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V.S. Barashenkov, A.S. Iljinov, V.D. Toneev

ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

INELASTIC INTERACTIONS OF PARTICLES AND NUCLEI AT HIGH AND SUPERHIGH ENERGIES

(Report submitted to the International Conference in the USA, June, 1970).

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1. In the late fifties it was generally agreed that the inelastic interactions of particles with nuclei at the energy $T \gg 1$ GeV proceed by means of the so-called "nuclear tube mechanism". It is just in this way that practically all the data obtained in cosmic ray experiments were interpreted. However, the analysis of the emulsion data obtained at $T = 9$ GeV by the group of K.D. Tolstov by means of a 10 GeV accelerator, put into operation at just that time, has shown that the tube model can very approximately explain only some details of a purely kinematic character which are related to the fact that the high energy emission proceeds mainly into a narrow cone. To describe qualitatively the characteristics of inelastic interaction it turned out to be necessary to use the ideas of the intranuclear cascade which were employed earlier at energies of the order of several hundreds of MeV /1-2/ . This was just the starting point of cascade calculations at our Laboratory.

2. One of the most serious difficulties which we have encountered at that time was the necessity of introducing in a compact way into the computer a large amount of detailed experimental information on elementary $N-N$ and $\pi-N$ interactions especially on multiple pion production processes which are extremely important at the energy $T > 1$ GeV. (In those cases when the experimental information is insufficient the results of the statistical calculations performed by means of pole peripheral models and the Fermi theory were used).

The experience accumulated at our Laboratory allows us to assert that the most simple and convenient method (especially for computers with a comparatively small storage) seems to be the one when as the initial data one utilizes instead of the angular and energy distributions of produced particles their polynomial approximations. To find such approximations a laborious numerical analysis of a large amount of experimental data is needed. However the approximation obtained in such a way can be used in calculating the cascades in various nuclei and at various energies.

It should be stressed that the energy dependence of the characteristics of elementary interactions turns out to be in this case continuous which considerably increases the accuracy of calculations and at the same time economizes the time of calculation.

In order to obtain the approximations mentioned one should use instead of the differential angular and momentum distributions in the c.m.s. $\omega_\theta(\cos\theta)$ and $\omega_p(p)$ the corresponding integral distributions

$$W_\theta(x) = \int_0^x \omega_\theta(2z-1)\,dz \Big/ \int_0^1 \omega_\theta(2z-1)\,dz, \qquad (1)$$

$$W_p(y) = \int_0^y \omega_p(p_{max} z)\,dz \Big/ \int_0^1 \omega_p(p_{max} z)\,dz \qquad (2)$$

and bear in mind that the inverse quantities

$$x = W_\theta^{-1}(\xi) \quad \text{and} \quad y = W_p^{-1}(\xi) \qquad (3)$$

are monotoneously increasing functions of a random number ξ uniformly distributed over the interval $[0,1]$. These functions are expressed in terms of the polynomials in ξ :

$$\cos\theta = 2\xi^{1/2}\left\{\sum_{n=0}^{N} a_n \xi^n + \left(1-\sum_{n=0}^{N} a_n\right)\xi^{N+1}\right\} - 1, \qquad (4)$$

$$p = p_{max}\, \xi^{1/2} \{ \sum_{n=0}^{N} b_n \xi^n + (1 - \sum_{n=0}^{N} b_n) \xi^{N+1} \}, \qquad (5)$$

where the momentum in the experimental distribution p_{max} and the coefficients a_n and b_n depend on the type of the reaction in question and on the colliding particle energy. The energy dependence of these quantities can also be represented in the form of the polynomials

$$a_n = \sum_{k=0}^{M} a_{nk} T^k, \quad b_n = \sum_{k=0}^{M} b_{nk} T^k, \quad p_{max} = \sum_{k=0}^{M} c_k T^k . \qquad (6)$$

Detailed calculations have shown that within the accuracy of the presently experiments the approximation by the polynomials of fourth degree (i.e. $N = 3$, $M = 3$), appear to be optium. Such polynomials are simple for calculations and at the same time approximate the available experimental data (see, for example, Figs. 1 and 2).

The tables of the coefficients a_{nk} , b_{nk} and c_k suitable for the energy range from several dozens of MeV to $T \approx$ 20-30 CeV are given in ref. /3/.

The polynomial approximation can be used not only for inelastic channels but also for the angular distribution of elastically scattered particles (see Fig. 3); the particle energy is unambiguously defined by the scattering angle). In the range of higher energies (for $T \cong$ 30-10 ^{3} GeV) the approximation has a more weakly logarithmic dependence of the coefficients (6):

$$a_n = \sum_{k=1}^{M} a_{nk} (\ln T)^{k-1} \text{ etc.} \qquad (7)$$

As an example, in Figs. 4 and 5 the calculated distributions for $\pi - N$ collisions at T = 60 GeV and the data for $N-N$ interactions at $T \approx$ 60 and 2000 GeV are compared with experiment (these calculations have been performed by S.M. Eliseev).

3. Another fact which essentially influences the accuracy of cascade calculations is the necessity for the energy and momentum conservation laws to be satisfied when each act of inelastic $\pi-N$ or $N-N$ interaction is simulated by the Monte-Carlo method. In order to calculate the integral average quantities like the average multiplicity and the average energy of secondaries it is sufficient to take into account these laws only statistically, i.e. on the average over a large number of interactions /4-6/. In so doing, one obtains quite good results also for the total angular and energy distributions.

Fig. 6 shows the distribution of the difference of the total particle energies before and after interaction for various kinds and different energies of projectiles. The mean value of ΔE does not practically differ from zero however the dispersion turns out to be surprisingly large and the "tail" of the distribution goes up to $\Delta E = T$ /6/ . This may lead to noticeable errors in characteristics such as the number of particles in a certain energy interval, the particle spectrum at a fixed angle and so on. The excitation energy of the residue nucleus and, consequently, the number of black prongs in the star are found to be especially vulnerable /7/ .

In order to avoid this trouble a special method of the Monte--Carlo simulation of the inelastic interactions of elementary particles with the exact account of the laws of conservation of energy and momentum in each act of interaction has been developed (For more detail see refs /3/.

4. The comparison of the intranuclear cascade model with experiment has been performed in many papers (see, in particular refs. /8-11/ where a further bibliography is given). However a rather detailed and diverse comparison is performed only for comparatively low energies where the meson production processes can be neglected.

At higher energies the experimental results were compared mainly with the average interaction characteristics and only in some cases the differential angular and momentum distributions were considered. Such a comparison allows to obtain a right general idea on the character of the interaction of a particle with the nucleus. However, some important detailes can in this case be omitted, especially as the calculations performed by various authors are related to various energy ranges, and the use of the experimental data averaged over broad and changing from paper to paper energy intervals for the description of $\pi - N$ and $N - N$ interactions inside the nucleus can mask anomalies in the behaviour of the desired quantities.

An additional source of the inaccuracy of the results may be the use of a rough nuclear model, the neglect of the potential acting on mesons inside the nucleus, the neglect of the low of conservation of energy and momentum.

For the exception of the region of very high cosmic energies, where experiments are very difficult, and the region $T \lesssim 200$ MeV, where the calculations are simplified due to the fact that here it is unnecessary to take into account pion production processes, the accuracy of the cascade calculations performed was lower than the experimental one.

All these considerations have stimulated us to carry out anew the calculations of pion - and nucleon-nuclear cascades so that to improve essentially their accuracy and to make a more detailed comparison with experiment over the whole energy range from several dozens of MeV to several dozens of GeV.

The calculations have been performed by scheme presented in our papers /3,12/ . An essential difference of these calculations from those carried out in all earlier papers consists, first of all, in a far more exact simulation of $\pi - N$ and $N - N$ collisions inside the nucleus. The diffuseness of the nuclear boundary and the nuclear potential was taken into account in our calculations (the nuclear density parameters were taken from experiments with electron scattering); it was taken into account that inside the nucleus the π -meson and the nucleon are affected by a non-zero potential, V_N and V_π ; the account was also made of a possibility of the absorption of the slow π -meson by the bound nucleons of the nucleus.

The decay of the excited nucleus was calculated by the Monte-Carlo method by the usual avaporation theory.

As a result of calculation a "atlas" was worked out including the main characteristics of inelastic interactions of π -mesons and nucleons with nuclei: multiplicity of secondaries of various kinds, their angular and energy distributions, excitation energies, average angular momenta and momenta of residual nuclei, their distribution over the mass and charge numbers and so on. These data are obtained for various targets and various energies of primaries and are a very convenient material for interpolating their intermediate values. To calculate more detailed characteristics the routines are available.

The examples of some quantities calculated in this way are given in Figs. 7-9 and in Table I.

The detailed comparison has shown a good agreement of the calculations with experiment in a wide energy region from several dozens of MeV to several GeV. For the π -mesons the account of the potential $V_{\pi} \cong 25$ MeV and their absorption by pairs inside the intranuclear nucleons (see Fig.10) /14/ has been found to be very essential.

Some disagreement mentioned in a number of papers at an energy $T \lesssim 1$ GeV are due to shortcomings of particular versions of the cascade models rather than to the violation of the cascade mechanism itself.

In the energy range $T \lesssim 300$ MeV where the pion production is nonessential the results of our calculations are close to the Bertini's data. However there are noticeable differences in the pion yield, especially at $T \cong 300$ MeV. Possibly this is due to a somewhat different choice of the meson-nuclear potential in our and Bertini's papers and for $T \cong 300$ MeV and also to the fact that Bertini has not taken into account the meson production processes. The comparison with the results of calculations at high energies published in refs./8,11,15/ shows the difference in quite a number of cases. The analysis has shown that the disagreement with the Metropolis's data is, for example, due to the fact that in refs./8/

a more rough nuclear model was used and a very simplified approach to the description of inelastic cascade particle collisions was used. All these differences are discussed in detail in ref./16/.

