сообщения
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E2-81-96

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THE PROCESS $\gamma N \to \gamma X$ IN THE THEORY WITH BROKEN COLOUR SYMMETRY

1981

1. INTRODUCTION

During many years there exists a widely spread opinion that the quark model with broken colour symmetry, of the type in refs.[1,2], contradicts the available experimental data. However, investigations of integer charged models, unifying the electromagnetic and strong interactions in the framework of gauge theories, have shown that the available extensive experimental information cannot give a unique answer to the question - what are true charges of quarks? The most essential argument against integer charge theory is the absence of the resonance in e^+e^--annihilation into muon pair through an intermediate heavy gluon[3]. The data[4] lead to the limitation on invariant charges of the unified model $g_1^2(\mu)/g_3^2(\mu) \lesssim 10^{-3}$ (where g_1 and g_3 are the singlet and octet charges and μ is the gluon mass) which can hold at $\mu \lesssim 0.3$ GeV only*. Concerning the anomalous magnetic moment of muon[6], it agrees with the predictions of the integer charged model, if the condition $\frac{g_1^2(|q^2| \ll \mu^2)}{g_3^2(|q^2| \ll \mu^2)} \lesssim 10^{-4}$ is fulfilled (the quantity $g_3(|q^2| \ll \mu^2)$ here is perfectly defined, since the gluon mass is not zero). If experiments in the future will necessitate decreasing of the gluon mass, this will support (but not prove) the exact colour symmetry models. The latter is caused by the fact that with the gluon mass tending to zero, the unified models of the type U(1)xSU(3) are splitted into QED, standard QCD and scalar fields. The averaging of the electric charge of quarks[7,8] over the colour in the lepton-hadron inelastic reactions made the predictions of QCD and unified models almost indistinguishable (at recent level of precision). Only a considerable breaking of the Callan-Gross relation[9] can be thought of as an argument in favour of unified theories. In our opinion, the investigations of deep inelastic reactions with participation of real γ-quanta are most convincing for the elucidation of the problem of colour symmetry. The processes $\gamma N \to \mu^- \mu^+$, $\gamma\gamma^* \to$ jets, $ep \to e\gamma X$ and $e^+e^- \to \gamma +$jets have been considered in papers[10-15]. All the above reactions contain only one real pho-

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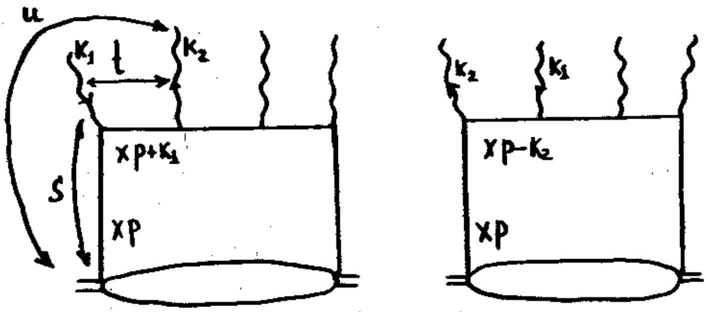
* Asymptotical properties of gauge U(1)xSU(3) model and limitations from electromagnetic data were investigated in ref.[5].

ton; this allows one, as has been shown by Witten[10], to define the true charge of a quark even if the accuracy of measurements is not high. Large virtuality of another photon is necessary for picking out the parton subprocesses. In this paper we propose to use for this aim the high P_T photon production in photon beam. In Sec.2 we formulate the conditions of applicability of the parton model for the $\gamma N \to \gamma X$ process with two real photons. In Sec.3 we define the characteristics which being measured, could be a good test for alternative quark models. In Sec.4 a possible interpretation of the experimental data[16] in the framework of QCD and unified model with integer charged quarks is discussed and argued that they are in the favour of the former model.

