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CENTRAL AND PERIPHERAL COLLISIONS BETWEEN FAST NUCLEONS II

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ABSTRACT

Theoretical momentum spectra of particles produced in nucleon collisions are compared with the experimental data obtained at $T=9$ BeV. The mean energy losses in inelastic nucleon collisions have been calculated. Central and peripheral collisions have been treated.

I. INTRODUCTION

A model of central and peripheral collisions between fast nucleons was considered in Ref./1/ (PP) and (pn) collisions at $T \simeq 9$ BeV were taken as an example to show that the experimental angular distributions of the produced particles may be explained, if the cross section for the peripheral collisions is not less than 20% of the cross section for all inelastic (NN) collisions:

$$\sigma_p \geqslant 0{,}2\,\sigma_{in}. \qquad (1)$$

Now consider the energy characteristics of inelastic nucleon collisions within the framework of the same model. The results of the calculations will be anew compared with the experimental data obtained with the Dubna synchrophasotron at an energy of $T \simeq 9$ BeV.

Special emphasis was given to the study of the mean energy losses of the nucleon per one act of (NN) collision ΔE. As is known, this magnitude attracted the attention of many authors who measured and widely discussed it. (see, e.g. Refs./2–10/) After the investigations/1/ had been carried out, the accuracy and reliability of the experimental values of ΔE increased appreciably. As for the mean experimental value of ΔE, it decreases if compared with that obtained earlier.

It is understood, that in the framework of our model still imperfect, one may hope to get only a rough agreement with the experiment. Therefore, our main purpose, like in/1/, is to establish, on the one hand, how and to what extent the account of the peripheral nucleon collisions change the theoretical predictions, and on the other, to draw the attention of the experimentalists to the measurements which require increased accuracy.

II. MOMENTUM DISTRIBUTIONS OF PARTICLES PRODUCED IN CENTRAL COLLISIONS

The momentum spectra $W = W(p)$ of various particles created in central (NN) collisions [1] are presented in Figs. 1-4. These spectra were calculated by the statistical theory of multiple production. In Fig. 3 and 4 are also given for comparison the experimental momentum distributions of charged pions and protons for the case of (PP) collisions from /12/. (28 pion tracks and 42 proton tracks were analyzed here). Mean statistical errors are indicated.

The experimental and theoretical values for the mean momenta of nucleons and pions are presented in Table 1. The theoretical values take into account only the central nucleon collisions. They are obtained by means of distributions given in Figs. 1–4. The experimental values of $\bar{p}$ for the c.m.s. are calculated by the experimental histograms of Figs. 3 and 4. A dispersion is given for the experimental values of $\Delta\bar{p} = \sqrt{\Delta p \sum_n N_n (p_n - \bar{p})^2 / \sum_m N_m}$.
The experimental values of $\bar{p}$ for the lab. system were obtained by the Lorentz transformation from the center-of-mass system under the assumption that in (PP) collisions the angular distributions of pions and nucleons in the c.m.s. are symmetrical with respect to the angle $\theta = \pi/2$. (This assumption corresponds to the theoretical and experimental results obtained in /1/,/6/:

$$\bar{p} \simeq \gamma \mathcal{E}_c \quad ; \quad \left((\gamma \mathcal{E}_c)^2 \gg m^2 \right), \tag{2}$$

where $\mathcal{E}_c$ is the mean energy of the produced protons or pions in the c.m.s. of the colliding protons:

$$\gamma = E_c / M \tag{3}$$

is the coefficient of the relativistic transformation; E_c is the primary proton energy in the c.m.s.; M is the nucleon mass; m is the mass of the particle under consideration.

1/ The momentum distributions of all the produced particles are given in the c.m.s. of the colliding nucleons and in the lab. system since for the analysis of the experimental data and for the preparation of new experiments it is important to know the momentum distributions in both these coordinate systems. Small difference of the pion and nucleon momentum spectra from analogous ones given in Ref. /7/ is due to a more precise account of the reactions involving strange particles and to a more accurate method of the calculation. When computing the spectra we made use of the method for calculating the energy phase volumes which was developed in our Laboratory by L.G. Zastavenko. /11/

The values of $\bar{p}$ thus obtained are close to those found in[2] from the analysis of the interactions between photoemulsion nuclei and 9 BeV protons $\bar{p} \simeq p_{sp} = (3,0 \pm 0,5)\ \frac{BeV}{c}$ for protons and $\bar{p} \simeq p_{s\pi} = (1,0 \pm 0,1)\frac{BeV}{c}$ for charged pions. Similar values were obtained also in[5,8,9].

It can be seen from Table 1 and Fig. 3 that within experimental errors there is no sharp discrepancy between the theoretical and experimental data for pions. However, the experimental momentum spectra are appreciably more 'soft' than those calculated theoretically. Large statistical errors do not allow so far to draw more definite conclusions.

The experimental momentum spectrum of protons is proved to be more 'hard' than that calculated theoretically.

The difference between the theoretical and experimental spectra can be understood qualitatively if one takes into account that in[12] as well as in[5,8–10] in measuring the spectra the central and peripheral collisions were not distinguished. However, the nucleon spectrum after the peripheral collision is more hard than that of the nucleons produced in the central collision. On the other hand, the spectrum of the pions produced in the peripheral collision is, on the average, more 'soft' than that of pions generated in central collisions.

These questions will be treated in more detail in Sec. V.

Theoretical values for the mean transversal momenta of the particles created in central collisions are given in Table II. (For nucleons $P_{\perp} \simeq 0.6$ BeV/c see[2]). The corresponding experimental measurements are not yet completed. There are only rough estimates for protons and charged pions obtained in studying 9 BeV proton interaction with photoemulsion nuclei[2]. These are not in contradiction with the calculated values of $P_{\perp}$.

III. ENERGY LOSSES IN CENTRAL COLLISIONS

The values are given for the relative energy loss of a proton for the production of particles of the i-kind

$$\Delta E_i = n_i \varepsilon_i / T \tag{4}$$

per one act of the central (NN) collision (Table II, the lab. system). Here ε_i is the mean energy, n_i is the average number of particles of the i-kind produced in the central nucleon collision; T is the kinetic energy of the primary proton. The values of ε_i have been calculated from the momentum spectra presented in Figs. 1 and 2; the values of n_i are taken from[13].

