria, such as: relative velocity (β), normalized grain density (g^*), and range (L) [11]. The interaction area of the two interacting nuclei is where the shower particles with $g^* < 1.4$ and $\beta > 0.7$ are classified as N_s. The target spectator region is producing grey particles, represented by N_g, with $0.7 < \beta > 0.3$, $L > 3$ mm, and $6.0 > g^* > 1.4$. With $\beta < 0.3$, $L < 3$ mm, and $g^* > 6.0$, the black particles, denoted by N_b, are leaving the target spectator region. Strongly ionized charged particles (N_h) are all black and gray particles. The N_h values determine the three types of emulsion targets: AgBr target, CNO target, and H target. *(i)* The N_h values for the H target are either 0 or 1. *(ii)* The N_h values for the CNO target range from 2 to 7. *(iii)* The N_h values of the AgBr target exceed 7 [12].

3. Result and discussion

In a brief period of time, shortly after the first phase of the interaction linked to particle formation, a thermalized system emits FTP. As the initial step of reflection, the produced particles depart from the hot hadronic matter created in the overlap zone between the projectile and target [14]. The remaining target portion advances toward thermalization during the initial stage of target fragmentation, at which point the FTP are released mainly in the forward direction. The second step, the final contact, is when the slow target protons vanish. For energy deposition and momentum transfer, FTP research is therefore highly beneficial. The tests on target fragments provide the observations that are pertinent to the nuclear limiting fragmentation [14, 15].

Figure 1 displays the AD of the FTP generated by the ^{84}Kr interactions with the AgBr, CNO, and Em targets of NED at 1 *A* GeV. Figure 1 shows that the mean angle ($\langle\theta_g\rangle$) of the emitted FTP is 57.75 ± 2.40, and the AD of the FTP has a universal form with a forward peak. As θ_g increases, the number of backward-emitted particles (*i.e.*, $\theta_g > 90^\circ$) decreases. These reverse angles have distributions that decline exponentially. Due to the limited energy range of FTP (30–400 MeV), the AD of the FTP is nearly constant for all interactions [13]. Figure 2 displays the correlation between $\langle\theta_g\rangle$ and projectile mass ($A_{\rm p}$) of the FTP released in the interactions of P, ^{4}He, ^{6}Li, ^{7}Li, ^{12}C, ^{16}O, ^{22}Ne, ^{24}Mg, ^{28}Si, ^{32}S [13], and ^{84}Kr [present work] with emulsion. A guideline at $\langle\theta_g\rangle \approx 60^\circ$ is shown by the dashed line. Figure 2 shows that the FTP $\langle\theta_g\rangle$ value is nearly independent of $A_{\rm p}$.

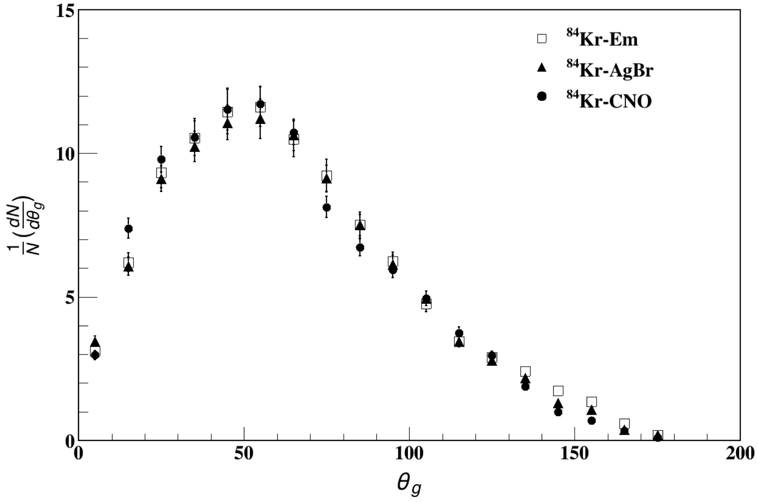

Fig. 1. AD of the FTP emitted in the interactions of the ^{84}Kr with AgBr, CNO, and Em targets of NED at 1 *A* GeV.

