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CHARACTERISTICS OF LEADING NUCLEONS IN HADRON-NUCLEUS INTERACTIONS AND NEUTRON AND PROTON FLUXES AT MOUNTAIN ALTITUDES

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А.П.ГАРЯКА, Э.А.МАМИДЖАНЯН

ХАРАКТЕРИСТИКИ ЛИДИРУЮЩИХ НУКЛОНОВ В АДРОН-ЯДЕРНЫХ ВЗАИМОДЕЙСТВИЯХ И ПОТОКИ НЕЙТРОНОВ И ПРОТОНОВ НА ВЫСОТАХ ГОР

Анализируются соотношения между коэффициентами упругости и неупругости перезарядки в нуклон-ядерных взаимодействиях и величинами потоков нейтронов и протонов на высотах гор. Оценена точность, необходимая в экспериментах в космических лучах, для определения характеристик лидирующих адронов с точностью ~ 10%.

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The relations between the elasticity and the inelastic recharge factors in nucleon-nucleus interactions and the values of neutron and proton fluxes at mountain altitudes were analyzed. The accuracy required in cosmic ray experiments for the determination of characteristics of leading hadrons with ~ 10% error is estimated.

Yerevan Physics Institute
Yerevan 1978

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YEREVAN PHYSICS INSTITUTE

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CHARACTERISTICS OF LEADING NUCLEONS IN HADRON-NUCLEUS INTERACTIONS AND NEUTRON AND PROTON FLUXES AT MOUNTAIN ALTITUDES

Yerevan 1978

The study of hadron-nucleus interactions properties in TeV range is nowadays the focal point in the nuclear physics aspect of cosmic rays.

Specifically, the knowledge of hadronic energy spectra at mountain altitudes and at the top of the atmosphere is necessary for the determination of both the integral and the individual characteristics of secondaries, the interactions products.

In the present work we pursue the aim of analyzing anew the relation between the proton and neutron fluxes at mountain altitudes and the characteristics of leading nucleons spectrum in hadron-nucleus interactions at energies > 1 TeV using both the recent accelerator[1] and cosmic ray data[2].

The expedience of such an analysis is also due to the fact, that in present day experiments[3] the share of protons in the flux of charged hadrons is directly determined at energies up to 5 TeV. Hence, to notably reduce the uncertainty in the determination of above characteristics, it is desirable to know the accuracy with which they could be measured.

The equations describing the passage of neutrons and protons are for large atmospheric depths:

$$\frac{\partial N_p(E,x)}{\partial x} = -\frac{N_p(E,x)}{\lambda_{p\,air}(E)} + \int_E^\infty \frac{N_p\, w_{op}\, dE'}{\lambda_{p\,air}(E')} + \int_E^\infty \frac{N_n\, w_{in}\, dE'}{\lambda_{n\,air}(E')}$$

$$\frac{\partial N_n(E,x)}{\partial x} = -\frac{N_n}{\lambda_{n\,air}(E)} + \int_E^\infty \frac{N_n\, w_{on}\, dE'}{\lambda_{n\,air}(E')} + \int_E^\infty \frac{N_p\, w_{ip}}{\lambda_{p\,air}(E')}, \qquad (1)$$

where $\lambda_{p(n)air}$ are the inelastic interaction paths in air for protons (neutrons);

$w_{op(n)}$ are the differential energy spectra of leading secondary nucleons charged as the primary one;

$w_{ip(n)}$ are those for nucleons with charges different from the primary nucleon charge.

Below, we shall assume in accordance with the available experimental data[5] that :

$$\lambda_{p\,air} = \lambda_{n\,air} = \lambda$$

$$w_{0p} = w_{0n} = w_0$$

$$w_{1p} = w_{1n} = w_1 .$$

For scale-invariant spectra of secondary particles, i.e. the dependence of the spectra only on the parameter $u = \frac{E}{E_0}$, the ratio of secondary to primary nucleons energies, Eqs (1) transform into the following ones:

$$\frac{\partial N_p(E,x)}{\partial x} = -\frac{N_p}{\lambda} + \int_0^1 \frac{N_p(E/u,x)\,\rho_0(u)}{\lambda}\frac{du}{u} + \int_0^1 \frac{N_n(E/u,x)\,\rho_1(u)}{\lambda}\frac{du}{u}$$

