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И Н С Т И Т У Т
ЯДЕРНОЙ ФИЗИКИ СОАН СССР

ПРЕПРИНТ И Я Ф 77 - 20

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Новосибирск
1977

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1. Introduction

Hadron-nucleus collisions have recently attracted much attention as a source of very interesting information on the space-time picture of hadronic reactions. Significant amount of experimental data are now accumulated, although they still are not very sistematical. The theory of the phenomenon is not much advanced, it provides qualitative explanations rather than methods of practical calculations. To large extend this is because main theoretical approaches like multiperipheral [1], parton [2], and hydrodynamical [3] models give asimptotical (in energy) predictions, while for the problem in question the main interest lies in the middle energies 10 ÷ 300 GeV, where dimensions of the interaction region have the same order of magnitude as the size of real nuclei.

In the present work some model of the phenomenon is proposed which we would like to call <u>the model of effective target</u> (MET). Its main idea is the separation of the target nucleus into two parts, playing essentially different role in the collision. The first is <u>effective target</u> which contains nucleous involved into collective interaction with the incoming hadron, similiar to usual hadron-hadron collisions. In this interaction the secondaries are produced as separate physical objects, which may interact with the rest of the target nucleus in the usual cascade way. Some estimates of the size of the effective target and some simple assumptions on the interaction with it provide a scheme, which is shown to reproduce most of experimental observations. We discuss in particular total multiplicity as a function of collision energy E_0 and atomic number A (§4); the spectra of secondaries (§5), also in the "cumulative" kinematical region; correlations with the number of nonrelativistic protons (§6) production of antiprotons (§7) and make some comments on nucleus-nucleus collisions (§8).

The proposed model is some further development of the tube model [ ] and agrees with it at high energies ($E_0 \gtrsim$

300 GeV). Nevertheless some details differs with the variant of the tube model recently discussed in [5, 6]. The asymptotical predictions of MET are close to those of Landau model [3, 4], but, which is very important, they deviates from predictions of parton model [7] and these deviations are confirmed by data. The possible meaning of it is discussed in § 2. In the same time we have found very reasonable agreement with calculations [7b,d] in parton cascade model at intermediate energies. The same may be said about MET and energy flux cascade model [5]: they are similar at intermediate energies but differ in asymptotics. As for the claster model [8], it deviates from MET both in high energy limit (our "claster" do not decay isotropically) and at intermediate energy (our "claster" in this case decay <u>inside</u> the nucleus). Note also, that at low energies ($E_0 \lesssim 5$ GeV) MET joints smoothly with the usual cascade model.

The advantages of MET are rather direct connection of space-time picture of the hadronic reactions with the observable quantities and also its simplicity, important for practical calculations. Of course, simplicity is due to some approximation and with further studies such type of models will be substituted by more consistent theories. But now we have to choose reasonable first approximation and the present work should be considered as such an attempt.

2. The model of effective target.

By the effective target we mean target nucleous which take part in the collective interaction with the incoming hadron. Outside this region secondarios exist as separate objects, but inside it they are not yet formed, so the system can be described either in terms of constituents of hadrons (parton model) or just by its energy and momentum (hydrodynamical and energy flux cascade models). We give no description of this stage of the process, but try to connect it with usual hadron-hadron collisions.

At high enough energies the effective target is <u>the tube</u> of nucleous met by incoming hadron on its way through nucleus [4]. At middle energies it is only its forward part of the length we are now going to estimate. All theories [1-3] agree that the distance $L(E)$ needed for particle of energy E to be formed is

$$L(E) \sim const \cdot E \tag{1}$$

with constant of the order of 1 fm/GeV. This is just consequence of average $p_\perp$ universality due to which secondaries come out at angles $\sim 1/E$ and are separated at distance (1). There exist many more ways to explain (1).

Our first approximation is the choice of some typical $L(E)$ representing collision as whole. One may take $L(E_{max})$ where E_{max} is the energy, corresponding to maximum of the spectrum, that is, to rest in CM frame:

$$L(E_{max}) = c_1 \cdot E_0^{1/2} \tag{2}$$

Another possible choice is $L(\bar{E})$, where $\bar{E}$ is average energy

$$L(\bar{E}) = \tilde{c}_1 \cdot E_0 / \langle n \rangle \tag{3}$$

Since these estimates are needed only for middle energies, the difference between (2), (3) is within the needed accuracy. Below we use (2) with $c_1 = 2 \cdot r_0 \cdot m_p^{-1/2}$ where r_0 and m_p are radius and mass of nucleon.

Determine mass of the effective target as

$$M_{eff} = m n \sigma_{in} L \tag{4}$$

where m is proton mass, n - nuclear density, σ_{in} - hadron-nucleon inelastic collision, and L - minimal of (2) or the geometrical tube length $L_0 = 2(R^2 - \rho^2)^{1/2}$; where R is nuclear radious and ρ - the impact parameter.

