Phenomenological quark model and its application to quantum-number-exchanged hadronic reactions*

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A phenomenological quark model is proposed based on the hypothesis that for hadronic reactions in the small-momentum-transfer region a hadron can be viewed as an assembly of quasifree dressed-up quarks and antiquarks, which interact only through short-range interactions. Only in the deep-inelastic regions does a dressed-up quark need to be decomposed into a bare quark and the surrounding neutral partons. The application of this model to K^+N backward elastic scattering leads to a nonshrinking differential scattering cross section which has an overall power damping as the incident energy increases, and which displays a typical diffractive scattering pattern when the differential scattering cross section is normalized by its own value at the exact backward direction. Other kinds of quantum-number-exchanged hadronic reactions are also discussed.

I. INTRODUCTION

The investigation of the substructure of hadrons has become increasingly important in recent years. Scaling behavior and other properties observed in lepton-induced deep-inelastic scattering are interpreted in the parton picture[1] as evidence that hadrons are composed of partons, and the charged partons are usually identified with spin-$\frac{1}{2}$ quarks. These deep-inelastic data also suggest the existence of neutral partons, the gluons, carrying a large fraction of the energy and momentum of the parent hadron. On the other hand, the SU(6) quark model[2] and the more recent charmonium models[3] seem to explain the properties of the hadronic resonances reasonably well, based on the scheme that a hadron is composed of a small number of valence quarks and antiquarks. From these rather contradictory observations it seems reasonable to hypothesize that a hadron in the low-energy region can be viewed as an assembly of dressed-up quarks and antiquarks, and only in the deep-inelastic scattering region do the dressed-up quarks need to be decomposed into the assemblies of charged and neutral partons explicitly. The interesting question which immediately follows is how high-energy hadronic reactions in the small-momentum-transfer region can be efficiently described, by the quark-partons or by the dressed-up quarks. If the quark-parton description[4] is used, the properties of the neutral partons and their interactions with the charged partons must be given in detail to make the description meaningful. Since the properties and the behavior of the neutral partons are highly unknown, the details of the description are somewhat arbitrary and make a phenomenological approach difficult. In this paper we will, rather, concentrate on the investigation of the dressed-up-quark description of high-energy hadronic reactions in the small-momentum-transfer region.

The dressed-up-quark description, of course, does not automatically lead to the free-quark approximation.[5] For example, the quark interpretation of the dual resonance model can be considered as a kind of dressed-up-quark description, but this is contrary to the free-quark approximation. This kind of strongly-bound-quark approach leads to the very well studied Regge phenomenology, which has achieved some qualitative successes, but which also has various shortcomings and unpleasant complications. Unsatisfied with the current status of Regge phenomenology, we instead investigate the implications of the free-quark approximation in the context of the dressed-up-quark concept in this paper, and search for the places where the natural predictions of the free-quark approximation can be checked and the behavior of the dressed-up quarks can be studied. We find that a class of quantum-number-exchanged hadronic reactions is best suited for this purpose, and among them the K^+p backward elastic scattering is the most accessible reaction for the test. The significant prediction of this approach is the nonshrinkage of the differential scattering cross sections of these quantum-number-exchanged hadronic reactions, in vast contrast with the shrinkage expected from simple Regge-pole exchanges.

The free-quark approximation in the context of the quark-parton picture has been applied to diffractive scattering,[4] but the qualitative predictions of these applications are not drastically different from the predictions of other models. Merely changing to the dressed-up-quark concept does not improve this situation. In this sense we consider the investigation of diffractive scattering not useful for our purpose, and it will not be discussed further.

The concept of dressed-up quarks has been introduced in the literature[6] and applied to deep-inelastic scattering, but the free-quark approximation in the small-momentum-transfer region is not discussed there. There are some works[7] implicitly consistent with the free-quark approximation in the context of the dressed-up-quark idea, and also are applied to the quantum-number-exchanged hadronic reactions. However, the authors have used Reggeon or hadron exchanges as the mutual interaction between two dressed-up quarks, while the bindings of the quarks inside a hadron, which we consider as due to the medium-range interactions like Reggeon or hadron exchanges, are ignored without any explanation. We consider that approach self-contradictory, and such handlings are carefully avoided in our discussion. Also, the additivity assumption[5,8] is not used as an assumption in our approach.