(2)

$$\frac{\partial N_n(E,x)}{\partial x} = -\frac{N_n}{\lambda} + \int_0^1 \frac{N_n(E/u,x)\,\rho_0(u)}{\lambda}\frac{du}{u} + \int_0^1 \frac{N_p(E/u,x)\,\rho_1(u)}{\lambda}\frac{du}{u} .$$

where $\rho_0(u)$ and $\rho_1(u)$ are scale-invariant spectra of secondary nucleons.

Eqs (2) have the exact solution at λ = Const[6] and $\lambda = \lambda_0(1+g\ln E)^{-1}$[7] where g is a constant.

Assuming that the primary spectrum has the form $N(E,0) = N(0)E^{-\gamma}$, where γ is the index of the differential energy spectra, the exact solution for the first case is:

$$N_p(E,x) = \frac{1}{2}N(E,0)\left[e^{-\frac{x}{L}} + \frac{1-\alpha}{1+\alpha}e^{-\frac{x}{L_\Delta}}\right]$$

(3)

$$N_n(E,x) = \frac{1}{2}N(E,0)\left[e^{-\frac{x}{L}} - \frac{1-\alpha}{1+\alpha}e^{-\frac{x}{L_\Delta}}\right] ,$$

which serves as a good approximation in the second case at $g \ll 1$[8].

Here

$$L = \lambda\left(1 - \langle u^{\gamma-1}\rangle\right)^{-1} \qquad (4)$$

$$L_\Delta = \lambda^{-1}\left[1 - \left(\langle u^{\gamma-1}\rangle_0 - \langle u^{\gamma-1}\rangle_1\right)\right] \tag{5}$$

$$\langle u^{\gamma-1}\rangle = \int_0^1 u^{\gamma-1}\rho(u)\,du \tag{6}$$

$$\alpha(0) = N_n(0)/N_p(0)\;. \tag{7}$$

The spectrum of all the secondary nucleons is the sum of spectra for recharged and non-recharged nucleons.

The spectrum $\rho_1(u)$ could be written as

$$\rho_1(u) = \eta(u)\,\rho(u)\;. \tag{8}$$

where $\eta(u)$ is the spectrum of inelastic recharge coefficient.

Then

$$L_\Delta = \lambda\left[1 - \left(\langle u^{\gamma-1}\rangle - 2\langle \eta u^{\gamma-1}\rangle\right)\right]^{-1} \tag{9}$$

It should be emphasized that

$$\langle \eta(u)\, u^{\gamma-1}\rangle \neq \eta\,\langle u^{\gamma-1}\rangle \;, \tag{10}$$

(confer with [9]),

where η is the constant, so-called inelastic recharge coefficient of nucleons equal to

$$\eta = \int_0^1 \rho_1(u)\,du/u \Big/ \int_0^1 \rho(u)\,du/u \tag{11}$$

The quantity $\langle \eta u^{\gamma-1}\rangle / \langle u^{\gamma-1}\rangle$ is defined as the effective coefficient of inelastic recharge, η_{eff} . Then the ratio of neutron-to-proton fluxes at X depth is

$$\frac{N_n(E,x)}{N_p(E,x)} = \frac{1 - \delta_0 e^{-\frac{2x}{\lambda}\eta_{eff}\langle u^{\gamma-1}\rangle}}{1 + \delta_0 e^{-\frac{2x}{\lambda}\eta_{eff}\langle u^{\gamma-1}\rangle}} \tag{12}$$

$$\delta_0 = (1-\alpha(0))/(1+\alpha(0))$$

Thus, the expressions (3) and (12) determine the dependence of neutron and proton fluxes at the atmospheric depth X both on the parameters γ and $\alpha(0)$ of the primary spectrum and the values characterizing secondary nucleons spectra in hadron-nucleus interactions, $\langle u^{\gamma-1}\rangle$ and η_{eff}.

Let us compare the obtained results with the available data on secondary nucleons spectra in nucleon-nucleon and nucleon-nucleus interactions.

