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THE MULTIPLICITY AND ANGULAR DISTRIBUTION OF CHARGED PARTICLES PRODUCED IN THE INTERACTION OF 200 GeV PROTONS WITH SOME NUCLEI OF NUCLEAR EMULSION

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Abstract: In this work the experimental results are reported on the average multiplicities of relativistic, grey, black and heavy tracks ($\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$ and $\langle N_h \rangle$) for proton interactions with the light and heavy nuclei of emulsion. The dependence of $\langle n_s \rangle$ and $\langle N_h \rangle$ on the atomic number of target nucleus A was established and the asymmetry of the emission of relativistic and low-energy particles was observed.

1. *Introduction*

Nuclear emulsions as detectors of ionizing radiation offer a possibility of investigating experimentally the interactions of high-energy particles with nuclei of various atomic number. The general characteristics of the interaction of 200-GeV protons with the medium nuclei of emulsion ($\langle A \rangle = 69$) are given in Refs.[1,2]. In the present work the interaction of 200 GeV protons with the light and heavy nuclei of emulsion is analyzed, (the light nuclei of emulsion CNO with $\langle A \rangle = 14$, and the heavy ones AgBr with $\langle A \rangle = 94$).

The particles emitted in an interaction are classified according to the ionization produced along their tracks. The usual notation is used:

n_s is the number of relativistic particles ($I \leq 1.4\, I_0$, where I_0 is the ionization of the incident protons,
n_g is the number of grey tracks ($I \geq 1.4\, I_0$ or $30 \leq E_p \leq 400$ MeV),
n_b is the number of black tracks ($E_p \leq 30$ MeV), and
$N_h = n_g + n_b$ is the number of heavy tracks.

2. Detection and classification of events

In this work use was made of Ilford K-5 nuclear emulsions exposed to protons at Batavia in 1972 (a part of an emulsion stack belonging to the Barcelona et al. Collaboration). By the »along the track« scanning a total of 263 events were found, of which 179 were measured and analyzed.

According to the criterion formulated in Ref.[3], all the interactions detected may be classified into the following three groups:

- »quasinucleon« group is constituted by p-p, p-n and coherent inelastic interactions,
- »light« group is composed of all interactions having $1 \leq N_h \leq 6$ with a black track of a length of $R \leq 80\,\mu$,
- »heavy« group comprises all interactions having $1 \leq N_h \leq 6$ with a black track of a length of $R > 80\,\mu$ (»heavy T_1« group) and all interactions having $N_h \geq 7$ (»heavy T_2« group).

TABLE 1.

E (GeV)	$\langle n \rangle$	»Quasinucl.«	»Light«	»T1«	»T2«
200	$\langle n_s \rangle$	8.5 ± 0.6	10.2 ± 1.1	11.7 ± 1.0	19.2 ± 1.1
	$\langle n_g \rangle$	0.31 ± 0.07	1.40 ± 0.28	2.14 ± 0.4	8.96 ± 0.6
	$\langle n_b \rangle$	0	1.68 ± 0.32	1.45 ± 0.3	7.11 ± 0.5
	$\langle N_h \rangle$	0.31 ± 0.07	3.10 ± 0.3	3.60 ± 0.3	16.1 ± 0.8
	N_{tot}	46	28	29	76
	$\langle n \rangle$	»T1« and »T2«	CNO	AgBr	All interactions
	$\langle n_s \rangle$	17.1 ± 0.9	9.6 ± 0.9	15.8 ± 0.8	13.8 ± 0.8
	$\langle n_g \rangle$	7.08 ± 0.55	0.99 ± 0.2	6.0 ± 0.51	4.44 ± 0.4
	$\langle n_b \rangle$	5.54 ± 0.45	1.05 ± 0.2	4.65 ± 0.38	3.51 ± 0.32
	$\langle N_h \rangle$	12.6 ± 0.8	2.0 ± 0.2	10.7 ± 0.8	7.9 ± 0.6
	N_{tot}	105	45	125	179

