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MULTIPARTICLE PRODUCTION IN ANTIPROTON PROTON COLLISIONS AND THE QUARK-PARTON MODEL

ANNA MAŠEJOVÁ* Bratislava

It is shown that the inclusive spectra of negative and positive pions produced in $\bar{p}p$ collisions at 100 GeV/c are well reproduced by the Monte Carlo quark-parton model by Černý et al.

We present also other predictions of this model which can be tested by future $\bar{p}p$ multiparticle data.

МНОГОЧАСТИЧНАЯ ПРОДУКЦИЯ В АНТИПРОТОН-ПРОТОННЫХ СТОЛКНОВЕНИЯХ И КВАРК-ПАРТОННАЯ МОДЕЛЬ

В работе показано, что инклюзивный спектр отрицательных и положительных пионов, рождаемых в $\bar{p}p$ столкновениях при 100 Гэв/с, можно хорошо воспроизвести с помощью кваркпартонной модели, основанной на методе Монте-Карло, которая была предложена В. Черны и коллективом. Приведены также некоторые другие предсказания этой модели, которые можно будет проверить после получения новых данных по многочастичной продукции в $\bar{p}p$ столкновениях.

I. INTRODUCTION

Multiparticle production is a typical feature of hadron collisions at high energies. The whole process is dynamically rather complicated and numerous attempts were performed to describe it in a phenomenological way. A considerable attention was devoted to the cluster and multiperipheral models. The former is purely phenomenological and its basic assumptions were rather simply extracted from experimental data (charge transfer between c. m. hemispheres, short range correlations in rapidity, etc.). A multiperipheral model is much closer to the field theory and describes naturally and in agreement with the data the ordering of particles in rapidity in multiparticle production. Apart from these two models many others like statistical, hydrodynamical, thermodynamical ones, etc. were also frequently used.

* Katedra teoretickej fyziky PFUK, Mlynská dolina, CS-816 31 BRATISLAVA.

To decide which of the models is the correct one is extremely dificult, because

— any model contains a few free parameters, which are adjusted (or fitted) to the data

— models are usually compared only with a relatively small subset of the available data. It seems nowadays that a serious test of the model requires a comparison with as many of the data as possible and this in turn indicates that Monte Carlo models are to be employed

— in spite of the multitude of the data it sometimes happens that just those which would test the model most efficiently are not available.

The progress in other fields of high energy physics during the past decade has been more rapid. The data on deep inelastic lepton-nucleon collisions have given rise to the quark-parton model. It seems that this model provides a more adequate description of the hadron structure than any other model available at present. It is therefore natural to try to apply this model also to multiparticle production in hadron collisions. In fact the approach has been pursued during the last five years and today there are already a few quark-parton models of multiparticle production.

The purpose of the present paper is to compare the predictions of one of these models with the data on $\bar{p}p$ interactions at 100 GeV/c.

The paper is organized as follows. In the remaining part of the introduction we shall briefly describe the quark-parton model of Anisovich and Shekhter and the quark-glue model by Van Hove and his collaborators. In Sect. 2 we shall give some details of the model by Černý et al. [1, 2]. In Sect. 3 this model will be compared with the data on $\bar{p}p$ interactions at 100 GeV/c. Some comments and conclusions are presented in Sect. 4.

The quark model by Anisovich and Shekhter is bases on the assumption that hadrons are systems of relatively weakly bound states (mesons consisting of a quark and antiquark and baryons consisting of three quarks). The multiparticle production is supposed to proceed the three stages [3, 4]. In the first two quarks (or quark and antiquark) collide and others are passive spectators. The collision of the two quarks leads to the production of numerous quarks and antiquarks. These newly formed constituents are referred to as the central block. During the second stage the fast spectator quarks and quarks and antiquarks from the central block recombine to stable and unstable hadrons. In the third, final, stage the unstable hadrons decay into stable ones. The model gives relationships between inclusive spectra in both fragmentation and central regions. It, however, contains several phenomenological parameters and even some phenomenological functions (the cross section for resonance production, suppression factors for the production of strange quarks, energy dependence of the average number of quark-antiquark pairs created during the first stage, etc.).

