Relativistic quark model and meson Regge trajectories

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Abstract

The D-and F-wave quark-quark amplitudes are constructed in the framework of the dispersion N/D-method. The mass values of meson multiplets with $J^{PC} = 1^{--}, 2^{--}, 2^{+-}, 3^{--}$ and $J^{PC} = 2^{++}, 3^{++}, 3^{+-}, 4^{++}$ are calculated.

The Regge trajectories of mesonic resonances with orbital numbers $L=0,1,2,3$ are obtained.

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I. INTRODUCTION

In soft processes, where small momentum transfers are essential, the perturbative QCD technique is not applicable. In this case the way of phenomenology based on QCD seems to be reasonable. One believes that such a phenomenology should include quark model results as well. In the framework of quark models there was obtained the important information on light-quark mesons [1-9] and baryons [10-16].

In the framework of the dispersion N/D-method with help of the iteration bootstrap procedure the scattering amplitudes of dressed quarks were constructed [17,18]. The mass values of the lowest mesons($J^{PC} = 0^{--}, 1^{--}, 0^{++}$) and their quark content are obtained. In the colour meson channel a bound state was found which corresponds to the constituent gluon with the mass $M_{G} = 0.67$ GeV. The qq-amplitudes in the colour state $\bar{3}$ have the diquark levels with $J^{P} = 0^{+}$ and the masses $m_{ud} = 0.72$ GeV and $m_{us} = m_{ds} = 0.86$ GeV. The interaction of dressed quarks appeared to be an effectively short-range one. The calculated amplitudes satisfy the Okubo-Zweig-Iisuka rule. The creation of mesons (pion included) is mainly due to the gluon exchange. The model under consideration proceeds from the assumption that the quark interaction forces are the two-component ones. The first, short-range component corresponds to the gluon exchange, the second, long-range component is due to the confinement. When the low-lying mesons are considered, the long-range component of the forces is neglected. But for the excited mesons the long range forces are important. Namely, the confinement of the $q\bar{q}$ pair with comparatively large energy is actually realized as the production of the new $q\bar{q}$ pairs. This means that in the transition $q\bar{q} \rightarrow q\bar{q}$ the forces appear which are connected with the contribution of box-diagrams [19]. These box-diagrams can be important in the formation of hadron spectra. We take into account the contribution of box-diagrams. It allows us to calculate the mass spectrum of P-wave mesons in the relativistic quark model [20].

In the present paper in the framework of relativistic quark model the mass values of D- and F-wave mesons are calculated. The Regge trajectories for the low-energy region, which describe the mesonic resonances with orbital numbers $L=0,1,2,3$, are constructed.

In section 2 the D- and F-wave quark-quark amplitudes in the framework of dispersion N/D-method are constructed. The mass values of meson multiplets with $J^{PC} =$
$1^{--}, 2^{++}, 2^{--}, 3^{--}$ and $J^{PC} = 2^{++}, 3^{+-}, 3^{++}, 4^{++}$ are calculated. The technique of the N/D-method procedure is presented in the Appendix. In the Conclusion the status of the considered model is discussed.

II. D- AND F-WAVE QUARK-QUARK AMPLITUDES

In the papers [17,18,20] we considered the scattering amplitudes of the constituent quarks of three flavours (u,d,s). The poles of these amplitudes determine the masses of the light mesons. The masses of the constituent quarks u and d are of the order of 300-400 MeV, the strange quark is 100-150 MeV heavier. The constituent quark is a colour triplet and quark amplitudes obey the global colour symmetry. The gluon interaction is assumed to be short-range. The quark scattering amplitudes for singlet colour states can be written as:

$$A(t, z) = \sum_i G_i(t, z)(\mathcal{O}^i q)(\mathcal{O}^i q'),$$ \hspace{1cm} (1)

where $\mathcal{O}^i$ is a full set of matrices 4x4 (see (A4)). $z$ is cosine of the scattering angle in c.m.s. Using the general amplitude $A(t, z)$ one can obtain the l-wave part $A_l(t)$, which determines the contributions of the l-wave quark-quark amplitudes ((A1)-(A5)). Then we must expand the amplitude $A_l(t)$ into the eigenstates ((A6)-(A8)) and calculate the first approach amplitudes with help of dispersion N/D-method ((A9)-(A14)) [17,18]. The poles of amplitudes $A_l(t)$ correspond to the value mass of l-wave meson multiplets. The detailed exposition of the construction of D- and F-wave quark-quark amplitudes in the Appendix is given.