5. A special attention should be paid to the calculation of inelastic interactions of fast particles with light nuclei. In this case, to obtain agreement with experiment it is necessary to take into account α -clasters. The decay of a high excited residual nucleus can be calculated using the phase volume according to the Fermi statistical theory. The results of calculations are found to be very close to the experimental data (see Fig.11and 12). Here it is very important to take into account a certain threshold i.e. the minimum excitation energy, below which the residual nucleus cannot be splitted. This essentially increases the fraction of the residual nuclei with mass numbers close to the mass number of the target-nucleus/17/.

6. The application of the cascade mechanism of the intranuclear collisions to the interactions of gamma quanta with nuclei leads to good agreement with experiment, too (see Figs. 13 and 14)/18/.

7. At energy $T \gtrsim 5$ GeV the disagreements of the abovementioned cascade model with experiment become noticeable and rapidly increase with increasing T . They are manifested, first of all, in the characteristics of the produced low-energy particles. For example, from Fig. 15 it is seen that the theoretical average multiplicities $\bar{n}_s$ and $\bar{n}_h$ in proton-nucleus collisions which are in good agreement with experiment at $T < 5$ GeV do not reflect the experimentally observed "saturation" at higher energies. The calculated $\bar{n}_s$ values are very close to the experimental ones up to $T \gtrsim 20$ GeV where there appear noticeable disagreements.

Similar results were obtained for pion-nuclear interactions. The difference between theoretical and experimental characteristics is revealed more clearly in considering the particle correlations. It is seen from Fig. 16 that at $T \lesssim 5$ GeV the dependence of $\bar{n}_s$ on the number of h -prongs in the star is in good agreement with experiment while at higher energies the calculation hystograms differ noticeably from the measured ones.

As to the dependence of the average number of grey tracks on the number of s -particles, at $T \gtrsim 5$ GeV it is impossible to speak of even qualitative agreement with experiment (Fig.17). At less higher energies there are no direct measurements, however, the character of the correlations at $T = 3.2$ GeV in proton-nuclear interactions is about the same as in π^--meson-nucleus collisions at $T = 1.87$ GeV, where one observes a decrease of the average number of g -prongs with increasing n_s /19/.

8. It is possible to indicate some causes of disagreements between the cascade calculations and experiment. First of all, we should beer in mind that in all the calculations performed up to the present time the fact is completely ignored that as the cascade develops it involves ever-increasing number of intranuclear nucleons. Owing to this the low-energy component of cascade particles encounters on its way smaller nuclear matter density. Correspondingly, the number of "evaporation" particles decreases, as well.

To take this effect into account we have considered, instead of a continuous distribution of matter, a nucleus consisting of separate nucleons the location of the centres of which is calculated by the Monte-Carlo method, according to the appropriate Saxon-Woods distribution with parameters taken from the Hofstadter papers. The following condition is imposed on the nucleon disposition: the distance between their centres should not be smaller than $2r_n$, where $r_n = 0.4 \times 10^{-13}$ cm is the nucleon core radius. The coordinates of all the intranuclear nucleons are remembered by the computer.

A fast particle (primary particle or that produced in the development of the intranuclear cascade) can interact with any intranuclear nucleon the centre of which is found in a cylinder of radius $r_0 + \lambda$, where $r \approx 1.3 \times 10^{-13}$ cm is the value close to the strong interaction radius, λ is the de Broglie wave length of the fast particle under consideration. To determine with which nucleon this particle will interact a binomial distribution is used. The probability κ of interaction of the particle with the nucleon can be obtained either from the transition to the limit of the Poisson distribution for the usually used in cascade calculations interaction probability to the binomial one which gives $\kappa = \sigma/\pi(r_0+\lambda)^2$ or from the condition that the both distributions give the same probability for the particle to pass without interacting a certain distance ℓ to which there corresponds $\kappa = 1 - \exp[-\sigma/\pi(r_0+\lambda)^2]$. The calculations were performed with the use of both formulas.

In following cascade particles the preference is given to faster particle which allows to calculate approximately the development of the cascade in time. The nucleon of the nucleus knocked out from its place is not then considered as the target nucleon. This allows to take into account automatically the change of the density of intranuclear nucleons as the cascade develops.

Figs. 18 and 19 show the energy dependence of the calculated probability of shower and slow particles. We see that the account of the decrease of the intranucleon density leads in fact to the effect desired.

It should be stressed that the results of calculations are very sensitive to the conditions of the selection of events according to n_h. In emulsion experiments this point is very delicate: the separation of the interactions with the emulsion hydrogen is, as a rule, made due to the criterion $n_h > 1$. However, in so doing, a considerable part of the interactions with nuclei may be lost, this, in turn, may essentially affect $\bar{n}_s$ and $\bar{n}_h$.

Fig. 19 shows the correlation $\bar{n}_g = \bar{n}_g(n_s)$ calculated taking into account the nuclear density change. The comparison with Fig. 17 shows that in this case, too, we have the necessary effect: the calculated curves assume the shape required by experiment.

The decrease of the intranuclear matter density as the cascade develops leads to "saturation" of the recoil nucleon number and the excitation energy of the residual nucleus. This makes it possible to account for a number of important facts concerning nuclear fragmentation and fission.

If the fragments are assumed to be nucleon associations knocked out of the nucleus by cascade nucleons or produced by evaporating from an excited residue-nucleus then the increase of their production cross sections slows down rapidly at energies of the order of several GeV. This has been observed in experiment.

Next, since the h -particles carry away the main part of the mass lost by the target-nucleus then the parameters charaterising the mass distribution as a function of energy T must also tend to the "saturation" at energies of the order of a few GeV. The analysis of the radiochemical measurements for nuclei in the middle of the Mendeleev table confirms this conclusion.

At energies higher than several hundreds of MeV, with further increasing T , the growth of the excitation energy compensates only partially the increase of the fission barrier which is due to still deeper spallation of nuclei. This leads to a decrease of the fission cross section σ_f with increasing T . However at energies of the order of few GeV and higher this decrease must slow down. The results of recent measurements confirm this conclusion, too/21,22/.

None of the effects just mentioned is explained by the usual cascade model. In addition to the change of the intranuclear nucleon density there is one more important effect which is not taken into account in cascade calculations and consists in that at energies higher than several GeV, in $\pi - N$ and $N - N$ collisions resonons are intensively produced which are then involved in the intanuclear cascade. At present the cascade calculations taking into account this effect have not yet been performed, however, from the kinematic point of view this is, to a certain extent, equivalent to the fact that the intranuclear nucleon interacts simultaneously with several "stuck together" particles and an effective account is made of the mechanism of "many-particle interactions" to the discussion of which we are just proceeding.

9. In passing to the region of very high energies $T \gg 10$ GeV, owing to relativistic contraction the angles of particles produced in $\pi - N$ and $N - N$ collisions become so small that any discrimination of the times of interactions of these particles with an intranuclear nucleon becomes meaningless. In other words, there occurs simul-

taneous scattering and absorption of several particles on one nucleon (in particular, the absorption of a resonon by a nucleon may be considered as a particular case of such an interaction).

Since at present we know nothing about the properties of multiple-particle interactions, it is advisable to consider the inverse problem: let us attempt to obtain some information on these interactions from the analysis of the experimental data on cosmic-ray experiments. We should begin the calculation, of course, from the most general assumptions on the character of multiple-particle interactions and then should introduce further details only as far as it becomes quite necessary for obtaining agreement between the calculation results and experiment. Such an approach would guarantee against the introduction to the theory of unjustified assumptions.

The calculations have shown that in this case one succeeds in obtaining a number of quite definite and rather general conclusions. In particular, the fact itself of the existence of the multiple-particle interactions as well as the fact that the characteristics of particles produced in such interactions are close to those observed in the usual two-particle interactions at high energies, e.g. the presence of the leading particle and the asymmetric character of the angular distributions of the remaining particles, may be considered to be reliably established.

The results related to the multiple-particle interactions which at 10 GeV amount to several dozens of percent are presented in detail in refs.[6] We have yet no new results.

Table II shows how well the calculated quantities taking into account multiple-particle interactions agree with experiment.

10. A considerable part of the information on strong interactions in the range of ultrahigh energies is now obtained from the analysis of inelastic nucleus-nucleus collisions. Therefore the study of the mechanism of such collisions is a very timely problem. It is extremely important to learn to calculate the processes proceeding in collisions of nuclei of energy higher than several hundreds of MeV by nucleons in connection with the calculations of radiation protection and the design of high-current accelerators.

However, none of such calculations have been performed to date. This is explained by both mathematical difficulties and uncertainties in the physical picture of the process.

The first step in these lines is the consideration of deuteron-nucleus collisions. The calculations carried out at our Lab. have shown that these collisions are well described by the intranuclear cascade mechanism. At the same time, in this case of importance is the account of peripheral diffractional deuteron splittings. It should be expected that such interactions are rather important for heavier incident nuclei, too.

Figs. 20 and 21 show how the results of calculations agree with experiment. More detailed data are given in refs.[23].

11. Thus, the intranuclear cascade model makes it possible to obtain agreement with experiment over the whole energy range from several dozens of MeV to several GeV, and with the account of the change of the intranuclear matter density and the multiparticle interactions - at still higher energies.

It is more difficult to obtain agreement for low-energy secondary particle with energies not exceeding several dozens of MeV, in particular, one does not succeed for the time being in explaining the properties of "evaporation" particles for one and the same set of parameters independent of the primary particle energy.

In order to improve the cascade-evaporation model it is interasting to study not so much the integral average characteristics as the differential distributions and the correlations between separate quantities. Of a special importance is the low-energy component of produced particles.

Much work is required for the explanation of the fragmentation phenomena and the emission of fast nuclei of deuterium, tritium, helium. In this domain the theory is somewhat behind the experiment.

