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B.Średniawa, E.Strugalska-Gola*

ON PARTICLE MULTIPLICATION IN HADRON-NUCLEUS COLLISIONS

* Space Research Center of the Polish Academy of Sciences, Warsaw, Poland

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1. INTRODUCTION

Hadron-nucleus collisions at high energies attracted in last twenty years increasing interest both in experimental[1-6] and theoretical[7-11] respect. In last years the interest in multiparticle production processes in hadron-nucleus collisions was triggered by at least two reasons: firstly by attempts to formulate a correct model of these processes and, secondly, by the fact that hadron-nucleus collisions offer the unique possibility of direct experimental study of particle production processes as well in their early stages as in their spacial and temporal development[12-24]. Particularly interesting is the "enigmatic simplicity"[7,25,26], known for over 25 years both in cosmic ray and in accelerator physics. According to it the average multiplicities and angular distributions of relativistic secondaries produced by hadrons on nuclei do not differ markedly from those emerging from hadron-nucleon collisions. We try to understand this reluctance of nuclei to multiply particles generated on one nucleon inside them by taking as the basis the free-parameterless model of hadron-nucleus collisions proposed by Z.Strugalski[11,27-32].

We regard our investigation as a part of our work aiming to elaborate a new experimental basis for the research in high energy astrophysics. In particular, we hope that the deeper understanding of the phenomenon of hadron-nucleus processes will allow to propose more correct experimental methods for investigation of the propagation of cosmic rays in various materials, particularly in Earth's atmosphere.

2. ABILITY OF THE TARGET NUCLEUS TO MULTIPLY PARTICLES PRODUCED ON ONE OF THE NUCLEONS INSIDE IT

Ability of the target nucleus to multiply particles produced on one of its nucleons was defined in different variants[1,27-29], each of them adopted to the technique of measurements. We assume here the definition adopted to CERN-HERA[36] tables on hadron-nucleon outcome used in this work. According to the mentioned data this ability can be conveniently expressed by the ratio

$$R_A = \frac{\langle n \rangle_{hA}}{\langle n \rangle_{hp}} , \qquad /1/$$

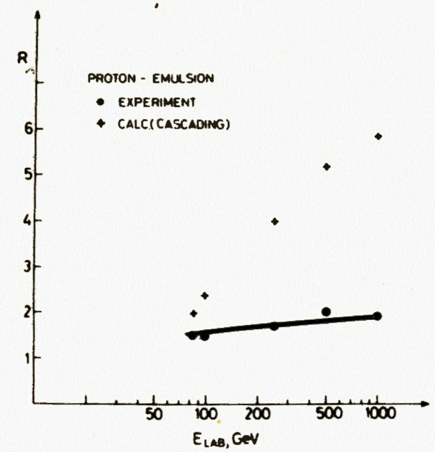

Fig.1. The dependence of R_A in proton-emulsion collisions on incident proton energy. Solid curve - calculation is for $p-{}^{64}_{29}Cu$ collisions (The A and Z for Cu are very close to those of average emulsion nucleus $\langle A\rangle_{em} = 66.6$, $\langle Z\rangle_{em} = 29.3$). Fig.1 is taken from Czyż lecture[25], only the solid curve is attached by us.

where $\langle n\rangle_{hA}$ is the average number of charged particles produced in an inelastic collision of the incident hadron h with the nucleus of the mass number A and $\langle n\rangle_{hp}$ is the average number of charged particles produced in an inelastic collision of the same hadron with a proton p. (Let us note that in nuclear emulsion experiments the numbers $\langle n_s\rangle_{hA}$ and $\langle n_s\rangle_{hp}$ of shower particles are used instead of $\langle n\rangle_{hA}$ and $\langle n\rangle_{hp}$).

The quantity R_A, calculated on the basis of intranuclear cascade model[33] showed striking disagreement with experimental data, especially for large energies of incident hadrons (see Fig.1).