2. KINEMATICS OF THE PARTON MODEL IN THE $\gamma N \to \gamma X$ REACTION

For elucidation of the kinematic region of the parton subprocesses, we consider the diagrams of figs.1a and b.



a) Fig.1 b)

Necessary conditions to pick out the parton subprocesses are 1) a large value of the invariant mass of the final state $m_x^2 \gg m_N^2$; 2,3) a large virtuality of momenta $xp+k_1$ and $xp-k_2$ that results in the inequalities $xS \gg m_N^2$, $xu \gg m_N^2$ and 4) $t \gg m_N^2$, where S, u and t are the Mandelstam variables. Upon passing to the variables $x = \frac{t}{S-u}$ and $y = u/S$, we get limitations in the following form:

$$1)\ (1-x) \gg \frac{m_N^2}{S(1-y)}, \qquad 3)\ yx \gg \frac{m_N^2}{S},$$

$$2)\ x \gg \frac{m_N^2}{S}, \qquad 4)\ x \gg \frac{m_N^2}{S(1-y)}.$$

An additional condition is caused by the necessity of picking out the final photons with large transverse momentum 5) $k_T^2 \gg m_N^2$ to separate the pionization region in which the standard perturbation theory is not applicable. In term of the variables x and y we get

$$5)\quad xy(1-y) \gg \frac{m_N^2}{S},$$

x and y are connected with k_T as follows:

$$x(1-y)\left[1-\frac{x(1-y)m_N^2}{yS}\right]=\frac{k_T^2}{yS}\ .$$

The above conditions are given in Fig.2, which shows that the most constrained is the condition (5).

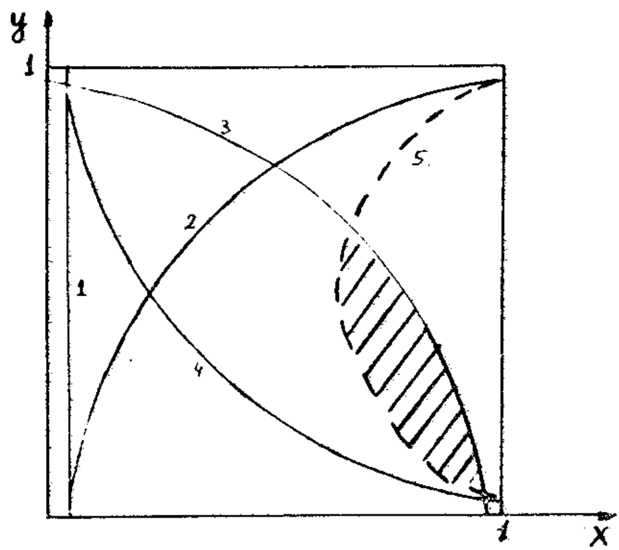


Fig.2

3. DEEP-INELASTIC COMPTON PROCESS IN THE U(1)xSU(3) MODEL

Let us investigate the $\gamma N \to \gamma X$ process in the framework of the U(1)xSU(3) model of electromagnetic and strong interaction. A part of the Lagrangian, describing the electromagnetic interaction of quarks and gluons, has the form

$$\mathcal{L}_{int}=-g_1\left(1+\frac{2Dg_1^2}{g_3^2}\right)^{-1/2} A_\mu\left[\sum_q\sum_i Q_i^{(q)}\bar{q}_i\gamma^\mu q_i+\sum_G Q_G j_G^\mu\right]+ \qquad (3.1)$$

$$+g_3^2(A_\mu A_\nu)\left(1+\frac{2Dg_1^2}{g_3^2}\right)\sum_G Q_G^2(G_\mu^+G_\nu^- - g_{\mu\nu}G_\rho^+G_\rho^-),$$

where

$$j^{\mu}_{F} = i[G^{-}_{\mu\nu} G^{+}_{\nu} - G^{+}_{\mu\nu} G^{-}_{\nu} + \partial_{\nu}(G^{+}_{\mu} G^{-}_{\nu} - G^{-}_{\mu} G^{+}_{\nu})];\ G^{\pm}_{\mu} = D^{\pm}_{\mu}, E^{\pm}_{\mu}, V^{\pm}_{\mu},$$

g_1 is the singlet gauge constant and g_3 is the octet gauge constant. The charges of quarks are chosen as following