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Table 1

The average angular momenta (in units $\hbar$) and the momenta of the recoil nuclei (in units MeV/c) produced in collisions of protons and neutrons with nuclei ^{100}Ru at an energy T.

T, GeV :	0,66		1,84		3,2	
primary particle	n	p	n	p	n	p
M	6.3±0.2	6.6± 0.I	8.6±0.3	8.4±0.3	I2.4±0.7	II.8±0.6
$M_{\perp}$	5.2±0.2	5.4± 0.I	7.0±0.3	6.8±0.3	I0.3±0.6	9.9±0.5
P	422 ±I4	427 ±8	64I ±25	6I5 ±24	900 ±50	773 ± 42
$P_{\parallel}$	273 ±9	260 ±5	430 ±I8	32I ±I5	553 ±3I	500 ± 28

Table 2

Comparison of the results of cascade calculations taking into account multiple-particle interactions with experiment.

T GeV	Interaction	Characteristic	Theory	Experiment[x]
I00	p +LEm	$\bar{n}_s$	7.9±0,4	7.4±0,5
		$\bar{T}_s$, Gev	3,I±0,2	2,9±0,3
	p + Em	$\bar{n}_s$	I0,3±0,5	8,0±0,5
		$\bar{n}_g$	3,6±0,2	5,0±I.6
		$\bar{T}_s$, Gev	2,8±0,2	2.4±0,9
200	π^- + LEm	$\bar{n}_s$	9.7±0.4	8.0±0,9
		$\theta^o_{1/2s}$	6,5±0,3	6.2±0.4
	π^- + Em	$\bar{n}_s$	II.2±0,6	I0.8±0,9
		$\theta^o_{1/2s}$	9.0±0.5	8,3±0,6
	π^- + HEm	$\bar{n}_s$	I5,4±0,7	I4,7±2,0
		$\theta^o_{1/2s}$	I2,0±0.6	II,0±I,I
500	p + Em	$\bar{n}_s$	I8,0±0,9	I8,8±4.2
		$\bar{n}_g$	3,7±0,2	4.0±0.8
10^3	p + LEm	$\bar{n}_s$	I2,I±0,6	9,9±I.4
	p + Em	$\bar{n}_s$	20,5±I.I	22,5±3.0
		$\bar{n}_g(6>)$	3.6±0.2	4 ±I.6

x/ For the bibliography see refs./6/

LEm , Em , HEm are medium-light, medium and medium-heavy emulsion nuclei (except the leading one); $\theta_{1/2}$ is the angle within which half of the s - particles are emitted (Lab. system).

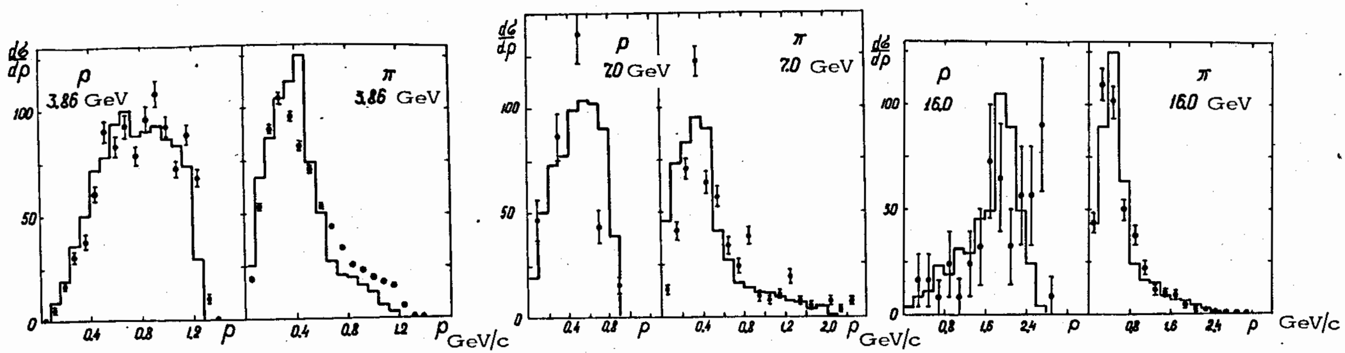


Fig.1. Momentum distributions of protons and pions in reactions $\pi^- + p \to N + n\pi$, $n > 2$. The energy of primary π^- -mesons is indicated in GeV. The histograms are the calculation by the Monte-Carlo method using the polynomial approximation.

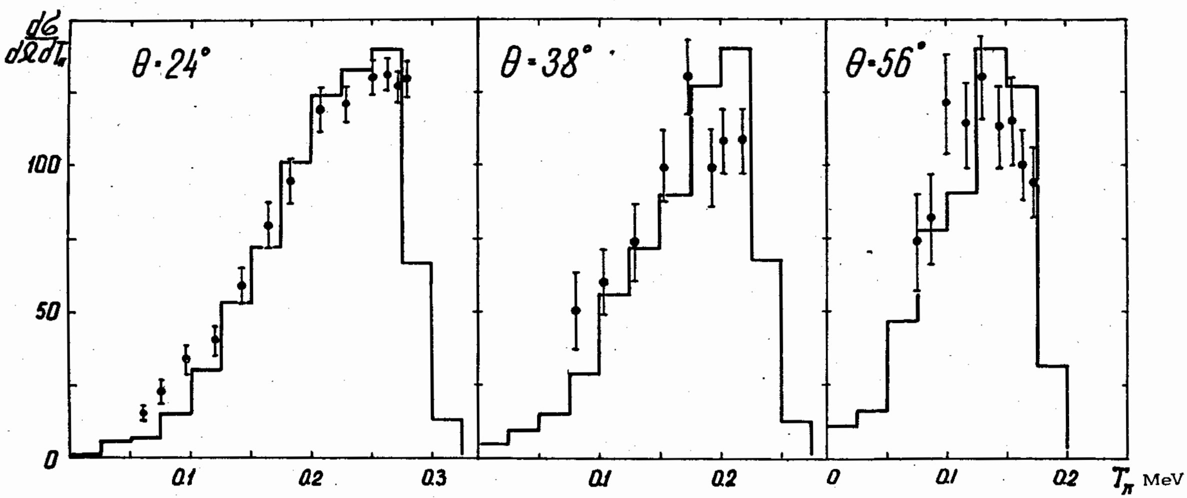
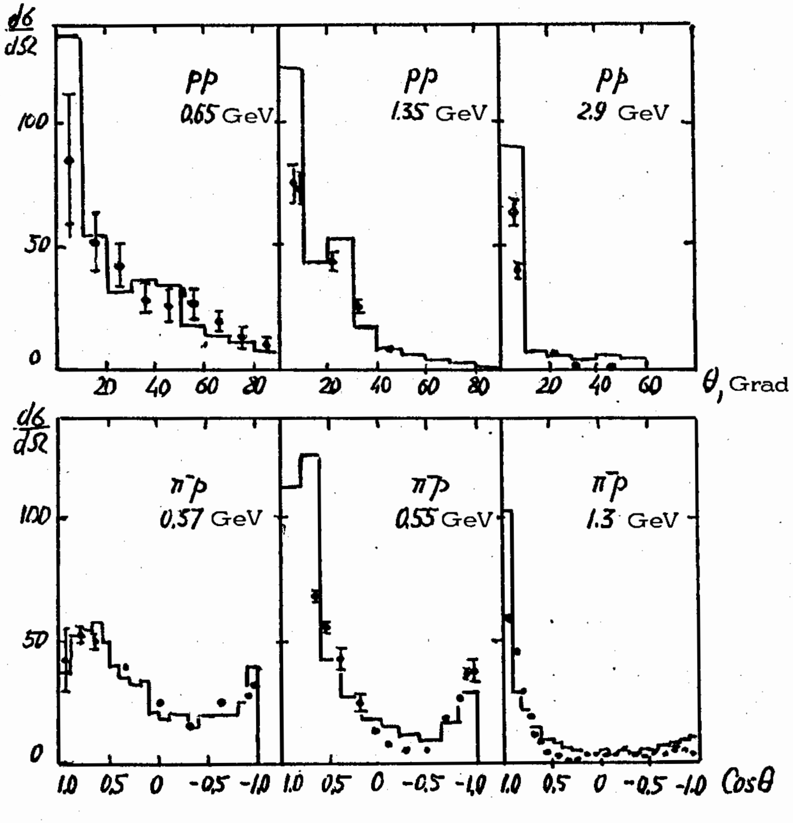


Fig.2. Energy spectra of $\pi^{\pm}$ -mesons at an angle θ in the reaction $p + p \rightarrow 2N + \pi$ at 670 MeV. The histograms are the calculation by the Monte-Carlo method with the use of the polynomial approximation.



g.3. Angular distributions of elastically scattered particles. The histograms are the calculation by the Monte-Carlo method using the polynomial approximation.