Thus, the mean energy which the incident proton losses for the production of new particles per one act of the central (NN) collision is

$$\Delta E_c = \sum_i \Delta E_i \simeq 58\% \tag{5}$$

of its initial energy $T = 9$ BeV. The energy losses for the production of Ξ -particles and antiparticles were not taken into account in the calculations. The estimates have shown, however, that only an insignificant inaccuracy is introduced into $\Delta E_c \lesssim 1\%$ We also supposed that $\varepsilon_{K^0} \simeq \varepsilon_{K^+}$ and $\varepsilon_{\bar{K}^0} \simeq \varepsilon_{K^-}$ (see Table III in[13]). The total energy losses of the primary proton per one act of the central collision is

$$\Delta E^c_{tot} = \Delta E_c + T_c/T \simeq 79\% . \tag{6}$$

Here $T_c \simeq 0{,}21\ T$ is the mean kinetic nucleon energy after the central collision.

IV. ENERGY LOSSES IN PERIPHERAL COLLISIONS

The energy which is lost for the production of new particles per one act of the peripheral (NN) collision is

$$\Delta E_p = \frac{1}{2}\left(\Delta E'_p + \Delta E''_p\right), \tag{7}$$

where $\Delta E'_p$ is the mean energy lost in the collision of the peripheral meson of an incident nucleon with the nucleon at rest;

$\Delta E''_p$ is the corresponding energy loss in the collision of an incident nucleon with the meson cloud of the nucleon at rest[2].

In the model of peripheral collisions without a residual isobar (see Fig. 2 from[1])

$$\Delta E'_p = \frac{2}{\sigma_p} \int_\mu^{\varepsilon^*} [\varepsilon - t_N(\varepsilon)]\, \sigma_{\pi N}(\varepsilon)\, q(\varepsilon)\, d\varepsilon \simeq \bar{\varepsilon} - T_N \tag{8}$$

where

$$T_N = \frac{2}{\sigma_p} \int_\mu^{\varepsilon^*} t_N(\varepsilon)\, \sigma_{\pi N}(\varepsilon)\, q(\varepsilon)\, d\varepsilon \tag{9}$$

2/ In the coordinate system where the incident nucleon is at rest, this energy is likely to be $\Delta E'_p$.

is the mean kinetic energy of a nucleon after its collision with the peripheral pion;

$$\bar{\varepsilon} = \int_{\mu}^{\varepsilon^*} \varepsilon\, q(\varepsilon)\, d\varepsilon / n \tag{10}$$

is the mean energy of the peripheral mesons;

$$\sigma_p = 2 \int_{\mu}^{\varepsilon^*} \sigma_{\pi N}(\varepsilon)\, q(\varepsilon)\, d\varepsilon \simeq 2\sigma_{\pi N} \cdot n \tag{11}$$

n is the average number of the peripheral mesons in the nucleon shell;

$$\varepsilon^* = E - \sqrt{M(E+M)/2} \tag{12}$$

is the upper limit of the spectrum of the peripheral mesons $q(\varepsilon)$; $E = T + M$; M is the nucleon mass.

In the model of peripheral collisions with an isobar (see Fig. 3) from/1/

$$\Delta E_p' \simeq \bar{\varepsilon} - T_N + E_\pi \tag{13}$$

where E_π is the mean energy of pions produced in isobar decay. Since in the rest system of an isobar the angular distribution of such mesons is isotropic, then in the transformation to the lab. system of coordinates

$$E_\pi = \frac{2\varepsilon_{is}}{\sigma_p} \int_{\mu}^{\varepsilon^*} \gamma_{is}(\varepsilon)\, \sigma_{\pi N}(\varepsilon)\, q(\varepsilon)\, d\varepsilon \simeq \frac{\varepsilon_{is}}{M'} (E - \bar{\varepsilon}) \tag{14}$$

where

$$\gamma_{is}(\varepsilon) = (E - \varepsilon)/M' \tag{15}$$

is the module of the relativistic transformation; $M' \simeq 1{,}3$ M is the mass of an isobar $\varepsilon_{is} \simeq 0{,}3 \frac{BeV}{c}$ is the mean energy of a meson generated during isobar decay in the coordinate system, where this isobar is at rest.

An expression for $\Delta E_p''$ may be easily obtained by the Lorentz transformation from the coordinate system where the incident proton is at rest :

$$\Delta E_p'' = \gamma(\Delta E_p' + \beta \Delta p') \tag{17}$$

Here

$$\gamma = E/M \; ; \quad \beta = 1 - \frac{1}{2}\left(M/E\right)^2 \tag{18}$$

$\Delta p'$ is the longitudinal component of the momentum of the newly produced particles:

$$\Delta p' \simeq -\frac{2}{\sigma_p}\int_{\mu}^{\varepsilon^*}\left[p(\varepsilon) - p_{\mathcal{N}}(\varepsilon)\right]\sigma_{\pi\mathcal{N}}(\varepsilon)\,q(\varepsilon)\,d\varepsilon \simeq -\bar{\varepsilon} + \mathcal{P}_{\mathcal{N}} \tag{19}$$

in the model of the peripheral collisions without the isobar and

$$\Delta p' \simeq -\bar{\varepsilon} + \mathcal{P}_{\mathcal{N}} \mp P_{\pi} \tag{20}$$

in the model with the isobar

$$\mathcal{P}_{\mathcal{N}} = \frac{2}{\sigma_p}\int_{\mu}^{\varepsilon^*} p_{\mathcal{N}}(\varepsilon)\,\sigma_{\pi\mathcal{N}}(\varepsilon)\,q(\varepsilon)\,d\varepsilon \tag{21}$$

the mean nucleon momentum after the collision with the peripheral pion; $p(\varepsilon) \simeq \varepsilon$ is the momentum of the peripheral meson;

$$P_{\pi} = -\frac{2\varepsilon_{is}}{\sigma_p}\int_{\mu}^{\varepsilon^*}\gamma_{is}(\varepsilon)\,\beta_{is}(\varepsilon)\,\sigma_{\pi\mathcal{N}}(\varepsilon)\,q(\varepsilon)\,d\varepsilon = -E_{\pi} + \frac{M'\varepsilon_{is}}{2n}\int_{\mu}^{\varepsilon^*}\frac{q(\varepsilon)\,d\varepsilon}{E-\varepsilon} \tag{22}$$

is the mean momentum of a pion generated in isobar decay.

Keeping in mind the inaccuracy of the values of $p_{\mathcal{N}}(\varepsilon)$ (see, below) we neglected the transversal component of the momenta $p_{\perp}(\varepsilon)$ and $\mathcal{P}_{\mathcal{N}\perp}$ in (19) and (20).