The basic assumptions used in our investigation are described in Sec. II. Section III is devoted to the application of the model to K^+N backward elastic scattering. The situations of other quantum-number-exchanged reactions are investigated in Sec. IV, and a summary is presented in the last section.

II. GENERAL CHARACTERISTICS OF THE PHENOMENOLOGICAL QUARK MODEL

The general characteristics of this phenomenological quark model are outlined in this section to provide a base for the discussions throughout this paper. We make the following assumptions:

(A) For hadron-hadron scattering processes in the small-momentum-transfer region we assume that a hadron can be viewed as an assembly of valence quarks and antiquarks and a sea of quark-antiquark pairs. A quark or an antiquark in this picture is assumed to be the dressed-up one, that is, it is composed of a bare quark and a surrounding cloud of neutral partons if viewed in the deep-inelastic region. However, in the small-momentum-transfer region the dressed-up quarks and antiquarks behave as nonbreakable constituents, and all the energy and momentum of a parent hadron is assumed to be carried by these dressed-up quarks and antiquarks alone. In other words we do not need to consider additional neutral constituents in this picture. The sea of quark-antiquark pairs is assumed to carry the quantum number of the vacuum and a small fraction of the energy momentum of the parent hadron. The effect of the sea in the formation of hadrons and resonances is assumed to be small, but its effect in hadronic scattering can be significant and must be considered seriously.

(B) The interaction between two quarks is classified into two categories, the medium-range interaction and the short-range interaction. The medium-range interaction is mainly responsible for the formation of hadrons and resonances and contains exchange forces like particle or Regge-pole exchanges as one of its subcomponents. If the quarks are confined, it is also the role of the medium-range interaction to achieve such a confinement. The short-range interaction between two quarks can be understood by taking a classical analogy with a dressed-up quark approximated by a small sphere (small compared to the size of a hadron). The short-range interaction then is describing the nonpenetrability of a dressed-up quark by another dressed-up quark in this analogy. In a reference frame where two incoming hadrons are moving very fast in opposite directions, the duration of the interaction time between the incoming hadrons becomes very short because of Lorentz contraction of the hadrons along the direction of their three momenta. We assume that the medium-range interaction between two quarks can be ignored during this short impulse of the interaction time due to time dilation. However, the short-range interaction cannot be ignored in the above argument. If we go into the extremely-high-energy region or the deep-inelastic region, it is the description of the dressed-up quarks which will fail, and the short-range interaction must be replaced by the description of how a dressed-up quark is composed of pointlike elementary constituents and the pointlike (infinitesimally short-range) interactions between two elementary constituents.

With the basic assumptions (A) and (B), the amplitude, which describes a hadron with N quasi-free constituents which interacts with another hadron and turns into n final-state hadrons, can be written using either the old-fashioned perturbation method[9] or the Lorentz-covariant method.[10] For our phenomenological approach it is convenient to use the Lorentz-covariant method. This method requires that the virtual mass of the constituents be restricted near the hadron mass, and this restriction is equivalent to the requirement of the transverse-momentum cutoff in the old-fashioned perturbation method. The amplitude is

$$\frac{1}{i(p_1+p_2)^2}A(p_1,p_2;r_1,\ldots,r_n)$$
$$=\int\left(\prod_{i=1}^{N}d^4k_i\right)\delta^4\left(\sum_{i=1}^{N}k_i-p_1\right)V(p_1,k_1,\ldots,k_N)$$
$$\times F(k_1,\ldots,k_N,p_2;r_1,\ldots,r_n)\,. \qquad (2.1)$$

The function $V(p_1,k_1,\ldots,k_N)$ is proportional to the amplitude describing how an initial hadron with four-momentum p_1 is composed of N quasi-free constituents with four-momenta $k_1,k_2,\ldots,k_N$, respectively. The function F describes the process in which N constituents of the first hadron interact with another hadron of four-momentum p_2 and turn into n final-state hadrons of four-momenta $r_1,r_2,\ldots,r_n$, respectively.