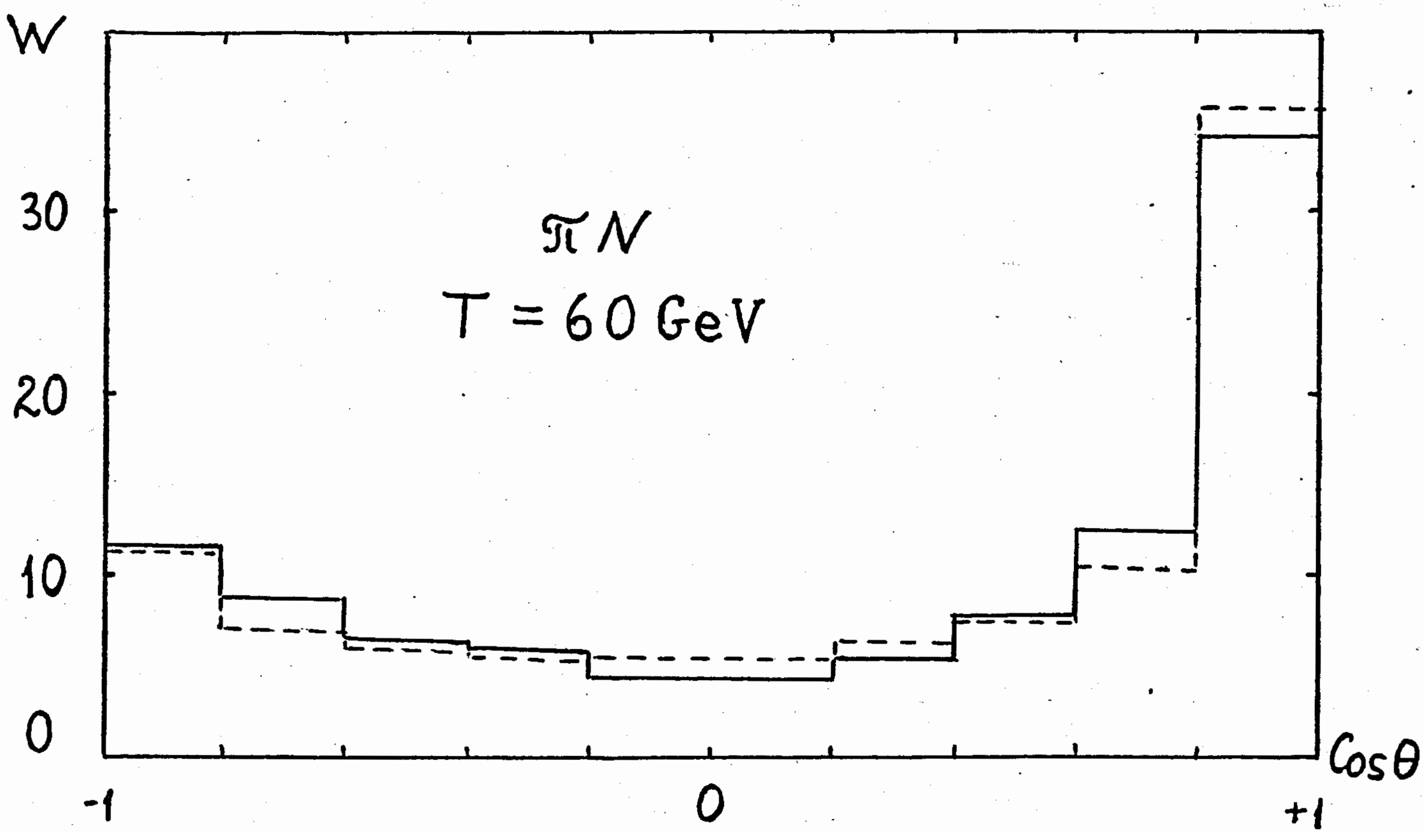


Fig. 4. Angular distributions of charged mesons produced in inelastic collisions at T = 60 GeV. The continuous histogram is the calculation, the dashed one is the experimental data obtained on the Serpukhov accelerator by K.D. Tolstov et al.

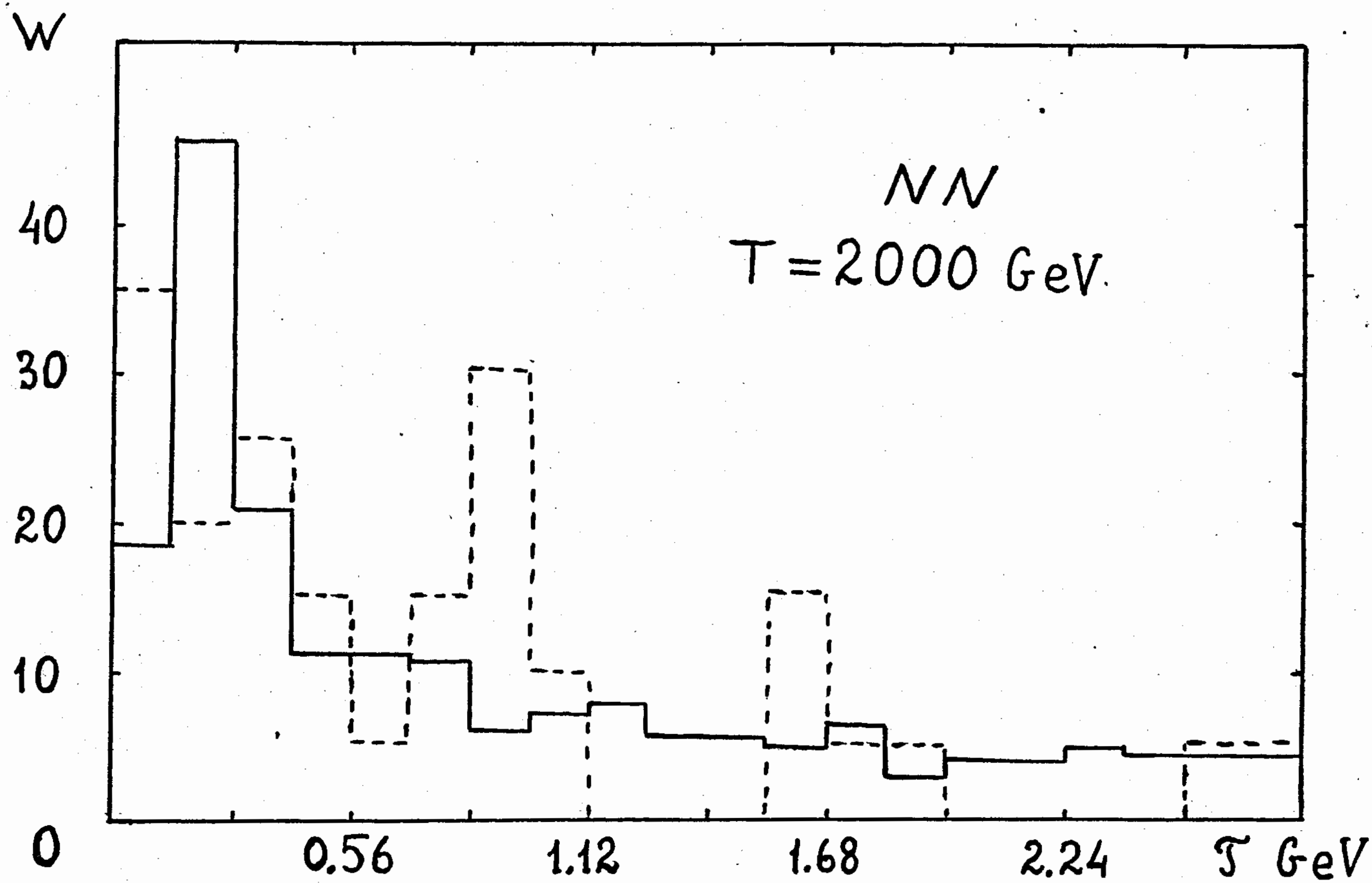


Fig. 5. Distribution of charged particles from inelastic collisions at T ≅ 2000 GeV over their kinetic energy. The continuous histogram is the calculation, the dashed line is the experiment.

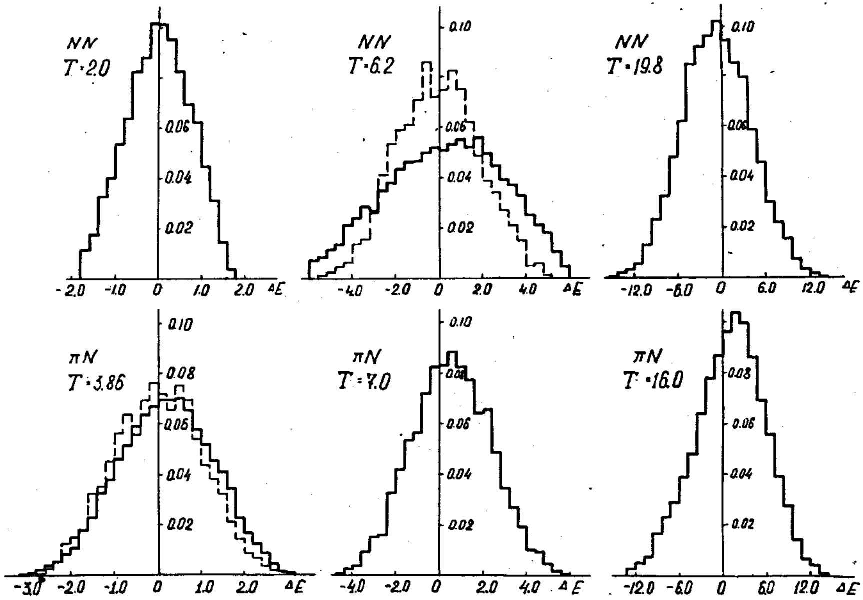


Fig.6. Distribution of the energy difference ΔE (GeV, Lab, system) for $\pi - N$ and $N - N$ interactions at an energy T GeV. The dashed line shows the distributions calculated under a simlified assumption on the isotropic emission of secondary particles.