Finally, for the energy ΔE_p, lost for the production of new particles we obtain

$$\Delta E_p = \frac{\bar{\varepsilon}}{2}\left(1 + M/2E\right) + \frac{1}{2}\mathcal{P}_{\mathcal{N}}\,E/M - \frac{1}{2}T_{\mathcal{N}}\left(1 + E/M\right) \tag{23}$$

$$\Delta E_p = 0{,}12\left(3{,}1\bar{\varepsilon} + E\right)\left(1 + M/2E\right) + \frac{1}{2}\left(\mathcal{P}_{\mathcal{N}} + \frac{0{,}2M^2}{n}\int_{\mu}^{\varepsilon^*}\frac{q(\varepsilon)\,d\varepsilon}{E-\varepsilon}\right)E/M - \frac{1}{2}T_{\mathcal{N}}\left(1 + E/M\right) \tag{24}$$

For the variants without the isobar and with it, respectively Since the mean energy of the nucleon recoil is not great in peripheral collisions ($T_{rec} \ll \Delta E_p$), then the total energy which the fast incident nucleon loses is close to the energy loss for the generation of new particles:

$$\Delta E^{p}_{tot} \simeq \Delta E_p \tag{25}$$

However, if the experimental conditions allow to measure the mean nucleon energy after the collision

$$\bar{T} = \frac{1}{2}\left(T - \Delta E_p\right) \qquad (26)$$

then, according to the definition, the experimentally measured total energy loss of the primary nucleon per one act of the peripheral collision is

$$\Delta E^{p}_{tot} \equiv T - \bar{T} = \frac{1}{2}\left(T + \Delta E_p\right). \qquad (27)$$

V. DISCUSSION

To calculate the values of ΔE_p by the given minimum impact parameter τ_o it is necessary to be aware of the momentum spectrum $p_N(\varepsilon)$ of nucleons produced in peripheral (π N) collisions. This spectrum may be calculated theoretically if we make use of the statistical theory of multiple production for the description of inelastic (πN) interactions (in more detail see/14/), whereas for the description of elastic (π N) collisions of the optical model (see, in more detail/15/). In this case

$$p_N = \left(\sigma_{in}\, p_N^{in} + \sigma_{el}\, p_N^{el}\right) / \left(\sigma_{in} + \sigma_{el}\right) \qquad (28)$$

where p_N^{in} and p_N^{el} are the values for the nucleon momenta of inelastic and elastic reactions, respectively: $\sigma_{el} \simeq 1/3\ \sigma_{in}$

The values of $p_N(\varepsilon)$ may be also obtained by interpolation of the well-known experimental values. However, the values thus found are not more accurate than those calculated theoretically as the experimental data in the energy region $T \geqslant 1$ BeV are available only for some points and with great statistical errors./16/ 3/. The values of the momentum $p_N(\varepsilon)$ and the corresponding values of the kinetic energy

$$t_N = \left(\sigma_{in}\, t_N^{in} + \sigma_{el}\, t_N^{el}\right) / \left(\sigma_{in} + \sigma_{el}\right) \qquad (29)$$

which were used in calculating the energy losses ΔE_p are presented in Fig.5.

On the other hand, the calculations have shown that the quantity ΔE_p changes slightly

3/ The authors are grateful to R.M. Lebedev who kindly acquainted us with the experimental spectra of nucleons for inelastic ($\pi^- p$) interactions at $T \approx 7$ BeV prior to publication.

with variation of $\mathcal{P}_N$ and T_N in wide limits of values. Therefore, it ought to be expected that in the framework of the model under consideration possible inaccuracies in the values of $P_N(\varepsilon)$ cannot change considerably the calculated values for the energy losses ΔE_p.

The computed values of $\mathcal{P}_N$ and T_N are plotted in Fig. 6 for the peripheral collisions of nucleons with the impact parameters $r \geq r_o$ at $T \simeq 9$ BeV. In the same Figure are given the mean energy losses in the peripheral collisions ΔE_p calculated for these values $\mathcal{P}_N$ and T_N. In Fig. 8 are presented the calculated values for the total energy losses per an act of inelastic interaction

$$\Delta E = (1-\xi)\,\Delta E_c + \xi\,\Delta E_p \qquad (30)$$

where the theoretical magnitude of the peripheral collision cross section $\sigma_p \equiv \xi\,\sigma_{in}$ is plotted against different values of r_o (Fig. 7).

As is seen from Figs. 6 and 8, the difference between the total energy loss ΔE and the energy loss in the central (NN) collision ΔE_c turns out not to be large. (The values of ΔE_p, ΔE_c are also found to be comparable).

The difference between the mean values of the energy losses for the variants with an isobar and without it amounts only to about 5% for $r_o = 3\hbar/Mc$ and decreases for larger values of r_o. It is understood that both the accuracy of experiments and theoretical calculations (as was shown above) are so far insufficient for distinguishing on this footing the variants of peripheral collisions.

The magnitude of ΔE_c alongside with ΔE may be reduced by some percent by decreasing the cross section for strange particle generation [4] and by increasing (within measurement errors σ_{in}) the value of the ratio of the cross section ξ. At the same time the minimum value of the energy loss ΔE for the variant with isobar generation is close to 50%.

The experimental values for the mean energy losses in (NN) collisions are presented in Table III. These values were obtained by several authors. As is seen, the theoretical values of ΔE exceed appreciably the mean experimental ones.

As the calculations have shown, the theoretical values of the mean momenta of nucleons and pions produced in (NN) collisions agree better with the experimental ones if the peripheral collisions are taken into account. But, like for ΔE a complete quantitative agreement cannot be achieved.

4/ The cross section for strange particle generation σ_s was calculated according to the phenomenological theory /18/. However, the experimental data on strange particle generation at $T > 1$ BeV allows such a decrease of the parameters predicted by this theory that at $T \simeq 9$ BeV the quantity σ_s decreases as much as one and a half or two times.

However, our knowledge of the experimental values is at present very poor. In most cases the values of ΔE have been obtained from the analysis of the interactions between the primary proton and nuclei. They may be treated as an approximate estimate of the energy losses in (NN) collision. (Usually, as the lowest estimate cf.[2]). The values of ΔE obtained from the analysis of (NN) interactions in the photoemulsion have also a preliminary character [5]. This concerns the experimental values of the mean momenta of particles produced in (NN) collisions. Therefore, it is still difficult to ascertain to what extent the experimental and theoretical values are inconsistent. The treatment proposed in the present paper as well as in[1] allows only to state that the agreement of angular and energy characteristics with the experiment is improved if the peripheral nucleon collisions are taken into account.

It is accurate experimental data which are necessary for further progress.

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5/ In particular, the value of $\Delta E < 45\%$ based upon the measurements of proton momenta may turn out to be underestimated since it does not take into account the statistical measurement errors.