Our next step is the main assumption. It makes use of the known remarkable similarity of spectra of secondaries in different hadronic reactions (the so called leading particles we now ignore). We assume that in the collision with effective target the spectra have the same shape as in collisions with hadrons, if they are taken each in its CM frame:

$$f(y-y_c, p_\perp, E_0, M_{eff}) \approx C(M_{eff}) \cdot f_{pp}(y-y_0, p_\perp, E_0) \quad (5)$$

where $f \equiv E\frac{dN}{d^3p}$ is the inclusive spectrum, depending on rapidity y and transverse momentum $p_\perp$ os secondaries, initial energy E_0 and the mass of effective target M_{eff} (4), $C(M_{eff})$ is the normalization factor; and y_c, y_0 correspond to those CM frames:

$$y_c = \frac{1}{2}\ln\frac{2E_0}{M_{eff}}; \qquad y_0 = \frac{1}{2}\ln\frac{2E_0}{m} \quad (6)$$

As we show below, many observations give support to relation (5), that is to the shift of spectra from y_0 to y_c. Now we are going to discuss why such phenomenon may take place. The reader may omit these speculations and consider (5) as phenomenological observation.

Begin with the note, that from the view point of parton model such shift can not take place asymptotically because partons, if energetic enough, must penetrate through nucleus without interaction. Data to be discussed below show such shift up to highest energies $\sim 10^4$ GeV, while the so called leading protons appear at energies $\sim$ 10 GeV in agreement with this prediction of parton model. So we meet some contradiction to the idea that the interaction of parton depend on its energy only. This contradiction may disappear if valence quarks and neutral glue interact differently (see 9). The former behaves as predicted by parton model and forms leading particles, while the glue together with the glue of effective target forms some excided system, decaying into other secondaries. So the rapidity shift is just a collective recoil of glue. Essential, that such a picture does not contradict to famous parton interpretation of deep enelastic lepron-hadron collisions, based mainly on valence quarks.

To prove or reject these speculations one needs new experiments. Anyway they show how strongly such studies are connected with the most interesting problems of the strong interaction physics.

3. Parametrization and averaging over impact parameter.

In order to give final expression for spectra in hadron-nucleus collisions we choose some parametrization of quantities which enter in (5). This choice is done for simplicity and is not of principal importance. The distribution on rapidity of $f_{pp}(y)$ we take to be of convenient gaussian shape:

$$f_{pp}(y-y_0, E_0) \equiv \frac{dN}{dy} = \frac{\langle n_{pp}\rangle}{\sqrt{2\pi D}} \exp\left[-\frac{(y-y_0)^2}{2D}\right] \quad (7)$$

The normalization $C(M_{eff})$ we take in the simple power form:

$$C(M_{eff}) = C_2 \cdot \left(\frac{M_{eff}}{m}\right)^{\alpha} \quad (8)$$

The use of (7), (8) allows to average over impact parameter in analitical form. Let us separate nucleus into the following three regions (see Fig.1): I - diffuse region, where nuclear density is small, so usual hN collisions takes place here. II - region where the tube length $L_{tube} < L(E_{max})$ and III - $L_{tube} > L(E_{max})$

Clear, that at high enough energy region III is absent. The contribution of these regionsinto inclusive spectum $f_{hA}(y, p_\perp, A, E_0)$ is

$$f_I = \frac{\sigma_{dif}}{\sigma_{tot}} \cdot \frac{n_{pp}}{\sqrt{2\pi D}} \exp\left(-\frac{(y-y_0)^2}{2D}\right)$$

$$f_{II} = \left(1-\frac{\sigma_{dif}}{\sigma_{tot}}\right) \cdot 2n_{pp} \cdot \left\{ erf\left[\frac{(y-y_0) - 2D\cdot(\alpha+2) + \frac{\ln \tilde{L}}{2}}{\sqrt{2D}}\right] - erf\left[\frac{(y-y_0) - 2D\cdot(\alpha+2)}{\sqrt{2D}}\right]\right\} \cdot \exp\{2D\cdot(\alpha+2)^2 - 2(y-y_0)\cdot(\alpha+2)\} \quad (9)$$

$$f_{III} = \left(1-\frac{\sigma_{dif}}{\sigma_{tot}}\right) \cdot (A^{2/3} - \tilde{L}^2) \cdot \frac{n_{pp}}{\sqrt{2\pi D}} \exp\left\{-\frac{\left[y-y_0+\frac{\ln(\tilde{L})}{2}\right]^2}{\sqrt{2D}}\right\}$$

$$\tilde{L} = \min(L(E_{max}, A^{1/3})$$

where $f_{hA} = C_2 \cdot (f_I + f_{II} + f_{III})$; $erf(X)$ is error function; and according to formfactor measurements

$$\frac{\sigma_{del}}{\sigma_{inel}} = \frac{1.89}{A^{1/3}} - \frac{0.905}{A^{2/3}} \qquad (10)$$

Our free parameters are C_2, α (8), C_1 (2) ; they are taken to be $C_2 = 1.13$; $\alpha = \frac{3}{4}$; $C_1 = 2 \cdot r_0 \cdot m_p^{-1/2}$.