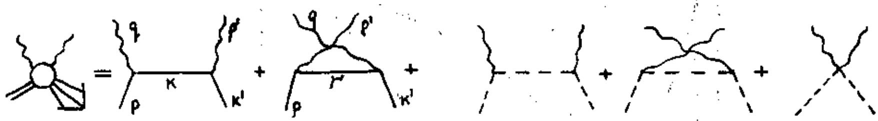
$$u(Q_1, Q_2, Q_3), \qquad D = \sum_{i=1}^{3} Q_i^2 - \frac{1}{3}(\sum_i Q_i)^2,$$

$$d(Q_1-1, Q_2-1, Q_3-1), \qquad Q_D = Q_1 - Q_2,\ Q_E = Q_1 - Q_3,\ Q_V = Q_2 - Q_3,$$

$$S(Q_1-1, Q_2-1, Q_3-1),$$

$$c(Q_1, Q_2, Q_3), \qquad Q_1 \geq Q_2 \geq Q_3,$$

which satisfies the condition $\sum_{i=1}^{3} Q_i = 2$ necessary for classification of elementary particles. Consider now the diagram contributing the subprocess in the unified model



a) b) c) d) e)

Fig.3

The wavy line denotes the photon; and the dashed and solid ones, the massive gluon and quark, correspondingly. The calculation of the diagrams a and b (Fig.3) is trivial. The Compton scattering on vector particles within the Pati-Salam model has been considered in refs. [17,18], however, some errors have been commited in cumbersome calculations of the differential cross section. Hence, the final result contains the term violating the unitarity. Moreover the presence of the term $\sim \sin^2\theta/\mu^2$ under recent restrictions on the gluon mass $\mu \lesssim 0.3$ GeV [5] would have caused the contradiction with the experimental data[16]. For this reason, we give the details of the calculations of the $\gamma G^{\pm} \to \gamma G^{\pm}$ subprocess. The simplest method of calculating the diagrams of Figs.3 is based on picking out the contributions violating unitarity just in the amplitude and on proving their cancellation. To this end we shall transform each of the amplitudes $\mathfrak{M}_G = \mathfrak{M}_c + \mathfrak{M}_d + \mathfrak{M}_e$ to the form

$$\mathfrak{M}_c^{(i,j)} \sim \frac{(Q_i - Q_j)^2}{k^2 - \mu^2} e_{p'}^{\beta} e_q^{\alpha} \{-2k_\alpha k_\beta + \frac{(k^2+\mu^2)^2}{\mu^2}(g_{\alpha\beta} - \frac{k_\alpha k_\beta}{k^2+\mu^2}) +$$

$$+ \frac{(k^2+\mu^2)}{\mu}[2k(e_p + e_{k'})\delta_\beta^\alpha + 2p_\beta e_p^\alpha - 2p^\alpha e_p^\beta + 2k'_\alpha e_{k'}^\beta - 2k'_\beta e_{k'}^\alpha - \quad (3.2)$$

$$- k^\beta e_p^\alpha - k^\alpha e_{k'}^\beta] + [2ke_{k'} g_{\nu\beta} + 2k'_\nu e_{k'}^\beta - 2k'_\beta e_{k'}^\nu - k_\nu e_{k'}^\beta] \times$$

$$\times [2ke_p g_{\nu\alpha} + 2p_\nu e_p^\alpha - 2p_\alpha e_p^\nu - k_\nu e_p^\alpha]\},$$

$$\mathfrak{M}_d^{(i,j)} \sim \frac{(Q_i - Q_j)^2}{r^2 - \mu^2} e_{p'}^{\beta} e_q^{\alpha} \{-2r_\alpha r_\beta + \frac{(r^2+\mu^2)^2}{\mu^2}(g_{\alpha\beta} - \frac{r_\alpha r_\beta}{r^2+\mu^2}) +$$

$$+ \frac{(r^2+\mu^2)}{\mu}[2r(e_p + e_{k'}) g_{\alpha\beta} + 2p_\alpha e_p^\beta - 2p_\beta e_p^\alpha + 2k'_\beta e_{k'}^\alpha - 2k'_\alpha e_{k'}^\beta -$$

$$- r^\alpha e_p^\beta - r_\beta e_{k'}^\alpha] + [2re_{k'} g_{\nu\alpha} + 2k'_\nu e_{k'}^\alpha - 2k'_\alpha e_{k'}^\nu - r_\nu e_{k'}^\alpha] \times \quad (3.3)$$

$$\times [2re_p g_{\nu\beta} + 2p_\nu e_p^\beta - 2p_\beta e_p^\nu - r_\nu e_p^\beta]\},$$

$$\mathfrak{M}_e^{(i,j)} \sim (Q_i - Q_j)^2 e_{p'}^{\beta} e_q^{\alpha} \{\frac{1}{\mu^2}(k_\alpha k_\beta + r_\alpha r_\beta - 2k'p\, g_{\alpha\beta}) +$$

$$+ \frac{1}{\mu}[k_\alpha e_{k'}^\beta + k_\beta e_p^\alpha + r_\beta e_{k'}^\alpha + r_\alpha e_p^\beta - 2(pe_{k'} + k'e_p)\, g_{\alpha\beta}] +$$

$$+(e_p^\alpha e_{k'}^\beta + e_p^\beta e_{k'}^\alpha - 2g^{\alpha\beta}(e_p e_{k'}))\}. \quad (3.4)$$