Table 1

	Pions		Protons	
	Experiment	Theory	Experiment	Theory
$\bar{P}$ Bev/c lab.syst.	1.0 ± 0.2	1.46	3.6 ± 0.5	2.90
$\bar{\bar{P}}$ BeV/c c.m.s.	0.4 ± 0.1	0.57	1.24 ± 0.25	0.79

Table II

A kind of particles	π	K^+	K^-	$\tilde{N}$	Λ	Σ
$P_\perp$ BeV/c	0.45	0.64	0.53	0.46	0.68	0.68
ΔE_i %	49	1.6	0.2	0.8	1.6	3.3

Table III

The value is taken from:	/3/	/5 /	/9/	/2/	/6/	/8/
ΔE %	~ 30	30 ± 10	33 ± 9	$\geq (40 \pm 10)$	$\sim 30; < 45$	35 ± 2

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*/ There are some misprints in /13/ : in formula (3) instead of t^{2n} there must be t^{2n-1} and $\alpha = \frac{E}{\Sigma M_i} - 1$. (The numerical results given in /13/ have been calculated by the correct formula. The statistical weight of the reaction $\Lambda\Sigma 2K\pi$ is $W, \% = 0{,}00053$ for E = 7 BeV. , the upper Table on page 125 is a continuation of Table II: the lower table on page 125 and the Tables on page 126 are the parts of Table III for E = 7 BeV and E = 10 BeV, respectively. On page 127 the fifth and the forth lines from below should be read:' one antinucleon per one-two hundred pions at E 10 BeV'.

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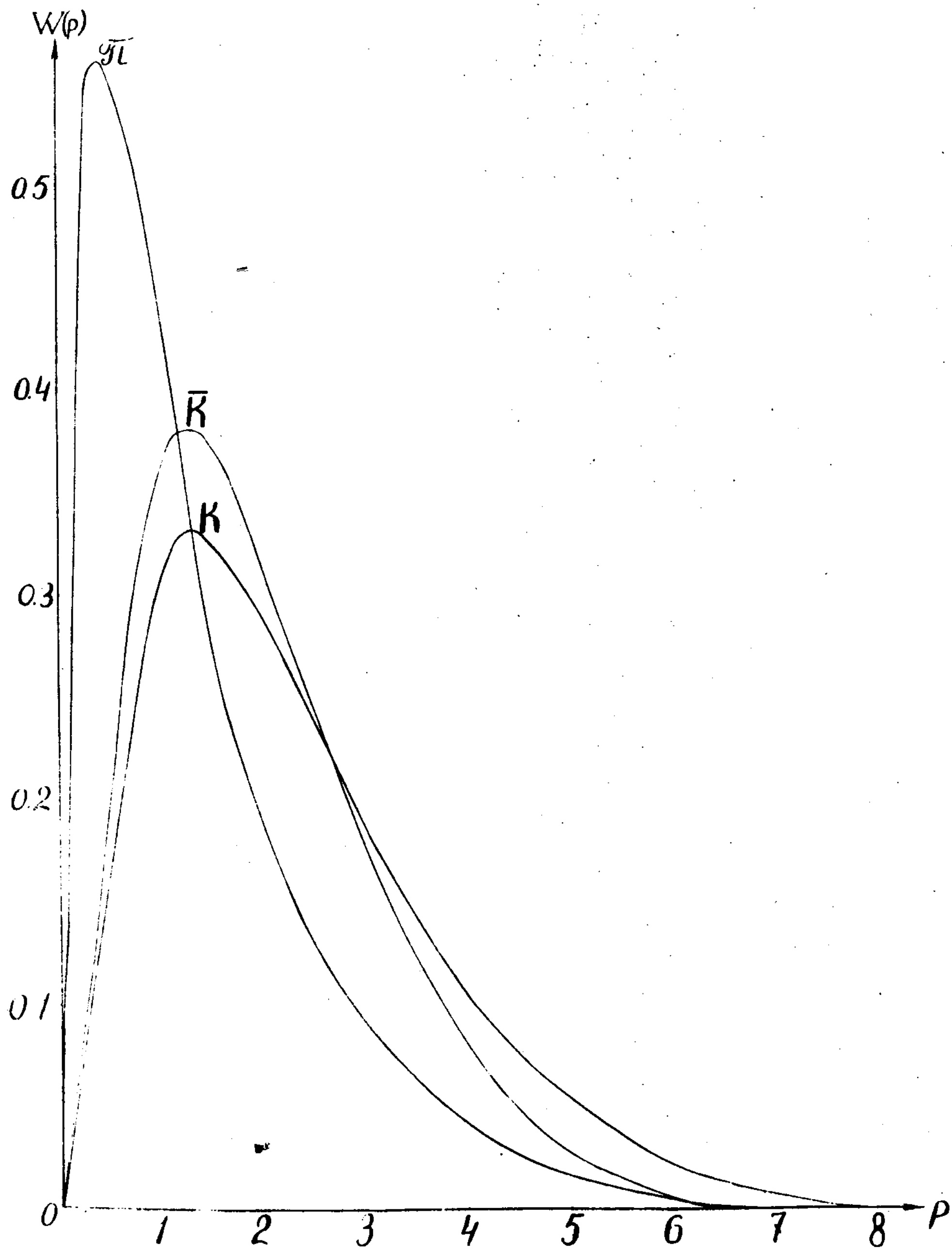

Fig. 1. ***Momentum spectra of π^-; K^-; $\bar{K}$ - mesons in the lab.system***
The momenta are given in the units of BeV/c.