The restriction on the virtual mass of the constituents is implemented by the vertex function V which damps out quickly if any $|k_i^2|$ becomes large compared to p_1^2. We adopt the simple approximation here that k_i^2 is restricted to be

$$k_i^2=x_i^2p_1^2\ ,\quad i=1,\ldots,N\ ,$$

where

$$x_i=\vec{k}_i\cdot\vec{p}_1/|\vec{k}_i|\cdot|\vec{p}_1|\,.$$

This approximation is the one used in the naive parton model,[11] and it is equivalent to neglecting all the transverse-momentum components of the constituents. In our application of this model, we need to make sure that the important conclusions are not affected by this simplifying approximation. With this approximation, the amplitude of Eq. (2.1) can be written as

$$\frac{1}{i(p_1+p_2)^2}A=\int_0^1 dx_1\cdots dx_N V(x_1,\ldots,x_N)\times F(x_1,\ldots,x_N,p_1,p_2;r_1,\ldots,r_n)\times\delta(x_1+\cdots+x_N-1)\,. \tag{2.2}$$

We note that the spin effects of the constituents are all ignored in our discussion, so this model is not adequate for the description of the processes with large spin effects.

III. K^+p BACKWARD ELASTIC SCATTERING

The application of this phenomenological quark model to K^+p backward elastic scattering is discussed in this section. The valence quarks involved in this process are u and $\bar{s}$ quarks of K^+, and u, u, and d quarks of the proton. The mechanism for this process is that the $\bar{s}$ quark of the incoming K^+ and the diquark system (ud) of the incoming p are scattered through nearly 180°, whereas two u quarks of the incoming K^+ and p are either scattered to small angles or not scattered at all. The samll-angle scattering of two u quarks will be peaking near the direction of the incident particles, and this will be the cause of the backward peak in the reaction, where the forward-going u quark of K^+ recombines with the nearly-180°-scattered (ud) system to form a nearly-forward-going final proton.

The scattering amplitude of this process can be written by extending Eq. (2.2) and with the following simplifications. We group the diquark system (ud) as one constituent. According to the basic assumption (A) in Sec. II, the sea quarks only carry a small fraction of the energy momentum of the parent hadron, and we can put all the x_i's corresponding to sea quarks equal to zero. Thus the integration variables $x_1,\ldots,x_N$ in Eq. (2.2) should be reinterpreted as the variables of the constituents not in the sea. Of course the effect of the sea quarks on the function F should not be ignored, as pointed out in assumption (A). Now the amplitude for K^+p backward elastic scattering can be written as

$$\begin{aligned}\frac{1}{i(p_1+p_2)^2}\ A=&\int_0^1 dx_1dy_1\delta(x_1+y_1-1)V_K(x_1)\int_0^1 dx_2dy_2\delta(x_2+y_2-1)V_p(x_2)\\&\times\int_0^1 dx_3dy_3\delta(x_3+y_3-1)V_p(x_3)\int_0^1 dx_4dy_4\delta(x_4+y_4-1)V_K(x_4)\delta(y_1-y_2)\\&\times\delta(y_2-y_3)\delta(y_3-y_4)H_x(x_1p_1,x_2p_2,x_3p_3,x_4p_4)H_y(y_1p_1,y_2p_2,y_3p_3,y_4p_4)\,.\end{aligned}\tag{3.1}$$

The variables x_1 (x_4) and y_1 (y_4) denote the fractions of the longitudinal momenta of the incoming (outgoing) K^+ carried by the u and $\bar{s}$ quarks, and similarly x_2 (x_3) and y_2 (y_3) are the fractions of the longitudinal momenta of the incoming (outgoing) proton carried by the u quark and the diquark system, respectively. The function $i(x_1p_1+x_2p_2)^2H_x$ is the scattering matrix element describing the near-forward scattering of u quarks, and the function $i(y_1p_1+y_2p_2)^2H_y$ is the amplitude of the near- 180° elastic scattering of the $\bar{s}$ quark and the diquark system (ud). Since we are using the Lorentz-covariant descritpion, energy and momentum must be conserved at the processes H_x and H_y. This energy-momentum conservation leads to the requirement of $y_1=y_2=y_3=y_4$, and it is represented by three δ functions in Eq. (3.1).

