

## Single-particle correlations in events with total disintegration of nuclei

M. K. Suleimanov,\* O. B. Abdinov, and A. M. Bagirov  
*Physics Institute, Azerbaijan Academy of Sciences, Baku, Azerbaijan Republic*

A. I. Anoshin  
*Nuclear Physics Institute, Moscow State University, Moscow, Russia*

J. Bogdanowicz  
*Soltan Institute for Nuclear Studies, Warsaw, Poland  
 and Joint Institute for Nuclear Research, Dubna, Russia*

A. A. Kuznetsov  
*Joint Institute for Nuclear Research, Dubna, Russia*

(Received 4 February 1998)

New experimental data on the behavior of the single-particle two-dimensional correlation functions  $R$  versus  $Q$  ( $Q$  is the number of nucleons emitted from nuclei) and  $A_p$  ( $A_p$  is the mass of projectile nuclei) are presented. The interactions of protons,  $d$ ,  ${}^4\text{He}$ , and  ${}^{12}\text{C}$  nuclei with carbon nuclei (at a momentum of 4.2 A GeV/c) are considered. The values of  $R$  are obtained separately for  $\pi^-$  mesons and protons. In so doing, the values of  $R$  are normalized so that  $-1 \leq R \leq 1$ . The value of  $R=0$  corresponds to the case of the absence of correlations. It has been found that the  $Q$  and  $A_p$  dependence of  $R$  takes place only for weak correlations ( $R < 0.3$ ). In the main (90%), these correlations are connected with the variable  $p_t$  and have a nonlinear character; that is, the regions with different characters of the  $Q$  dependence of  $R$  are separated: there is a change of regimes in the  $Q$  dependences of  $R$ . The correlations weaken with increasing  $A_p$ , and the variable  $R$  gets the lowest values of all the ones considered in  ${}^{12}\text{C}$  interactions. Simultaneously with weakening the correlations in the region of large  $Q$ , the character of the  $Q$  dependence of  $R$  changes. [S0556-2813(98)07206-9]

PACS number(s): 25.70.Pq, 25.45.-z, 22.55.-e

### I. INTRODUCTION

The aim of this paper is to give information on the values of single-particle correlation functions ( $R$ ) in nucleus-nucleus collisions and in events with total disintegration of nuclei (TDN).

The study of correlation effects in particle production is the source of information on the dynamics of interactions supplementing the information obtained from single-particle inclusive distributions, the analysis of the mean characteristics, and so on [1]. In this paper, we present the results of investigating the  $Q$  dependence<sup>1</sup> of  $R$  for  $\pi^-$  mesons and protons emitted in nucleus-nucleus collisions. Such an experiment allows us to obtain the necessary information.

Interest in the processes of TDN is determined by the fact that they are extreme cases. It is supposed that in these cases anomalously large densities of nuclear matter can be realized, and the effects associated with the collective properties of nuclear matter are revealed. We think that the processes of

TDN correspond to qualitatively new states of nuclear matter, and the transition to these states goes through "critical" values of  $Q \rightarrow Q^*$ . The presence of  $Q^*$  should lead to changing the  $Q$  dependences of event characteristics in the region near  $Q^*$ . Therefore, it is suggested to use the condition  $Q \geq Q^*$  as an event selection criterion with the total disintegration of target nuclei.

The probability distributions of observing  $p\text{C}$ ,  $d\text{C}$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  events with the given values of the variable  $Q$  are studied in Ref. [2]. The  $Q$  dependences of the mean characteristics and the inclusive spectra of secondary  $\pi$  mesons and protons are studied in Refs. [3,4].<sup>2</sup> The results, obtained in these papers, confirm our assumption that a critical value of  $Q^*$  for  $Q$  exists (its excess leads to TDN).

The single-particle two-dimensional correlation function  $R(x,z)$  is used in the analysis. It is connected with the fact that the correlations strengthen when passing to high orders of  $R$  [5-7]. The values of  $R(x,z)$  for the variables  $x,z$  were calculated by the following formula:

$$R(x,z) = (Exz - ExEz) / [\sigma(x)\sigma(z)].$$

Here  $Exz$  is the mixed mathematical expectation of quantities  $x$  and  $z$ ,  $Ex$  and  $Ez$  are the mathematical expectations

\*Now at the Laboratory of High Energies, JINR, 141980 Dubna, Russia. Electronic address: mais@sunhe.jinr.ru

<sup>1</sup>The values of  $Q$  were determined as  $Q = N_+ - N_{\pi^-}$  ( $N_+$  and  $N_{\pi^-}$  are the numbers of positive charged particles and  $\pi^-$  mesons, respectively). The variable  $Q$  is proportional to the number of protons emitted from nuclei during the interaction. For details, using the variable  $Q$ , see Ref. [2].