The quark-glue model [5, 6] of hadron collisions at high energies is actually based on the information on hadron structure obtained from the deep inelastic

lepton-nucleon scattering. In the model one assumes that the nucleon consists of

— three valence quarks carrying the charge and about a half of the nucleon momentum

— $Q\bar{Q}$ pairs (quark-antiquark) with rather small total momentum

— a neutral hadronic matter, called "glue", which carries about a half of the nucleon momentum and does not interact with photons and leptons.

This model naturally describes [6] the leading particle effect and, if combined with some plausible additional assumptions, gives a qualitatively correct description of the production of central neutral clusters. In this model the "glue" plays an active role in the collision (quite similar to Feynman's wee partons [7]) and the quarks act as passive constituents. In the last stage of the collision these passive spectators are picking up the correspoding amount of the glue and form leading hadrons. Particle production in the central region is supposed to be dominated by products of neutral cluster decays.

Later on the experimental data have shown the model using only neutral clusters cannot describe the data and it seems at present that the correlation between the hadrons in the final stage can be obtained from resonance decays.

In the next section we shall discuss in some detail the quark parton model [1, 2] which leads naturally to these global features of the process.

II. MULTIPARTICLE PRODUCTION IN A MONTE CARLO QUARK-PARTON MODEL

The Monte Carlo quark-parton model [1, 2] of multiparticle production is to a large extent based on the information extracted from the data on deep inelastic lepton-nucleon scattering and in particular on the quark-parton interpretation [7, 8] of these data. Hadrons are considered to be coherent superpositions of valence quarks, "sea" quarks and antiquarks and gluons. The interaction of "wee" partons during the first stage of the collision destroys this coherence and leads to the formation of the plateau consisting of $Q\bar{Q}$ pairs and gluons.

The rapidity density of hadrons in the final state is about 3/RU (RU = rapidity unit). If we assume that these hadrons are formed by the recombination of $Q\bar{Q}$ to mesons (and less frequently of QQQ to baryons and $\bar{Q}\bar{Q}\bar{Q}$to antibaryons), the density of $Q\bar{Q}$ pairs prior to recombination has to be also about $2-3$/RU. Data from the deep inelastic lepton-hadron scattering indicate that the rapidity density of $Q\bar{Q}$ pairs from the sea (in a free nucleon) is about 0.6/RU. The difference has to be provided by the recombination of gluons to $Q\bar{Q}$ pairs. It is known that gluons carry about 4-times more momentum than $Q\bar{Q}$ pairs from the sea. If they both do have a similar distribution in rapidity it is natural to expect that the converted gluons provide about $4\times 0.6=2.4$ $Q\bar{Q}$ pairs/RU. Together with the original 0.6/RU this gives roughly the required number.

It is than assumed [1, 2] that just after the conversion of gluons to $Q\bar{Q}$ pairs, the two colliding hadrons form a compound system consisting to 6 valence quarks (3 for each of the nucleons) and of $Q\bar{Q}$ pairs. The quarks and antiquarks are distributed according to the cylindrical phase space (gaussian cut-off on transverse momenta) modified by the Kuti-Weisskopf [9] factor $\sqrt{x_i}$ for each of the valence quarks (this effectively pushes valence quarks to higher values of momentum fractions), by weight factors for identical particles and by a corresponding power of the "coupling constant" G (this regulates the average multiplicity of Q' s and $\bar{Q}'$ s in the central region).