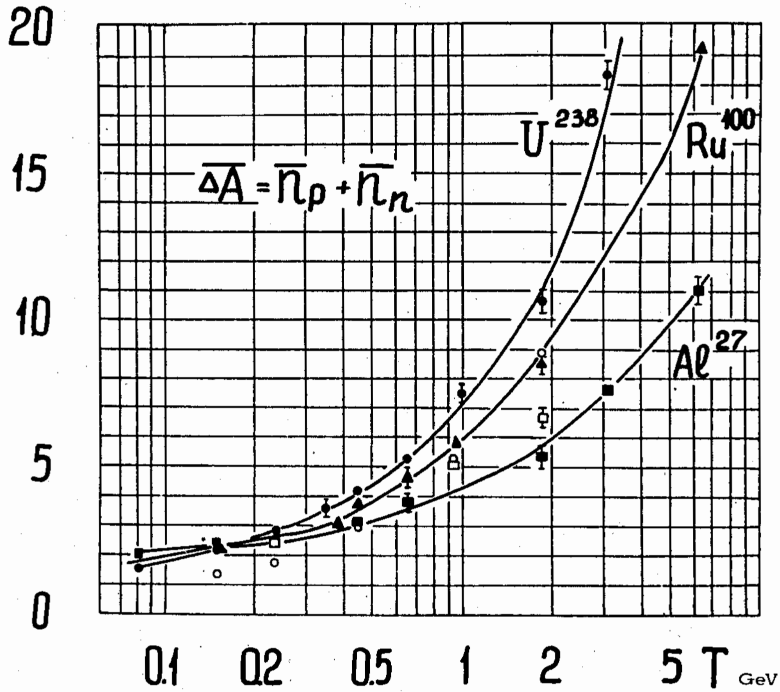


Fig.7. Average number of cascade nucleons knocked out from nuclei by protons of an energy T . The squares, triangles and circles are related to nuclei ^{27}Al , ^{100}Ru , ^{238}U , respectively. The light marks denote the results of calculations by Metropolis et al./8/, the shaded one are our results.

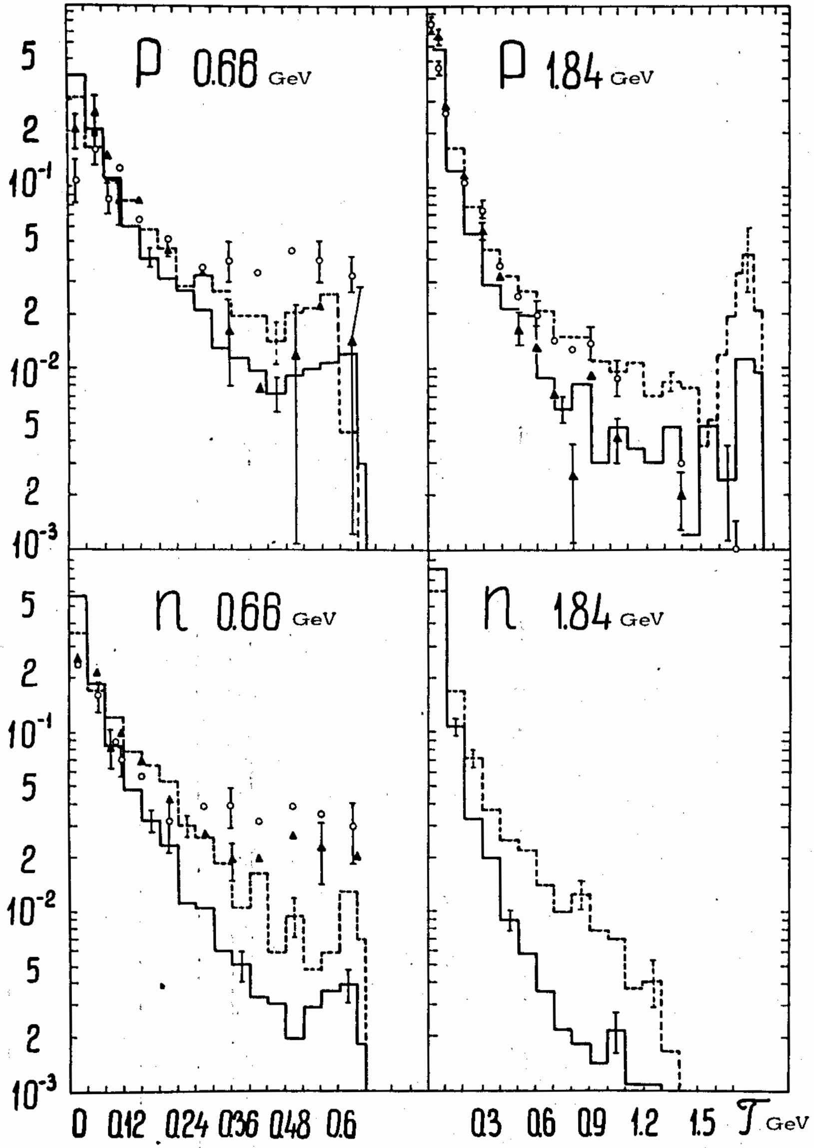


Fig.8. Energy spectrum of cascade protons and neutrons produced in the interactions of protons with nuclei ^{27}Al (dashed histogram) and ^{238}U (continuous one) at T = 0.66 and T = 1.84 GeV. The circles and triangles indicate the data obtained at T = 0.66 GeV by Denisov et al./11/ for ^{28}Si and ^{197}Au and at T = 1.84 GeV by Metropolis et al./8/ for ^{27}Al and ^{238}U .

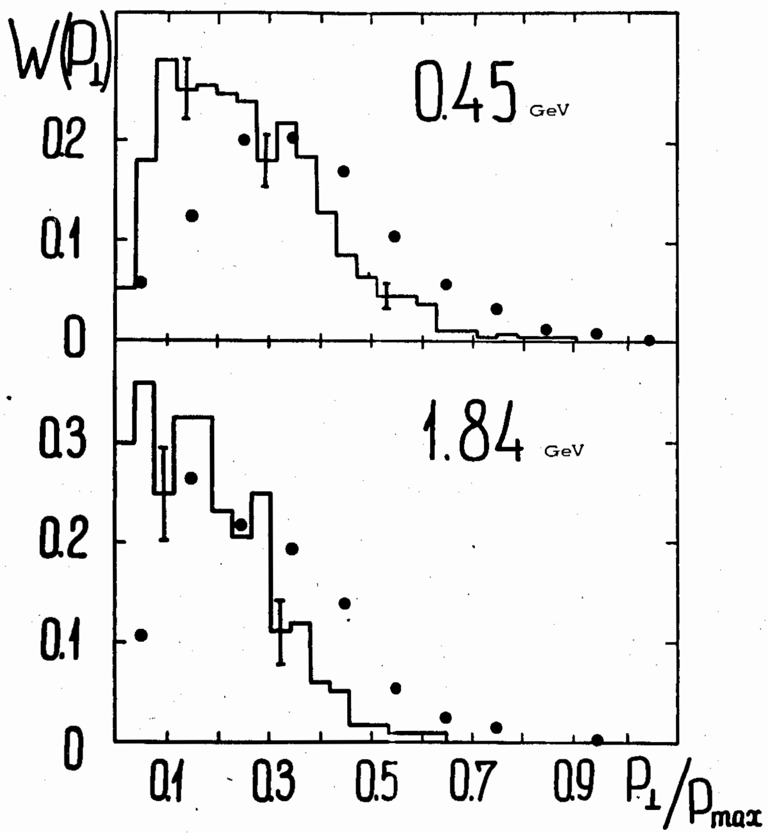


Fig.9. Distribution over the transverse momentum of residual nuclei produced in the collisions of protons with the lead nuclei. The points are the Porile results/15/ for vismuth.

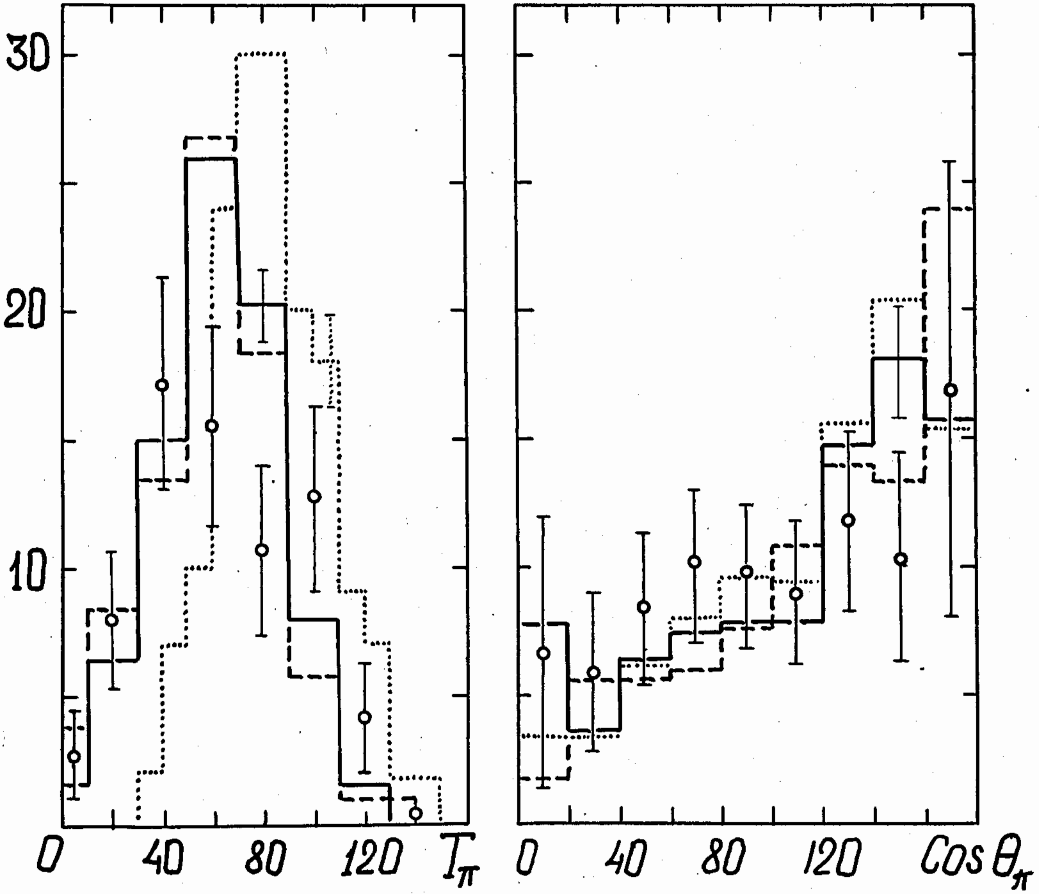


Fig.10. Angular distribution and the energy spectrum of π^--mesons inelastically scattered by emulsion nuclei in the range $90^0 \leq \theta \leq 180^0$ (in arbitrary units, the T_π values are in MeV).