The cascading outside the effective target does not affect much the number and spectra of relativistic particles and is neglected. The exceptions are antiproton production (§7) and correlations with nonrelativistic particles (§6) where cascading is essential.

4. Average multiplicity of secondaries.

The set of data on average multiplicity in proton-nucleus collisions is shown at Fig. 2 as the ratio R

$$R(A, E_0) = \frac{\langle n_{pA} \rangle}{\langle n_{pp} \rangle} \qquad (11)$$

where, as usual, nonrelativistic particles ($\frac{v}{c} < 0.7$) are excluded. The left part of Fig.2 shows energy dependence for 1) C, N, O ; 2) Al ; 3) Nuclear emulsion; 4) Pb, W nuclei and the right one - the A dependence at high energy ($E_0 \gtrsim$ 300 GeV). The solid lines correspond to our calculations.

Analysis of these data we begin from high energy limit, for which MET predicts

$$R(A, E_0) = f_1(A) \quad for\ E_0 > E_{critical}(A) \qquad (12)$$

where $E_{critical}(A)$ is determined from simple condition: $L(E_{max})$ reaches nuclear diameter. Note, that in parton model (12) is not valid and at $E_0 \to \infty$ $R(A, E_0) \to 1 + const \cdot A^{1/3} / \ln E_0$ [7]. In the hydrodynamical model [3, 4] asymptotics is in agreement with (12). The function $f_1(A)$ is shown at Fig.2 (right part), it is not of simple power form as it was often assumed. The reason is simple: light nuclei are less dense, than heavy

ones. For $A >$ 15 this function is close to $A^{1/4}$ (dashed curve), corresponding to α = 3/4 (8). In the parton model and preasymptotic energies $R \sim A^{1/3}$ [7], in the hydrodynamical model the power value is somehow smaller 0.22 ÷ 0.25 [3, 4]. In papers [6] the empirical relation $R(E_0, A) = R(A^{1/3}E, 1)$ was proposed, which gives too weak dependence like $A^{1/12}$, see Fig. 2.

At intermediate energies 10-300 GeV behaviour of $R(E_0, A)$ is determined by the interplay of geometrical factors and the effective target length (2). As Fig.2 shows, the model gives a very good description of the data.

5. Spectra of secondaries

The available data on momentum spectra of secondary particles cover different kinematical regions, targets, initial energies etc. and they are difficult to compare. Fortunately, the $p_\perp$ dependence is universal and angular distribution is almost the same as rapidity distribution. At Fig. 3 we show data on pseudorapidity distributions of charged secondaries from collisions with Cr and W nuclei at E_0 = 300 GeV [14]. The solid curves are MET predictions. The general shift of spectra is seen in data and reproduced by the model. Note, that both maxima positions and normalizations depend on the same quantity: the mass of effective target (4).

It is interesting, that at high energy end of spectrum the A -dependence becomes inverse: the heavier is the target, the smaller particle yield. The explanation is simple: this kinematical region is dominated by collisions with diffuse region near nuclear edge, which gives smaller part of the cross section for havier nuclei.

The most clear indication to collective nature of collisions with nucleus is the so called "cumulative" effect [16], the production of secondaries outside the kinematical bounds of collisions with one nucleon. Note, that the spectrum in this region is the smooth continuation of that for typical collisions, so they are of similar origin.

To describe the spectra of secondaries in the cumulative region we need to modify assumption of § 3 about gaussian shape of rapidity distribution, not valid at far "tail" of spectra we now are interested in. Since experiments [16] were done at rather low energies 6 ÷ 8 GeV it is sufficient to assume, that in the collision with effective target some claster is produced, which decays isotropically in the statistical way:

$$E\frac{dN}{d^3p}(p_\perp=0) = const(E_0)\cdot exp\left[-\frac{m\,ch(y-y_0)}{T}\right] \quad (13)$$

This, of course, coinsides with gaussian for small $y-y_0$.

At Fig. 4 data [16] for π^- at D, Al, Pb are shown, together with data [13] "transformed" to E_0 = 8.4 GeV/c from 19.6 GeV/c with the help of Feynman scaling, shown for the comparison. The curves correspond to M_{eff} = 2.4 m_p, and $M_{eff}=m_p$, that is, for pp-collisions. As seen from the Figure, data are well described by the shifted spectrum in agreement with our estimates (4) for M_{eff}, which for 8.4 GeV give $\approx 2.4 m_p$. Such approach to cumulative effect can easily explain why the slope of the spectra do not depend on A for $A \gtrsim 27$: the M_{eff} is not changed, all heavy nuclei for such small $L(E_{max})$ works identically. The account of edges makes agreement even better. Note, that similar "claster" explanations of the effect have already been proposed in [4c] and [17], and in [4c] even the value of M_{eff} has been estimated to be 2.4 m_p.