Expressions (3.2-4) are derived by separating the terms k'_ν/μ and p_ν/μ from the polarization vectors of gluons and contain the terms $\sim 1/\mu$ and $1/\mu^2$ violating unitarity of the amplitude. However, in the sum of matrix elements these contributions are reduced, and after simple mathematical transformations we get

$$\mathfrak{M}_G^{(i,j)} = \mathfrak{M}_c^{(i,j)} + \mathfrak{M}_d^{(i,j)} + \mathfrak{M}_e^{(i,j)} \sim (Q_i - Q_j)^2 e_{p'}^{\beta} e_q^{\alpha} \{4(\frac{1}{2} g_{\beta\alpha} - \frac{k_\alpha k_\beta}{k^2+\mu^2} - \frac{r_\alpha r_\beta}{r^2+\mu^2}) +$$

$$+ \frac{1}{k^2 - \mu^2}[2(k e_{k'}) g_{\mu\beta} + 2k'_\mu e_{k'}^\beta - 2k'_\beta e_{k'}^\mu - k_\mu e_{k'}^\beta] \times$$

$$\times [\, 2(ke_{p})g_{\alpha\mu} + 2p_{\mu} e^{p}_{\alpha} - 2p_{\alpha} e^{\mu}_{p} - k_{\mu} e^{\alpha}_{p'}] +$$

$$+ \frac{1}{r^2 - \mu^2} [\, 2(r e_{k'})g_{\alpha\mu} + 2k'_{\mu} e^{\alpha}_{k'} - 2k'_{\alpha} e^{k'}_{\mu} - r_{\mu} e^{\alpha}_{k'}] \times \tag{3.5}$$

$$\times [\, 2(re_{p})g_{\mu\beta} + 2p_{\mu} e^{\beta}_{p} - 2p_{\beta} e^{\mu}_{p} - r_{\mu} e^{\beta}_{p}] +$$

$$+ e^{\alpha}_{p} e^{\beta}_{k'} + e^{\beta}_{p} e^{\alpha}_{k'} - 2(e_{p} e_{k'}) g^{\alpha\beta} \} + O(\frac{\mu}{|k|}, \frac{\mu}{|r|}) .$$

The above cancellation is a natural consequence of renormalizability of the theory.

Using the amplitude (3.5), we get for the gluon subprocesses

$$|\mathfrak{M}^{(i,j)}_{G}|^2 \sim \frac{1}{3}(Q_i - Q_j)^4 \{20 + 8[(\frac{s}{u} + \frac{u}{s})^2 - 2(\frac{s}{u} + \frac{u}{s})]\} . \tag{3.6}$$

The differential cross section of the reaction $\gamma N \to \gamma X$ with quark and gluon contributions has the form

$$\frac{d^2\sigma_{unif}(\gamma N \to \gamma\gamma X)}{d\epsilon_2\, d\Omega} = \frac{\alpha^2 \sum_a' \bar{Q}_a [\, q_a(x) + \bar{q}_a(x)]}{2m_N \epsilon_1^2 [\, 1 - \sqrt{1 - k_T^2/\epsilon_1^2 y^2}\,]} \times \tag{3.7}$$

$$\times (y + \frac{1}{y}) \{1 + \frac{1}{3} R_N(x) [\, 10(y + \frac{1}{y})^{-1} + 4(y + \frac{1}{y}) - 8]\} .$$

