сообщения
объединенного
института
ядерных
исследований
дубна

E1-81-623

A.Abdelsalam*

INELASTIC INTERACTIONS OF p, d, ^{4}He AND ^{12}C PROJECTILES WITH LIGHT (CNO) AND HEAVY (AgBr) NUCLEI AT 4.5 GEV/C PER NUCLEON

* On leave from Faculty of Science,
Cairo University, Egypt

1981

I. INTRODUCTION

In case of hadron-nucleus and nucleus-nucleus interactions the experimental data analysis in terms of the number of heavy ionizing particles (particles with $\beta < 0.7$), N_h, shows that this number is a good parameter to describe the target fragmentation degree /1/.

This paper is devoted to a study of some features of the experimental characteristics of p, d, He^4 and C^{12} inelastic interactions with nuclear emulsion nuclei at an incident momentum of 4.5 GeV/c per nucleon. In addition, a criterion is adopted to separate the number of events with light (CNO) and heavy (AgBr) target nuclei. This criterion is also tested for other experimental data at energies around 2.1 GeV per nucleon.

In the first papers /2-4/ devoted to a study of p, d, He^4 and C^{12} inelastic interactions with emulsion nuclei at 4.5 GeV/c per nucleon it has been found that

a) There is no considerable difference between the N_h distributions, except the high N_h region where the number of C^{12}-Em events is somewhat larger than the numbers of He^4 and d events. Both are enriched with the events of high N_h as compared to the case of incident protons.

b) Increasing the mass number of the projectiles leads to a small increase in $\langle N_h \rangle$, while the average number of shower particles, $\langle n_s \rangle$, grows rapidly (see Table 1).

Table 1

	p	d	He^4	C^{12}
$\langle N_h \rangle$	8.0±0.3	7.8±0.1	9.3±0.2	10.6±0.2
$\langle N_s \rangle$	1.6±0.1	3.1±0.1	3.9±0.1	8.8±0.2

c) The frequency distribution with respect to the number of n_s particles (mainly pions) changes strongly with the mass number of the incident projectiles, A_{proj}.

II. EMISSION OF CHARGED TARGET FRAGMENTS

Figure 1 shows the integral frequency distributions for the events as a function of N_h for different projectiles p, d, He^4 and C^{12}. In these figures the integral frequencies for all events for the interactions of a certain projectile with emul-

