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Characteristics of Emitted Particles in Pion-Nucleus Interactions

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Abstract: *This paper deals mainly with the general characteristics of pseudo-central collision events observed in pion-nucleus interactions. To study the interactions, the nuclear emulsion technique has been used. The results discussed are the probability of occurrence of central collision events and the mean values of the produced particles and their dependence on incident beam energy. The mean normalized multiplicity seems to vary linearly with energy for pion and proton interactions both. Regarding the variation of mean normalized multiplicity with the number of collisions made by the incident particle inside the target nucleus, we have studied its dependence on the number of grey particles because grey particles are considered as the best measure of encounters. The dependence of compound particle multiplicity on projectile energy has also been discussed.*

Keywords: *Grey, black, shower and heavily ionizing particles, nuclear emulsion, mean normalized multiplicity*
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I. Introduction

The multi-particle production process in nuclear interactions has been extensively studied in the past for inclusive data as well as central collision data [1-15]. The investigation of central collisions which is sometimes also called events of total disintegration or catastrophic destruction of heavy emulsion nuclei may provide some very useful information regarding the mechanism of multi-particle production. We find that less attention was paid to study central collisions in the case of pion-nucleus (π^{-}A) interactions.

In this paper, the mechanism of the particle production is being investigated by using the nuclear emulsion technique [16]. Nuclear emulsion is a detector that detects only the charged particles. It provides a unique particle detection system with 4π geometry coverage. The nuclear emulsion consists of hydrogen (H), carbon C, nitrogen (N), oxygen (O), silver (Ag), and bromine (Br). When a beam of the high-energy particle also called projectile interacts with the emulsion nuclei, secondary particles are produced. These particles are categorized as shower, grey, and black particles. Most of the shower particles are pions and are emitted in the forward cone. Grey tracks are produced by recoil protons and black tracks are due to evaporation of residual nuclei which consists of protons and other light fragments. The selection criteria for these tracks/particles are discussed in the next section, i. e., experimental details.

In the case of the complete destruction of heavy emulsion nuclei, Ag and Br, the impact parameter value is nearly zero. The importance of the study of central collisions may be judged from the fact that the nuclear matter is compressed to several times its normal density and many new phenomena may occur. In emulsion experiments, the sum of gray and black particles in an event is called as heavily ionizing particle and its number is denoted by N_h. Most of the workers in the field have used heavily ionizing tracks/particles (N_h) as the parameter for the selection of central collision events with $N_h \geq 28$[7-14]. When we started the analysis, we found only one event with $N_h \geq 28$ out of 568 inelastic interactions which are less than 1%, M El-Nadi et al [17]also reported less than 1% of such events at 340-GeV. Thus it was not possible to extend the analysis with just one event so we applied some other criteria for the selection of the central collision events, i. e, based on the number of charged shower particles in an event. We opted to perform a study on the events which are different from the normal events. Thus we analyzed the events which are beyond 2 standard deviations (σ) from the mean value of charged shower particles. The value of σ for inclusive data is equal to 6.48 ± 0.54 and the mean value of relativistic charged particles is 14.18 ± 0.08. In this way, the number of charged shower particles (N_s) becomes $<N_s>+2\sigma$, which comes out to be 27.14. Thus events with $N_s \geq 28$ are considered for the study performed in this paper. Therefore, we can assume that these events are not identical to the central collision events but can be considered as pseudo-central collision events.

In this article, we have attempted to study the probability of occurrence of central collisions in hadron-nucleus interactions. The dependence of the mean number of secondary particles and the mean of compound particle multiplicity on energy has been discussed. One of the very important parameters in nuclear collisions is the mean normalized multiplicity, R_A, the dependence of R_A on energy has been investigated for pion and proton projectiles in the energy range (50-800) GeV. The number of grey particles is considered as the best measure of the number of collisions made by the incident particle inside the target nucleus, thus the variation of R_A with N_g is presented [18]. Finally, some aspects of compound particles, which is defined as the sum of the numbers of grey and shower particles taking together have also been discussed.