But only the present model explains the value of M_{eff} and connects it naturally to many other observations on hadron-nucleus collisions.

6. Correlations to nuclear response

In the discussion above an essential role was played by geometrical factors and nuclear density distribution. It is desirable to eliminate such trivial factors from the consideration. To some extent it can be made by the studies of correlations with nuclear response, for example, by studies instead of A -dependence the N_h dependence, where N_h is a number of ninrelativistic protons seen in emulsion. One may think that N_h is in strong correlation with effective target mass M_{eff} with relatively small fluctuations. If $M_{eff}(N_h)$ is determined, we can use directly (5) without averaging over impact parameter (§ 3).

For high enough energy MET leads to factorization of dependence, similar to A -dependence (12):

$$R(E_0, N_h) = f_2(N_h) \quad (14)$$

As is shown in [11], for E_0 = 70 ÷ 10^4 GeV agrees with (14). The comparison of $f_2(N_h)$ and $f_1(M_{eff})$ give the relation $N_h^{0.45} = (M_{eff})^\alpha$ and so we are able to calculate spectra $f(y, N_h)$. They are shown at Fig.5 together with data [15] at 200 GeV. Again, like in the case of A -dependence, one can see the shift of spectra toward smaller rapidities. For very large $N_h \gtrsim 30$ the observed shift becomes larger than predicted by MET. To ascribe this to higher M_{eff} is difficult for M_{eff} then turns out to be unreasonable large. More possible explanation is that events with large N_h corresponds to developed cascade and additional shift is just widening of angular distribution due to rescattering. To clarify this point further studies are needed. For typical N_h the agreement is reasonable.

7. Production of antiprotons

The data on $\bar{p}$ production at Be, Pb targets at 24 GeV [18] are shown at Fig. 6 together with predictions of MET. The agreement is very nice, but one has to remember that Pb data are only for rather energetic $\bar{p}$. Due to relatively large annihilation cross section for $\bar{p}$ with momenta less than 1 GeV they may be absorbed. So in this case the cascading is very significant. This may give better understanding where inside nucleus such particles are produced.

Some estimates from below is the account of the contribution of regions I and II (see Fig.1) only, assuming that of region III to be completely screened out. This is shown by the dashed curve at Fig.6. To have some data on this will be very interesting. This question have important applications for $p\bar{p}$ - colliding beams projects prepared now in Novosibirsk, FNAL and CERN. The absence of data on slow $\bar{p}$ on heavy targets do not allow to estimate the efficiency of the conversion system.

8. Nucleus-Nucleus collisions

This topic is not, of course, so fundamental, but still it is going to be studied, first, because it is more suitable for colliding beams and second, it can lead to heavy particle production which are not available now for pp - collisions.

Our comment is that in nonasymptotical region both parton and hydrodynamical models give the same and very simple prediction:

$$\frac{dN_{AA}(E_0)}{dy} = const \cdot A \cdot \frac{dN_{pp}(E_0)}{dy} \qquad (15)$$

where E_0 is CM energy per nucleon. At $E \gtrsim$ 100 GeV parton model predicts dip in the middle, where $\frac{dN}{dy} \sim A^{2/3}$; while in the hydrodynamical model (15) is valid for any energy.

9. Conclusions

Interaction with the effective target as whole is shown to explain the shift of the spectrum to lower rapidities. All data, from cumulative effect at 8 GeV [16] to correlations with N_h at 10^4 GeV [15], clearly shows such shift in quantitative agreement with our estimates on the effective target dimensions. The absolute number of secondaries is given by these estimates for various nuclei and energies with 10% accuracy. Whether such shift is only phenomenological or it has some deeper ground still remains to be seen.

Figure captions.

Fig. I. Three regions of nucleus. I - diffuse region, II - region, where the tube length $L_{tube} < L(E)$, III - $L_{tube} > L(E)$.

Fig. 2. a) Energy dependence of $R_A = \frac{\langle n_{hA} \rangle}{\langle n_{pp} \rangle}$. Solid curves are the model predictions for collisions with nuclei CNO (A=I4), Al (A=27), Emulsion, AgBr (A=95), W - (A=I84) and Pb (A=207). Data are taken from: x - C [5]; △ - $(CH_2)_n$ [IOa]; o - CNO [IOb]; ▼ and ▼ - Al [IOc ; IOa] respectively; ● - Emulsion [IOd,5]; ◇ - W [I4]; □ - Pb [IOc].
b) Dependence of R_A on the atomic number at the high energies $E_0 \gtrsim$ 200 Gev. Solid curve is our model predictions. Dashed curve is a simple power form parametrisation $R_A = 0.63\, A^{1/4}$. Dashed-dotted curve is the prediction of the model, proposed in [6]. Designation of the datun points are the same, except ● , which correspond here to Cr [I4]; Emulsion [5] and AgBr [IOb] respectively.

Fig. 3. Pseudorapidity distributions of charged secondaries in pW (a), pCr (b) and pp (c) collisions for the primary proton momentum p_0 = 300 gev/c. Data are from [I4] o - pW; ● - pCr.