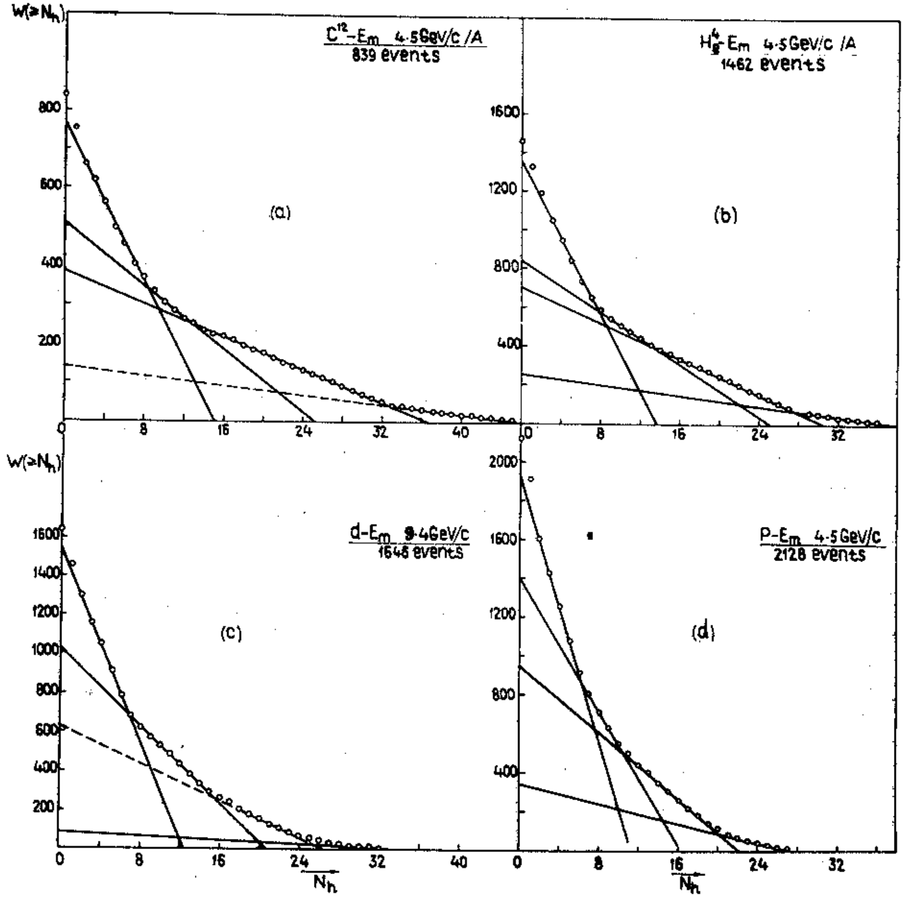

Fig.1

sion nuclei as a function of N_h are denoted by four distinct straight lines (in general). These lines represent nearly the same intervals of N_h for different projectiles and at different incident momenta. (This behaviour is also studied here for O^{16}, N^{14} and p interactions at energies around 2.1 GeV per nucleon/5-7/, and the results of these studies are included). This phenomenon is also observed in case of He^4 interactions with emulsions enriched with light nuclei (HCO) (LE -emulsions) at an incident momentum of 4.5 GeV/c per nucleon. This behaviour of the integral N_h distributions is independent of the mass of the projectile, and it is target-dependent.

Table 2

	First line	χ^2/DF	Second line	χ^2/DF	Third line	χ^2/DF	Fourth line	χ^2/DF
C^{12}	$100.0-6.92N_h$	0.12	$65.70-2.65N_h$	0.10	$48.08-1.34N_h$	0.02	$30.52-0.72N_h$	0.18
$He^4_{(a.u.)}$	$100.0-7.38N_h$	0.57	$62.67-2.47N_h$	0.02	$51.59-1.69N_h$	0.03	$19.17-0.52N_h$	0.14
$He^4_{(L.U.)}$	$100.0-10.52N_h$	0.14	$36.35-1.61N_h$	0.04	$21.80-0.72N_h$	0.04	$10.28-0.28N_h$	0.03
d	$100.0-8.0N_h$	0.82	$68.74-3.22N_h$	0.05	$40.93-1.54N_h$	0.60	$5.77-0.16N_h$	0.03
p	$100.0-8.8N_h$	0.012	$72.9-4.44N_h$	0.042	$48.85-2.21N_h$	0.146	—	—
O^{16}	$100.0-7.93N_h$	0.091	$55.09-1.86N_h$	0.02	$50.30-1.56N_h$	0.16	$24.5-0.65N_h$	0.20
N^{14}	$100.0-8.10N_h$	0.40	$59.90-2.21N_h$	0.08	$53.30-1.13N_h$	0.20	$28.4-0.82N_h$	0.30
p	$100.0-8.8N_h$	0.13	$73.5-4.18N_h$	0.03	$35.27-1.68N_h$	0.24	—	—

Table 3

Line number	P=4.5 GeV/c/A					P=2.88 GeV/c/A		
	p	d	He^4(a.u.)	He^4(L.U.)	C^{12}	p	N^{14}	O^{16}
1	3.12±0.25	3.15±0.10	3.24±0.28	3.03±0.20	3.25±0.11	3.32±0.13	3.11±0.14	3.37±0.28
2	10.81±0.50	11.50±0.40	10.89±0.28	11.29±0.36	10.60±0.40	11.22±0.80	10.60±0.80	11.14±1.30
3	18.44±1.30	19.95±1.17	20.48±1.03	20.31±1.30	21.01±1.00	18.42±1.80	19.78±1.50	20.71±1.80
4	—	31.80±4.00	32.79±1.90	33.41±2.50	35.22±2.50	—	31.40±3.20	33.50±5.00

Table 2 summarizes the parameters of each straight line $W = b + aN_h$ obtained as a result of the best data fit in each interval of N_h for different projectiles. The normalized number of events is used in such fits. The last line (fourth) in each integral distribution is due to the central collisions of each projectile with Ag nuclei. These events with $N_h > 28$ represent the complete destruction of the Ag nuclei [8]. (The fourth line does not appear in case of incident protons).