The quantity $R_N(x)$ in (3.7) characterized the violation of the Callan-Gross relation and is determined from the deep inelastic ep-scattering

$$R_N(x) = \frac{1}{3} [\, (Q_1 - Q_2)^4 + (Q_1 - Q_3)^4 + (Q_2 - Q_3)^4] \, \frac{(G^+(x) + G^-(x))}{\sum_a \bar{Q}_a (q_a(x) + \bar{q}_a(x))} , \tag{3.8}$$

where $\bar{Q}_q = \frac{1}{3} \sum_i Q^4_{i(q)}$, for the integer charged model $D = 2/3$. $G^{\pm}(x)$ are the gluon distribution functions, and $q(x)$, $\bar{q}(x)$ are the quark distribution functions inside the nucleon. The experiments on the isoscalar nuclear target are most desirable from the viewpoint of the theory. The fact is that the main uncertainty of formula (3.7) is caused by inaccuracy of the fit of the parton distribution functions inside the hadron. If the differential cross section of the production of γ-quanta with large k_T on the isoscalar target is normalized to the differential cross section of the process $eM_{i.s.} \to eX$ (under the same definitions of x and y through the Mandelstam variables), then the parton distribution functions will be cancelled and for the integer charged model we have

$$\frac{d^2\sigma^{\gamma M_{i.s.}}_{unif}}{d\epsilon_2 d\Omega} / \frac{d^2\sigma^{eM_{i.s.}}_{unif}}{d\epsilon_2 d\Omega} = \frac{9}{5}(y+\frac{1}{y})\{1+\frac{20}{9}R\ (x)[10(y+\frac{1}{y})^{-1}+$$

$$+4(-2+y+\frac{1}{y})]\}/\{1+\frac{y(1+R_d(x))}{(1-y)^2}[1+\sqrt{1-k^2/y^2\epsilon_1^2}]\} . \tag{3.9}$$

The transition to QCD from expression (3.9) can be realized by substituting the coefficients 9/5 by 17/45 and by equating $R_d(x)$ to zero. The value of $R_d(x)$ is known from the deep inelastic lepton-hadron processes [19] and in the region of not small values of x it is actually the constant ($R_d \simeq 0.15 + 0.2$)*. Assuming the energy of the photon in the bremsstrahlung beam $\epsilon_1 = 40$ GeV, we obtain the curves for $k_T = 3$ GeV which are represented in Fig.4. The solid line is the results of calculation by (3.9) and the dashed line the QCD predictions.

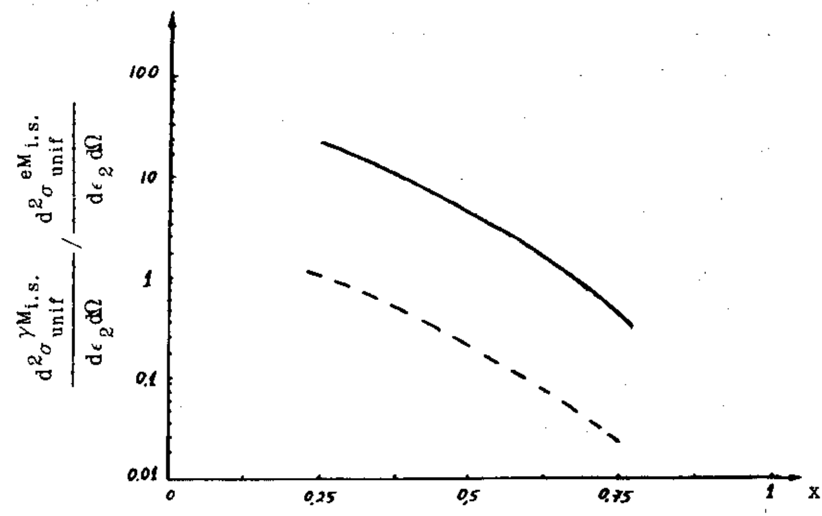


Fig.4

* Within the unified model the value of R_d can be calculated theoretically, the result $R \simeq 0.15$ being in good agreement with experiment.