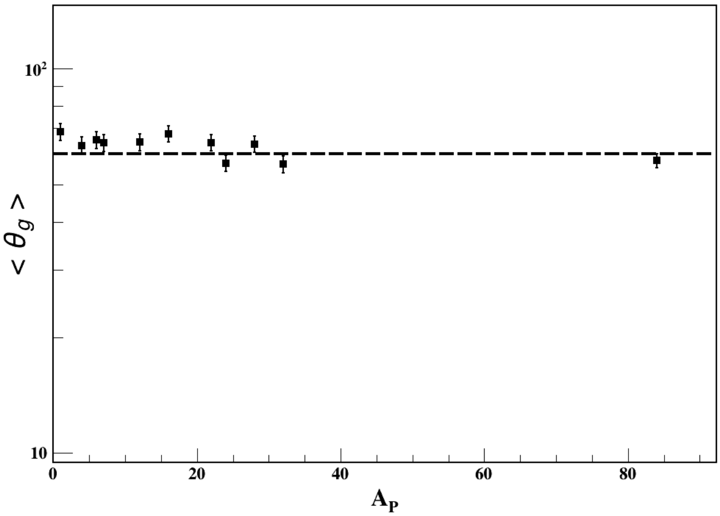

Fig. 2. $\langle\theta_g\rangle$ of the FTP emitted in the interactions of P, ^{4}He, ^{6}Li, ^{7}Li, ^{12}C, ^{16}O, ^{22}Ne, ^{24}Mg, ^{28}Si, ^{32}S [13], and ^{84}Kr [present work] with emulsion. The dashed line represents a guideline at $\langle\theta_g\rangle \approx 60°$.

Important information on the target and projectile fragmentation may be found in the PD of the secondary particles released in relativistic-energy nucleon–nucleus and nucleus–nucleus interactions. The quasi-invariant η values in the emulsion experiment are specified as $\eta = -\ln\tan\frac{\theta}{2}$, where θ is the emission angle. Figure 3 displays the PD of the FTP released when ^{32}S [13] and ^{84}Kr [present work] interact with emulsion. The emulsion data are then separated into two target groups (AgBr and CNO) of NED in order to examine the features of the FTP emitted system with respect to various target sizes. Since the H nucleus contains only one proton and its fragmentation produces an emission of one proton at most as grey or black particles, the events related to interactions of the H target of NED are excluded from data analysis. Figures 4 and 5 display the PD corresponding to events released from the interaction of ^{32}S [13] and ^{84}Kr [present work] with the AgBr and CNO targets, respectively. For ^{32}S [13] and ^{84}Kr [present work], the PD range is between -2.5 and $+3.5$ in all interactions, as shown in figures 3–5. This occurred as a result of the FTP set energy range (30–400 MeV), which produces the same angular spread for all interaction groups [13]. When we switch from the CNO-target to the AgBr-target interactions, the peak position shift to the zero-point PD diminishes. It occurred as a result of the heavier target experiencing more cascade collisions [13].

