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SPACE-TIME PICTURE OF PHOTON-NUCLEON INTERACTION
IN QCD BORN APPROXIMATION

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ABSTRACT

A model of photon-nucleon interactions in which the high-energy photon is transformed into a $q\bar{q}$ pair in a pointlike way is considered. The interaction of this pair with a nucleon takes place via one gluon exchange. In such an approach, one can obtain the value of the photon-nucleon cross-section $\sigma(\gamma N)$ with meaningful values of α_s ($\alpha_s^2 \approx 0.5$). Using an independent fragmentation model, we calculate the x -dependence of the inclusive photoproduction spectra for π^0 mesons which is in agreement with the experimental data.

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INTRODUCTION

The main interest in the processes of the interaction of high-energy photons with nucleons and nuclei is due to the fact that they allow to study the hadronic structure of the photon [1]. The existence of a hadronic component in the photon wave function is usually formulated in the framework of the vector dominance model (VDM) or its modifications.

In such a type of models the total photon-nucleon cross-section can be expressed in terms of the total cross-sections of the vector meson interactions with nucleons $\sigma(VN)$ in a simple way:

$$\sigma(\gamma N) = \sum_v \frac{4\pi\alpha}{g_v^2} \sigma(VN) \quad (1)$$

where $g_v^2/4\pi$ are the coupling constants of vector mesons with the photon. They can be determined from the decay modes of vector mesons into a lepton pair. If one sums over all well-established vector mesons [2] in Eq. (1), namely, $v = \rho, \omega, \phi, \rho'(1600), \phi'(1680)$, then to obtain the experimental value of the photon-nucleon total cross-section [$\sigma(\gamma N) \approx 115 \mu\text{b}$ at energies $E_\gamma \gtrsim 30 \text{ GeV}$], one has to assume that the total cross-sections of the interaction of heavy vector mesons with nucleons decrease with the mass of these mesons [1] $\sigma(VN) \sim 1/M_v^2$. This assumption is difficult to understand within the framework of the modern approaches. Thus, if the impulse approximation for the quark model is valid, then the cross-sections for mesons with identical quark composition must be equal.

On the other hand, in the framework of the Low-Nussinov model [3], one can describe [4] the total cross-sections for hadron-nucleon interaction, which depend on the hadron sizes. The mesons with large masses are radial excitations of the ground state mesons (ρ, ω, ϕ), so in such an approach their cross-sections must increase with the mass rather than falling off.

This discrepancy can be removed [5] if one takes into account the colour screening effect in the quark-antiquark pair. It is well known [1] that the mean lifetime of a real photon in a hadronic or $q\bar{q}$ state is determined by its energy v and the mass of this state M , $\tau = 2v/M^2$. If the transition $\gamma \rightarrow q\bar{q}$ takes place at a distance z from the target, then one can easily obtain [6] that the transverse separation r between $q\bar{q}$ is $r = \langle p_\perp \rangle z / vx(1-x)$. Here $\langle p_\perp \rangle$ is the quark mean-transverse momentum; x is the fraction of the photon momentum carried by the quark. As long as the pair produced by the photon is a colour dipole, its interaction cross-section with a nucleon is small at small r . Thus the $q\bar{q}$ pairs which are created near the target interact with it with a small cross-section, in contrast to the VDM type models where there is no distance dependence.

The same effect takes place in QED [7]: the electric charge screening in the process of lepton pair photoproduction from an external field. In the papers [4] the total cross-sections of hadron-hadron interactions were calculated in the two-gluon exchange approximation for the forward scattering amplitude. In such an approach, one can see the importance of the colour-screening effect. In what follows, we consider the total cross-section and inclusive spectra of photon induced reactions in an analogous way.

1. - THE PHOTON-NUCLEON CROSS-SECTION

In the lowest order of non-covariant perturbative theory, the process of photon-nucleon interaction takes place in two steps: a high-energy photon is transformed into a $q\bar{q}$ pair which then interacts with a nucleon via one gluon exchange (Fig. 1a,b). The cross-section for producing a quark with transverse momentum $p_{\perp}$ and fraction of longitudinal momentum x can be expressed as follows:

$$d\sigma = \frac{2}{3} (4\pi\alpha_s)^2 \sum_i |\Psi_i(x, p_{\perp}) - \Psi_i(x, p_{\perp}+n)|^2 \frac{|A(n)|^2}{n^4} \frac{dn^2}{(2\pi)^2} \frac{d^2 p_{\perp}}{(2\pi)^2} \frac{dx}{2(2\pi)x(1-x)} \quad (2)$$