The probability to find a system composed of 6 valence quarks with rapidities and transverse momenta $y_1, \boldsymbol{p}_{T1}, \ldots, y_6, \boldsymbol{p}_{T6}$ and n quarks with $y_i, \boldsymbol{p}_{Ti}$ ($i=7, \ldots, n+6$) and n antiquarks with $y_j, \boldsymbol{p}_{Tj}$ ($j=n+7, \ldots, N=2n+6$) is then given by the expression (1):

$$dP_N(y_1, \boldsymbol{p}_{T1}, \ldots, y_N, \boldsymbol{p}_{TN}) = KW_{id}G^n \left[\prod_{i=1}^{6} |x_i|^{1/2}\right] \exp\left(-\sum_1^N p_{Ti}^2/R^2\right) \times \tag{1}$$

$$\times\, \delta\left(\sum_1^N \boldsymbol{p}_{Ti}\right) \delta\left(\sum_1^N p_{Li}\right) \delta\left(E-\sum_1^N E_i\right) \prod_1^N dy_i dp_{Ti}^2 ,$$

where $x_i = x(y_i)$ is the momentum fraction of the i-th quark, p_{Li} is the longitudinal, $\boldsymbol{p}_{Ti}$ the transverse momentum and E_i the energy of the quark (or an antiquark). E is the total energy of the colliding hadrons, G is the coupling constant and W_{id} is the factor for identical particles. K is an overall energy independent normalization constant. The factor $\exp\left\{-\sum_1^N p_{Ti}^2/R^2\right\}$ represents a cut-off on the transverse momenta of quarks and antiquarks.

The Monte Carlo program [1,2] simulates the assumed mechanism of the multiparticle production. Any generated event is assigned the weight given by Eq. (1). The generation of an event proceeds in a few stages:

— the specification of the number of partons (hereafter a parton means a Q or an $\bar{Q}$) in the event. One generates the number of partons between 6 and ($2n_{max}+6$) and the distribution of multiplicities is regulated by the weight of the event. The production of strange $Q\bar{Q}$ pairs is phenomenologically suppressed. The set of partons is ordered in the sequence

(3 valence quarks — n $Q\bar{Q}$ pairs — 3 valence quarks).

In the next step the sequence is re-ordered with the supplementary condition that left (right) valence quarks remain in the left (right) half of the sequence.

— the generation of rapidities and transverse momenta of partons and the calculation of the weight of the event. The calculation is based on Eq. (1) and makes use of a part of Jadach's program GENRAP [10];

— the recombination of $Q\bar{Q}$ pairs to mesons, QQQ triplets to baryons and $\bar{Q}\bar{Q}\bar{Q}$ triplets to antibaryons. At this stage the program knows already the momenta and energies of individual partons and their quantum numbers. It is assumed that only the partons which are close in rapidity can recombine the hadrons. The program starts on the left half of the sequence and considers always a triplet of partons. If there is a $Q\bar{Q}$ pair, it is supposed to recombine to a meson and one parton is left. The program then takes further two quarks and proceeds further to the right. If there are three quarks (antiquarks), the program forms a baryon (an antibaryon) and takes the nearest three partons. After having formed $Q\bar{Q}$ pairs and QQQ and $\bar{Q}\bar{Q}\bar{Q}$ triplets, the program decides (another random number generation) what hadron is formed. The relative weights are given by the SU (6) Clebsch-Gordan coefficients averaged over spins. The momentum of the hadron formed in this way is assumed to be given by the vector sum of the momenta of recombining partons;

— resonance decays. In this step resonance and unstable particles decay. Branching ratios are given by the Particle Data Group Tables. Any resonance is supposed to decay isotropically and the angle is generated at random. There is an option to declare any particle as stable. Its decays are then forbidden and it appears in the final state. This is important for the comparison with the data, since in an electronic experiment the stable particles are only p, $\bar{p}$, n, $\bar{n}$, $\pi^\pm$, $K^\pm$, K_L^0 and photons, whereas in bubble chambers one measures (considered as stable) also Λ, Σ, K_S^0 and sometimes also Ξ hyperons.