The N-function of the first approach for the calculation of low-lying meson spectra (Table I) are used [17,18]. $N_i(t)$-functions depend weakly on the energy and therefore can be parametrized in our case:

$$N^S(t) = -0.728 - \frac{2.85}{t + 2.92}, \quad N^A(t) = -0.318 - \frac{0.798}{t + 3.05},$$

$$N^V(t) = 0.336 + \frac{1.50}{t + 2.60}, \quad N^P(t) = 0.690 + \frac{2.86}{t + 3.30},$$

$$N^T(t) \approx 0$$ \hspace{1cm} (2)
These functions were obtained by help of iteration bootstrap procedure with the four-fermion interaction as an input [17,18]:

$$g V(\gamma_\mu \lambda^a q)(\bar{\gamma} \gamma_\mu \lambda^a q'),$$

(3)

where $\lambda^a$ are the Gell-Mann matrices. The point-like structure of this interaction is motivated by the above-mentioned idea of the two characteristic sizes in the hadron. On the other hand, the applicability of (eq.3) is verified by the success of the De Rujula-Georgi-Glashow quark model [1], where only the short-range part of the Breit-Fermi potential connected with the gluon exchange Fig.1(a) is responsible for the mass splitting in hadron multiplets. But for the excited mesons the long-range forces are important. The box-diagrams Fig.1(b) can be important in the formation of hadron spectra. We do not see any difficulties in taking into account the box-diagram with help of the dispersion technique. For the sake of simplicity one restrict to the introduction of quark mass shift $\Delta_l$, which are defined by the contribution of the nearest production thresholds of pair mesons $\pi \pi, \pi \eta, K \bar{K}, K \eta$ and so on. We suggest that the parameter $\Delta_l$ takes into account the confinement potential effectively: $m^* = m + \Delta_l$, $m^*_s = m_s + \Delta_l$ and changes the behaviour of pair quark amplitudes. It allows us to construct the D- and F-wave mesons amplitudes and calculate the mass spectra by analogy with the P-wave meson spectrum in the relativistic quark model (Table II) [20]. The calculated values of mass D- and F-wave mesons are shown in the Tables III, IV respectively. One can see that the obtained mass values of the D-wave mesons ($J^{PC} = 1^{--}, 2^{+-}, 2^{--}, 3^{--}$) are in good agreement with experimental ones [21]. The absence of experimental data for the F-wave mesons does not allow to verify the detailed coincidence. The $\Delta_l$-parameters can be determined by mean of fixing of masses $\rho_3$ (D-wave) and $f_4$ (F-wave) mesons: $\Delta_D = 0.460$ GeV, $\Delta_F = 0.640$ GeV respectively. The calculated mass values of D- and F-wave mesons are in good agreement with the other model results [7-9].

Using the obtained mass values of S- and P-wave meson multiplets [18,20] and the results of the present paper, one can construct the meson Regge trajectories $\alpha_l(t) = \alpha_l(0) + \alpha_l' t$ for the mesonic resonances with orbital numbers $L=0,1,2,3$ (Table V). These results are in good agreement with experimental data [21] and other papers results [22-24]. The corresponding Regge trajectories $(\rho, \omega; a_0, f_0; a_1, f_1)$ have the exchange degeneracy,
excluding the $\alpha_\pi$ and $\alpha_\eta$ trajectories. The $\alpha_\pi$-Regge trajectories differs from the straight only in the low-energy range.

\section*{III. CONCLUSION}

In the framework of the approach developed for the S- and P-wave mesonic multiplets \cite{18,20}, the D- and F-wave mesons are calculated. In present paper we suggest also, that the parameters $\Delta_l$ take into account the contribution of box-diagram Fig.1(b). This is more important, that in the framework of $1/N_C$-expansion \cite{25,26} both diagrams Fig.1(a,b) have the equal order $\sim 1/N_C$, where $N_C = N_f$ are the colour and flavour numbers respectively. In the recent papers \cite{27,28} the high energy asymptotic of multi-colour QCD is considered, that allows to construct the Bethe-Salpeter equation for the n reggeized gluons. Then the author obtained the Pomeron trajectory as the bound state of two reggeized gluons. Therefore is important to obtained the meson Regge trajectories for the low-energy region in the framework of the relativistic quark model, which is based on the principles of multi-colour QCD.