In Fig.1 the $d\sigma/dM^2$ spectra of protons[1], the products of primary proton and neutron fragmentation, are shown as the function of the invariant mass M^2. We would remind, that M^2 is related to the Feynman variable X as $M^2 \simeq s(1-X)$. When $E \gg m$, $X \approx u$.

The spectrum of inelastically recharged nucleons (points) is seen in the figure to be below the non-recharged spectrum (solid histogram) and to drop to zero at $X \to 1$. Quantitative estimates based on this spectrum show that in the nucleon-nucleon collisions $\eta_{eff} \gtrsim 0.8\eta$. The analysis of available accelerator data[10] indicates that the values of η can't exceed the limits 0,3 - 0,5, i.e. $\eta_{eff} \gtrsim 0{,}24$.

In hadron-nucleus interactions at high energies the energy spectra of secondary particles are softer as compared with nucleon-nucleon processes implying as a matter of fact the increase of inelastic factor K with atomic number A.

At 24 GeV, the softening was observed at the accelerator both for protons and for mesons [1, Echten et al].

In cosmic ray experiments the increase of inelastic factor as a function of A was observed at 1-5 TeV [2, Mamidzhanyan et al.] for $A \geq 12$.

In Ref [1,Chaney , D et al.] it was shown that in the range of incident particle fragmentation ($0{,}3 \leq X \leq 1{,}0$) the spectra of secondary hadrons in hadron-nucleus collisions are softer than that in hadron-hadron ones, the difference increasing at $X \to 1$.

This leads to the reduction of $\langle u^{\gamma-1}\rangle$ and also may cause the nearing of recharged and non-recharged nucleons spectra, i.e. $\eta_{eff} \to \eta$.

We can finally take that

$$0.24 \le \eta_{eff} \le 0.5 \tag{13}$$

The parameter $\langle u^{\gamma-1}\rangle$ is most sensitive to changes in the region of spectrum near $u \approx 1$.

If we take the ratio of spectra as $\rho_{NN}(u)/\rho_{NA}(u) \sim A^{\beta}$, where β is a parameter depending on u, then $\beta = 0{,}2$ at $u \approx 1$ [1, Chaney, D et al.] and $\beta = C$ at $u \approx 0.2$.

Hence follows the inequality $\langle u^{\gamma-1}\rangle_{N air} \le 0.7 \langle u^{\gamma-1}\rangle_{NN}$

$$\langle u^{\gamma-1}\rangle_{NN} \simeq 0.37 \quad \text{, i.e.} \tag{14}$$

$$\langle u^{\gamma-1}\rangle_{N Air} \le 0.28 \, .$$

These estimates are at variance with the value $\langle u^{\gamma-1}\rangle_{NN} = 0.27$ obtained from the analysis of CERN group data[11].

From the parameters of the primary flux only the spectrum of primary protons is known[12]. Assuming that equal numbers of protons and neutrons are produced at the spallation of cosmic ray nuclei (mainly the light ones), the primary proton flux is the difference between the total proton flux and the neutron flux.

The absorption paths L_Δ and L are determined by measuring $N_p(E,x)$ and $N_n(E,x)$

$$L_\Delta = X \Big/ \ln\left(\frac{N_p(0,E) - N_n(E,0)}{N_p(x,E) - N_n(E,X)}\right) \tag{15}$$

$$L = X \Big/ \ln\left(\frac{N_p(0,E) + N_n(0,E)}{N_p(x,E) + N_n(x,E)}\right) = X \Big/ \ln\left(\frac{(1+\alpha)\,N_p(0,E)}{N_p(x,E) + N_n(x,E)}\right) . \tag{16}$$

It is interesting to find the dependence of L and L_Δ on the value of pion-to-proton flux ratio at different atmospheric depths. In Fig.2 such a dependence for $x = 700\ g/cm^2$ depth is plotted at the fixed ratio of charged-to-neutral particle fluxes equal to 3,07 [13].

The share of neutrons in the nucleon flux at the top of the atmosphere is unknown at E = 1 TeV. Hence, we can only calculate the upper limit on the nucleon absorption path depending on N_π/N_p (see the formula (16)). It is shown in the same figure (upper curve).