The first line for each distribution represents interactions with (CNO) nuclei in addition to peripheral collisions with (AgBr) nuclei. The second and third lines represent a certain phenomenon as a superposition between central collisions with Br nuclei and peripheral interactions with Ag nuclei.

The average number of heavy ionizing particles, $\langle N_h \rangle$, in each group of events is shown in Table 3. From fig.1 one can conclude that each line represents a specified target nucleus from the constituents of the emulsion nuclei. As is seen from Table 3, $\langle N_h \rangle$ for each line in a certain interval of N_h for different incident projectiles are equal within the statistical errors. (The boundaries of each line change with the mass number of the projectile). This means that the degree of disintegration of the struck nucleus does not change very much with changing the mass number of the incident projectile. Therefore we try to separate the number of events with light (CNO) and heavy (AgBr) nuclei using the above integral distribution in case of each projectile. Let us consider the number of events under the second, third and fourth lines which represent the interactions with (AgBr) nuclei. The events under the first line obviously represent the interactions with (CNO) and (AgBr) nuclei (peripheral collisions with AgBr). If the second line is extrapolated to the region of the first line, the events above this line in this region represent the interactions with (CNO) nuclei while the events below this line represent the interactions with (AgBr) nuclei. According to

Table 4

projectile	From the Integral dist		Equation (1)		Other experiments	
	CNO	AgBr	CNO	AgBr	CNO	AgBr
C^{12}	34.3	65.7	34.3	65.7	—	—
He^4	37.3	62.7	32.4	67.6	—	—
He^4	64.7	35.3	63.9	36.1	—	—
d	33.3	66.7	—	—	—	—
p	27.8	72.2	25.1	74.9	26.0	74.0^a
O^{16}	44.9	55.1	—	—	42.4	57.5^b
N^{14}	40.0	60.0	—	—	36.6	63.4^c
p	26.5	73.5	—	—	—	—

the above separation, the number of interactions with each group of (CNO) and (AgBr) nuclei is presented in Table 4 for different incident projectiles (in per cent).

The authors of ref. /9/ have calculated the inelastic interaction cross sections of p, He^4 and C^{12} projectiles with different specified targets of mass number A (Li , C , Al , Cu , pd) at an incident momentum of 4.5 GeV/c per nucleon and have found the following relationships:

$$\sigma_{in}(C^{12}, A) = 224\,A^{0.47},$$
$$\sigma_{in}(He^4, A) = 112\,A^{0.57}, \qquad (1)$$
$$\sigma_{in}(p, A) = 44.7\,A^{0.70}.$$

Using these equations of inelastic cross sections for different projectiles and concentrations of atomic chemical compositions for emulsions, one can calculate the number of events for the interactions of each projectile with (CNO) and (AgBr) nuclei. The percentage of the calculated values is listed in Table 4 as well. In case of the incident proton, the values coincide with those predicted by the Florian et al. /10/ method of separation. In the Florian method the interaction cross sections of protons with different emulsion nuclei are assumed to be proportional to $A^{2/3}$. The last column in Table 4 contains the results obtained by the authors of ref. /5/ in case of O^{16} projectiles using the short range tracks for separation and in case of N^{14} using the statistical method described in detail in ref. /11/. The number of inelastic interaction events of any projectile with emulsion hydrogen can be calculated from the integral distributions. It is equal to the difference between the total number of events and the number of events at the intersection of the first line with the ordinate one. The percentage of the probabilities of the inelastic interactions of any projectile with emulsion hydrogen is presented in Table 5. As is seen, these probabilities increase as the mass number A_{proj} of the projectile increases. (These values are very sensitive to the possibility of the scanning efficiency for the events of low multiplicity and $N_h = 0$).

Table 5

Projectile	p=4.5 GeV/c/A					p≈2.89 GeV/c/A		
	C^{12}	He^4 (SE)	He^4 (LE)	d	p	O^{16}	N^{14}	p
%	10.8	7.0	6.8	6.8	8.5	10.2	9.0	5.5

From the foregoing it follows that it is possible to divide the inelastic interactions of any projectile (nucleon or nucleus) with emulsion nuclei into three categories of events with H, (CNO) and (AgBr) nuclei using the N_h integral distribution of all inelastic interactions. As seen from fig.1, the boundary of separation between the events with (CNO) and (AgBr) nuclei changes and increases with increasing the mass number of the projectile. It varies from 6 in case of proton to 8 in case of incident C^{12} .