II. Experimental Details

To collect the data for the present investigation, an Ilford G5 emulsion stack exposed to a 340-GeV negative pion beam at CERN-SPS has been used. The size of the plates was (7.5 x7.5 x 0.063) cm^3. In such experiments, when a high energy particle known as primary is incident on the target, it interacts with the emulsion nuclei and a large number of secondary particles are produced. After the development of emulsion, these particles appear in the form of tracks. These are categorized as black, grey, and shower tracks. Shower tracks are mostly pions and they are produced in the forward cone. Black and grey tracks are recoil protons. The description of these particles is given based on their specific ionization, g^* ($= g / g_0$), where g is the track ionization and g_0 is the ionization of the primary. The tracks/particles having $g^* < 1.4$, $1.4 \leq g^* \leq 10$ and $g^* > 10$ are designated as shower, grey, and black particles, their numbers in an interaction are denoted by N_s, N_g and N_b respectively. The number of heavily ionizing particles in an event is given by N_h ($= N_g + N_b$). An interaction/event in the emulsion is called a star because of its very characteristic look.

The plates were scanned by M4000 Cooke's series microscopes. For measurements, a 100X oil immersion objective was used. To make sure that the data does not include any secondary interaction, the primaries of all the events were followed back up to the edge of the pellicles.

III. Results and Discussion

The probability of occurrence of central collision events (W) at different energies for pion and proton projectiles is listed in table 1. We have plotted W with the natural log of energy (ln E) in Fig. 1.

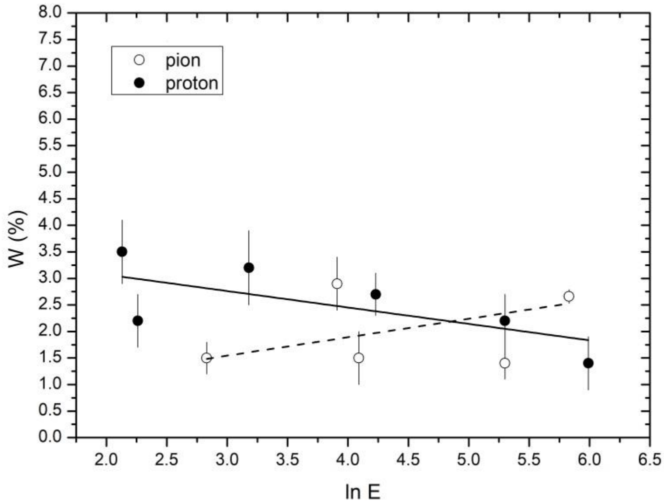

Fig. 1. Variation of probability of occurrence of central collision events with natural log of projectile energy.

A decreasing trend in W with ln E for pA interactions data is observed whereas it increases with energy for $\pi^- A$ collisions data. Straight lines in the figure are due to the following equations.

$$W = (0.50 \pm 1.24) + (0.34 \pm 0.23) \ln E \quad \text{for pion,} \qquad (1)$$

$$W = (3.74 \pm 0.83) + (-0.33 \pm 0.20) \ln E \quad \text{for proton.} \qquad (2)$$

Thus the probability of occurrence of total break up of Ag/Br nuclei depends on the energy in both the cases, i. e., for pion and proton.

Table 1. Probability (W) of central collision events at different projectile energies.

Type of beam	Energy (GeV)	W (%)	Reference
π^-	17	1.50±0.30	19
	50	2.90±0.50	8
	60	1.50±0.50	19
	200	1.40±0.30	19
	340	2.66±0.13	This work
P	8.4	3.50±0.60	7
	9.60	2.20±0.50	7

24	3.20±0.70	8
69	2.70±0.40	7
200	2.20±0.50	20
400	1.40±0.50	8
800	<3	9

Table 2 shows the average values of different kinds of secondary particles, i. e., $<N_g>$, $<N_b>$, and $<N_s>$. We have reproduced these values in Fig. 2. From the figure, we note that $<N_g>$ and $<N_b>$ are almost independent of energy and projectile within statistical errors. Though, the mean values of grey and black particles observed by us show some deviation. This may be because our data is not exactly central collision data but pseudo-central collision data.

Table 2. Mean values of gray, black, shower and compound particles at different projectile energies.