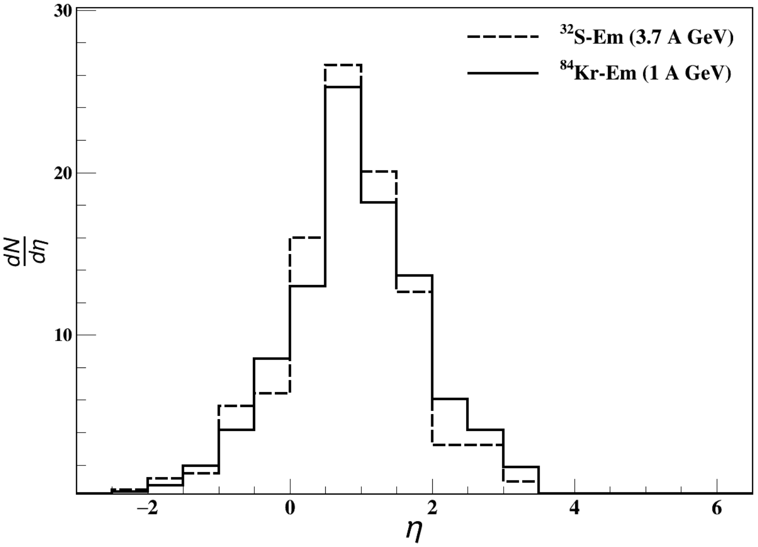

Fig. 3. The PD of the FTP emitted in the interactions of ^{32}S [13], ^{84}Kr [present work] with emulsion.

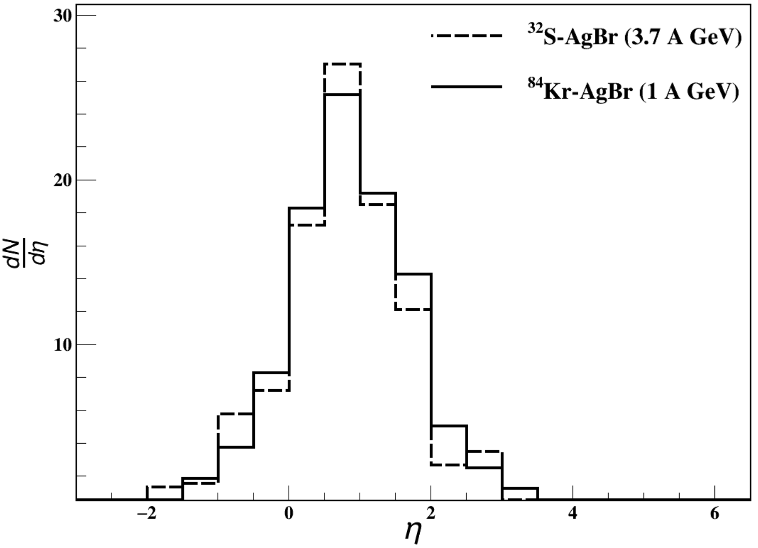

Fig. 4. The PD of the FTP emitted in the interactions of ^{32}S [13], ^{84}Kr [present work] with the AgBr target of NED.

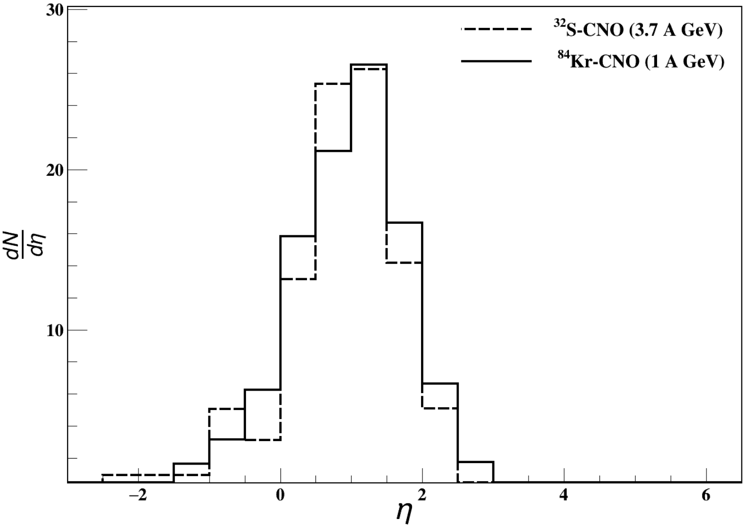

Fig. 5. The PD of the FTP emitted in the interactions of ^{32}S [13], ^{84}Kr [present work] with the CNO target of NED.