III. FAST PARTICLE MULTIPLICITY

Some multiplicity characteristics of fast particles are discussed in this section. The dependence of the mean number of emitted shower particles, $\langle n_s \rangle$, on N_h for different projectiles is plotted in fig.2. We have also investigated the dependence of $D/\langle n_s \rangle$ on N_h (fig.3a). One can see that $\langle n_s \rangle$ seems to change linearly with N_h , and the line slope increases with increasing the mass number of the projectile or the number of interacting nucleons from the projectile (see Table 6).

Table 6

	№ of events	a	b	χ^2/DF
p	2128	-0.024±0.01	1.78±0.03	0.02
d	1646	0.10±0.01	2.42±0.13	0.02
He^4	1462	0.22±0.02	2.79±0.11	0.04
C^{12}	839	0.43±0.10	3.08±0.30	0.073

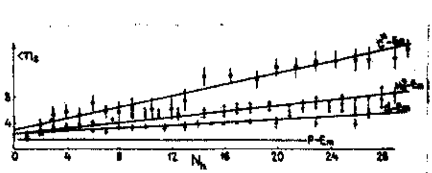

Fig.2

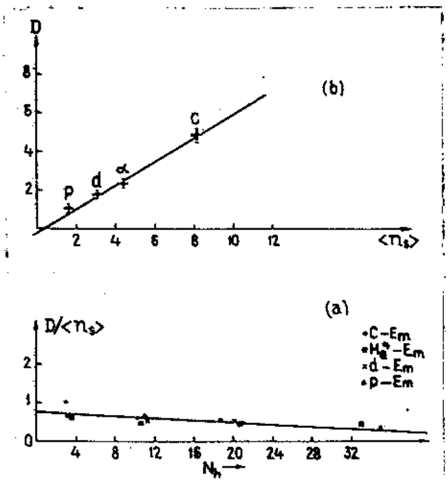

Fig.3

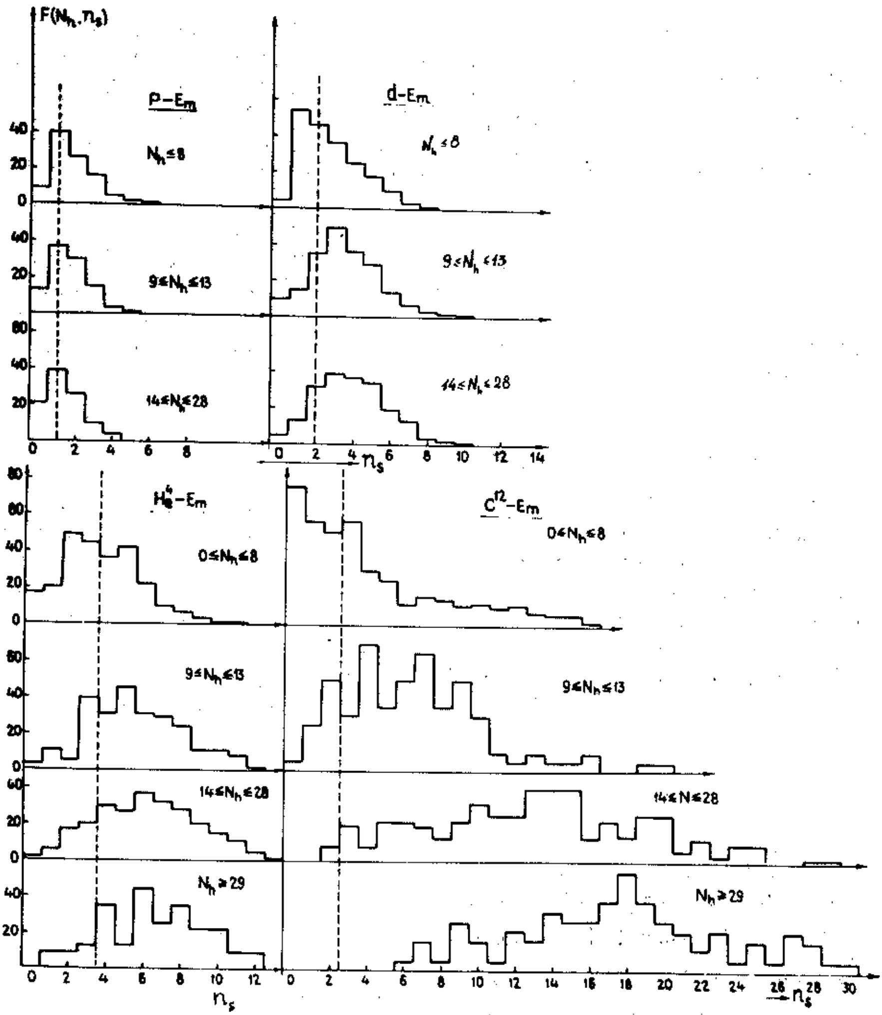

Fig.4

It is also seen that $D/\langle n_s\rangle$ are nearly equal for each projectile for all events. Summing all the data for each projectile, we present the dependence of D on $\langle n_s\rangle$ in fig.3b. The data have been fitted by a straight line with X^2/DF of 0.01 at 4.5 GeV/c per incident nucleon.

$$D = (0.59 \pm 0.03)\langle n_s\rangle - (0.03 \pm 0.01). \qquad (2)$$

In order to investigate the dependence of multiparticle production on both target and projectile nuclei, it is interesting to study the n_s distributions for all events for p , d , He^4 and C^{12} in the following intervals of N_h ($0 \leq N_h \leq 8$, $9 \leq N_h < 14$, $14 \leq N_h \leq 28$ and $N_h > 28$). The distributions are plotted in fig.4. The average number of shower particles and the dispersion of each distribution are listed in Table 7. From the data shown in fig.4 and Table 7 one can conclude the following:

1) In case of 4.5 GeV/c incident protons no charge is observed in the distributions of n_s particles with N_h . However, the increase of the target nucleus excitation can be explained by the reabsorption of some produced pions passing through the target nucleus (i.e., low rapidity pion) in case of AgBr nuclei. This behaviour is also observed in the correlation between $\langle n_s \rangle$ and N_h , fig.3. This phenomenon occurs in case