Type of beam	Energy (GeV)	$<N_g>$	$<N_b>$	$<N_s>$	$<N_c>$	Reference
π^-	7.50	7.40 ± 0.90	22.40 ± 1.40	3.10 ± 0.90	10.5±1.71	19
	17	11.30±0.90	18.80±1.40	8.40±1.00	19.70±1.90	19
	50	11.70±0.60	21.90±0.80	12.40±0.70	24.10±1.09	8
	60	12.30±0.80	16.30±0.90	13.60±1.10	25.90±2.01	19
	340	6.40±0.89	10.80±1.30	30.93±0.70	37.33±1.38	This work
P	8.40	11.70±0.60	19.70±0.40	3.40±0.20	15.10±0.64	7
	9.60	10.00±0.70	20.80±1.00	4.00±0.40	14.00±0.86	7
	24	11.90±0.80	21.80±1.00	11.70±0.60	23.60±1.16	8
	69	14.20±0.80	15.80±0.50	19.00±1.00	33.20±1.80	7
	400	11.61±1.29	21.71±1.76	31.70±2.13	43.71±5.82	8
	800	-	-	37.50±1.00	-	9

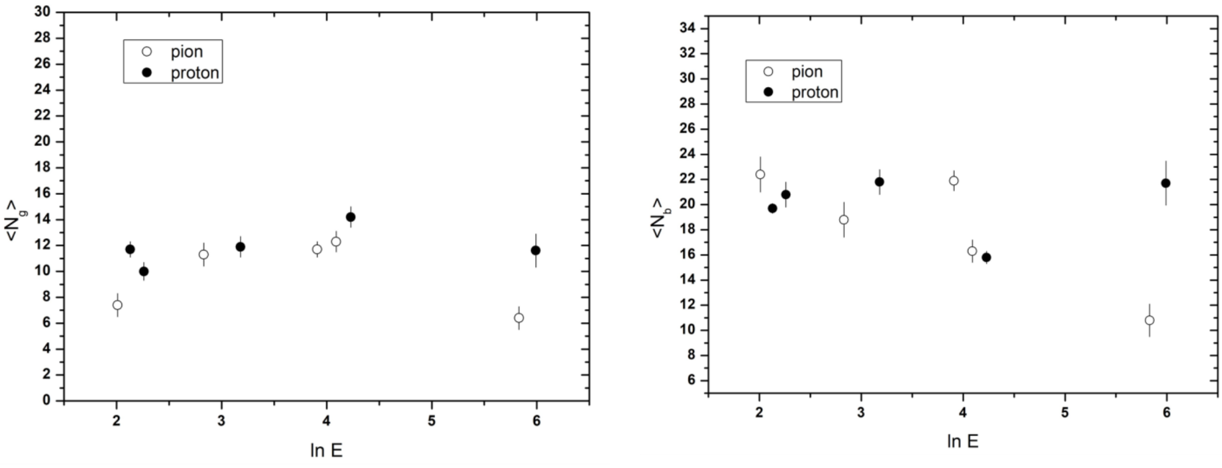

Fig. 2 (a) Fig. 2 (b)

Fig. 2 (a, b). Variation of mean number of grey and black particles with natural logarithmic value of projectile energy.

We have plotted the average values of the relativistic charged shower particles as a function of energy in Fig. 3. The line drawn in the figure is of the following equation

$$<N_s> = (-12.07 \pm 0.90) + (7.19 \pm 0.30) \ln E. \quad (3)$$

Thus we infer that $< N_s >$ depends strongly on energy for pion and proton projectiles both. Khushnood et al [8] have also reported a linear relationship but with different values of the constants and slopes. An increasing trend is observed in the mean values of relativistic charged shower particles which shows that when incident energy is high, the production of relativistic charged secondaries is also high.