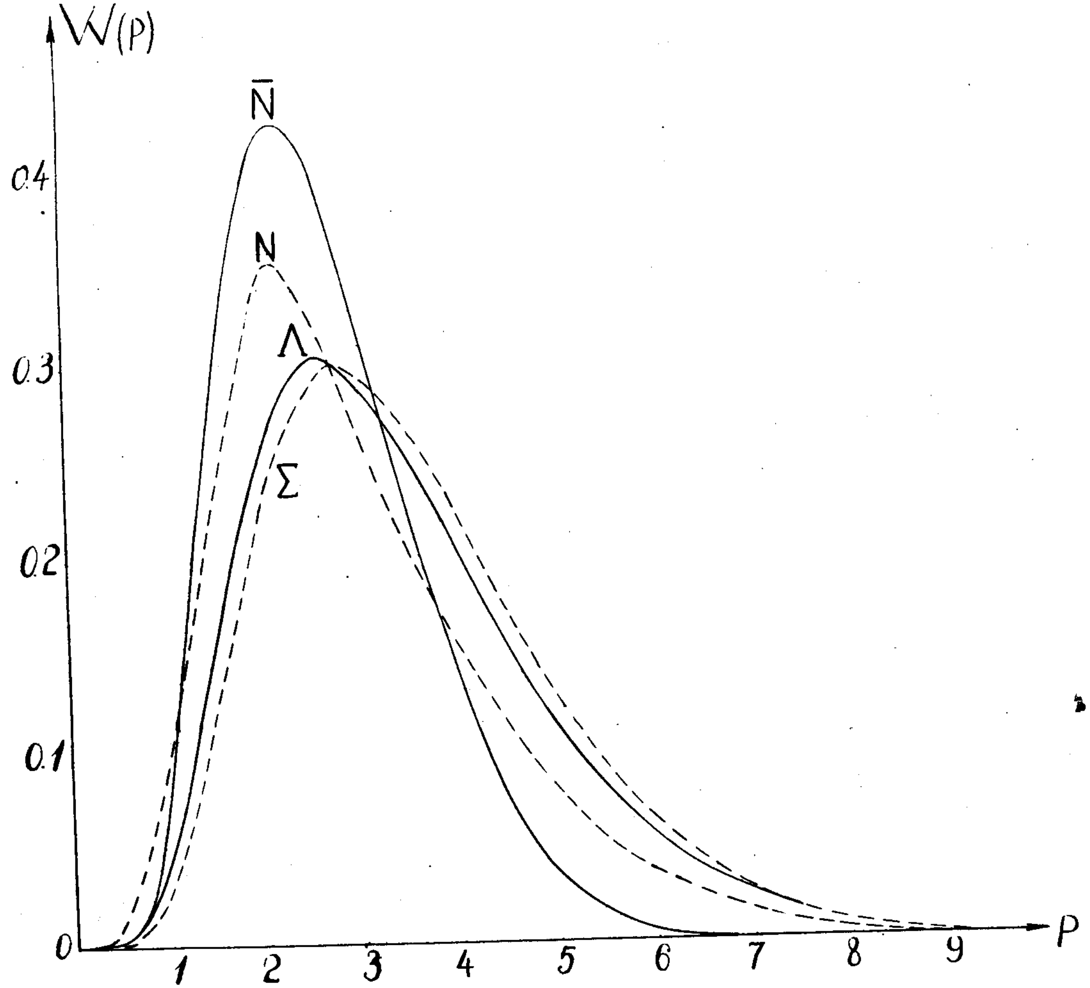

Fig. 2. *Momentum spectra of nucleons, antinucleons, Λ-and Σ-hyperons in the lab.system. The dotted lines show the spectra of nucleons and Σ-hyperons. The momenta are given in the units of BeV/c.*

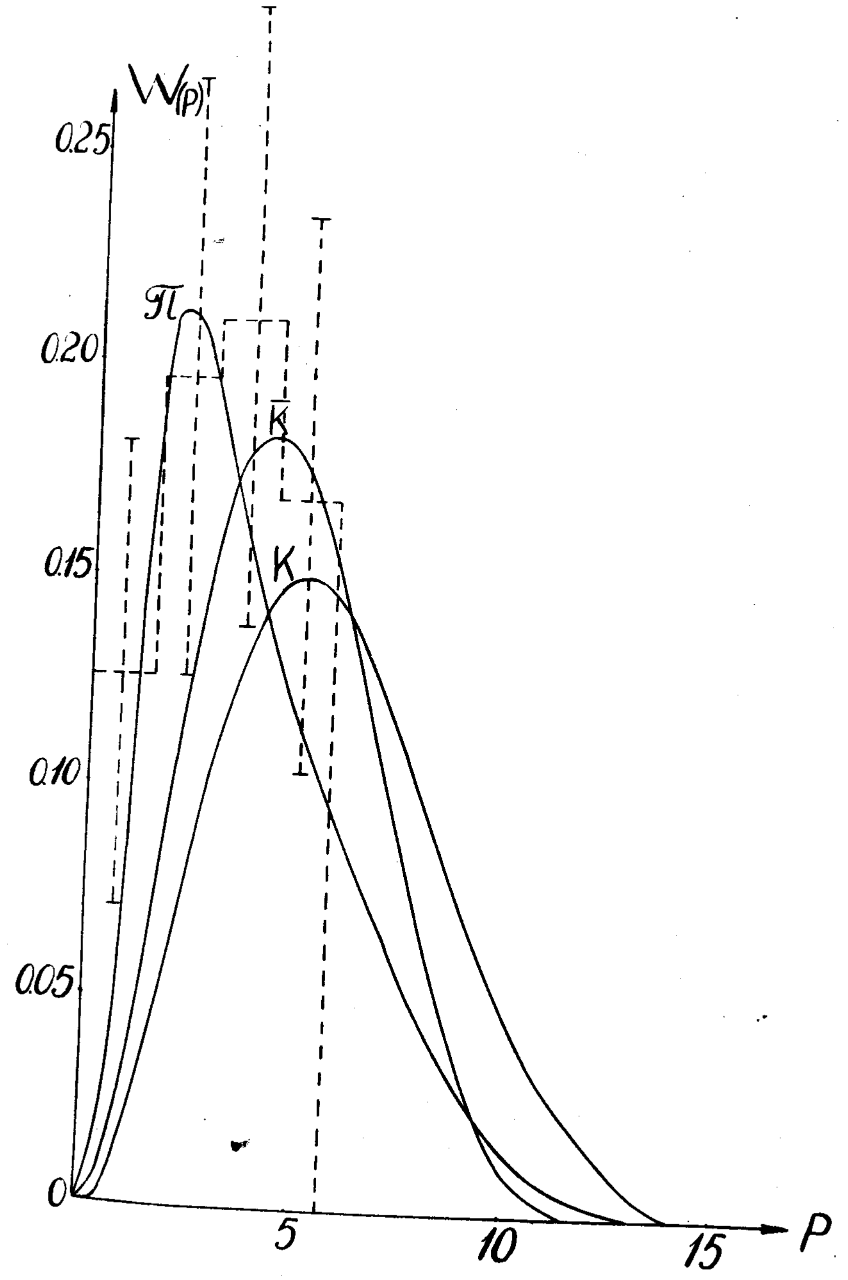

Fig. 3. Momentum spectra of π^-; K^-; $\bar{K}$- mesons in the c.m.s. of the colliding nucleons. The dotted curve is the experimental histogram for π mesons. The momenta are presented in the units of $m_\pi c$ where m_π is the pion mass.