of one nucleon (proton) incident on emulsion target nuclei. But in case of d , He^4 and C^{12} projectiles the number of events with low shower particle multiplicity decreases gradually with increasing N_h (i.e., with decreasing the impact parameter); at the same time the number of created events with high multiplicity increases. This indicates that the number of interacting nucleons from the projectile increases with increasing the number of events with high multiplicity. This is also observed from the average values of n_s particles for different groups of N_h in case of d , He^4 and C^{12} projectiles (Table 7).

Table 7

	$\langle N_s \rangle$			
	$0 \leq N_h \leq 8$	$9 \leq N_h < 14$	$14 \leq N_h \leq 28$	$N_h > 28$
p	1.62 ± 0.04	1.63 ± 0.03	1.33 ± 0.05	—
d	2.72 ± 0.08	3.47 ± 0.23	3.80 ± 0.21	—
$He^4_{(S.E)}$	3.56 ± 0.11	5.55 ± 0.42	6.35 ± 0.35	6.77 ± 0.30
$He^4_{(L.C)}$	3.66 ± 0.16	5.84 ± 0.26	6.21 ± 0.77	7.09 ± 1.30
C^{12}	4.30 ± 0.19	6.57 ± 0.60	13.0 ± 1.05	17.85 ± [illegible]

Table 8

	$N_h \leq 8$		$8 < N_h < 14$		$14 \leq N_h \leq 28$		$N_h > 28$		all events	
	N	γ	N	γ	N	γ	N	γ	N	γ
d	1071	1.68	236	2.00	339	2.00	—	—	1646	1.8
He^4	985	2.20	155	3.40	329	3.89	57	3.9	1462	2.9
C^{12}	503	2.65	100	4.00	153	8.13	92	11.0	839	4.8

2) Comparing the values of $\langle n_s \rangle$ for each group of particles in each interval of N_h in case of d , He^4 and C^{12} with the corresponding values in case of incident protons, we have found the values presented in Table 8. In general, for the total n_s distribution of each projectile

$$\langle n_s \rangle_{c-Em} / \langle n_s \rangle_{p-Em} = 4.97 \pm 0.20,$$

$$\langle n_s \rangle_{He^4-Em} / \langle n_s \rangle_{p-Em} = 2.70 \pm 0.10,$$
$$\langle n_s \rangle_{d-Em} / \langle n_s \rangle_{p-Em} = 1.88 \pm 0.10. \qquad (3)$$

Compare these values with those[2] of the number of interacting nucleons from each projectile (in case of carbon only) calculated experimentally using the identified number of non-interacting nucleons from the projectile in each event. These values are nearly equal. From these results nucleus-nucleus interactions can be interpreted, in a simple way, as a superposition of nucleon-nucleon collisions in this incident momentum range.