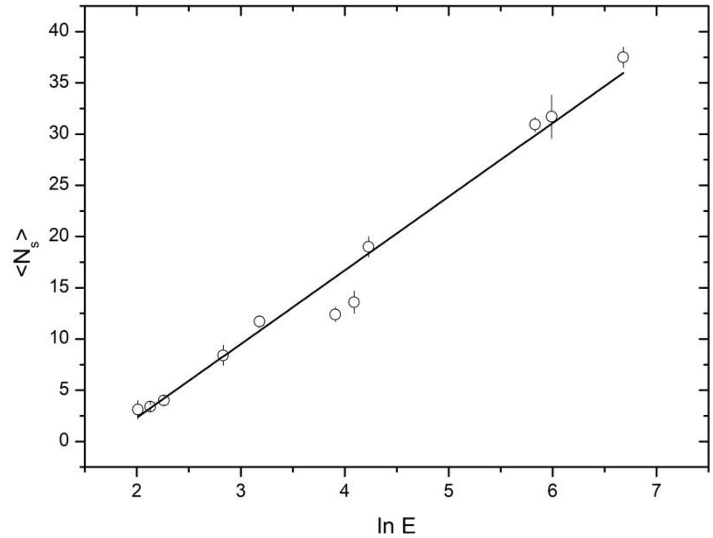

Fig. 3. Variation of mean relativistic charged shower particles with the natural log of projectile energy.

The other parameter which is of paramount importance is the mean normalized multiplicity, R_A (say R_{A1}). In the beginning, the parameter was defined as

$$R_{A1} = < N_s > / < N_{ch} > \quad (4)$$

where $<N_s>$ and $<N_{ch}>$ are respectively the mean number of relativistic charged particles produced in hadron-nucleus and hadron-hadron interactions. But as work on multi-particle production progressed, Aziz et al [21, 22] reported a new definition in terms of created charged particles in the following way for (π^-A) and (pA) interactions.

$$(R_{A2})_{\pi^- A} = <N_s>_{Cr}/<N_{ch}>_{cr} , \quad (5)$$

$$(R_{A2})_{\pi^- A} = (< N_s > - 0.50) / (< N_{ch} > - 1.40), \quad (6)$$

$$(R_{A2})_{pA} = (< N_s > - 0.67) / (< N_{ch} > - 1.33). \quad (7)$$

The dependence of R_{A1} and R_{A2} on energy is given in Fig. 4. The data is best represented by the following lines

$$R_{A1} = (0.26 \pm 0.19) + (0.47 \pm 0.03) \ln E \qquad \text{for pion,} \quad (8)$$

$$R_{A2} = (1.26 \pm 0.05) + (0.36 \pm 0.01) \ln E \qquad \text{for proton.} \quad (9)$$

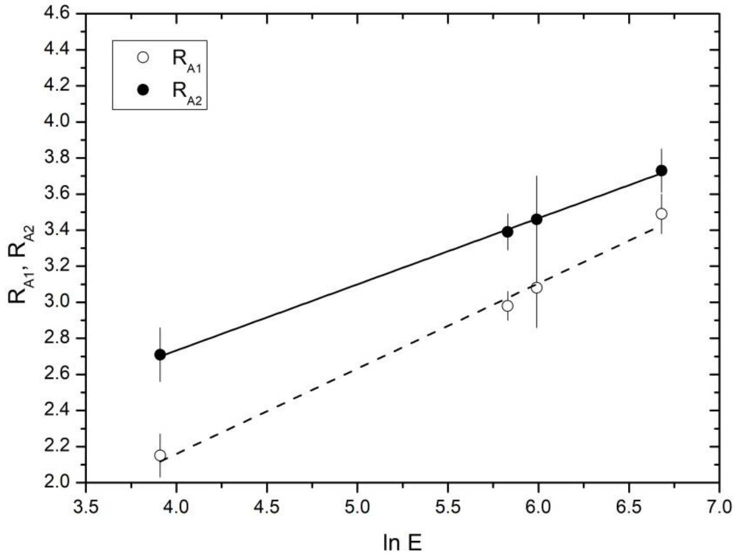

Fig. 4. Variation of mean normalized multiplicity (R_{A1} and R_{A2}) with the natural log of projectile energy.

From Fig. 4 we find that the values of R_{A1} and R_{A2} increase with energy. Our observation of an increase in R_{A1} and R_{A2} agrees quite well with the results reported by Anzon et al [23] for pion-nucleus interactions at 200-GeV.

To check the variation of R_{A1} and R_{A2} on the number of encounters made by the incident particle inside the target nucleus, we have plotted these parameters against grey particle multiplicity, N_g, as N_g is considered to be one of the measures of the number of collisions in Fig. 5. From the figure, we note that there is almost no variation in the values of R_{A1} and R_{A2} with the number of collisions made by the incident hadron inside the target nucleus.