As the final result of the generation of an event one obtains the set of hadrons with specified quantum numbers, rapidities, transverse momenta and each event as assigned its weight. There are three free parameters in themodel. They were determined [1, 2] by comparing the results with the data on multiparticle production in pp collisions at 150 GeV/C. The coupling constant $G=1.15$, the parameter $R=0.20$ GeV^2/c^2 on the basis of transverse momentum spectra and the suppression of strange pairs is expressed by the parameter λ (=probability that a given pair is $s\bar{s}$)$=0.1$. The masses of quarks were fixed [2] at values $m_u = m_d = 0.01$ GeV/c^2, $m_s = 0.16$ GeV/c^2. These values are preferred [11] by the data on multiparticle production of muon pairs in hadronic collisions.

This model [1, 2] gives a rather good description of the multiparticle production (in qualitative fearures) in pp collisions for $p_{LAB} = 150$, 300 and 1500 GeV/c (energy dependence of average multiplicities, rapidity spectra, transverse momentum spectra, resonance production, etc.). Some discrepancies, however, still remain in the description of particles which are less frequently produced.

The Monte Carlo quark-parton model of multiparticle production has also some problems:

— it requires a considerable amount of computer time,

— the correlation between identical particles are not built in,

— the recombination process is described in an oversimplified way,
— diffraction dissociation is not explicitly taken into account.

A further evolution of the model can be stimulated both by more extensive comparisons with the data and by a deeper theoretical understanding of the dynamics of hadronic collisions. In this paper we are trying to contribute to the former by comparing the resluts with the data on $\bar{p}p$ interactions at 100 GeV/c.

III. THE COMPARISON OF THE RESULTS WITH DATA ON $\bar{p}p$ INTERACTIONS AT 100 GeV/c

In this section we shall compare our results with the data on $\bar{p}p$ collisions at 100 GeV/c. It has to be stressed that all the parameters R, G, λ were fixed on values found previously [1, 2] in a study of pp collisions at p_{LAB} between 100 and 1500 GeV/c. In this sense our model contains no free parameters.

A typical feature of quark-parton models, where hadrons are formed by recombination of partons [1, 2, 3, 4, 12], is the copious production of resonances. In Table 1 we give a list of the average multiplicities of directly produced (e.g. prior

Table 1

Average multiplicities of particles directly produced in $\bar{p}p$ collisions at 100 GeV/c as calculated in the Monte Carlo quark-parton model. The results were symmetrized for particle and antiparticle production and the errors were estimated as explained in the text. The errors of the average multiplicities of neutral particles were roughly estimated making use of the errors for charged particles.

	Mesons $\langle n \rangle$	Baryons and antibaryons $\langle n \rangle$	
π^+, π^-	0.16 ± 0.02	$p, \bar{p}$	0.17 ± 0.02
π^0	0.23 ± 0.02	$n, \bar{n}$	0.066 ± 0.008
K^+, K^-	0.036 ± 0.001	$\Lambda, \bar{\Lambda}$	0.014 ± 0.001
$K^0, \bar{K}^0$	0.030 ± 0.002	$\Sigma^+, \bar{\Sigma}^+$	0-011 ± 0.002
η	0.09 ± 0.01	$\Sigma^0, \bar{\Sigma}^0$	0.016 ± 0.002
X^0	0.23 ± 0.04	$\Sigma, \bar{\Sigma}^-$	0.0045 ± 0.0005
		$\Xi^0, \bar{\Xi}^0$	0.0003 ± 0.0001
		$\Xi^-, \bar{\Xi}^-$	0.0002 ± 0.0001
ϱ^+, ϱ^-	0.53 ± 0.02	$\Delta^{++}, \bar{\Delta}^{++}$	0.094 ± 0.006
ϱ^0	0.58 ± 0.02	$\Delta^+, \bar{\Delta}^+$	0.36 ± 0.01
K^{*+}, K^{*-}	0.090 ± 0.003	$\Delta^0, \bar{\Delta}^0$	0.16 ± 0.02
K^{*0}, K^{*0}	0.064 ± 0.006	$\Delta^-, \bar{\Delta}^-$	0.018 ± 0.002
ω	0.55 ± 0.05	$Y^{*+}, \bar{Y}^{*+}$	0.021 ± 0.005
Φ	0.03 ± 0.01	$Y^{*-}, \bar{Y}^{*-}$	0.015 ± 0.005
		$Y^{*0}, \bar{Y}^{*0}$	0.040 ± 0.002
		$\Xi^{*0}, \bar{\Xi}^{*0}$	0.0010 ± 0.0004
		$\Xi^{*-}, \bar{\Xi}^{*-}$	0.0002 ± 0.0001
		$\Omega^-, \bar{\Omega}^-$	0.00006 ± 0.00006