4. Conclusion

This work examines potential methods that might produce the FTP from interactions between the ^{84}Kr nucleus and emulsion nuclei at an energy of $1\,A$ GeV. This analysis shows that the $\langle\theta_g\rangle$ of the FTP emitted by various projectiles is almost independent of the projectile's incident energy and $A_{\rm p}$. In order to examine the properties of the FTP emitted system for various target sizes (CNO and AgBr groups of events), the PD of the generated FTP is also examined. This study shows that when we switch from the CNO-target to the AgBr-target interactions, the shift of peak position to the zero-point PD reduces because there are more cascading collisions in the heavier target.

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Data availability statement

The data will be available upon reasonable request with corresponding author.

REFERENCES

[1] M.K. Singh, «Study of the pseudo-rapidity fluctuations in nucleus–nucleus interactions at relativistic energy», *Indian J. Phys.* **99**, 3429 (2025).

[2] V.V. Begun *et al.*, «Multiplicity fluctuations in relativistic nuclear collisions: Statistical model versus experimental data», *Phys. Rev. C* **76**, 024902 (2007).

[3] S. Bhattacharyya, M. Haiduc, A.T. Neagu, E. Firu, «Event-by-event pseudo-rapidity fluctuations in high energy nucleus–nucleus interactions», *Phys. Lett. B* **726**, 194 (2013).

[4] M.K. Singh, A.K. Soma, R. Pathak, V. Singh, «Two source emission behavior of projectile fragments alpha in ^{84}Kr interactions at around 1 GeV per nucleon», *Indian J. Phys.* **85**, 1523 (2011).

[5] M.K. Singh, «Investigation of secondary charged particles emerged in the interaction of ^{84}Kr + emulsion at 1 A GeV», *Sci. Rep.* **15**, 34207 (2025).

[6] S. Kumar, M.K. Singh, V. Singh, R.K. Jain, «Characteristics of the grey particles emission at relativistic energy», *Eur. Phys. J. Plus* **136**, 115 (2021).

[7] B. Kumari, M.K. Singh, «Forward–Backward Multiplicity Relationship of Target Fragments Produced in the Interaction of $^{84}\mathrm{Kr}_{36} + \mathrm{Em}$ at 1 A GeV», *J. Phys. Soc. Jpn.* **92**, 124203 (2023).

[8] U. Rawat, M.K. Singh, M. Goyal, «Emission characteristics of the shower particles produced in the interaction of ^{84}Kr with emulsion 1 Gev per nucleon», *J. Kor. Phys. Soc.* **83**, 411 (2023).

[9] M.K. Singh, B. Kumari, «Study the emission feature of shower particles and slow particles using multisource thermal model at relativistic energy», *Iran. J. Sci.* **49**, 1489 (2025).

[10] U. Singh, M.K. Singh, V. Singh, «Emission Characteristics of Charged Particle Production in Interactions of ^{84}Kr with the Nuclear Emulsion Detector at Relativistic Energy», *J. Kor. Phys. Soc.* **76**, 297 (2020).

[11] B. Kumari, M.K. Singh, R. Singh, V. Singh, «Emission feature of the shower particles produced in backward hemisphere in the interaction of $^{84}\mathrm{Kr}_{36} + \mathrm{Em}$ at 1 A GeV», *Int. J. Mod. Phys. E* **31**, 2250061 (2022).

[12] M.K. Singh, R. Pathak, V. Singh, «Characteristics of alpha projectile fragments emission in interaction of nuclei with emulsion», *Indian J. Phys.* **84**, 1257 (2010).

[13] S. Kamel, E. El-Falaky, A. Saber, «Pseudorapidity distributions of fast target protons in ^{32}S–Em collisions at Dubna energy», *Int. J. Mod. Phys. E* **29**, 2050002 (2020).

[14] Kajal, M.K. Singh, «Emission feature of the singly-charged and doubly-charged projectile fragments emitted in the interaction of $^{84}\mathrm{Kr}_{36} + \mathrm{Em}$ at 1 GeV per nucleon», *Int. J. Mod. Phys. E* **31**, 2250073 (2022).

[15] M.K. Singh, S. Karmakar, V. Singh, «Emission characteristics of the target fragments at relativistic energy», *Int. J. Mod. Phys. E* **31**, 2250036 (2022).