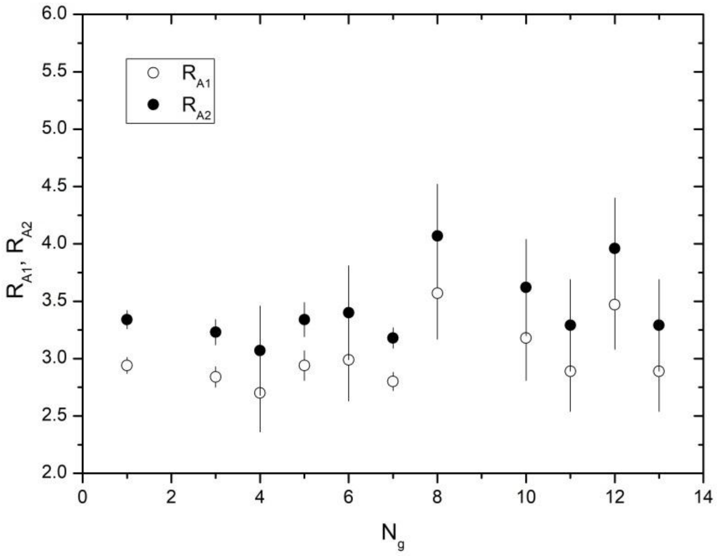

Fig. 5. Variation of mean normalized multiplicity (R_{A1} and R_{A2}) with grey particle multiplicity.

Compound particle multiplicity was first defined by Jurak et al [24] as the sum of grey and shower particle multiplicities, i. e., $N_c = N_g + N_s$. The variation of mean compound particle multiplicity, $\langle N_c \rangle$, with energy, is depicted in Fig. 6. Again a linear relationship is observed which is given by the following line.

$$\langle N_c \rangle = (0.57 \pm 1.80) + (6.50 \pm 0.57) \ln E \quad (10)$$

Therefore we say that mean compound multiplicity also depends strongly on incident energy.

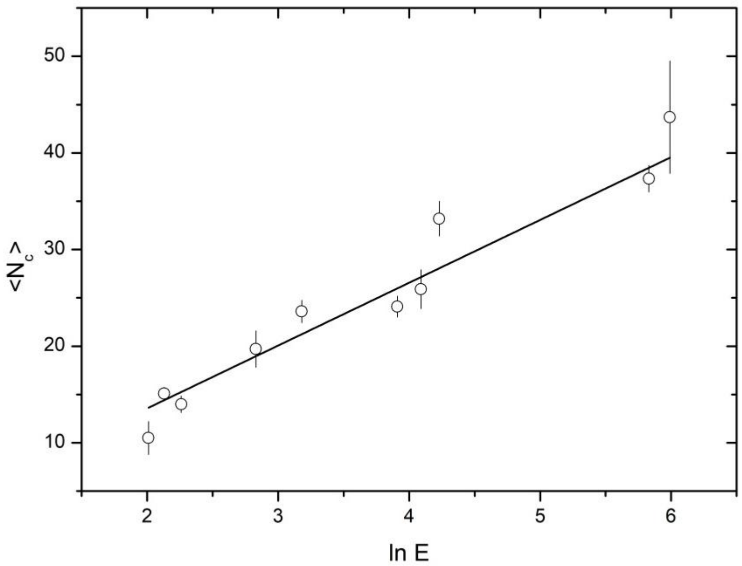

Fig. 6. The dependence of compound particle multiplicity on the natural logarithmic value of projectile energy.

IV. Concluding Remarks

Based on the results discussed, the following conclusions may be drawn.

(i) The probability of occurrence of central collision events increases with energy for pion projectile whereas it shows a decreasing trend for proton projectile.

(ii) Averaged multiplicities of grey and black particles are observed to be energy-independent.

(iii) Mean multiplicity of relativistic charged shower particles and compound particle multiplicity depends strongly on energy for pion and proton projectiles.

(iv) Mean normalized multiplicity is observed to increase with energy.

(v) Almost no variation in the values of mean normalized multiplicity with the number of collisions is observed.

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