3) From the correlation between the dispersion D and $\langle n_s \rangle$ in fig.3b it follows that the n_s distribution of events in case of any projectile can be presented by the invariant distribution on some scaled variable.

IV. ANGULAR DISTRIBUTIONS

It is suitable to present the angular distribution of relativistic particles as a function of pseudorapidity variable $\eta = -\ln(\tan\theta/2)$, where θ is the laboratory angle of relativistic particles relative to the primary direction. The pseudorapidity distributions of relativistic particles emitted in the interactions of p and C^{12} projectiles with emulsion nuclei at a momentum of 4.5 GeV/c per nucleon are shown in fig.5. The two distributions are normalized to the same number of interactions. A cut-off is made at $\eta = 4.0$ due to the limitation of the angle at which the projectile fragments are emitted in

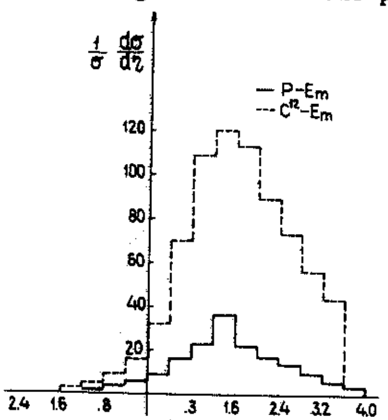

Fig.5

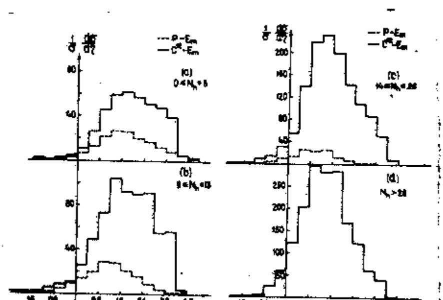

Fig.6

case of C^{12} interactions. The pseudorapidity distributions of relativistic particles emitted in the interactions of p and C^{12} with emulsion nuclei at different intervals of N_h are plotted in fig.6. The particles in the region of low η (≤ 0.4) are associated with the target fragmentation, and the particles in the region of high η (>0.4) with the pionization (pion creation) and projectile fragmentation. The number of relativistic particles in the target fragmentation regions depends on the number of heavy ionizing tracks, N_h /12/. The average numbers of relativistic particles in the target fragmentation region per event for different groups of N_h at $C^{12}-Em$ and $p-Em$ interactions are presented in Table 9. From the above it should be noted that

1) The pseudorapidity distributions of relativistic particles emitted in $C^{12}-Em$ interactions are enriched with the particles with low pseudorapidities (percentage of the number of particles in the target fragmentation region) as compared to the corresponding ones in $p-Em$ interactions (see Table 9).

2) As N_h increases, the relative number of relativistic particles in the target fragmentation region increases rapidly in case of C^{12}–Em interactions, and it increases slowly in case of p -Em. This means that this increase for $C^{12}-Em$ is due to increasing the number of interacting nucleons from the carbon projectile. The result becomes clear after calculating the ratio:

$$2 < n_s >_c \; / < n_s >_p = 2 \times 2.577 = 5.15,$$

where $\langle n_s \rangle_c$, $\langle n_s \rangle_p$ are the numbers of relativistic particles in the target fragmentation region for $C^{12}-Em$ and $p-Em$ interactions, respectively. This ratio is also related to the average number of interacting nucleons from the carbon projectile with emulsion nuclei calculated in section III.

3) In case of $C^{12}-Em$ the number of interactions with $N_h >$ >28 is due to the purely central collisions of C^{12} with Ag nuclei /8/. This is also supported in calculating the above ratio in this interval nearly equal to 12.