Equation (3.1) can easily be reduced, by integrating out the δ functions, to

$$\frac{i}{is}\ A=\int_0^1 dx\,dy\,\delta(x+y-1)V_K^2(x)V_p^2(x)\times H_x(x^2s,x^2u)H_y(y^2s,y^2u)\ ,\tag{3.2}$$

where we have introduced two Lorentz scalars $s=(p_1+p_2)^2$ and $u=(p_1-p_3)^2$. Imitating the behavior of quark-parton distribution functions near $x=1$ observed in the deep-inelastic lepton-nucleon scatterings, we write

$$V_A(x)=(1-x)^{\gamma_A/2}\phi_A(x)\,, \tag{3.3}$$

where $\phi_A(1)=0$. The coefficient γ_A is not exactly equal to the corresponding coefficient of the quark-parton distribution since the constituents in our model are the dressed-up quarks rather than quark-partons, but we will introduce some inequalities between γ_A and the corresponding coefficient in the quark-parton distribution function later.

The elastic scattering of $\bar{s}$ and u quarks will not give a peak at the backward direction since $\bar{s}$ and u quarks cannot annihilate. Therefore the function $H_y(y^2s,y^2u)$ varies slowly in the small-$|y^2u|$ region and can be approximated as a function of y^2s only. The asymptotic behavior of H_y is parametrized as $(y^2s)^{-\beta}$. Considering the fact that H_y must be finite as $y^2s\to 0$, it can be effectively parametrized as

$$H_y\approx C_y(y^2s+\Delta)^{-\beta}\,, \tag{3.4}$$

where Δ and C_y are two constants. The small-angle scattering of two u quarks, represented by the function H_x, does not involve the exchange of any hadronic quantum numbers. In that sense it is reasonable to assume that the process resembles diffractive scattering of hadrons and that $H_x(x^2s,x^2u)$ is independent of x^2s.

Substituting Eqs. (3.3) and (3.4) into Eq. (3.2) and using the notion that H_x is independent of x^2s, the amplitude A becomes

$$A\approx iC_y s^{1-\beta}\int_0^1 dx(1-x)^{\gamma}\,[(1-x)^2+\Delta/s]^{-\beta}\times\phi_K{}^2(x)\phi_p{}^2(x)H_x(x^2u)\,, \tag{3.5}$$

where

$$\gamma=\gamma_K+\gamma_p\,.$$

In Eq. (3.5) a value β_0, defined as

$$\beta_c\equiv(\gamma+1)/2\,,$$

plays the role of a critical number. If $\beta\geq\beta_c$, the asymptotic behavior of the integral in Eq. (3.5) is controlled by the region near $x=1$. The asymptotic behavior of the amplitude A is thus classified into two cases:

$$A_1\sim iC_y s^{1-\beta}\int_0^1 dx(1-x)^{\gamma-2\beta}\,\phi_K{}^2(x)\phi_p{}^2(x)H_x(x^2u)\quad\text{if }\beta<\beta_c\,, \tag{3.6}$$

or

$$A_2\sim iC_y(s/\Delta)^{(1-\gamma)/2}\phi_K{}^2(1)\phi_p{}^2(1)H_x(u)\quad\text{if }\beta>\beta_c\,. \tag{3.7}$$

Equations (3.6) and (3.7) show that the amplitude is factored into two parts, a part with the factor s^n and a function of the variable u only. It immediately implies nonshrinkage of the differential scattering cross section no matter which inequality between β and β_c is chosen. This result does not depend on the approximation of neglecting the transverse momentum of the constituents, and it is the consequence of the two basic assumptions (A) and (B) in Sec. II and the intuitively reasonable arguments about the properties of the functions V, H_y, and H_x. In this sense the nonshrinkage of the differential scattering cross section is a natural result of this model, and it is also vastly different from the expectation of the simple Regee-pole-exchange models.