A simple formula for R_A was derived by Z.Strugalski in his free-parameterless model of hadron-nucleus collisions[11,27-32]. According to this model, the collision of the incident hadron with one of the intranuclear nucleons may result in the creation of the intermediate object of the lifetime $\tau \geq 10^{-22}$ sec. This object moves predominantly along the course of incident hadron and behaves in this passage through nuclear matter like the usual hadron. In a massive nucleus it can create a quasi-one-dimensional cascade of secondary intermediate objects. Having left the parent nucleus, all these objects decay into commonly known particles and resonances. The result of hadron-nucleus collision is, therefore, the composition of some number m of the outcomes of hadron-nucleon collisions.

If we denote the energy of the primary hadron by E_h and the average number of outcomes by $\langle m\rangle$, then the average collision energy is equal to $E_h/\langle m\rangle$. The quantity $\langle m\rangle$ is given by the formula

$$\langle m\rangle = e^{t}, \qquad (2)$$

where

$$t = \frac{\langle\lambda\rangle}{\langle\lambda_0\rangle}; \qquad (3)$$

$\langle\lambda\rangle$ is the average thickness of the target nucleus, determined by the diameter of the nucleus and nucleon distribution in it[34], $\langle\lambda_0\rangle$ is the mean free path for hadron-nucleon inelastic collision in target nucleus, connected with the corresponding cross-section σ_0 for elementary hadron-nucleon collisions by the formula

$$\langle\lambda_0\rangle = \frac{k}{\sigma_0}. \qquad (4)$$

The lengths $\langle\lambda_0\rangle$ and $\langle\lambda\rangle$ are measured in units equal to nucleon number per area $S = \pi D_0^2$, where D_0 is the diameter of the nucleon; the cross section σ_0 is measured in S per nucleon. The experimentally determined coefficient $k \approx 3$.

The quantity R_A in Strugalski's model is given by the simple formula

$$R_A = \langle m\rangle \frac{\langle n(E_h/\langle m\rangle)\rangle_{hN}}{\langle n(E_h)\rangle_{hN}}. \qquad (5)$$

Here $\langle n(E_h)\rangle_{hN}$ and $\langle n(E_h/\langle m\rangle)\rangle_{hN}$ are average numbers of charged particles produced in hadron-nucleon collisions hN at the energies E_h and $E_h/\langle m\rangle$, respectively. The energy dependence of R_A is here contained in the free path $\langle\lambda_0\rangle$ via the dependence of the cross section σ_0 on the energy of the incident particle. R_A depends on A through the average thickness $\langle\lambda\rangle$ of the target nucleus, since $\langle\lambda\rangle$ depends[35] on A.

Formula (5) for R_A is valid without limitation for all energies of incident hadrons larger than the energy threshold for the process of pion production.

3. CALCULATIONS OF R_A AND COMPARISON WITH EXPERIMENTAL DATA

The quantity $\langle m\rangle$ was determined from the data for the average thickness of nuclear matter $\langle\lambda\rangle$, contained in the work of Strugalski and Pawlak[35]; the values for $\langle\lambda_0\rangle$ were taken from the data for σ_0 in CERN-HERA[36] tables according the formula (4), table 1. The dependence of the average number $\langle n\rangle_{hN} \doteq \langle n\rangle_{hp}$ on the incident hadron momentum was also taken from CERN-HERA tables[36] and from the work of Goldschmidt-Clermont[37] and is shown in Fig.2.