Using now the inequality (14) and taking into account the relation $\langle w^{\gamma-\pi}\rangle_{max} = 1 - \frac{\lambda}{L^{max}}$ we have the following restriction on L_Δ:

$$\lambda < L_\Delta < 0.5\lambda\left(1 + \frac{\lambda}{L}\right)$$

Hence we have for N_π/N_p

$$0.8 < N_\pi/N_p < 1.6 . \tag{17}$$

The consideration of neutrons at the top of atmosphere would only result in the shift of the lower limit to higher N_π/N_p values.

In Fig.3 the N_π/N_p -dependence of the effective recharge coefficient is shown. The upper solid line corresponds to $\alpha = 0$ case, and the dashed one to $\alpha = 1/3$.

The dependence in the region $0.8 < \frac{N_\pi}{N_p} < 1.6$ is nearly linear, i.e. the accuracy of η_{eff} determination is nearly the same as that of N_π/N_p measurement.

To compare theoretical calculations with data on the measurement of proton-to-neutron flux ratio at different atmospheric depths x , it is interesting to calculate the ratio N_n/N_p by the formula (12). This dependence is shown in Fig.4 for two values $\eta_{eff} = 0.25$ and $\eta_{eff} = 0.5$.

The problem of the share of nucleons with energy E > 1 TeV/nucleon, contained in nuclei, in the flux of free protons with the same energy is widely discussed now in connection with the measurements of μ^+/μ^- ratio [14]. Some authors believe, that to account for the observed value of μ^+/μ^- -ratio, one should assume that in nuclei nearly as many nucleons are contained as are free protons, i.e. $\alpha(c) = 1/3$

The value $\alpha = 1/3$ leads to the value $< u^{\alpha-1} > \simeq 0.21$ credible for the average elasticity $\langle u \rangle \leqslant 0.4$ that doesn't contradict to direct measurements of the inelasticity coefficient $(1 - \langle u \rangle) = 0{,}58 \pm 0{,}09$ for carbon[2].

In conclusion we thank Avakyan V.V., Amatuni A.Ts., and Matinyan S.G. for useful discussions.

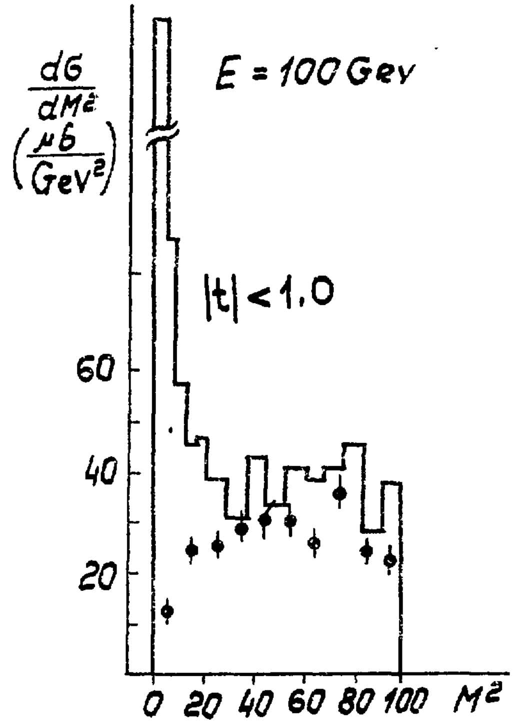
$\frac{d\sigma}{dM^2}$ $\left(\frac{\mu b}{GeV^2}\right)$
E = 100 Gev
|t| < 1.0
60
40
20
0
20
40
60
80
100
M^2