The energy of primary π^--mesons is $T = 160$ MeV. The continuous and point histograms are related to the case $V_\pi = 25$ MeV and $V_\pi = 0$, respectively; in both cases the absorption of mesons in the nucleus is taken into account. The dashed line is the histograms for the case when $V_\pi = 25$ MeV and the absorption is not taken into account. The experimental points are taken from ref./13/.

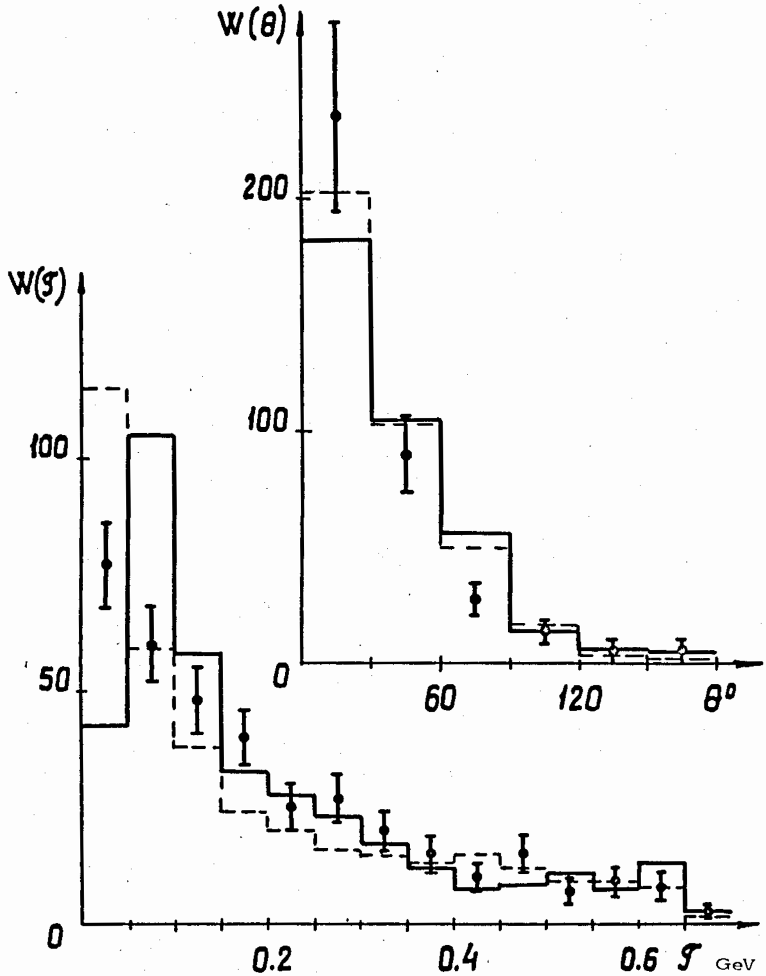


Fig.11. Energy and angular distributions of secondary protons from the interactions $p+{}^{12}C$ at T = 660 MeV. The histograms are the calculation result. For comparison the dashed line shows the data obtained without the account of the nuclear boundary diffuseness and the meson production processes.

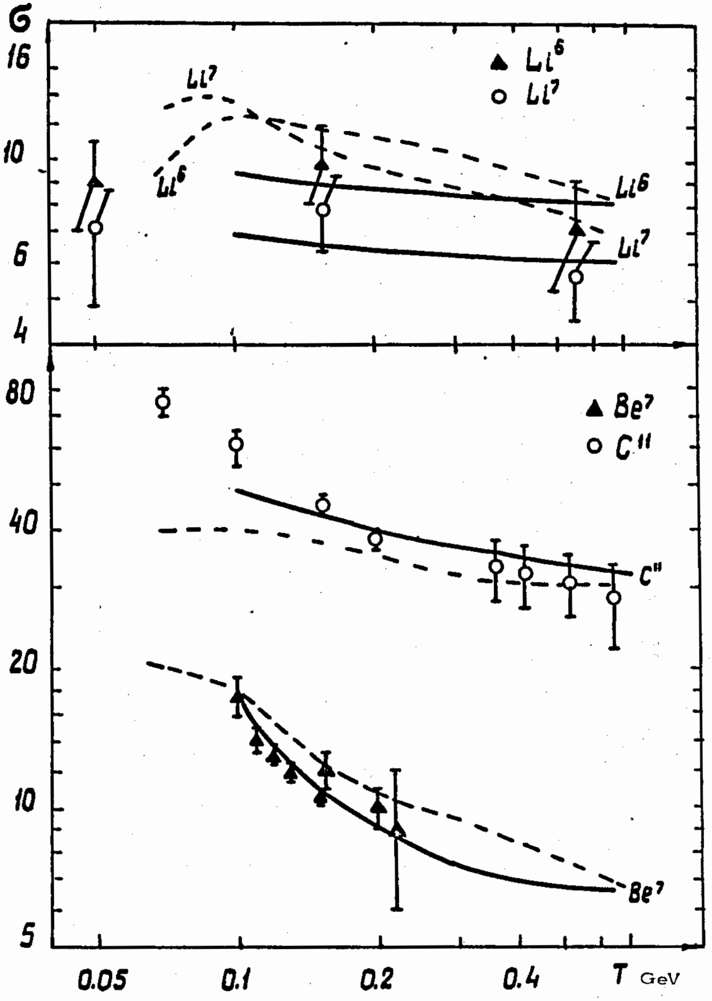


Fig. 12. Energy dependence of production cross section for different isotopes in reactions $p + {}^{12}C$ (in mb). The curves are the result of calculation. The dashed lines are the data obtained without the account of the nuclear boundary diffuseness and the meson production processes.

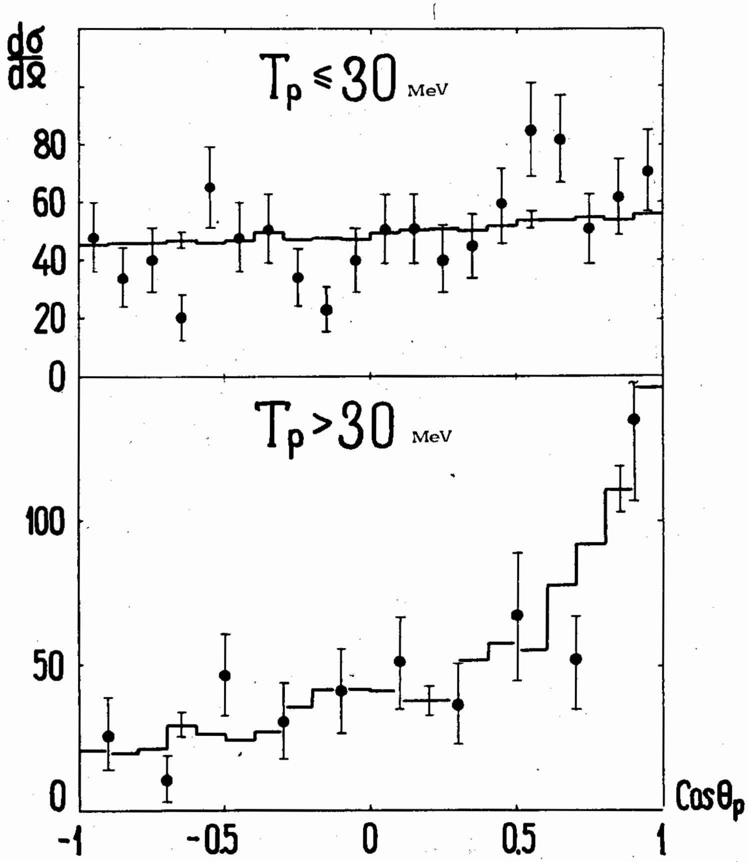


Fig. 13. Comparison with theory of the experimental angular distributions of protons from stars with the number of prongs $n \geq 2$ produced in irradiating the emulsion by gamma quanta of energy T_{max} = 1150 MeV (in arbitrary units). The histograms are the calculation for ^{100}Ru .

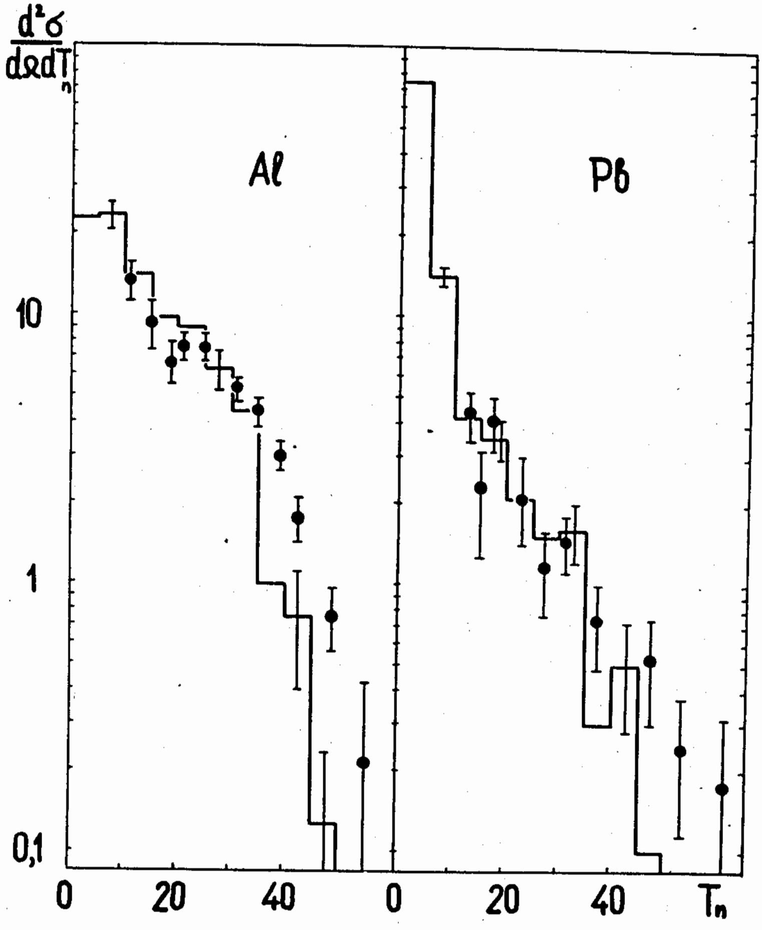


Fig. 14. Comparison with theory of the neutron experimental spectra at an angle $\theta = 67.5^{\circ}$ for the reactions $\gamma + {}^{27}Al$ and $\gamma + {}^{207}Pb$ at $T_{max} = .85$ MeV (in relative units, T_n in MeV).