Table 2

Comparison of results on multiplicities in $\bar{p}p$ collisions at 100 GeV/c with the data. The average numbers of π^0, K^0_S, Λ and $\bar{\Lambda}$ were read and the errors were roughly estimated from the Figures in Ref. [13]. The errors of our calculations are estimated in the same rough way as in Table 1

average multiplicity of	calculation	data [13]
negative particles	3.07 ± 0.02	3.37 ± 0.03
π^0	2.93 ± 0.02	2.84 ± 0.06
K^0_S	0.12 ± 0.01	0.13 ± 0.01
$\Lambda, \bar{\Lambda}$	0.10 ± 0.01	0.05 ± 0.01

to resonance decays) stable and unstable particles. In our Monte Carlo calculations we obtain — due to fluctuations — different values for the average number of particles and antiparticles produced per an inelastic collision. For instance we get $\langle n_p \rangle = 0.19$ and $\langle n_{\bar{p}} \rangle = 0.15$. On the basis of this result we roughly estimate the average value and the error as $\langle n_p \rangle = \langle n_{\bar{p}} \rangle = 0.17 \pm 0.02$. Table 1 contains results and errors obtained in this way.

Table 2 presents those particles which can be compared with the available data [13]. In this table the unstable particles are already decayed (K^0_S, Λ, $\bar{\Lambda}$, Ω^-, $\bar{\Omega}^-$, Σ^+, $\bar{\Sigma}^+$, Σ^-, $\bar{\Sigma}^-$, Ξ^0, Ξ^-, $\bar{\Xi}^0$, $\bar{\Xi}^-$ were declared as stable ones since the data come from the bubble chamber). It is seen that the results reproduce well the average multiplicities of all negative particles, of π^0 and of K^0_S, but fail to reproduce the production of Λ and $\bar{\Lambda}$.

In Fig. 1 we compare the rapidity distribution of positive pions with the data [14]. On a qualitative level, the agreement is satisfactory.

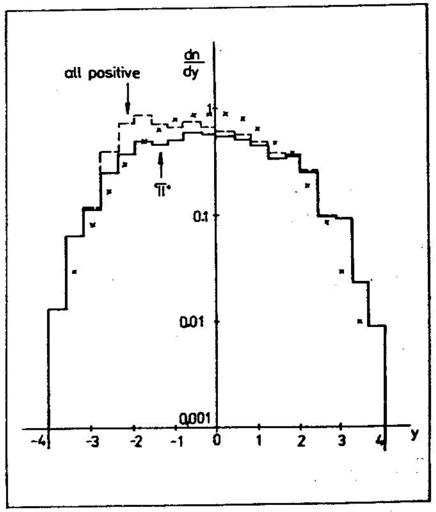

Fig. 1. The comparison of the data on π^+ rapidity distribution with the calculations. Crosses — experimental data from [14], solid line — calculated results of π^+ distribution, dashed line — calculation for all positive particles. Notation: $dn/dy = \sigma^{-1}_{inel} d\sigma/dy$.