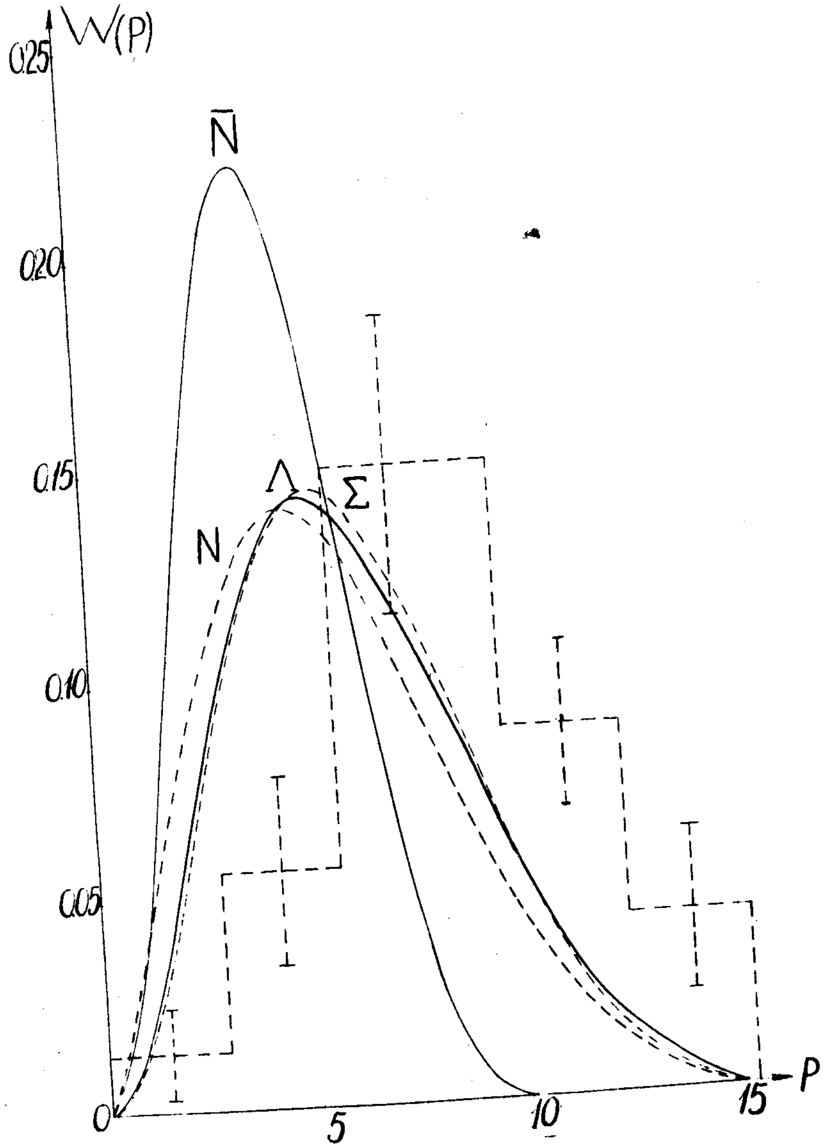

Fig. 4. Momentum spectra of nucleons, antinucleons, Λ-and Σ-hyperons in the c.m.s. of the colliding nucleons. The dashed line represents the theoretical nucleon spectrum, the corresponding experimental histogram and the spectrum of Σ -hyperons. The momenta are given in the units of $m_\pi c$ where m_π is the pion mass.