<sup>2</sup>For this, the groups of events with  $Q \geq 1, 2, 3, \dots$  were defined. Then, the mean characteristics and invariant inclusive spectra were obtained for each group.

TABLE I. Values of  $b$  for  $\pi^-$  mesons.

Type of events	$pC$	$dC$	${}^4\text{HeC}$	${}^{12}\text{CC}$
$R(p, \theta)$	-0.49	-0.52	-0.49	-0.48
$R(p, p_t)$	0.62	0.52	0.49	0.50
$R(p, y)$	0.67	0.71	0.70	0.69
$R(p, \beta^0)$	-	-	-0.22	-0.19
$R(\theta, p_t)$	-	-	-	-
$R(\theta, y)$	-0.93	-0.92	-0.91	-0.90
$R(\theta, \beta^0)$	0.83	0.78	0.79	0.78
$R(p_t, y)$	-	-	-	-
$R(p_t, \beta^0)$	0.31	0.42	0.43	0.45
$R(y, \beta^0)$	-0.79	-0.73	-0.73	-0.71

TABLE II. Values of  $b$  for protons.

Type of events	$pC$	$dC$	${}^4\text{HeC}$	${}^{12}\text{CC}$
$R(p, \theta)$	-0.67	-0.68	-0.63	-0.63
$R(p, p_t)$	-	-	-	-
$R(p, y)$	0.97	0.96	0.93	0.93
$R(p, \beta^0)$	-	-0.85	-0.80	-0.78
$R(\theta, p_t)$	-	-	-	-
$R(\theta, y)$	-0.80	-0.81	-0.80	-0.82
$R(\theta, \beta^0)$	0.90	0.90	0.92	0.93
$R(p_t, y)$	-	-	-	-
$R(p_t, \beta^0)$	-	-	-	-
$R(y, \beta^0)$	-0.94	-0.95	-0.94	-0.94

of  $x$  and  $z$ , respectively, and  $\sigma(x)$  and  $\sigma(z)$  are the rms deviations of  $x$  and  $z$ , respectively.

To evaluate  $Exz$ ,  $Ex$ ,  $Ez$ ,  $\sigma(x)$ , and  $\sigma(z)$ , the following formulas were used:

$$Exz = \frac{1}{N} \sum_{i=1}^{40} \sum_{j=1}^{40} N_{ij} x_i z_j,$$

$$Ex = \frac{1}{N} \sum_{i=1}^{40} N_i x_i,$$

$$Ez = \frac{1}{N} \sum_{j=1}^{40} N_j z_j,$$

$$\sigma(x) = [Ex^2 - (Ex)^2]^{1/2}, \quad \sigma(z) = [Ez^2 - (Ez)^2]^{1/2},$$

$$Ex^2 = \frac{1}{N} \sum_{i=1}^{40} N_i x_i^2, \quad Ez^2 = \frac{1}{N} \sum_{j=1}^{40} N_j z_j^2.$$

In these formulas,  $N_{ij}$  is the number of particles hitting an  $(i, j)$ th cell:

$$N = \sum_{i=1}^{40} \sum_{j=1}^{40} N_{ij}, \quad N_i = \sum_{j=1}^{40} N_{ij}, \quad N_j = \sum_{i=1}^{40} N_{ij}.$$

During the construction of the two-dimensional distributions for the chosen variables, the intervals, corresponding to them, were divided into 40 subintervals.

## II. METHODS OF THE EXPERIMENT

The experimental data have been obtained from the 2-m propane bubble chamber of LHE, JINR [8,9]. The chamber, placed in a magnetic field of 1.5 T, was exposed to beams of light relativistic nuclei at the Dubna Synchrophasotron. Practically all secondaries, emitted at a  $4\pi$  total solid angle, were detected in the chamber. All negative particles, except those identified as electrons, were considered as  $\pi^-$  mesons. The contaminations by misidentified electrons and negative strange particles do not exceed 5% and 1%, respectively. The average minimum momentum for pion registration is about 70 MeV/c. The protons were selected by a statistical method applied to all positive particles with a momentum of

$p > 500$  MeV/c (we identified slow protons with  $p \leq 700$  MeV/c by ionization in the chamber). In this experiment, we used 5284  $pC$ , 6735  $dC$ , 4852  ${}^4\text{HeC}$ , and 7327  ${}^{12}\text{CC}$  interactions at a momentum of 4.2A GeV/c (for methodical details see [9]). The available statistical material was separated into groups of events with the following values of  $Q$ :

$$Q \geq 1, 2, 3, \dots, Q^*, \dots \quad (1)$$

The values of  $R$  were determined for  $\pi^-$  mesons and protons from these groups of events. In this case, we considered only  $\pi^-$  mesons and protons with the errors in measuring the momenta not exceeding 30%.