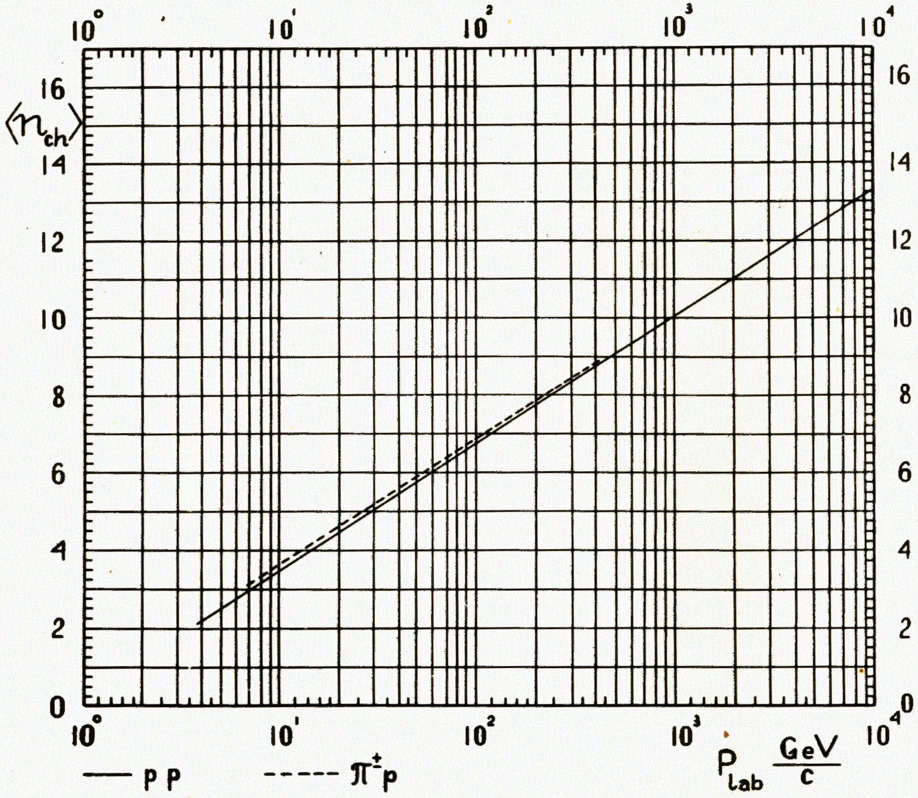

Fig.2. The dependence of the average numbers $<n>_{ch}$ of charged particles produced in πp and pp collisions on the momentum of incident pions and protons in Lab. Experimental data are from the works [36,37].

The R_A-values, calculated from formula (5) for 24 target nuclei ranging from $^{12}_{6}C$ to $^{238}_{92}U$ are presented in Table 2 for pions of momenta p_π in laboratory system in the range from 8.1 GeV/c to 147 GeV/c and in Table 3 for protons in the momentum p_p range in Lab. from 12 GeV/c to 1480 GeV/c.

In Fig.3 A-dependences of R_A in pion-nucleus collisions for pions of incident momenta equal to 100 GeV/c and 175 GeV/c are plotted and compared with corresponding experimental data given in Busza's review [1]. In Fig.4 the A-dependences for protons of incident momenta from 12 GeV/c to 1480 GeV/c are compared with available experimental data [1].

Figure 5 contains the dependence of R_A for $^{64}_{29}Cu$, where atomic weight and atomic number are very close to those of "average emulsion nucleus" ($<A>_{em}$ = 66,6, $<Z>_{em}$ = 29.3) (ref. [24]) and compared with experimental data from [1].

Table 1

Hadron momentum dependence of the mean free path $<\lambda_0>$ for hadron-nucleon inelastic collisions in target nucleus, calculated from formula (4). D_0 is nucleon's diameter

$(P_\pi)_{Lab}$ GeV/c	$<\lambda_0>$ Nucl/πD_0^2
8.05	14.466
11.2	14.556
16.0	14.469
18.5	14.586
50.0	14.700
147.0	14.700

$(P_p)_{Lab}$ GeV/c	$<\lambda_0>$ Nucl/πD_0^2
12	10.374
19	10.362
24	10.089
32	10.257
60	9.741
102	9.678
205	9.603
290	9.558
405	9.414
500	9.216
1070	8.802
1480	8.655

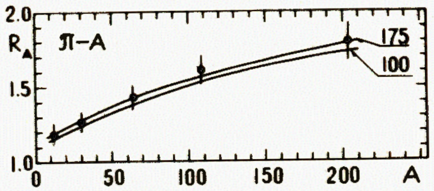

Fig.3. The curves of R_A - dependence on mass number A calculated for incident proton momenta in Lab. equal to 100 and 175 GeV/c. Experimental data ranging between 100 and 175 GeV/c are from Busza's review [1].