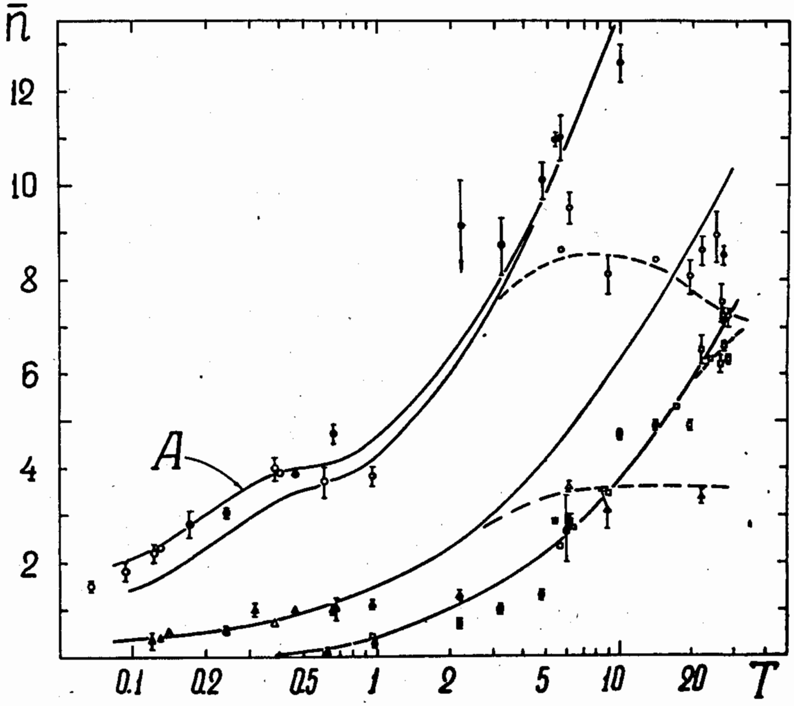


Fig. 15. Dependence of the average number of s-, g- and h-particles in emulsion stars on the primary proton energy. The continuous curves are the calculation; the curve A is the calculation $\bar{n}_h(T)$ for stars with $n_h > 1$. The dashed lines are the curves approximating the most reliable experimental points. The marks o , Δ and □ are the experimental values of $\bar{n}_h$, $\bar{n}_g$ and $\bar{n}_s$ respectively obtained by scanning "along track", the shaded marks are related to the values obtained by scanning "over the area".

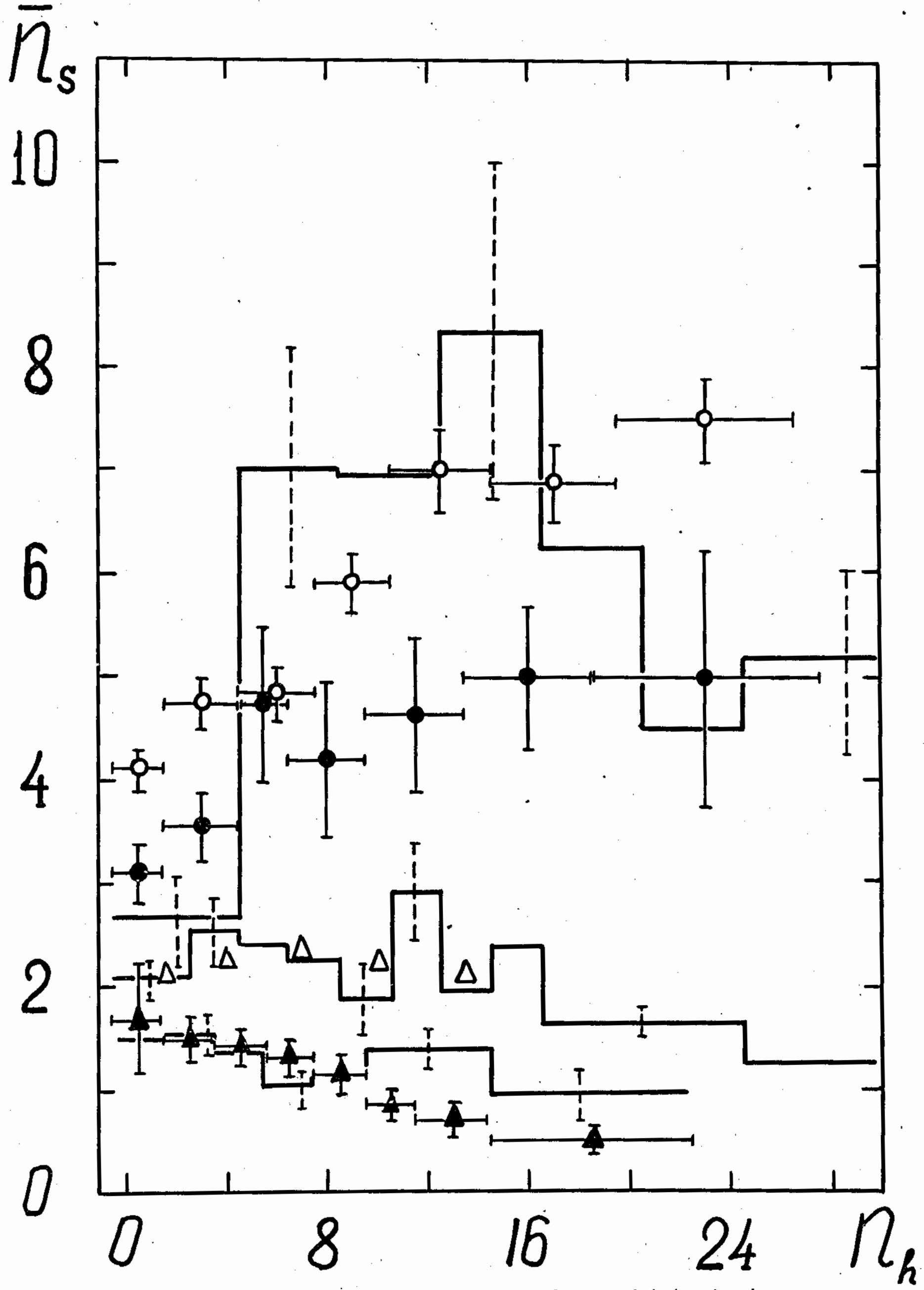


Fig. 16. Correlation of the average number of s- and h-tracks in emulsion nuclei produced by π^- -mesons. The marks ▲, Δ and ●, O show the experimental data for T = 1 . 87; 4.2; 10 and 16.1 GeV respectively. The histograms are the calculation for T = 1,87; 4.2 and 16.1 GeV.

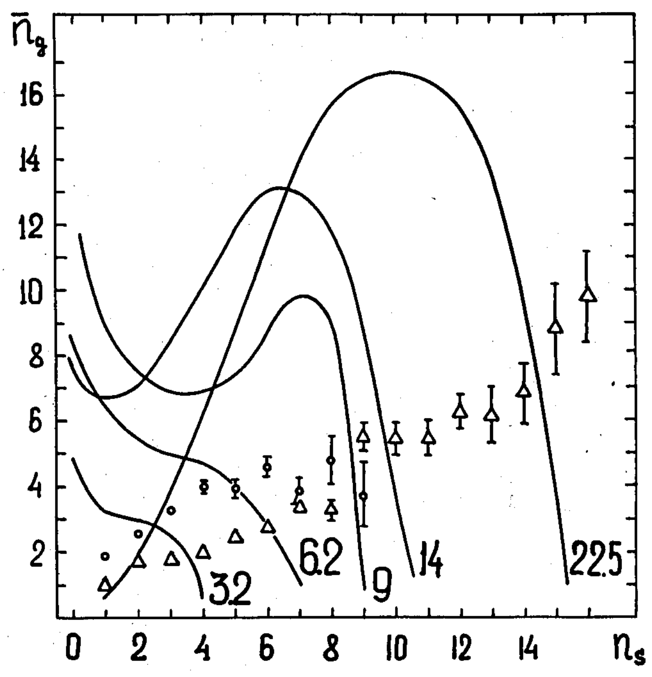


Fig. 17. Dependence of the average multiplicity of g -tracks on the number of s-particles in emulsion stars produced by protons, the curves are the calculation; the numbers near the curves indicate the primary proton energy in GeV. The circles and triangles give the experimental Winzeler's data for T = 6.2 and 22,5 GeV respectively.