We considered the following correlation functions:  $R(p, \theta)$ ,  $R(p, p_t)$ ,  $R(p, y)$ ,  $R(p, \beta^0)$ ,  $R(\theta, p_t)$ ,  $R(\theta, y)$ ,  $R(\theta, \beta^0)$ ,  $R(p_t, y)$ ,  $R(p_t, \beta^0)$ , and  $R(y, \beta^0)$ , where  $p$  are the momenta in the laboratory coordinate system (LCS),  $\theta$  the emitted angles in the LCS,  $p_t$  the transverse momenta,  $y$  the rapidities in the LCS, and  $\beta^0$  the orders of cumulativity [here  $\beta^0 = (E - p_L)/m_N$ ,  $E$  is the total energy (in the LCS),  $p_L$  the longitudinal momentum (in the LCS), and  $m_N$  the nucleon mass].

The correlations between  $p_t$  and  $p_L$  for  $\pi^-$  mesons, produced in  $dC$  interactions at 1.7 and 4.2 GeV/c per nucleon, were studied in Ref. [10]. The dependence of the distribution density of  $\pi^-$  mesons on these variables was observed. The forms of these distributions turned out to depend on the beam energy. The  $y$  and  $p_t$  distributions of protons were measured in S+W, O+W, and  $p$ +W reactions at 200 GeV/nucleon [11]. The density of the  $y$  distribution was found to grow linearly with increasing transverse energy for all three reactions. However, the slope in  $p$ +W is sharper than in O+W and S+W. The rapidity density in  $p$ +W is much larger than was predicted on the basis of summing nucleus-nucleus collisions without taking into account nuclear effects, pointing to the importance of rescattering effects. The results, obtained in Refs. [10,11], show a good perspective of using the  $R$  function for revealing qualitatively new phenomena in interactions of relativistic nuclei.

In our experiment, the parameters  $\beta^0$ ,  $\theta$ , and  $y$  were chosen in the intervals  $0 \leq \beta^0 \leq 3$ ,  $0 \leq \theta \leq 180^\circ$ , and  $-2 \leq y \leq 3.5$  in all cases.

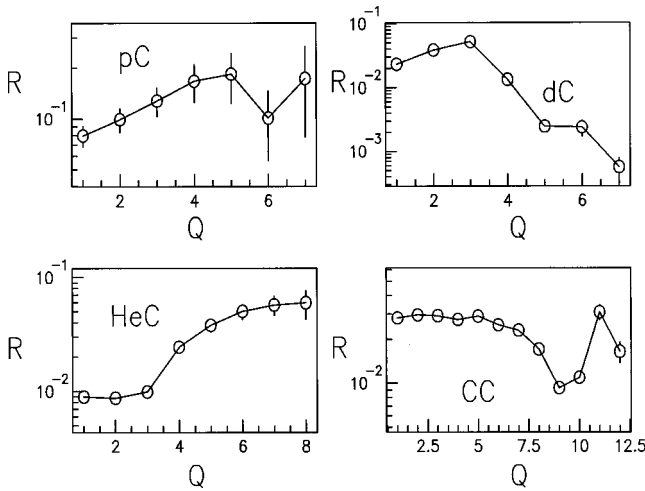


FIG. 1.  $Q$  dependence of  $|R(\theta, p_t)|$  for  $\pi^-$  mesons in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions. The values of  $R$  shown at  $Q = 1, 2, 3, \dots$  correspond to the groups of events with  $Q \geq 1, 2, 3, \dots$ , respectively.

The parameters  $p$  and  $p_t$  in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions were chosen from the intervals  $0.07 \text{ GeV}/c \leq p \leq 10 \text{ GeV}/c$  and  $0.07 \text{ GeV}/c \leq p_t \leq 4 \text{ GeV}/c$  both for protons and for  $\pi^-$  mesons.