The average multiplicities of relativistic $\langle n_s \rangle$, grey $\langle n_g \rangle$, black $\langle n_b \rangle$ and heavy tracks $\langle N_h \rangle$ were calculated for interactions classified in the above quoted way (Table 1). In order to infer the characteristics of proton interactions with the light and heavy nuclei of nuclear emulsion, according to Ref.[3] the »light« and »heavy« groups have to be supplemented by events from the »quasinucleon« group (5% of the interactions take place on H, 25% on CNO, and 70% on AgBr). The calculated values of $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$ and $\langle N_h \rangle$ for proton interactions on CNO and AgBr are given in Table 1.

3. Dependence of $\langle n_s\rangle_{pA}$ and $\langle N_h\rangle_{pA}$ on the atomic number of target nucleus A

If the dependence of the average multiplicity of relativistic particles $\langle n_s\rangle_{pA}$ on the atomic number of target nucleus A is expressed as $\langle n_s\rangle_{pA} = \langle n_s\rangle_{pp} \cdot A^a$ (where $\langle n_s\rangle_{pp}$ is the average multiplicity of relativistic particles produced in p-p interactions, which, according to Ref.[4], at an energy of 200, GeV amounts to $\langle n_s\rangle_{pp} = 7.65 \pm 0.17$), then from the data given in Table 1, it is found that $a_{CNO} = 0.085 \pm 0.042$, $a_{Em} = 0.139 \pm 0.018$, and $a_{AgBr} = 0.159 \pm 0.016$.

TABLE 2.

E (GeV)	27	60,67	200	300	3500
$\langle N_h\rangle_{CNO}$		2.4 ± 0.2	2.0 ± 0.2	2.7 ± 0.3	2.2 ± 0.4
$\langle N_h\rangle_{Em}$	7.2 ± 0,2		7.9 ± 0.6	8.1 ± 0.5	6.5 ± 0.9
$\langle N_h\rangle_{AgBr}$		9.0 ± 0.4	10.7 ± 0.8	10.6 ± 0.6	15.3 ± 3.6
Ref.	1)	3)	present work	9)	10)

For predictions of the EFC[5] and CPM[6] models the ratio $R = \frac{\langle n_s\rangle_{pA}}{\langle n_s\rangle_{pp}}$ is characteristic. Using results from Table 1, it is found that $R_{CNO} = 1.25 \pm 0.15$, $R_{Em} = 1.80 \pm 0.14$ and $R_{AgBr} = 2.07 \pm 0.15$. If these results are fitted by a function of the form $R_A = \frac{1}{2}(C\,A^{\beta} + 1)$, as predicted by the CPM models, then a value of $R_A = \frac{1}{2}(0.64 \cdot A^{0.33} + 1)$ is obtained, which indicates that the average number of proton-nucleus collisions[6] is $\bar{\nu}_A\,A^{0.33}$ (Fig. 1).

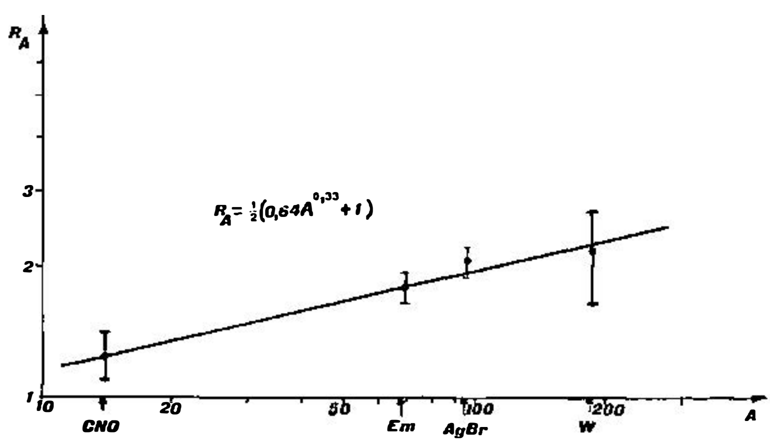

Fig. 1.