4. ANALYSIS OF THE COMPTON EFFECT ON PROTON

The experimental investigation of the deep-inelastic Compton scattering has been carried out at the Stanford Linac six years ago and the results of measurements are published in paper [26]. The secondary photon in the initial photon beam 21 GeV has been registered. The π^0 -meson contribution has been controlled by two photon events and subtracted while analysing the data. However, the value of the photon transverse momentum was limited by $k_T^2 \leq (1.7\ \mathrm{GeV})^2$. We shall analyse the data with $k_T^2 = (1.7\ \mathrm{GeV})$ though this value can be hardly considered as large enough. A further ambiguity due to fitting of the parton distribution functions lead to provisional and approximate interpretation of the experimental data [16] in the framework of the parton model. The greatest ambiguity is caused by fitting of the gluon distribution functions, though in the unified theory there is additional information concerning this problem. The recent measurements of $R_p = \sigma_L/\sigma_T$ [19] show the existence of the prominent x -dependence. Let us take the quark distribution function similar to ref. [20]. Taking into account the relation of $R_p(x)$ with the quark and gluon distribution function (see ref. [21]), we get a satisfactory agreement of the values of $G^+(x) + G^-(x) = 2.3\frac{(1-x)^{3.5}}{x}$ with the data of ref. [19]. The relevant curve is shown in fig.5. Compare the calculated differential cross section of photon production with large k_T in the framework of the unified model and of the standard QCD with the measurements of ref. [16].

$$\frac{d^2\sigma_{unif}^{(\gamma p\to\gamma x)}}{d\epsilon_2\, d\Omega} = \frac{\alpha^2[2(u(x)+\bar{u}(x))+d(x)+\bar{d}(x)]}{6m_N\epsilon_1^2[1-\sqrt{1-k^2/\epsilon_1^2 y^2}]}\Big\{ y + \frac{1}{y} + \tag{4.1}$$

$$+\frac{2(G^+(x)+G^-(x))}{3[2(u(x)+\bar{u}(x))+d(x)+\bar{d}(x)]}[10+4(y+\frac{1}{y})^2 - 8(y+\frac{1}{y})]\Big\},$$

$$\frac{d^2\sigma_{QCD}^{(\gamma p\to\gamma X)}}{d\epsilon_2\, d\Omega} = \frac{\alpha^2(y+1/y)[16(u(x)+\bar{u}(x))+d(x)+\bar{d}(x)]}{162 m_N\epsilon_1^2[1-\sqrt{1-k_T^2/\epsilon_1^2 y^2}]}\,. \tag{4.2}$$

In fig.6 the solid line is the result obtained within the $U(1)\times SU(3)$ model; and the dashed line, within the QCD.

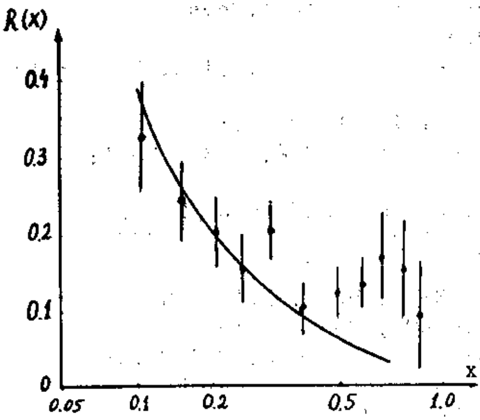


Fig.5

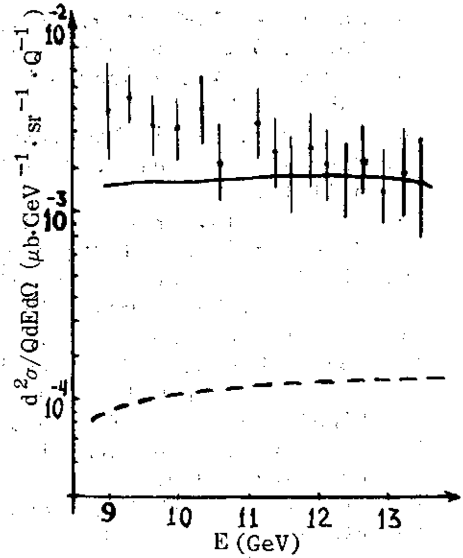


Fig.6

Though the predictions of the unified model are in better agreement with experiment than QCD, the limitations defined in Sec.2 do not allow us to state that the quark charges are integer. More definite conclusions could be obtained on the photon beam with the energy 40÷100 GeV and transverse momentum of secondary photons $k_T \sim 3-5$ GeV. In this case, as has been mentioned in Sec.3, the measurements on the isoscalar target are most desirable. The result of such an experiment might be crucial for the elucidation of the electromagnetic charge of quarks (the contribution of high perturbation orders is insignificant if the difference is of an order of 10 /22/).

ACKNOWLEDGEMENTS

The authors are grateful to D.V.Shirkov, V.A.Matveev and G.M.Vereshkov for helpful discussions.

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Received by Publishing Department
on February 9 1981.