Fig. 4. "Cumulative" effect. Solid lines represent spectra for collisions with effective mass $M_{eff} = 2.4\, m_p$ (a) and $M_{eff} = m_p$ (b). Dashed and lines at the left and right side show the kinematical bounds for π^- production in pp-collisions. Data are ● - pPb; o -pAl, ■ -pd [I6]; □ - pPb, △ - pBe [I3].

Fig. 5. Pseudorapidity distributions of secondaries for fixed N_h for primary proton momentum p_0 = 200 Gev/c. I) N_h =5, 2) N_h = I5, 3) N_h =30. Points ● , ⊕, o respectively are the datum parametrisation, obtained in [I5].

Fig. 6. Rapidity distributions of antiprotons produced in pBe (I,3) and pPb (2,4) collisions. Curves (I,2) and (3,4) correspond to primary proton momentum p_o = 24 and 300 Gev/c respectively. Dashed line shows the yield for pPb collisions with p_o =24 Gev/c omitting the contribution of the region III. Shaded area shows uncertainty due to absorbtion of antiprotons inside the nucleus. Data are o - Be [I8a]; ● - Be, ▽ - Pb [I8b].

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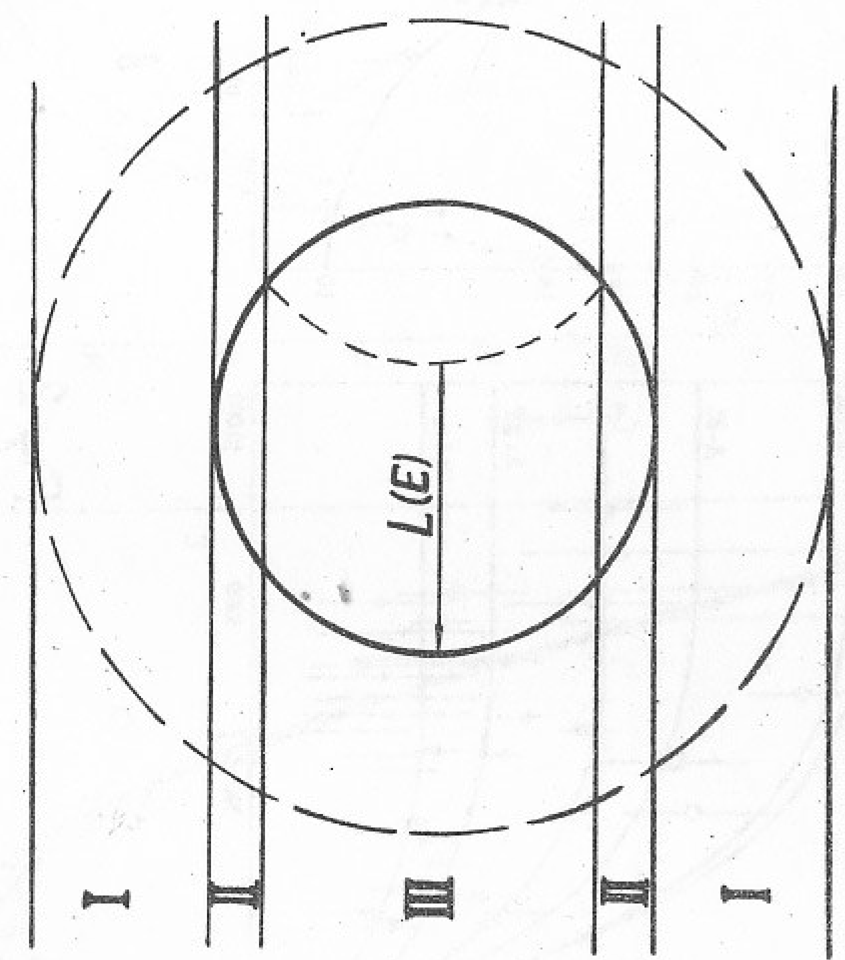
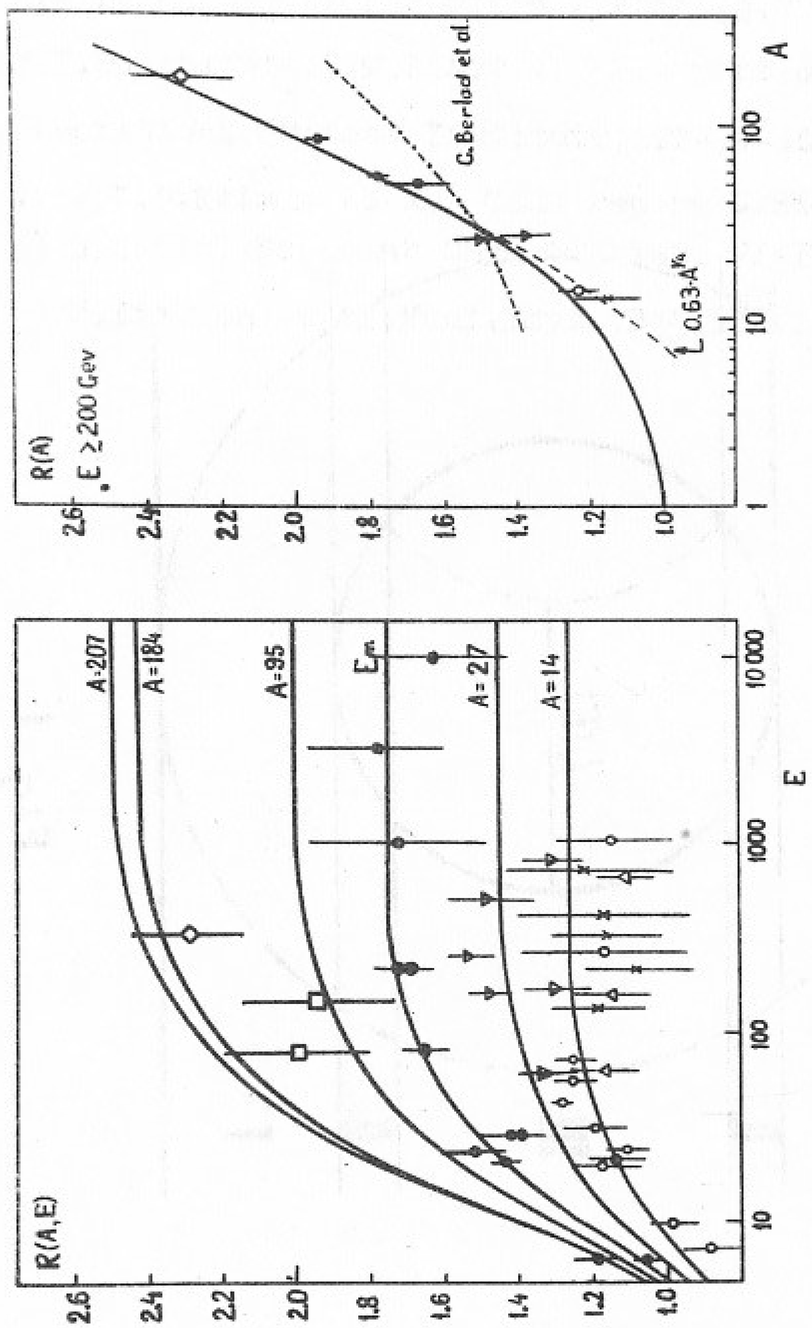