The results on $\langle N_h \rangle_{pA}$ from Table 1 compared to those obtained at incident particle energies of 27, 67, 300 and 3000 GeV (Table 2) indicate that $\langle N_h \rangle_{pA}$ is energy independent. If it is assumed that $\langle N_h \rangle_{pA}$ is dependent on the atomic number of target nucleus as $\langle N_h \rangle_{pA} = K \cdot A^{\gamma}$, then by fitting the experimental results obtained at energies of 200 and 300 GeV by a function of this form it is found that $K = 0.29$ and $\gamma = 0.79$ (Fig. 2).

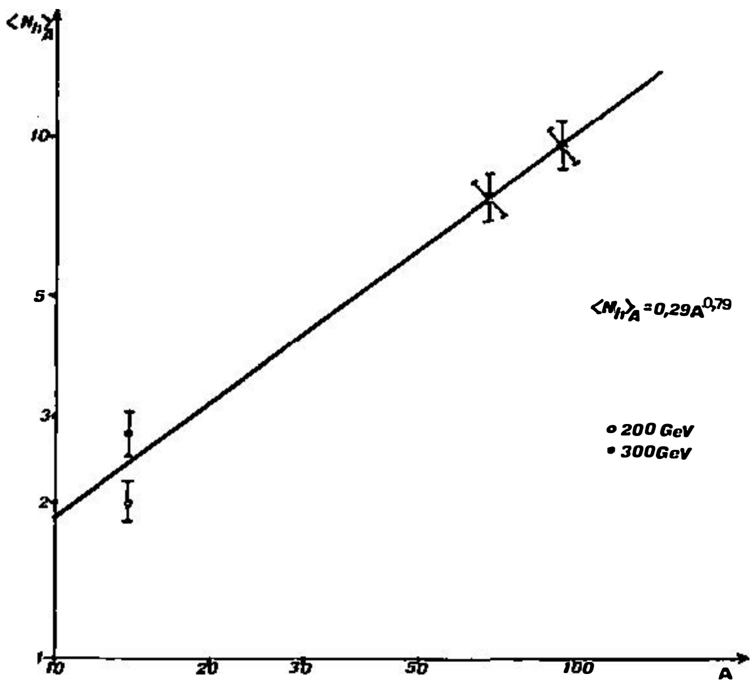

Fig. 2.

4. *Angular distribution of relativistic and low-energy particles*

From the measured angle Θ between the directions of motion of the incident proton and secondary relativistic particles the value of variable $U_L = \log \tan \Theta$ was calculated for all the groups of interactions (Table 3). The symmetry analysis of the secondary relativistic particle emission in the center-of-mass system was made by means of coefficient $m = \log \left(\frac{\gamma_s}{\gamma_c}\right)$, where $\gamma_c = 10.4$ and γ_s ($\log \gamma_s = -$ $- \langle \log \tan \Theta_i \rangle$) are the Lorentz factors of the center-of-mass system and of the system wherein the relativistic particle emission is symmetric. From the results presented in Table 3 it is seen that the relativistic particle emission in the CM system is asymmetric. The asymmetry is strongly dependent on the number of

TABLE 3. (a)

Group of interactions	$\langle \log \mathrm{tg}\, \Theta_t \rangle$	σ	$\langle N_h \rangle$
»Quasinucleon«	-1.07 ± 0.03	0.59	0.31 ± 0.07
»Light«	-0.88 ± 0.04	0.60	3.1 ± 0.3
»Heavy T1«	-0.87 ± 0.03	0.62	3.6 ± 0.3
»Heavy T2«	-0.75 ± 0.02	0.60	16.1 ± 0.8
»Heavy T1 and T2«	-0.77 ± 0.01	0.60	12.6 ± 0.8
All interactions	-0.83 ± 0.01	0.61	7.9 ± 0.6