Fig.1

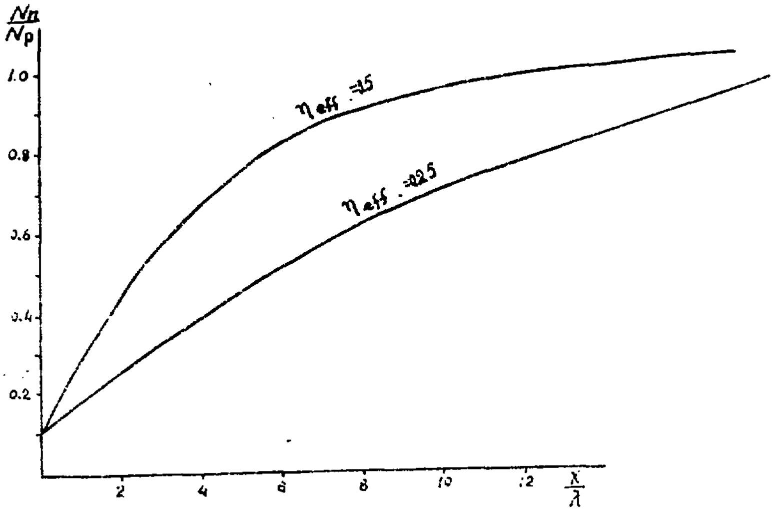
Nπ / Np
1.0
0.8
0.6
0.4
0.2
2
4
6
8
10
12
x / λ
η eff = .15
η eff . =025

Fig.2

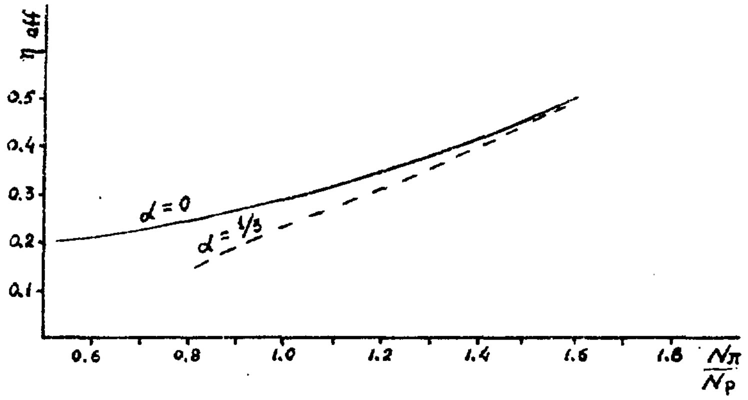
η eff
0.5
0.4
0.3
0.2
0.1
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Nπ / Np
α = 0
α = 1/3

Fig.3

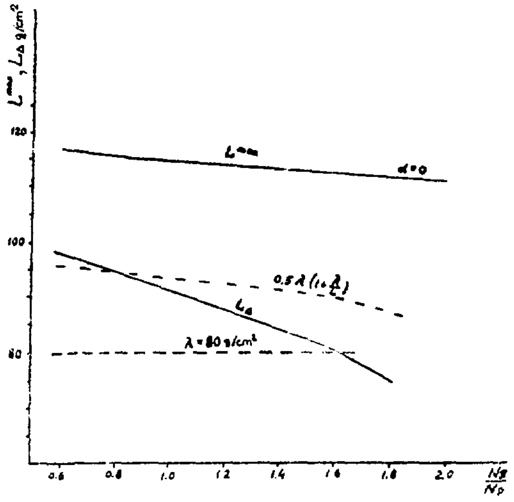
L^{max}, L_{Δ} g/cm^2
120
100
80
L^{max}
$\alpha = 0$
$0.5\lambda(1+\frac{\lambda}{L})$
L_{Δ}
$\lambda = 80$ g/cm^2
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
$\frac{Ng}{Np}$

Fig.4

FIGURE CAPTIONS

Fig.1 The spectraof protons, the products of the primary proton (solid histogram [1 Chapman et al] and the primary neutron (points [1 Hanlon et al]).

Fig.2 The dependence of absorption paths L_Δ and L on the ratio of pion flux to protons at X = 700 g.cm and the ratio of charge-to-neutral hadron fluxes = 3 07.

Fig.3 The dependence of the effective recharge factor on the ratio of pion-to-proton fluxes (solid line α = 0, dashed line $\alpha = 1/3$)
$X = 700\ g/cm^2$, $N_{ch}/N_{neutral} = 3.07$

Fig.4 The dependence N_n/N_p on the atmospheric depth at two extreme values of recharge coefficients η_{eff} = 0,25 and η_{eff} = 0,5 ,
$\alpha(t)$ = 0,1

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