4) The number of relativistic particles in the pionization region for $p-Em$ in each interval of N_h is almost fixed while for $C^{12}-Em$ this number grows due to increasing the number of interacting nucleons from the carbon nucleus.

5) The average pseudorapidity, $\langle \eta \rangle$, per created particle in case of incident C^{12} and p is shown in Table 10 for different intervals of N_h. The $\langle \eta \rangle$ decreases as $\langle N_h \rangle$ increases (the impact parameter decreases), and this is due to the relaxation of the rapidity of created particles when they pass through the nucleuar matter of the target nucleus. On the

Table 9

Interactions	$0 \leq N_h \leq 8$	$9 \leq N_h \leq 13$	$14 \leq N_h \leq 28$	$N_h > 28$	Totally
p-Em	0.22	0.32	0.37	—	0.26
C^{12}-Em	0.23	0.53	1.94	2.46	0.66

Table 10

Projectile \ N_h	0–8	9–13	14–28	≥28	Totally
C^{12}	1.97	1.89	1.60	1.42	1.71
p	1.61	1.16	0.9	—	1.40

other hand, the values of $\langle\eta\rangle$ for any interval for incident C^{12} are larger than the corresponding values for incident protons. This result can reveal the existence of collective effect in case of C^{12}-Em interactions. However, this result can be also interpreted according to the effect of variation of the impact parameter between each nucleon in the carbon projectile and the target nucleus.

V. CONCLUSIONS

From the study of the interactions of p , d , He^4 and C^{12} with emulsion nuclei at 4.5 GeV/c per nucleon, the following conclusions can be drawn:

1) The integral distribution of all events for the interactions of any projectile with emulsion nuclei as a function of N_h can be presented by four distinct straight lines.

2) The integral distribution can be used to separate the events occurring with (CNO) and (AgBr) nuclei in the statistical way.

From the study of the shower particle multuplicity distribution and the pseudorapidity distribution for p-Em and C^{12}-Em interactions we can find:

a) The $\langle n_s\rangle$ changes linearly with N_h (for $N_h < 22$), and the slope of the linearity relation increases with increasing the mass number of the projectile.

b) The dispersion of the shower particles produced in p , d , He^4 and C^{12} interactions with emulsion nuclei can be presented by a general relation.

c) Some features $\langle\eta\rangle$ and $\langle n_s\rangle$ can be explained by collective type models.

ACKNOWLEDGEMENTS

The author appreciates the guidance and advice given him by Prof. K.D.Tolstov in the analysis and interpretation of the data. Also he would like to thank Dr. G.S.Shabratova for numerable helpful discussions and reading the manuscript. Sincere thanks are to Mrs. N.Ali-Mossa for her fruitful help in the calculations. He thanks all members of the BDKLMTW collaboration, particularly M.Sumbera and S.Vokal.

REFERENCES

1. Busze W. The VIth Int.Conf. on High Energy Phys. and Nucl.Struct., Los Alamos and Santa Fe, 1975.
2. BWDKLMT Collaboratiob. JINR, E1-10838, Dubna, 1977.
3. BWDKLMT Collaboration. JINR, P1-8318, Dubna, 1974.
4. Bogachev N.P., Tolstov K.D., Shabratova G.S. JINR, P1-6877, Dubna, 1972.
5. Kullberg R. et al. Nucl.Phys., 1977, A280, p.491; B.Jakobsson, Kullberg R. Preprint Lund-CR-75-14, 1975.
6. Chernov G.M. et al. Nucl.Phys., 1977, A280, p.478; Gudima K.K. et al. JINR, P2-1022, Dubna, 1976.
7. Bagdanski M. et al. Helv.Phys.Acta, 1969, 42, p.485.
8. Tolstov K.D. Dubna-Frankfurt Cooperation and Comments to the Int.Conf. on Extreme States in Nucl.Syst., GDR, February, 1980.
9. Abdurakhimov A.U. et al. JINR, E1-80-598, Dubna, 1980.
10. Florian J.R. et al. Report submitted to the Meeting of the Division of Particles and Fields, Berkeley, California, 1973.
11. BWDKLMT Collaboration. JINR, P1-9364, Dubna, 1975.
12. Otterlund I. et al. Nucl.Phys., 1978, B142, p.445.

Received by Publishing Department
on September 29 1981.