Fig. 1



a b

Fig. 2

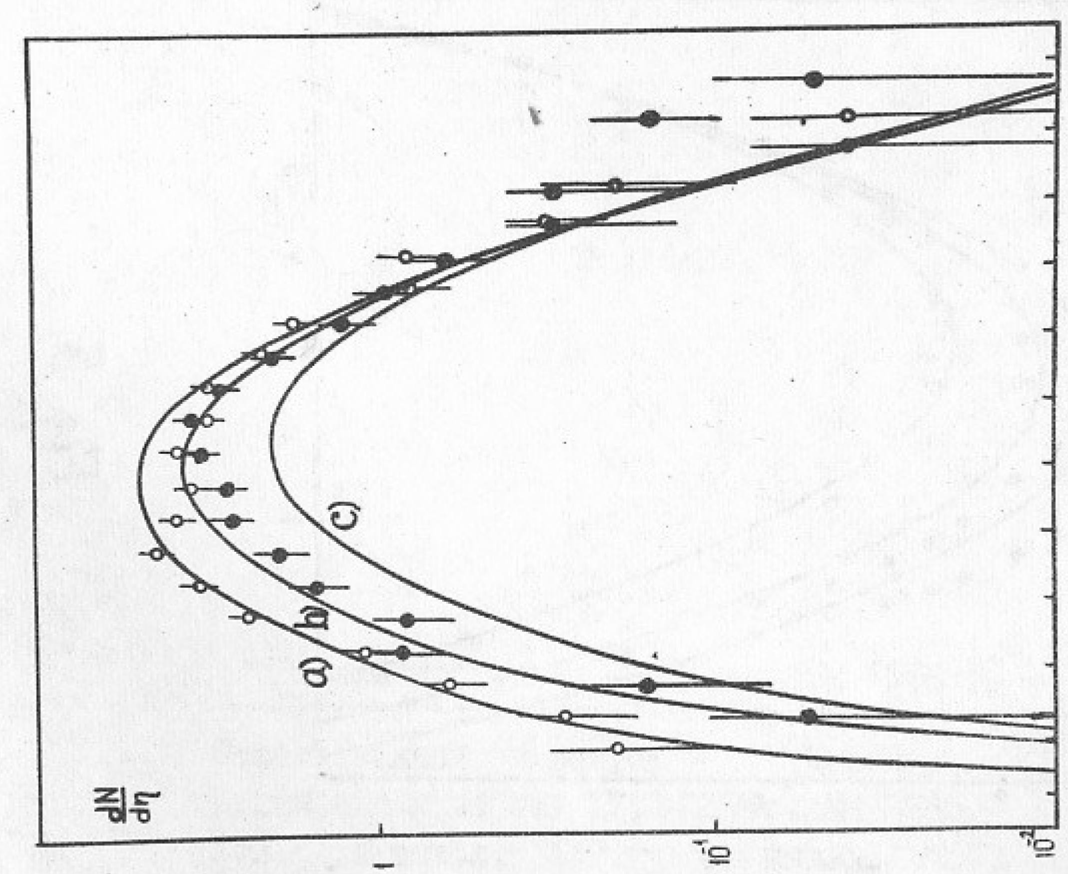


Fig. 3

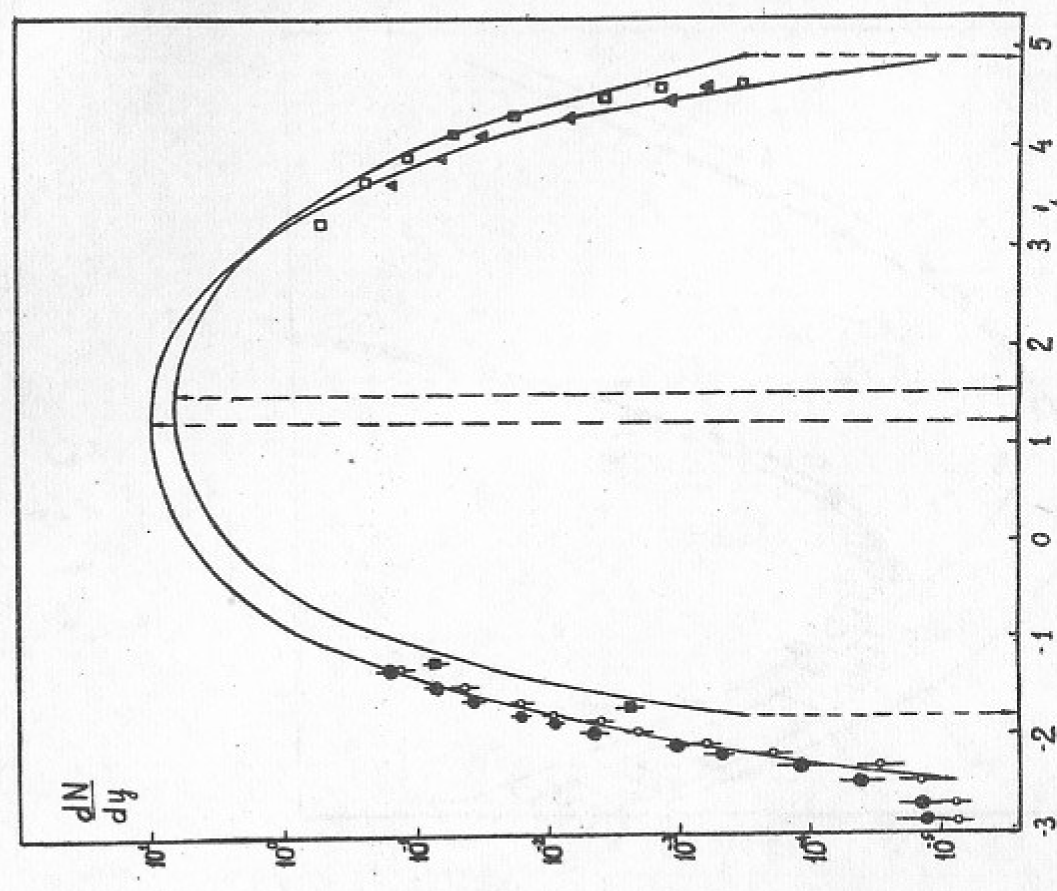


Fig. 4

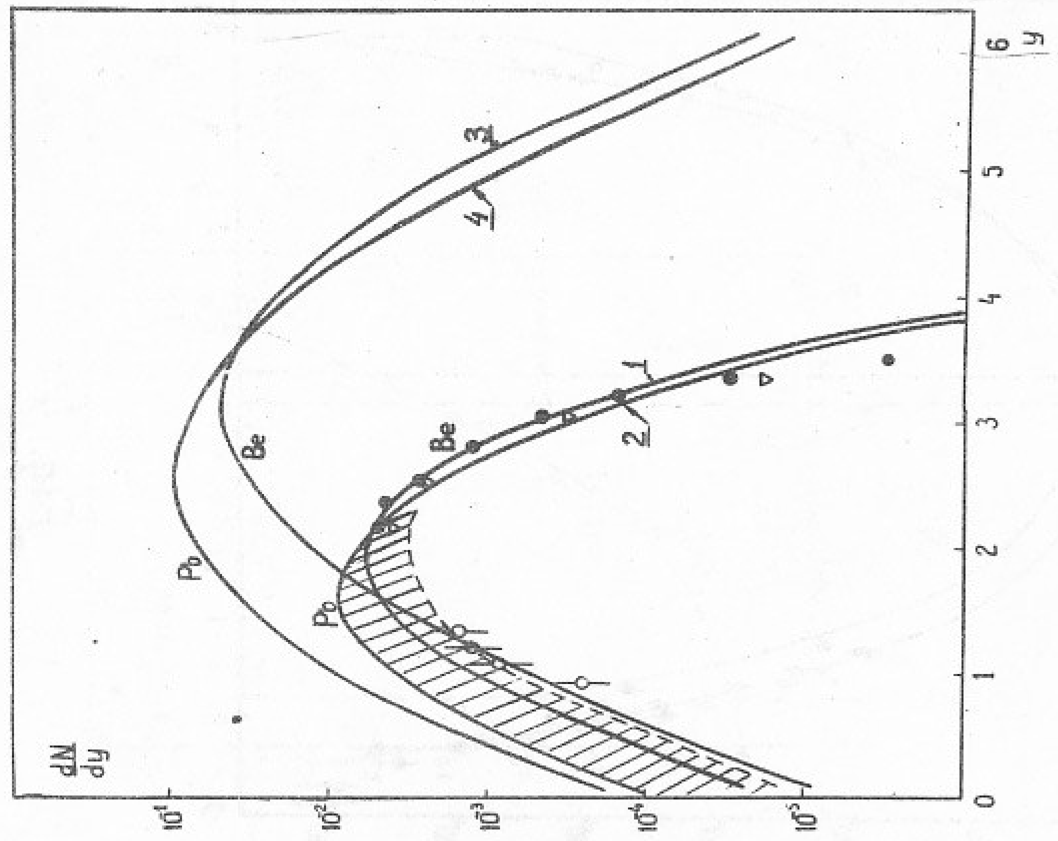