With the further help of the quark-parton picture, the choice of the inequalities between β and β_c can be determined. For a u quark-parton in a proton, the coefficient corresponding to γ_p is taken to be 3, following the theoretical consideration[12] of the behavior of νW_2 near $x=1$ in the deep-inelastic lepton-proton scattering. Since a dressed-up u quark contains a u quark-parton, it will be easier to concentrate a large fraction of the energy momentum of the parent hadron on a dressed-up u quark than on a u quark-parton, and it becomes reasonable to introduce the inequality

$$\gamma_p<3\,.$$

To estimate γ_K, we first consider γ_π. From Field and Feynman[13] the corresponding coefficient in the quark-parton picture will be zero. From similar arguments as for the proton, we expect

$$\gamma_\pi<0\,.$$

Then from SU(3) invariance, we adopt the inequaltiy

$$\gamma_K<0\,.$$

From the inequalities $\gamma_p<3$ and $\gamma_K<0$, we obtain

$$\beta_c<2\,.$$

On the other hand, dimensional analysis[14] and its subsequent extension to multiconstituent scattering amplitudes[15] indicate that the large-angle scattering amplitude of three incoming and three outgoing constituents will behave like s^{-1}. For the function iy^2sH_y, which is the near-180° scattering amplitude of an $\bar{s}$ quark and a diquark system (du), we assume its asymptotic behavior to be $s^{-(\beta-1)}$, with $\beta-1>1$, since the constituents in our model are the dressed-up quarks and they are more difficult to be scattered to large angle than quark-partons owing to their complexity. From these considerations, we obtain the inequality

$$\beta > 2 > \beta_c$$

and the amplitude of Eq. (3.7),

$$A \sim iC_y(s/\Delta)^{(1-\gamma)/2}\phi_K{}^2(1)\phi_p{}^2(1)H_x(u) \tag{3.8}$$

becomes the correct asymptotic form of K^+p backward elastic scattering.

The function $H_x(u)$ can be given more explicitly by implementing the assumptions (A) and (B) in Sec. II. The function is $H_x(s,u)$, going back to the stage before the s dependence in H_x is ignored, is the S-matrix element of near-forward scattering of two u quarks. We ignore the possibility that two u quarks may interact directly via the short-range interaction compared to the chance for each u quark to interact with some sea quarks. Using the optical model,[16] we write $H_x(s,u)$ as

$$H_x(s,u) = C_2\delta(u) - is^{-1}[\tilde{F}(s,u)]^2\,, \tag{3.9}$$

where

$$\tilde{F}(s,u) = iP\int_0^R db\, J_0(\sqrt{-u}\, b) \times\{1-\exp[if(P)(R^2-b^2)^{1/2}/P]\}\,, \tag{3.10}$$

$$f(P) = \frac{3}{R^3}\, b(R^2-b^2)^{1/2}\sum_j n_j f_j(P)\,,$$

and

$$P \approx \tfrac{1}{2}\sqrt{s}\ .$$

The constant R is the average radius of a hadron and n_j is the number of the jth kind of quarks in the sea with $j=1,2,\ldots$ standing for u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$, and so on. Each sea quark is assumed to have a uniform probability distribution inside a sphere of radius R when at rest, and the effect of Lorentz contraction has also been taken into consideration. The function $f_j(P)$ is the forward elastic scattering amplitude between a u quark of momentum P and a stationary jth quark in the sea. To achieve s independence of the function H_x, as used previously from the analog with diffractive scatterings, we assume

$$f_j(P) \sim P \text{ as } P\to\infty\,,$$

and Eq. (3.10) becomes

$$\tilde{F}(s,u) = \frac{i\sqrt{s}}{2}\int_0^R db\, J_0(\sqrt{-u}\, b)[1-e^{iBb(R^2-b^2)}]\,. \tag{3.11}$$