(b)

Group of interactions	γ_s	$\log \gamma_s$	$\Theta_{1/2}, S°$	$\log \frac{\gamma_s}{\gamma_c}$	$\langle N_h \rangle$
	13.49	1.13 ± 0.02	4.24	0.11 ± 0.02	0
	9.33	0.97 ± 0.04	6.12	-0.05 ± 0.04	1
»Quasinucl.«	11.74	1.07 ± 0.03	4.86	0.042 ± 0.03	0.31 ± 0.07
»Light«	7.58	0.88 ± 0.04	7.50	-0.137 ± 0.04	3.1 ± 0.3
»T1«	7.41	0.87 ± 0.03	7.68	-0.147 ± 0.03	3.6 ± 0.3
»T2«	5.62	0.75 ± 0.02	10.08	-0.267 ± 0.02	16.1 ± 0.8
»T1 and T2«	5.89	0.77 ± 0.01	9.64	-0.246 ± 0.01	12.6 ± 0.8
All interactions	6.76	0.83 ± 0.01	8.41	-0.187 ± 0.01	7.9 ± 0.6

heavy tracks N_h. In all the group of interactions, except of the »quasinucleon« group, a larger number of relativistic particles are emitted into the backward hemisphere of the center-of-mass system. The functional dependence $m = f(N_h)$ was established by fitting the experimental results by a function of the form $m = \frac{a(1 + bN_h)}{1 + dN_h}$ (Ref.[7]), the coefficients a, b and d being evaluated to be $a = 0.102$, $b = - 1.500$ and $d = 0.528$ (Fig. 3). In the present work the function $f(N_h)$ was used to determine $\langle \log \tan \Theta_t \rangle$ for interactions on the light and heavy nuclei of emulsion. For the values $\langle N_h \rangle_{CNO} = 2.0 \pm 0.2$, $\langle N_h \rangle_{AgBr} = 10.7 \pm 0.8$ and $\log \gamma_c = 1.014$ we find that $\langle \log \tan \Theta_t \rangle_{CNO} = -0.92 \pm 0.06$ and $\langle \log \tan \Theta_t \rangle_{AgBr} = - 0.78 \pm 0.03$, to which correspond the angles $(\Theta_{1/2,S})_{CNO} = \left(6.9 \begin{smallmatrix} + 1.0 \\ - 0.9 \end{smallmatrix}\right)$ and $(\Theta_{1/2,S})_{AgBr} = 9.4 \begin{pmatrix} + 0.7 \\ - 0.6 \end{pmatrix}$, respectively, (the angle $\Theta_{1/2\,S}$ is the angle in laboratory system into which one half of relativistic particles are emitted).

A rough estimation of symmetry of the low-energy particle emission may be made from the ratio of their tracks in the forward and backward hemispheres

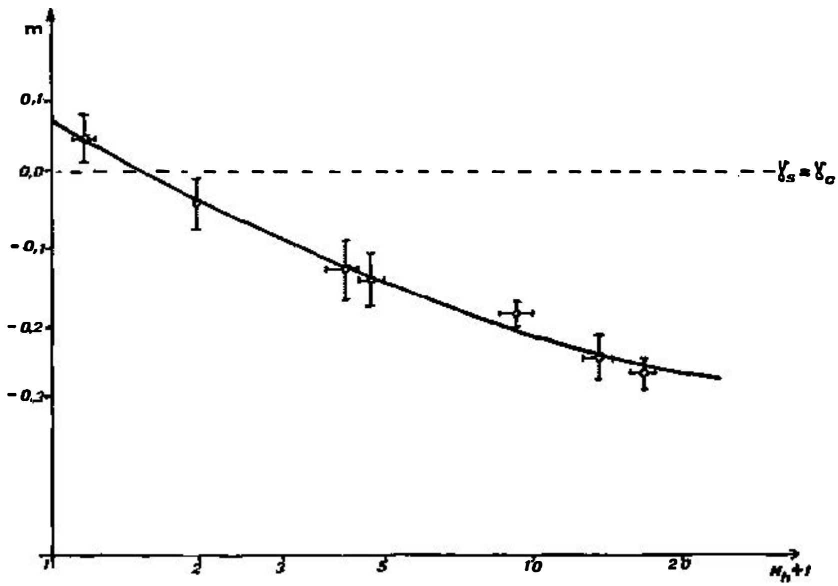

Fig. 3.