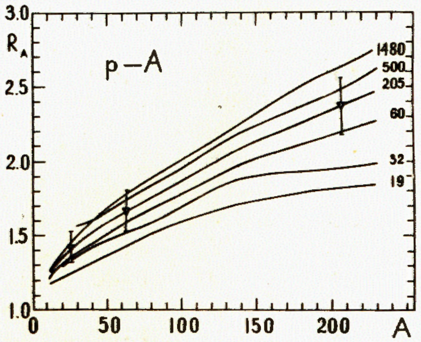

Fig.4. The curves of R_A- dependence on mass number A calculated for incident proton momenta in Lab., written on the right-hand side of the curves. Experimental data at 200 and 300 GeV/c were taken from Busza's review [1].

4. RESULTS AND DISCUSSION

1. The values R_A for π-nucleus collisions evaluated for the momenta of incident pions in the range 8.1-147 GeV/c and for all 24 target nuclei (from $^{12}_{6}C$ to $^{238}_{92}U$) vary between 1.1 and

Table 2

R_A -values calculated from formula (5) for 24 target nuclei and for six incident pion momenta p_π. Pion momenta in Lab. are given in GeV/c. Target nuclei are: $^{12}_{6}C$, $^{14}_{7}N$, $^{16}_{8}O$, $^{19}_{9}F$, $^{20}_{10}Ne$, $^{27}_{13}Al$, $^{28}_{14}Si$, $^{32}_{16}S$, $^{40}_{18}Ar$, $^{52}_{24}Cr$, $^{56}_{26}Fe$, $^{59}_{27}Co$, $^{64}_{29}Cu$, $^{65}_{30}Zn$, $^{73}_{32}Ge$, $^{80}_{35}Br$, $^{108}_{47}Ag$, $^{127}_{53}I$, $^{151}_{54}Xe$, $^{181}_{73}Ta$, $^{184}_{74}W$, $^{197}_{79}Au$, $^{207}_{82}Pb$, $^{238}_{92}U$

A \ p_π	8.2	11.2	16.0	18.5	50.0	147
C	1.10	1.13	1.12	1.11	1.17	1.17
N	1.10	1.13	1.12	1.11	1.17	1.17
O	1.12	1.13	1.13	1.13	1.20	1.19
F	1.15	1.16	1.16	1.14	1.23	1.20
Ne	1.15	1.16	1.16	1.14	1.23	1.20
Al	1.20	1.19	1.18	1.17	1.20	1.24
Si	1.20	1.20	1.19	1.17	1.20	1.29
S	1.20	1.21	1.19	1.17	1.22	1.27
Ar	1.21	1.24	1.22	1.18	1.29	1.30
Cr	1.24	1.27	1.26	1.21	1.32	1.34
Fe	1.25	1.28	1.28	1.22	1.30	1.30
Co	1.27	1.28	1.26	1.22	1.34	1.37
Cu	1.27	1.28	1.28	1.30	1.39	1.40
Zn	1.27	1.28	1.28	1.31	1.39	1.40
Ge	1.29	1.31	1.32	1.33	1.39	1.42
Br		1.33	1.33	1.32	1.41	1.45
Ag		1.35	1.39	1.37	1.47	1.53
I		1.41	1.44	1.41	1.53	1.58
Xe		1.42	1.45	1.43	1.54	1.59
Ta		1.40	1.53	1.53	1.66	1.72
W		1.51	1.51	1.54	1.62	1.72
Au			1.56	1.47	1.66	1.76
Pb			1.53	1.56	1.66	1.76
U			1.58	1.61	1.72	1.64

1.9 (Table 2). For each nucleus they increase nearly 10% in the whole energy range. The A-dependence curves for constant p_π increase also slowly, about 50-60% in the whole investigated energy range.