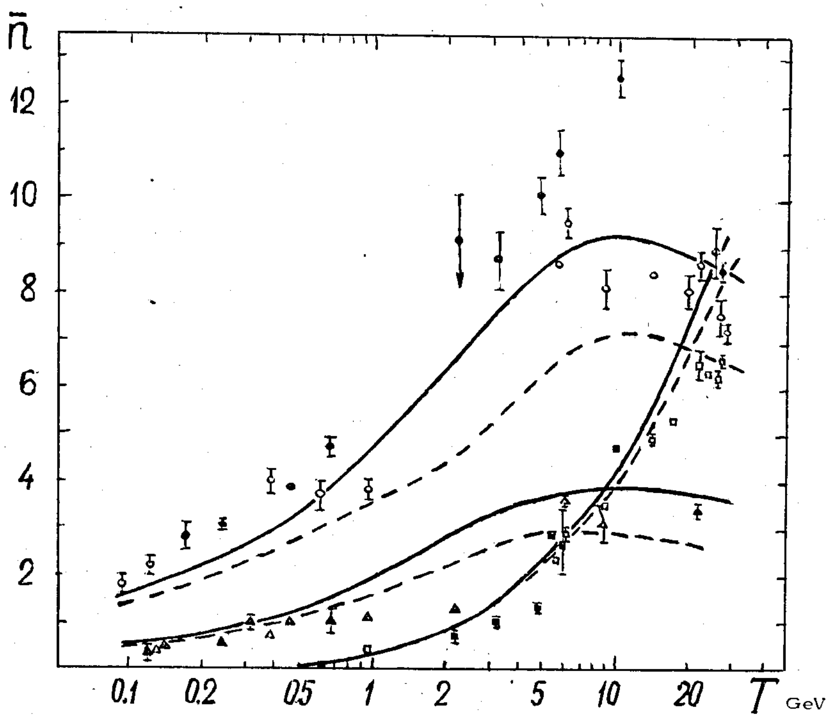


Fig. 18. Energy dependence of the average multiplicity of s-, g- and h-particles calculated taking into account the nuclear density change. The continuous curve is the caculation for the parameters $r_n = 1.3 \times 10^{-3}$ cm the dashed line is the calculation for $r_n = 1.3 \times 10^{-13}$ cm under the condition $n_h > 1$.

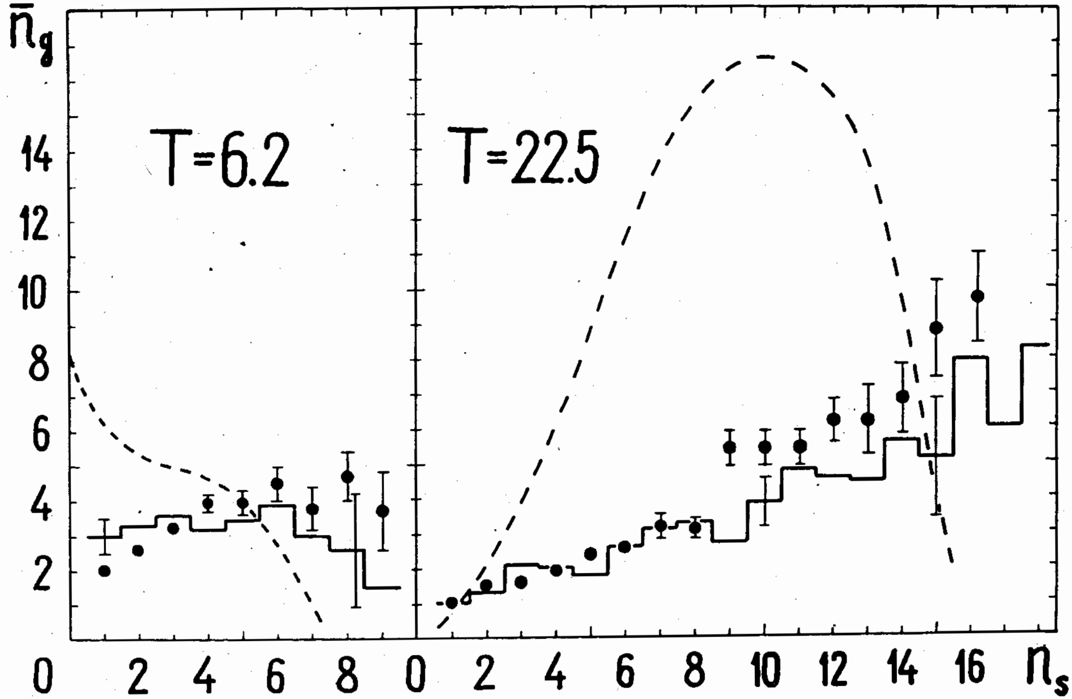


Fig. 19. The same as in Fig. 17.
The calculation results with the account of the change of intranuclear density $r_n = 1.3 \times 10^{-13}$ cm.

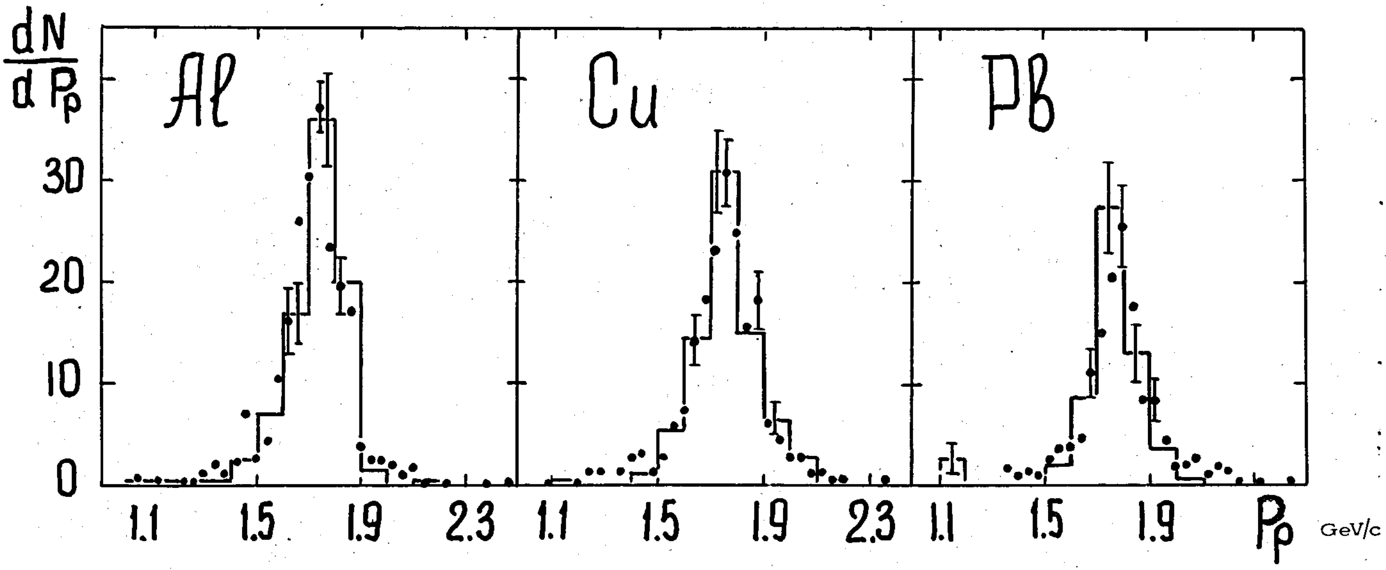


Fig. 20. The momentum distributions of protons produced in inelastic collisions of deuterons with nuclei at T = 2.1 GeV the histograms are the calculation by the cascade model.

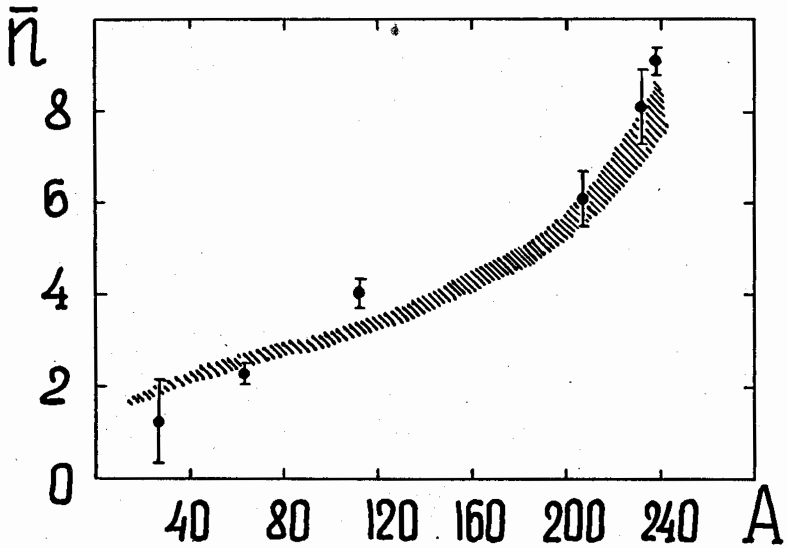


Fig. 21. The average number of neutron produced in the inelastic deuteron-nuclear interaction at T = 160 MeV. The shaded area corresponds to the uncertainty in the calculation of "evaporation" neutrons. The experimental points are taken from ref. /20/.

E2-5282

Барашенков В.С., Ильинов А.С., Тонеев В.Д.

Неупругие взаимодействия частиц и ядер при высоких и сверхвысоких энергиях

Обзор, посвященный монте-карловским каскадным расчетам неупругих столкновений частица плюс ядро и ядро плюс ядро при энергиях от нескольких десятков Мэв до тысяч Бэв.

Сообщения Объединенного института ядерных исследований

Дубна, 1970

E2-5282

Barashenkov V.S., Iljinov A.S., Toneev V.D.

Inelastic Interactions of Particles and Nuclei at High and Superhigh Energies

The methods and the results of the cascade calculations of inelastic interactions of particles and nuclei in the energy range from several dozens of MeV to several thousands of GeV are discussed. The discussion is based mainly on the work performed at Dubna. Special attention is paid to the cases in which the calculations performed by the usual cascade model are in disagreement with experiment. Various ways of improving the theory are considered, in particular, the account of the change of the nuclear density as the cascade particle shower develops.

Communications of the Joint Institute for Nuclear Research.

Dubna, 1970