of the laboratory system, $\frac{\langle n_g \rangle_F}{\langle n_g \rangle_B}$ and $\frac{\langle n_b \rangle_F}{\langle n_b \rangle_B}$ (where subscripts F and B denote tracks in the forward and backward hemispheres of the laboratory system, respectively). The results are given in Table 4. It may be seen that in all the groups of interactions the particles are emitted preferentially into the forward hemisphere of the laboratory system. The asymmetry is more pronounced in grey tracks (cascade particles) due to the development of cascade in the direction of motion of the incident particle. The slight asymmetry in black tracks is indicative of a small momentum transfer in the proton—nucleus interaction.

TABLE 4.

Group	$\langle n_b \rangle_F$	$\langle n_b \rangle_B$	$\frac{\langle n_b \rangle_F}{\langle n_b \rangle_B}$	$\langle n_g \rangle_F$	$\langle n_g \rangle_B$
CNO	0.58 ± 0.11	0.47 ± 0.09	1.23 ± 0.47	0.66 ± 0.14	0.33 ± 0.07
AgBr	2.49 ± 0.22	2.17 ± 0.16	1.15 ± 0.19	3.64 ± 0.30	2.36 ± 0.20
All	1.88 ± 0.18	1.63 ± 0.14	1.15 ± 0.21	2.71 ± 0.23	1.73 ± 0.17
Group	$\frac{\langle n_g \rangle_F}{\langle n_g \rangle_B}$	$\langle N_h \rangle_F$	$\langle N_h \rangle_B$	$\frac{\langle N_h \rangle_F}{\langle N_h \rangle_B}$	
CNO	2.0 ± 0.85	1.24 ± 0.20	0.79 ± 0.12	1.57 ± 0.49	
AgBr	1.54 ± 0.28	6.13 ± 0.44	4.53 ± 0.30	1.35 ± 0.19	
All	1.57 ± 0.29	4.60 ± 0.39	3.36 ± 0.27	1.37 ± 0.23	

5. Conclusion

The dependence of $\langle n_s \rangle_{pA}$ and $\langle N_h \rangle_{pA}$ on the atomic number A was established, whereby the parameters were found to increase with increasing A. An analysis of the obtained values of $\langle \log \tan \Theta_l \rangle$ for proton interactions on CNO and AgBr by means of the function $f(N_h)$ shows that the asymmetry of relativistic particle emission in the center-of-mass system is more pronounced in interactions on the heavier nuclei.

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MULTIPLICITET I UGAONA RASPODJELA NAELEKTRISANIH ČESTICA DOBIJENIH PRI INTERAKCIJI PROTONA OD 200 Gev SA LAKIM I TEŠKIM JEZGRAMA NUKLEARNE EMULZIJE

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Sadržaj

U članku su dani eksperimentalni podatci o srednjem multiplicitetu produkcije naelektrisanih čestica prema njihovim brzinama pri interackiji protona od 200 GeV sa laganim i teškim jezgrama nuklearne emulzije. Prema brzinama tragovi čestica u emulziji razvrstani su kao relativistički, sivi, crni i teški, tj. respektivni srednji multipliciteti bili bi $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$ i $\langle N_h \rangle$.

Istražena je zavisnost $\langle n_s \rangle$ i $\langle N_h \rangle$ od atomskog broja jezgra mete i opažena je asimetrija emisije kako relativističkih tako i nisko-energetskih čestica.