Fig. 6

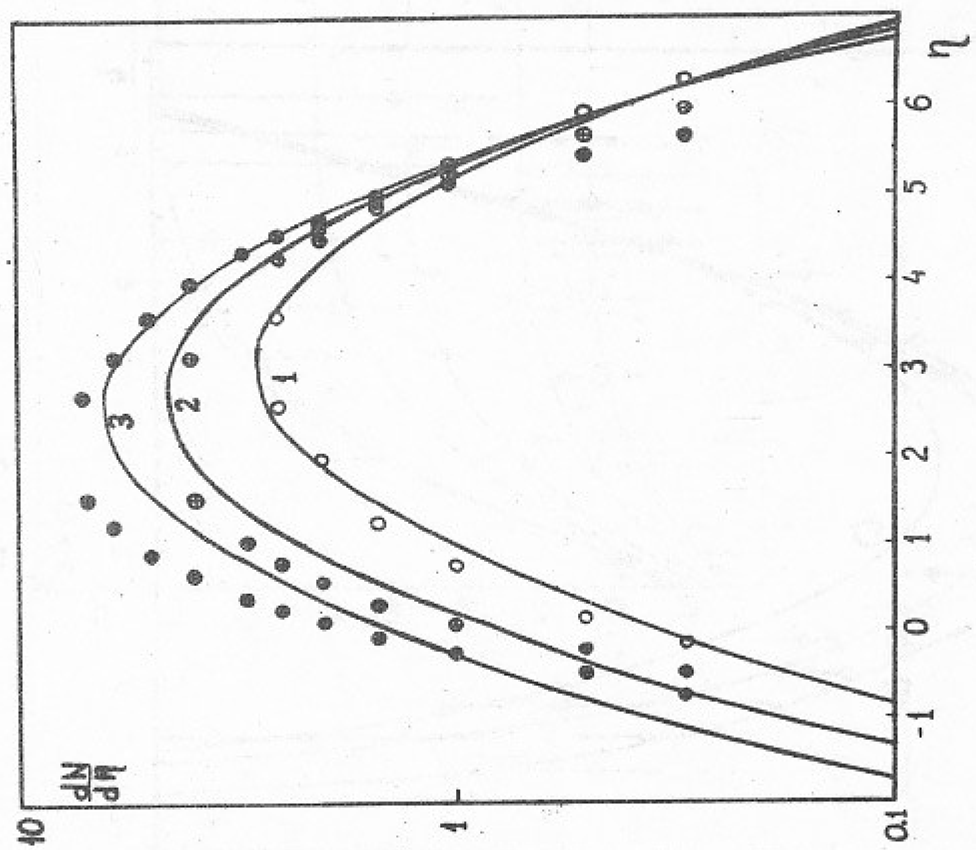


Fig. 5

Работа поступила - 29 декабря 1976 г.

Ответственный за выпуск - С.Г.ПОПОВ
Подписано к печати 17.II-1977г. МН 02659
Усл. 1,4 печ.л., 1,0 учетно-изд.л.
Тираж 170 экз. Бесплатно
Заказ № 20.

Отпечатано на ротапринте ИЯФ СО АН СССР