We need to notice the effect of our approximation of neglecting the transverse momentum of the quarks. The effect of this simplification is manifest in the presence of the δ function in Eq. (3.9), which of course is not realistic. Introducing a transverse-momentum distribution, $\exp(-a\sqrt{-u}\,)$, for the fast-going u quarks, we finally obtain the asymptotic form of the amplitude of K^+p backward elastic scattering,

$$A(s,u) \sim Cs^{(1-\gamma)/2}G(u)\,,$$

with

$$G(u) = C_2 e^{-a\sqrt{-u}} + \int_0^\infty dz\, e^{-a|z-\sqrt{-u}|}F^2(z)$$

and (3.12)

$$F(z) = \tfrac{1}{2}\int_0^R db\, J_0(zb)[1-e^{iBb(R^2-b^2)}]\,,$$

The constant C_2 is related to the abundance of the sea quarks. If there are many sea quarks, the chance for two u quarks to come out without interaction is small and so becomes the constant C_2 and vice versa. The model does not give a clear prediction about the magnitude of C_2.

The experimental data[17] of K^+p backward elastic scattering at relatively low energy regions implies that the amplitude behaves like $s^{-0.8}$. This indicates the value of γ is approximately 2.6, which is consistent with our interpretation of the fast u quark as a dressed-up quark.

IV. OTHER QUANTUM-NUMBER-EXCHANGED REACTIONS

Some meson-meson scattering processes, e.g., $\pi^+K^+\to K^+\pi^+$, $K^+K^0\to K^0K^+$, and so on, are very similar to the case of K^+p backward elastic scattering. The near-180° scattering of a single $\bar{s}$ quark and a diquark system (ud) now is replaced by the near-180° scattering between two single quarks in these reactions.

For π^+p backward elastic scattering, the $\bar{d}$ quark of the incoming π^+ and the diquark system (ud) of the incoming p are scattered through nearly 180°. Since the $\bar{d}$ quark and the d quark of the diquark system (ud) can annihilate, the simple parametrization of the function H_y, like the one of Eq. (3.4), fails, and this model loses its predictive power. The situation for π^-p backward elastic scattering is equally complicated. Some meson-meson scattering processes, e.g., $\pi^\pm\pi^0\to\pi^0\pi^\pm$, $\pi^+K^0\to\pi^0K^+$, and so on, belong to the some category as $\pi^\pm p$ backward elastic scattering.

The charge-exchange reaction $pn\to np$ belongs to the same category as K^+p backward elastic scattering. But in this reaction there are two diquark systems scattered to small angles, and this makes the application of the optical model difficult. The πN charge-exchange reactions belong to the category of $\pi^{\pm} p$ backward elastic scattering, and in addition it has similar complication as pn charge-exchange reactions.

In the reactions where spin-flip processes are dominant, e.g., πN charge-exchange and KN charge-exchange processes, strong Regge-pole-like shrinkages are usually observed. The extension of this kind of model to include spin effects will be very important.

The assumption that exchanged quarks in the quantum-number-exchanged hadronic reactions are all slow quarks[18] is not necessarily true in this model. It is true only when $\beta > \beta_c$ is true as in K^+p backward elastic scattering process discussed in Sec. III.

V. SUMMARY

This phenomenological quark model leads to explicit predictions of the amplitude of K^+p backward elastic scattering. The nonshrinkage prediction is a natural result of the basic assumptions in this model and several intuitively reasonable assumptions. With some thereotical ideas of the parton picture as additional inputs, we obtain an explicit amplitude, Eqs. (3.12), for this reaction. More detailed measurements of the reaction can provide a test of this model, and can also provide more information about the behavior of hadronic constituents. The situations of other quantum-number-exchange reactions are laid out in Sec. IV, and the separation of the spin-nonflip and the spin-flip processes are important to push our understanding about the behavior of hadronic constituents further.

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