### III. THE RESULTS OF THE EXPERIMENT AND DISCUSSION

The values of  $R$  at different  $Q$  for different pairs were obtained using the method described above. In all, the  $Q$  dependences for 100  $R$  functions were obtained (ten types of  $R$  functions separately for  $\pi^-$  mesons and protons in five types of interactions; see above). According to the character of the  $Q$  dependence of  $R$ , the data can be divided into two groups: group I, the data on the  $Q$  independence of  $R$ , and group II, the data showing the  $Q$  dependence of  $R$ . The data from the first group were fitted with an  $a \cdot Q + b$  expression, where  $a$  (for this group of data, the values of  $a$  turned out to be close to zero) and  $b$  are the fitting parameters.<sup>3</sup>

The values of  $b$  are presented in Tables I and II. The cases from the second group are denoted by dashes. The absolute values of  $R$  depending on  $Q$  for this group of data are shown in Figs. 1–5 (the curves are hand drawn).<sup>4</sup>

From the data in Tables I and II, one can see the following.

- (i) The  $Q$  dependence of  $R$  is not observed in 71% of the

<sup>3</sup>We do not present the measured errors of  $b$  but take them into account in our conclusions.

<sup>4</sup>We do not present the data on (a) the values of  $R(p, \beta^0)$  depending on  $Q$  in  $pC$  interactions (for  $\pi^-$  mesons and protons) and  $dC$  interactions (for protons). For these cases, the values of  $R(p, \beta^0)$  decrease with increasing  $Q$ . In so doing, this dependence has a linear character for  $\pi^-$  mesons and almost a logarithmic character for protons. We also do not present the data on (b) the values of  $R(p_t, \beta^0)$  as in this case the behavior of  $R$  versus  $Q$  for  $pC$ ,  $dC$ , and  ${}^4\text{HeC}$  interactions is similar to those shown in Figs. 3–5. For  ${}^{12}\text{CC}$  interactions, the behavior of  $R(p_t, \beta^0)$  as a function of  $Q$  is in line with a “break” in its character.

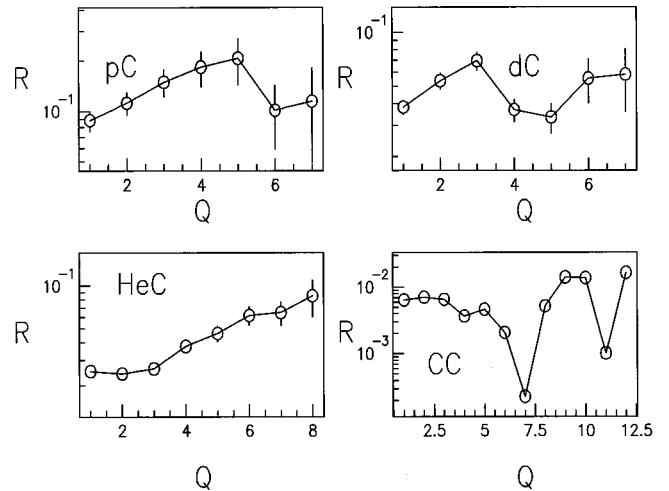


FIG. 2.  $Q$  dependence of  $|R(p_t, y)|$  for  $\pi^-$  mesons in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions. The values of  $R$  shown at  $Q = 1, 2, 3, \dots$  correspond to the groups of events with  $Q \geq 1, 2, 3, \dots$ , respectively.

cases (of 100, group I of data), and the function  $R$ , respectively, depends on  $Q$  (group II of data) in 29% of the cases.

- (ii) In 90% of the cases of group II the  $Q$  dependence of  $R$  is mainly due to the variable  $p_t$ .

- (iii) The data from group I also point to the independence of the behavior of the projectile mass ( $A_p$ ) in nucleus-nucleus interactions.

From Figs. 1–5, one can draw the following conclusions.

In 75% of the cases, the  $Q$  dependence of  $R$  has a non-linear character; i.e., the regions with different  $Q$  dependences of  $R$  are separated or the change of regimes takes place in these dependences. The totality of these data allows one to determine the “critical” values of  $Q = Q^*$  corresponding to the transition from one region to another. These values of  $Q^*$  mainly coincide with those obtained in the previous papers [1–3] and are used for event selection with TDN. Thus, we have that the correlation analysis also confirms that events with TDN qualitatively differ from “usual”