where α_s is the gluon-quark (gqq) coupling constant

$$\Psi_i(x, p_{\perp}) = e e_i x(1-x) \frac{\bar{u}_i(x, p_{\perp}) \hat{E} V_i(x, p_{\perp})}{p_{\perp}^2 + m_i^2} \quad (3)$$

is the photon wave function composed of the quarks with flavour i ($i = u, d, s, \dots$); $|A(n)|^2$ is the square of the $gp \rightarrow 3q$ transition amplitude integrated over the phase space. Expressing this quantity in terms of the nucleon form factor as in Ref. [4] and transforming the photon wave function (3) in the transverse space representation, one obtains from (2) and (3) the following relations:

$$d\sigma = \frac{8}{3} \alpha_s^2 (1 - J_0(nz)) (1 - F(3n^2)) |\Psi(x, z)|^2 \frac{dn^2}{n^3} \frac{dz^2}{2} dx \quad (4)$$

$$|\Psi(x, z)|^2 = 3 \frac{2\alpha}{\pi} \sum_i e_i^2 m_i^2 \left[K_0^2(m_i^2 z) + (x^2 + (1-x)^2) K_1^2(m_i^2 z) \right] \quad (5)$$

Here J_0 , K_0 , K_1 are the Bessel functions and $F(n^2)$ is the nucleon form factor. One can see that the cross-section considered can be expressed in a factorized form:

$$d\sigma = \sigma(z) |\Psi(x, z)|^2 dz dx \quad (6)$$

Here

$$\sigma(z) = \frac{8}{3} d_s^2 \int (1 - J_0(nz)) (1 - F(3n^2)) \frac{dn}{n^3} \quad (7)$$

is the imaginary part of forward scattering amplitude for the system $q\bar{q}$ with transverse separation r on a nucleon. Note that (7) has no infra-red divergences which are usually present in QED. Using the dipole parametrization for the nucleon form factor, $F(q^2) = 1/(1+q^2/M^2)^2$, we derive from (7) the following expression:

$$\sigma(z) = \frac{16\pi d_s^2}{M_0^2} \left[1 - \frac{M_0^2}{\sqrt{3}} K_1\left(\frac{M_0 z}{\sqrt{3}}\right) + 4 \left(c + \ln \frac{M_0 z}{\sqrt{3}} + K_0\left(\frac{M_0 z}{\sqrt{3}}\right) + \frac{2\pi M_0 z}{\sqrt{3}} \left(\bar{J}_1\left(\frac{M_0 z}{\sqrt{3}}\right) - J_1\left(\frac{M_0 z}{\sqrt{3}}\right) \right) \right) \right]$$

where J_1 and $\bar{J}_1$ are the Bessel and Anger functions, $c = 0.577$ is the Euler constant. At small r the expressions (5) and (8) behave like

$$|\Psi(z)|^2 \sim \frac{1}{z^2} \quad (9)$$

$$\sigma(z) \sim z^2 \ln \frac{M_0 z}{\sqrt{3}} \quad (10)$$

Note that the behaviour (10) differs from the frequently used [7,8] dipole formula $\sigma \sim r^2$. The reason is that the authors of Ref. [7] expand the expression of type (7) under the integral, whereas the asymptotic (10) was obtained after exact integration in (7). From (6) one can immediately obtain the following expression for the photon-nucleon interaction cross-section:

$$\frac{d\sigma}{dx} = 4 d_s^2 x \sum_i \frac{\xi_i^2}{m_i^2} \left[C_1(m_i) + (x^2 + (1-x)^2) C_2(m_i) \right] \quad (11)$$

where

$$C_1(m_i) = \int \frac{\sinh \theta - \theta}{\cosh \theta - 1} \frac{\cosh \theta - 1 + 2\xi_i^2}{(\cosh \theta - 1 + \xi_i^2)^2} d\theta$$

$$C_2(m_i) = \int \frac{\theta \cosh \theta - \sinh \theta}{\cosh \theta - 1} \frac{\cosh \theta - 1 + 2\xi_i^2}{(\cosh \theta - 1 + \xi_i^2)^2} d\theta$$