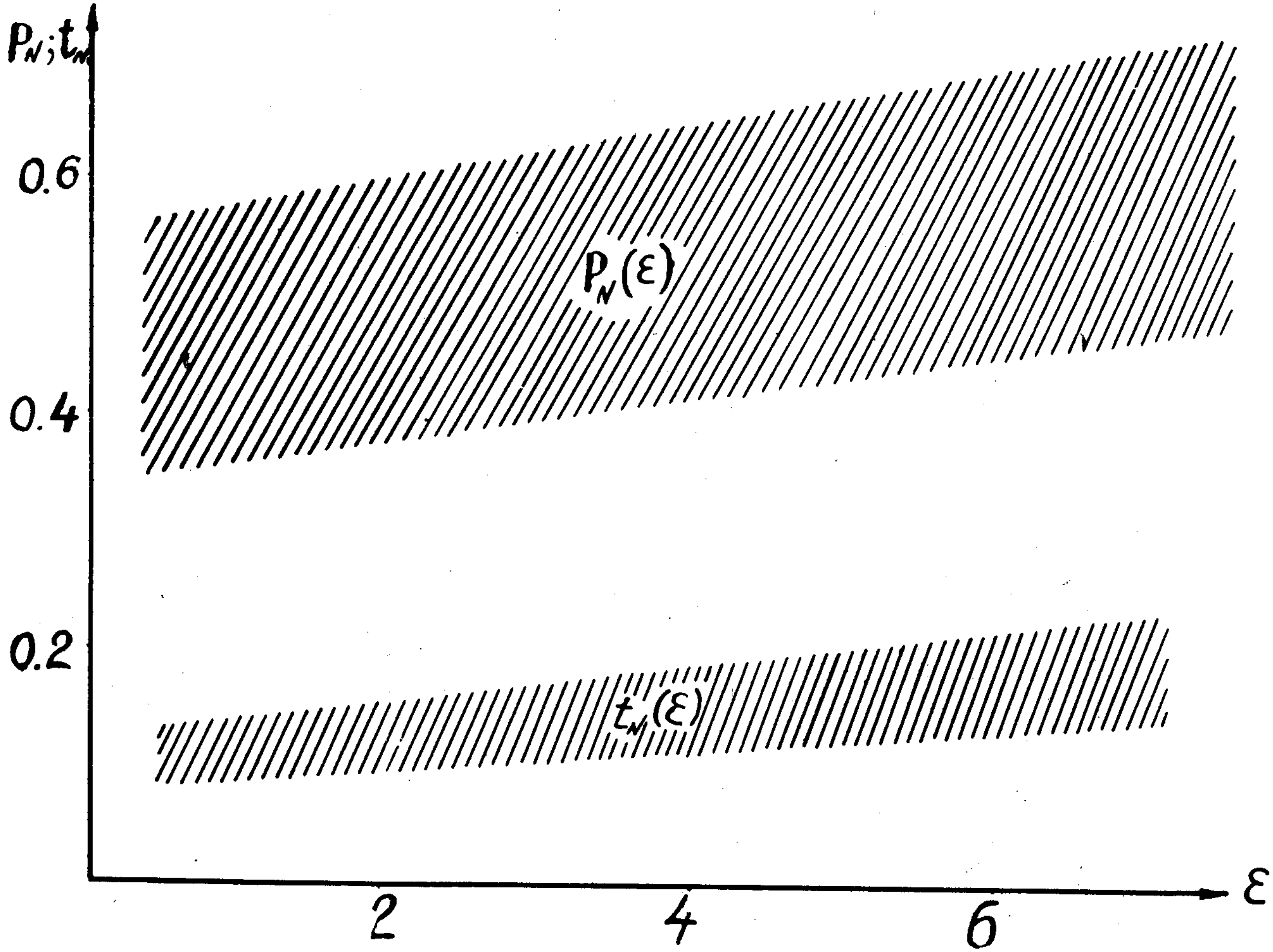

Fig. 5. Mean kinetic energy t_N and the nucleon momentum p_N after the collision with the peripheral pion of an energy ε. The regions of values of t_N and p_N allowed by the statistical measurement errors are shaded. The values of t_N and P_N are expressed in BeV, the values of t_N, P_N in BeV/c. Laboratory system of coordinates.

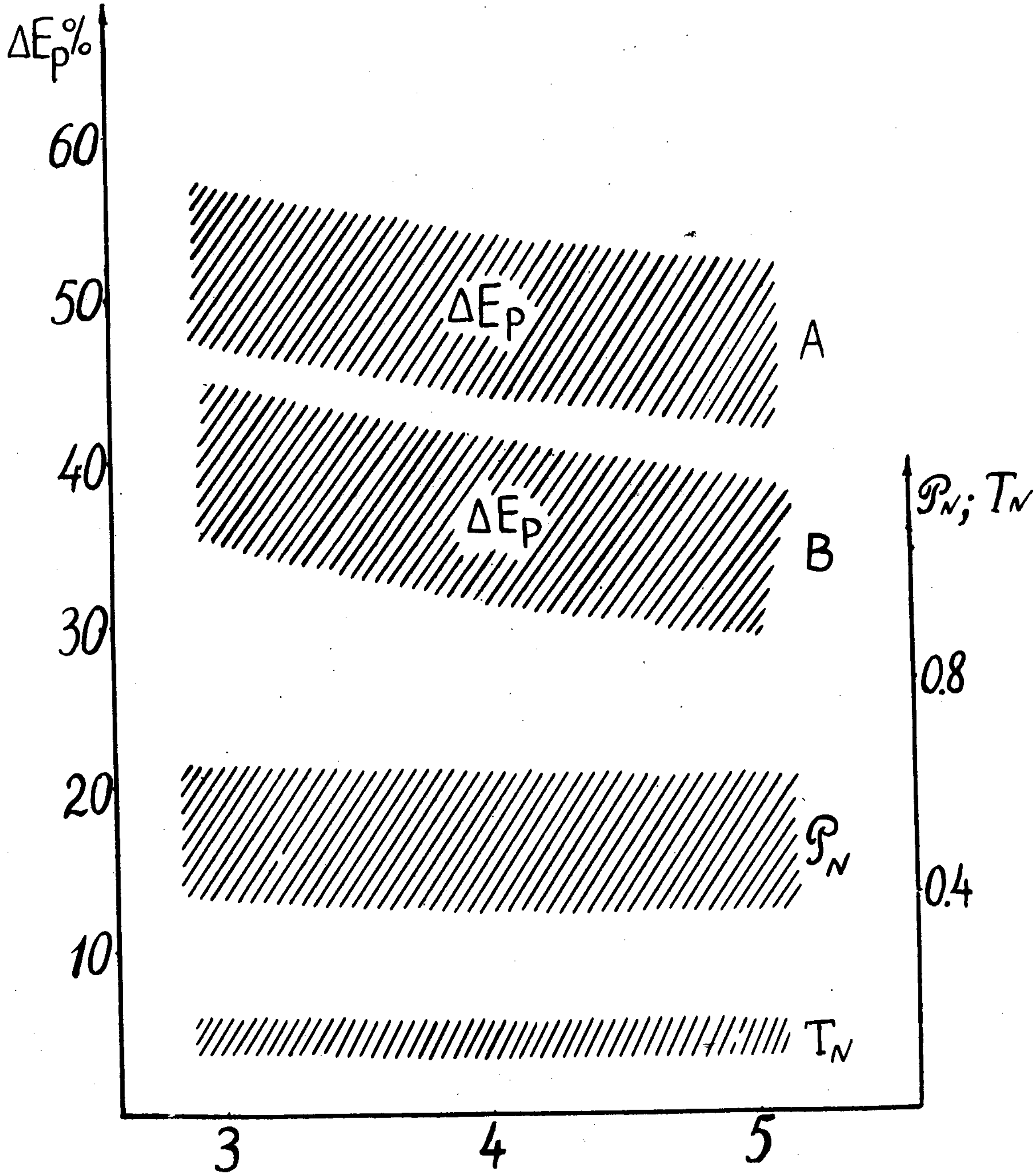

Fig. 6. The values of T_N , $\mathcal{P}_N$ and ΔE_p are plotted against the minimum impact parameter: A- variant with the isobar, B- variant without the isobar. The regions allowed by the statistical measurement errors are shaded.

The values of T_N are given in BeV; the values of $\mathcal{P}_N$ - in BeV/c; the values for the minimum impact parameter - in the units of $\hbar/MC = 2.1 \cdot 10^{-14}$cm.