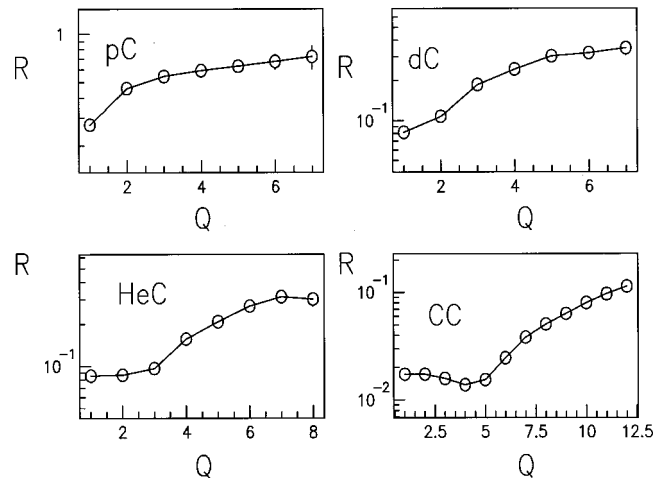


FIG. 3.  $Q$  dependence of  $|R(p, p_t)|$  for protons in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions. The values of  $R$  shown at  $Q = 1, 2, 3, \dots$  correspond to the groups of events with  $Q \geq 1, 2, 3, \dots$ , respectively.

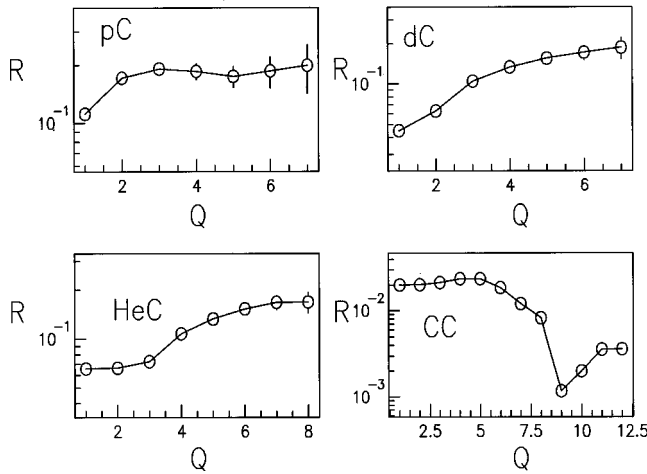


FIG. 4.  $Q$  dependence of  $|R(\theta, p_t)|$  for protons in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions. The values of  $R$  shown at  $Q = 1, 2, 3, \dots$  correspond to the groups of events with  $Q \geq 1, 2, 3, \dots$ , respectively.

events, and it is necessary to use condition (1) for their separation. This confirms our main affirmation that the TDN processes are those in which such a large (“critical”) fraction of nuclear nucleons is emitted whose excess leads to showing qualitatively new properties (see Ref. [2]). In particular, from the analysis results presented in the above figures, it has been found that 82% of the cases from group II have  $R < 0.3$ ; i.e., weak correlations related to the variable  $p_t$ , and depending on  $Q$ , mainly take place; and in all the considered cases, a strong change of the form of the  $Q$  and  $A_p$  dependences of  $|R|$  is observed. For example, the correlations weaken with increasing  $A_p$ , and the variable  $R$  gets the lowest values of all the considered ones in  ${}^{12}\text{CC}$  interactions. The character of the  $Q$  dependence of  $|R|$  also changes simultaneously with the weakening of the correlations in the region of large  $Q$  (TDN region). This dependence is in line with a “break” for  $pC$  and  $dC$  interactions; it is of the step-by-step form for  ${}^4\text{HeC}$  interactions and of the “zigzag” form for  ${}^{12}\text{CC}$  interactions. It is possible that the “zigzag” form is the result of the influence of density fluctuations of nuclear matter in the TDN region on these dependences. In an earlier paper [12] (in the studies of the multiplicity distributions and their second moments for negative charged particles produced in “central” collisions and in interactions of minimum trigger in  ${}^{32}\text{S}+{}^{32}\text{S}$  collisions at 200A GeV over different rapidity intervals), it has been found that the models of FRITIOF and VENUS mainly describe the dependence of second moments on rapidity intervals for events with a minimum trigger and not for “central” collisions. The conclusion has been drawn that the behavior of second moments for “central” collisions indicates increasing the multiplicity fluctuation. These obser-