$$\xi_i^2 = \frac{M_0^2}{6 m_i^2}$$

Choosing the usual value $M_0^2 = 0.71 \text{ GeV}^2$ and the quark masses [9] $m_u = m_d = 300 \text{ MeV}$, $m_s = 500 \text{ MeV}$, one can see that the experimental value of the total photon-nucleon cross-section is obtained if $\alpha_s^2 \approx 0.5$. The small value of α_s despite the Born approximation calculations for soft processes indicates that the main features of the photon-nucleon interaction are well described by the above picture. What are

the reasons why such a simple model works? The typical momentum transferred giving the main contribution in (7) is not small, $n \approx 0.5$ GeV. If for a rough estimate, one uses the well-known expression

$$\alpha_s(n) = \frac{4\pi}{11 - \frac{2}{3}n_f} \frac{1}{\ln \frac{n^2}{\Lambda^2}}$$

and takes $\Lambda = 180$ MeV, one finds that the $\alpha_s(0.5) \approx 0.7$. Above, we did not take into account the mutual interaction in the $q\bar{q}$ pair. This can be motivated by the fact that the asymptotic behaviour of the photon wave function (5) is determined by the Bessel functions K_0 and K_1 which have exponential dependence for high values of their arguments. So the main contribution to the cross-section comes from the $q\bar{q}$ pairs with small transverse separation $r \lesssim 1/2m \approx 0.3f$.

We repeat all the above calculations for the interaction of high-energy pions with nucleons. The only difference from the photon case is the wave function of the pion which is chosen to be

$$\psi_i(x, p_\perp) = g e_i \frac{\bar{u} \gamma_5 V}{m_\pi^2 - \frac{p_\perp^2 + m_i^2}{x(1-x)}} \quad (12)$$

The constant g can be calculated from the decay $\pi \rightarrow \mu\nu$. If one uses the value $\alpha_s = 0.7$ as in the photon case the total pion-nucleon cross-section will be $\sigma(\pi N) = 1.5$ mb, which is smaller than the experimental one by an order of magnitude. This is a reflection of the fact that the physical pion is an extended object and couples with the $q\bar{q}$ pair in a non-pointlike way in contrast with assumption (12).

2. - INCLUSIVE SPECTRA OF MESONS IN PHOTOPRODUCTION

Next we apply the above results to the calculation of the inclusive spectra of mesons initiated by photons. In the independent fragmentation models these spectra can be expressed as follows [10]:

$$\frac{d\sigma}{dx} = \sum_i \int_x^1 \frac{d\sigma_i}{dx'}(x') D_i^M\left(\frac{x}{x'}\right) \frac{dx'}{x'} \quad (13)$$

Here $d\sigma_i/dx$ is the inclusive spectrum for photoproduction of a quark of type "i" on a nucleon; $D_i^M(x)$ is the fragmentation function for transforming a quark "i" into a meson M which we took from Ref. [10]. It is convenient to calculate the ratio $(1/\sigma)(d\sigma/dx)$ which does not depend on α_s . In Fig. 2 the results for the x -dependence of this quantity for the process $\gamma p \rightarrow \pi^0 X$ are presented. The upper

curve was calculated with the help of Eq. (13) with the spectra $d\sigma_i/dx$ from Eq. (11). The lower curve was calculated with the inclusive spectrum of the quark from Ref. [12]. There, the colour-screening effect due to the interference between diagrams of Fig. 1 was ignored and the form of the quark distribution $d\sigma_i/dx \sim x^2+(1-x)^2$ corresponds to massless QED. As can be seen from Fig. 2 the experimental data are well described in the framework of the present work.

CONCLUSIONS

We have proposed a simple approach to describe the photon-nucleon interaction at high energy. In spite of the lowest order approximation of QCD, this approach gives meaningful results for total cross-sections and inclusive spectra of mesons. What we want to stress here is that the photon-nucleon interaction can be described not only by VDM-type models, but also in the picture where the photon transforms in a pointlike way to a free $q\bar{q}$ pair which then interacts with the target. It is obvious that these two mechanisms must be taken into account for the complete description of photon induced reactions. So, further investigations are necessary in order to understand the relative contribution of each mechanism and the domain of their applicability.

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FIGURE CAPTIONS

- Fig. 1 : The lowest-order non-covariant diagrams for the interaction of the high-energy photon with the nucleon.
- Fig. 2 : The x-dependence of the ratio $(1/\sigma)(d\sigma/dx)$ for the process $\gamma p \rightarrow \pi^0 x$. Experimental data [11] are presented for different energy intervals of primary photons. The solid curve is a prediction of the present work. The dashed curve was calculated with the fractional momentum distribution of a quark in a photon as in Ref. [12].

Fig. 1

Fig. 2