Fig. 2 shows the distribution of pions in a transverse momentum. It si seen that the agreement is quite good for p_T^2 below 0.6 GeV/c. For larger values of p_T the agreement with the data [15] seems to be worse. This would be also quite natural; our model takes into account only soft collisions intitiated by wee partons. For the production of particles with transverse momenta around 1 GeV/c the genuinely hard processes begin to dominate (over the soft ones).

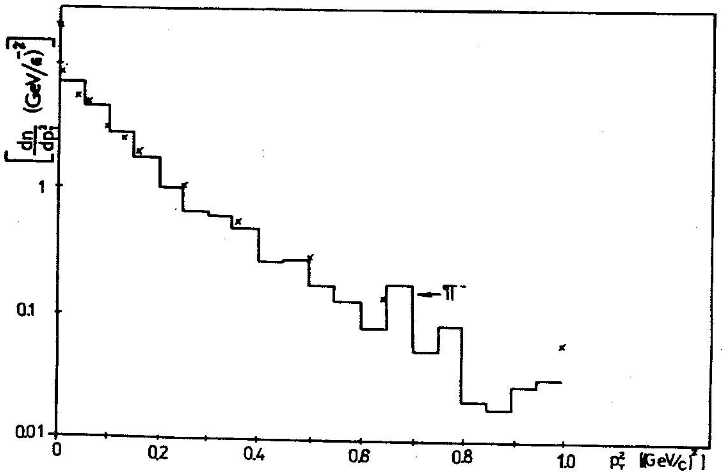

Fig. 2. The transverse momentum squared distribution for backward cm π^- production in $\bar{p}p$ interactions at 100 GeV/c compared with the calculations. Crosses — experimental data from [15], histogram — calculation. Notation: $dn/dp_T^2 = \sigma_{inel}^{-1} d\sigma/dp_T^2$.

In Fig. 3a we show the asymmetry between the production of π^+ and π^- as predicted by our model. Fig. 3 b displays our predictions for the rapidity distribution of protons and antiprotons in $\bar{p}p$ collisions at 100 GeV/c. The rapidity distribution of K_L^0, K^+ and K^- are shown in Figs. 3c and 3d. Unfortunately, the identification of particles in bubble chambers is rather difficult and there are no data with which we could compare these results.

In Fig. 4 we finally present the distribution of the electric and baryonic charges in rapidity. Summarizing this result we can say that the model predicts, as expected, that the quantum numbers of hadrons are conserved in their fragmentation regions. The connection of this result with the more interesting question of quark quantum number retention is, however, neither obvious nor direct.