2. The values of R_A for p-nucleus collisions are for the same nuclei and the wider momentum range, between 12 GeV/c and 1480 GeV/c, comprised between 1.2 and 2.8 (Table 3). The curves for A- and p_p-dependences for proton-nucleus collisions are similar to those for pion-nucleus collisions, beeing only somewhat steeper.

3. The agreement of calculation results with available experimental data is very good in the whole momentum range and for very different nuclei (Figs.3-5). The discrepance, called "enigmatic simplicity" (mentioned in §1) disappeared.

4. The agreement of experimental data with calculated results seems to give strong support to the correctness of the free-parametrless model of Z.Strugalski, where only the total cross-section for hadron-nucleon collisions and the thickness of the target nucleus determine the properties of high-energy hadron-nucleus collisions.

Remark. We took in our calculations the value k = 3 (see §2), following the arguments contained in Strugalski's publications [24, 38]. Now, recent measurements of Z.Strugalski indicate that the value of k can be lowered at most about 15%. If it is so, our results should be, as control calculations showed, raised at most about 10%, remaining still in agreement with experimental data.

The authors are very indebted to Professor Z.Strugalski for many enlightening and interesting discussions, especially on the properties of free-parameterless model.

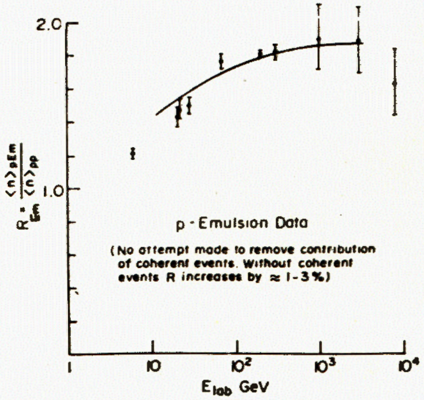

Fig.5. R_A-dependence in proton-emulsion collisions on incident proton energy. Solid curve is that of Fig.1. Fig.5 differs from Fig.1 by plotting experimental errors in larger scale.

Table 3

R_A-values calculated from formula (5) for the same target nuclei as in Table 2 and for twelve incident proton momenta p_p. Proton momenta in Lab. are given in GeV/c