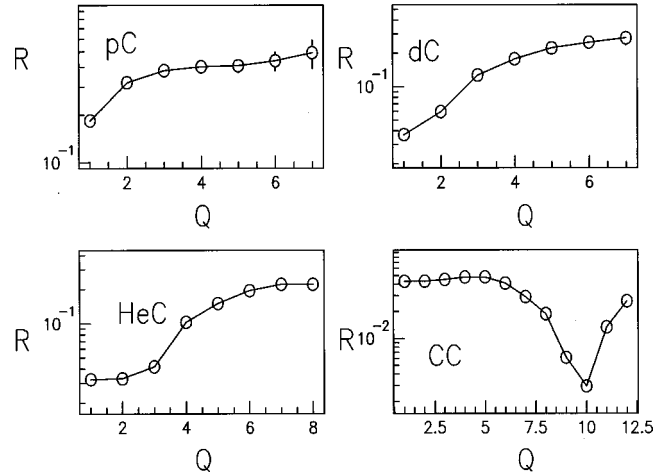


FIG. 5.  $Q$  dependence of  $|R(p_t, y)|$  for protons in  $pC$ ,  $dC$ ,  ${}^4\text{HeC}$ , and  ${}^{12}\text{CC}$  interactions. The values of  $R$  shown at  $Q = 1, 2, 3, \dots$  correspond to the groups of events with  $Q \geq 1, 2, 3, \dots$ , respectively.

vations support the conclusions from the analysis of entropy. The entropy for central  ${}^{32}\text{S}+{}^{32}\text{S}$  is larger than that expected in the models. The results of the present paper also confirm this conclusion. We also think that the “zigzag” form in events with the total disintegration of nuclei can be connected with the density fluctuations of nuclear matter at large  $Q$ .

Under these experimental conditions, we have observed a strong  $Q$  dependence of the mean values of the kinetic energy of  $\pi^-$  mesons in  ${}^{12}\text{CC}$  interactions in the region  $Q \geq Q^*$  of the total disintegration of nuclei. The present results show that this is possibly due to the fluctuations of the nuclear density in events with the total disintegration of nuclei. It has already been concluded [13] that the transparency of nuclear matter in “central” collisions decreases significantly. In the authors’ opinion, it is testimony of a high baryon density reached in the investigated interactions. We assume that at our energies they are mixed states corresponding to different degrees of freedom, as well as quark-gluon degrees of freedom; for protons, the behaviors of  $R(\theta, p_t)$  (Fig. 4) and  $R(p_t, y)$  (Fig. 5) versus  $Q$  are similar and differ from the behavior of the  $Q$  dependence of  $R(p, p_t)$  (Fig. 3).

#### ACKNOWLEDGMENTS

The authors would like to thank the staff of the 2-m propane bubble chamber for giving the experimental material, N. Amelin and A. Golokhvastov for useful discussions, O. Rogochevsky for his help, and also A. M. Baldin for his permanent attention to the work. This work was performed at the Laboratory of High Energies, JINR and was supported by Grant INTAS-96-0678.

[1] E. A. De Wolf, I. M. Dremin, and W. Kittel, *Usp. Fiz. Nauk* **163**, 3 (1993).

[2] O. B. Abdinov *et al.*, JINR Report No. 1[75], 1996, p. 51.

[3] O. B. Abdinov *et al.*, JINR Report No. 1[81], 1997, p. 109.

[4] O. B. Abdinov *et al.*, JINR Report No. E1-97-178, 1997, p. 1.

[5] P. Abreu *et al.*, *Phys. Lett. B* **247**, 137 (1990); A. De Angelis, *Mod. Phys. Lett. A* **5**, 2395 (1990).

[6] I. V. Ajenko *et al.*, *Phys. Lett. B* **222**, 306 (1989); I. V.

- Ajienko *et al.*, *ibid.* **235**, 373 (1990); N. M. Agababyan *et al.*, *ibid.* **261**, 165 (1991).
- [7] C. Albajar *et al.*, Nucl. Phys. **B345**, 1 (1990).
- [8] The BBCDHSSTTU-BW Collaboration, A. U. Abdurakhimov *et al.*, Phys. Lett. **39B**, 371 (1972).
- [9] N. Akhababian *et al.*, JINR Report No. 1-12114, 1979.
- [10] K. N. Ermakov, O. V. Rogochevskiy, and M. V. Stabnikov, RAS Report No. 2012, 1994, p. 1.
- [11] T. Akesson *et al.*, Z. Phys. C **53**, 183 (1992).
- [12] J. Bachler *et al.*, Z. Phys. C **56**, 347 (1992).
- [13] J. Berrette *et al.*, Phys. Rev. C **50**, 3047 (1994).