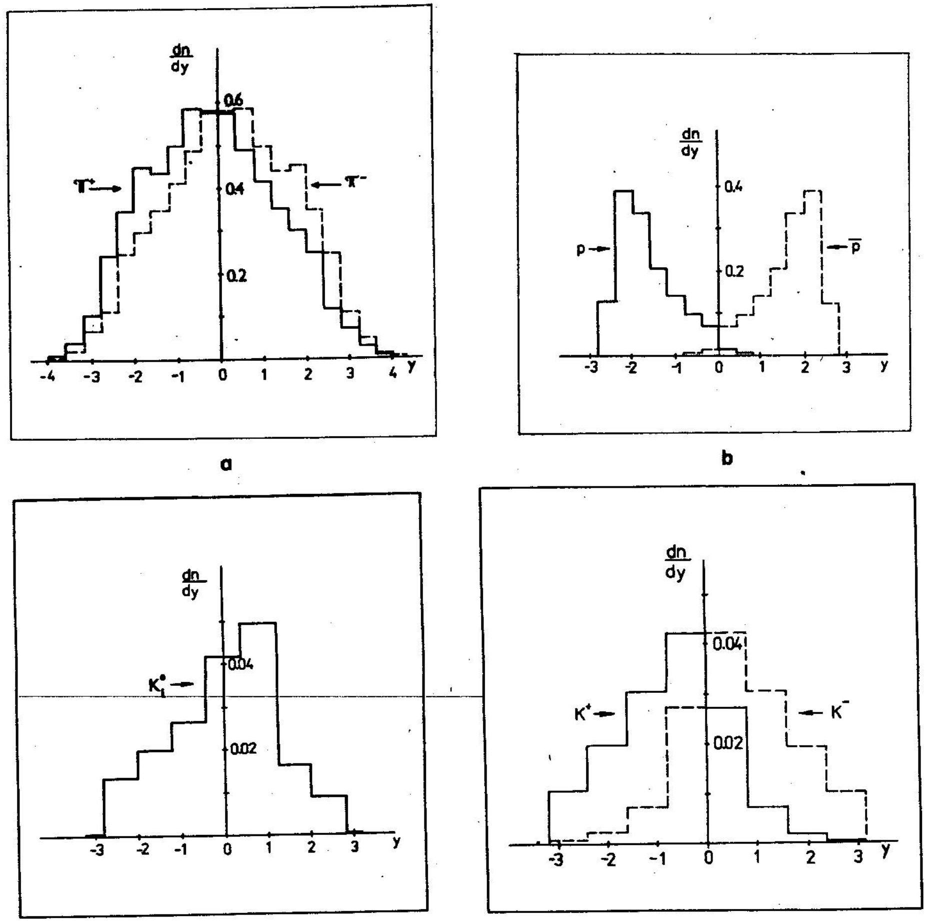

Fig. 3. Predictions for asymmetries in rapidity distribution of a) pions, b) proton and antiproton, c) K_L^0, d) charged kaons, in $\bar{p}p$ interactions at 100 GeV/c. Solid lines $-\pi^+, p, K^0, K^+$, dashed lines $-\pi^-, \bar{p}, K^-$. Notation: $dn/dy = \sigma_{inel}^{-1} d\sigma/dy$.

IV. COMMENTS AND CONCLUSIONS

The comparison of the results obtained from the Monte Carlo quark-parton model [1, 2] with the data on multiparticle production in $\bar{p}p$ collisions at 100 GeV/c shows that the dynamics of $\bar{p}p$ interactions at very high energies is governed by the same dynamics as pp interactions at similar energies.

Unfortunately, the identification of particles in bubble chambers is rather difficult and the currently available data do not permit a detailed study of various dynamical questions. This concerns in particular the asymmetries in particle-antiparticle rapidity spectra and the whole complex of questions related to the resonance production.

In cases where a comparison with the data is possible, i.e., the rapidity distribution of charged particles and the p_T — spectra of negative pions (Figs. 1 and 2), the agreement with the data is quite satisfactory.

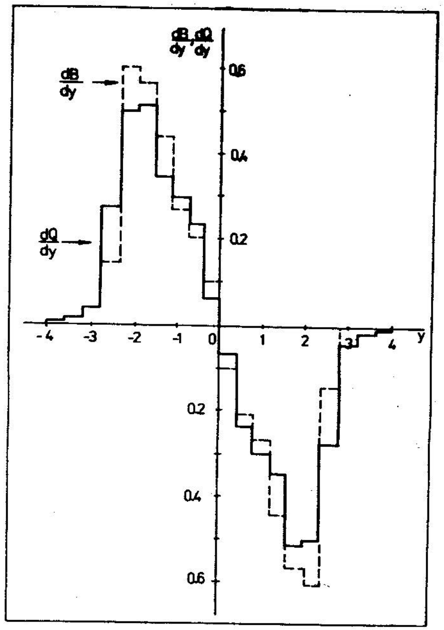

Fig. 4. The distribution of electric and baryonic charge in rapidity in $\bar{p}p$ collisions at 100 GeV/c as calculated in the model. Solid line — charge distribution, dashed line — baryonic charge distribution.

There are still some topics which were not cnsidered in the present paper but can be studied even with the currently available data, for instance topological cross sections and their differences in pp and $\bar{p}p$ cases.

We hope to be able to discuss these items and the related question of the contribution from the diffractive dissociation in the near future.

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