A\\P_p	12	19	24	32	60	102	205	290	405	500	1070	1480
C	1.20	1.18	1.22	1.23	1.25	1.25	1.23	1.28	1.30	1.28	1.31	1.26
N	1.21	1.20	1.23	1.24	1.26	1.28	1.24	1.31	1.33	1.31	1.39	1.29
O	1.21	1.20	1.24	1.25	1.28	1.28	1.31	1.32	1.34	1.32	1.37	1.31
F	1.26	1.23	1.27	1.27	1.31	1.33	1.34	1.43	1.39	1.38	1.42	1.36
Ne	1.23	1.22	1.26	1.32	1.31	1.31	1.33	1.32	1.39	1.36	1.41	1.36
Al	1.31	1.27	1.33	1.32	1.37	1.38	1.41	1.42	1.45	1.45	1.49	1.59
Si	1.31	1.27	1.33	1.37	1.38	1.38	1.41	1.43	1.46	1.46	1.49	1.60
S	1.32	1.25	1.35	1.37	1.40	1.40	1.44	1.46	1.49	1.49	1.47	1.47
Ar	1.36	1.32	1.39	1.43	1.44	1.48	1.52	1.54	1.58	1.60	1.62	1.58
Cr	1.40	1.38	1.43	1.49	1.49	1.54	1.57	1.61	1.67	1.63	1.79	1.64
Fe	1.42	1.39	1.46	1.50	1.50	1.56	1.61	1.64	1.66	1.67	1.75	1.68
Co	1.43	1.39	1.45	1.52	1.54	1.56	1.60	1.66	1.67	1.68	1.66	1.69
Cu		1.46	1.51	1.52	1.59	1.64	1.68	1.70	1.73	1.76	1.82	1.75
Zn		1.46	1.51	1.52	1.59	1.64	1.67	1.70	1.72	1.75	1.81	1.74
Ge		1.50	1.55	1.56	1.63	1.70	1.72	1.75	1.80	1.80	1.88	1.82
Br		1.52	1.57	1.58	1.68	1.67	1.71	1.73	1.77	1.85	1.91	1.88
Ag		1.60	1.65	1.72	1.81	1.90	1.90	1.94	1.97	1.99	2.11	2.04
I		1.67	1.71	1.75	1.92	1.95	2.02	2.04	2.13	2.12	2.28	2.17
Xe		1.69	1.72	1.77	1.94	1.95	2.04	2.01	2.15	2.15	2.27	2.20
Ta		1.78	1.90	1.92	2.12	2.15	2.28	2.29	2.47	2.39	2.57	2.54
W		1.78	1.90	1.95	2.12	2.14	2.28	2.29	2.41	2.39	2.58	2.54
Au		1.80	1.90	1.94	2.17	2.17	2.35	2.36	2.42	2.36	2.59	2.61
Pb		1.80	1.92	1.94	2.20	2.23	2.36	2.42	2.49	2.48	2.67	2.64
U		1.89	2.02	2.04	2.32	2.37	2.51	2.56	2.66	2.66	2.69	2.61

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Šреднява Б., Стругальска-Голя Э. E1-83-277

О размножении частиц в столкновениях адронов с ядрами

Исследуется увеличение числа частиц в столкновениях адрон-ядро, выраженное соотношением R_A между кратностью частиц в столкновении адрон-ядро и в столкновении адрон-нуклон. Рассчитаны зависимости R_A от энергии налетающего адрона и от массового числа ядра-мишени для 24 ядер, от $^{12}_{6}C$ до $^{238}_{92}U$ при использовании формул, выведенных в модели без свободных параметров З. Стругальского: для столкновений пион-ядро в области импульсов адрона 8.1-147 ГэВ/с и для столкновений протон-ядро в области 12-1480 ГэВ/с. Значение R_A для столкновений пион-ядро содержится между 1.1 и 1.9; значения для столкновений протон-ядро меняются от 1.2 до 2.8. Во всех случаях A-зависимости при постоянных значениях момента налетающей частицы и зависимости от момента при постоянном A медленно и регулярно возрастают. Обнаружено хорошее согласие имеющихся экспериментальных данных с результатами расчета во всем диапазоне импульсов налетающих адронов.

Работа выполнена в Лаборатории высоких энергия ОИЯИ.

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On Particle Multiplication in Hadron-Nucleus Collisions

Multiplication of particles in hadron-nucleus collisions, expressed by the ratio R_A between the multiplicity of particles in hadron-nucleus collisions and the multiplicity of particles in hadron-nucleon collisions, is analysed. Energy- and A-dependence of R_A for 24 target nuclei from $^{12}_{6}C$ to $^{238}_{92}U$ are calculated using formulas derived in Strugalski's free-parameterless model: for pion-nucleus collisions in the range 8.1-147 GeV/c and for proton-nucleus collisions between 12 and 1480 GeV/c. The R_A-values for pion-nucleus collisions are comprised between 1.1 and 1.9, those for proton nucleus collisions vary between 1.8 and 2.8. In all cases R_A-dependence at constant momentum of incident particle and momentum dependences at constant A increase regularly and slowly. The agreement of calculation results with available experimental data is very good in the whole A- and energy range.

The investigation has been performed at the Laboratory of High Energies, JINR.

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