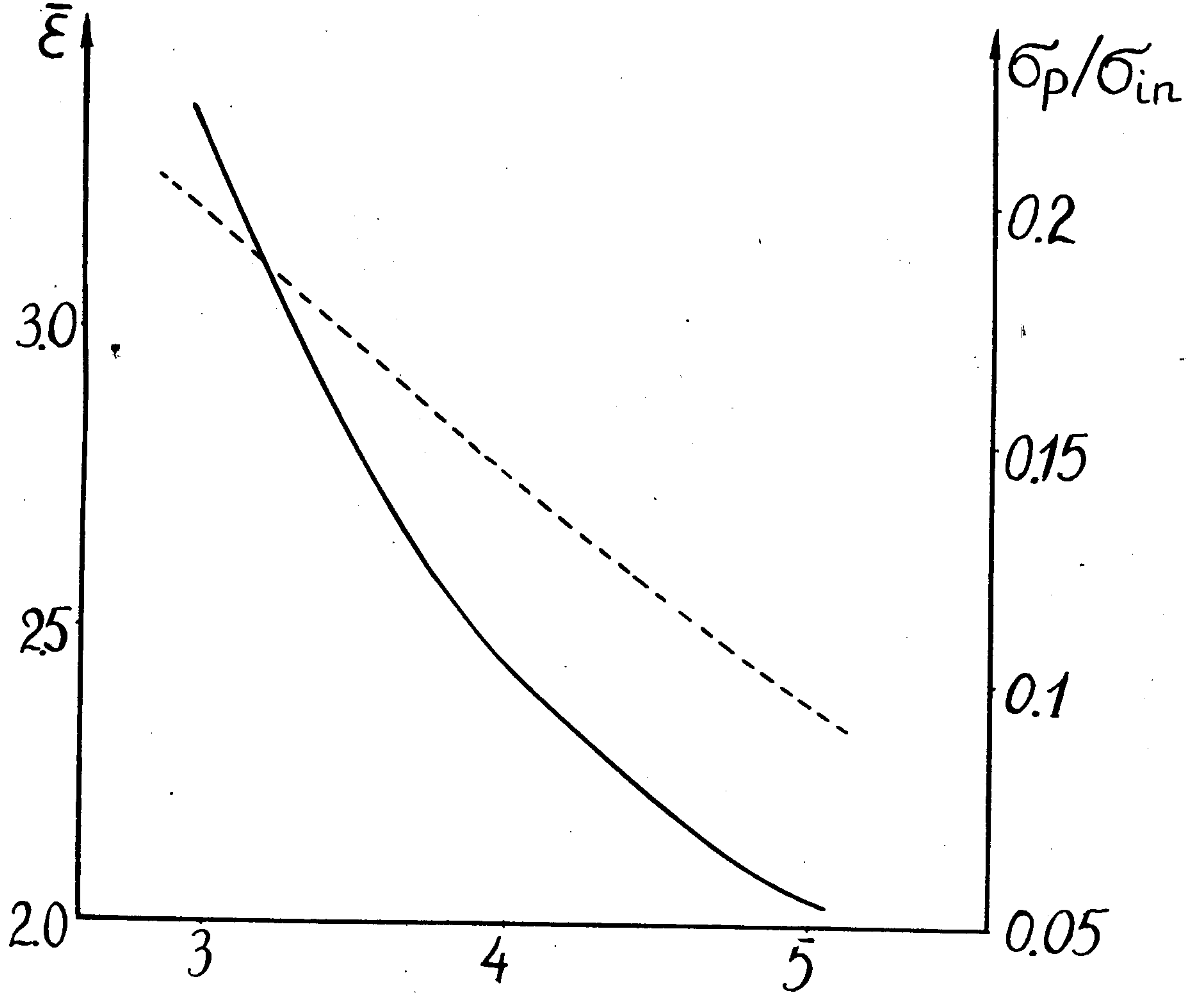

Fig. 7. Mean energy of the peripheral mesons (dotted line) and the cross sections for the peripheral collisions σ_p (solid line) are plotted against the magnitude of the minimum impact parameter τ_o . The values of $\bar{\varepsilon}$ are given in BeV, the values of τ_o in the units of $\hbar/MC$

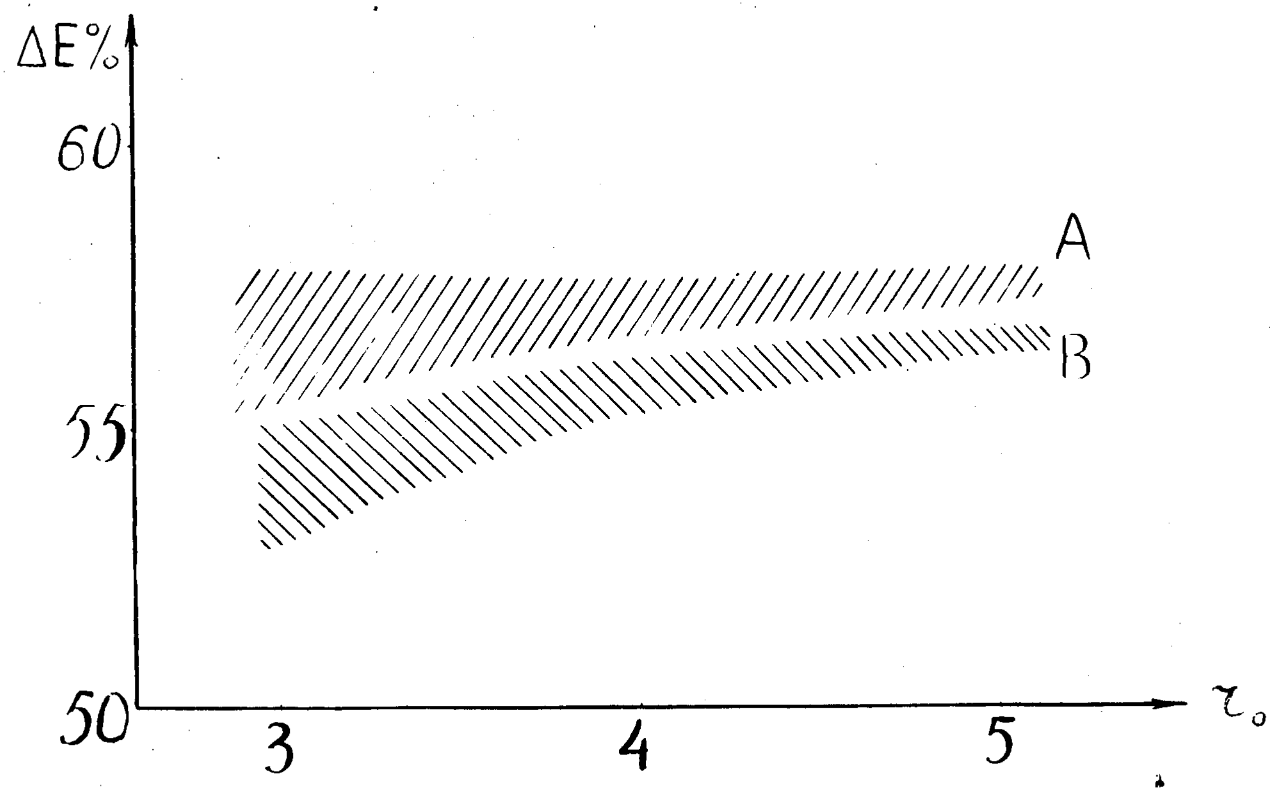

Fig. 8. *The total energy loss in (NN) collision as a function of the magnitude of the minimum impact parameter τ_0. A-variant with the isobar, B- variant without the isobar. The regions of values of ΔE allowed by the statistical errors are shaded. (the values of τ_o were assumed exact). The values of τ_o are given in the units of $\hbar/mc$.*