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\section*{APPENDIX}

The calculation of the quark-quark amplitude for the singlet colour states with the accounting of high excited states for the orbital numbers $L=0,1,2,3$ is performed using the dispersion N/D-method:

\[ A(t,z) = \sum_i (N_{S,D}^i(t) + zN_{P,F}^i(t) + z^2N_D^i(t) + z^3N_F^i(t))M_i^I = \]
\[ = A_{S,D}(t) + A_{P,F}(t) + A_D(t) + A_F(t), \quad (A1) \]
where

\[ N^i_l(t) = \int_{-1}^{1} \frac{dz}{2} P_i(z) G^i(t, z), l = S, P, D, F \]  \hspace{1cm} (A2)

The estimation of the contributions of high exitation give rise to the renormalization of input parameters of S- and P-wave meson amplitudes, does not change the mass spectra of these mesons. Here we introduce the matrix element \( M^i_t \):

\[ M^i_t = (\bar{q} O^i q)(\bar{q}^\prime O^i q') \]  \hspace{1cm} (A3)

where \( O^i \) are the operators of different types of the four-fermion interaction (i=S,V,T,A,P):

\[ O^i = 1, \gamma_\mu, \frac{i}{\sqrt{2}} \sigma_{\mu\nu}, i\gamma_\mu \gamma_5, \gamma_5 \]  \hspace{1cm} (A4)

For the brevity the colour and flavour indices in the equation (A3) are omitted. For the processes with quarks of different flavours the amplitude should contain the sixth invariant,

\[ k'_\mu (\bar{q} \gamma_5 \gamma_\mu q)(\bar{q}^\prime \gamma_5 q') + k_\mu (\bar{q} \gamma_5 q)(\bar{q}^\prime \gamma_5 \gamma_\mu q') \]  \hspace{1cm} (A5)

where \( k_\mu \) and \( k'_\mu \) are relative momenta of quarks from the initial and final states. Our calculation shows that the contribution of the sixth invariant into the quark-quark amplitudes is small and can be neglected. Using the dispersion N/D-method [17,18,20] one can expand the D- and F-wave amplitude in the t-channel \( q\bar{q} \) states in the following way:

\[ A_D(t) = \sum_{JPC,i,\rho\rho',\sigma\sigma'} M^i_{\rho\rho'\sigma\sigma'}(J^{PC}) N^i_D(t) n_\rho n_\rho'n_\sigma n_\sigma' \]  \hspace{1cm} (A6)

\[ A_F(t) = \sum_{JPC,i,\rho\rho',\sigma\sigma',\lambda\lambda'} M^i_{\rho\rho'\sigma\sigma'\lambda\lambda'}(J^{PC}) N^i_F(t) n_\rho n_\rho'n_\sigma n_\sigma'n_\lambda n_\lambda' \]

where \( \vec{n} \) is the unity vector directed along the relative momentum in an intermediate state. Futher we consider the construction of D-wave amplitude in detail. The F-wave amplitude can be obtained analogously. Here the matrix element \( M^i_{\rho\rho'\sigma\sigma'}(J^{PC}) \) is used:

\[ M^i_{\rho\rho'\sigma\sigma'}(J^{PC}) = (\bar{q} O^i q)d^i_{\rho\rho'\sigma\sigma'}(J^{PC}) (\bar{q}^\prime O^i q') \]  \hspace{1cm} (A7)

The projectors \( d^i_{\rho\rho'\sigma\sigma'}(J^{PC}) \) for the D-wave are defined as:
\[d^S_{\rho\rho'}(1^-) = D_{\rho\rho'}, d^P_{\rho\rho'\sigma\sigma'}(2^+) = D_{\rho\rho'}D_{\sigma\sigma'},\]
\[d^A_{\mu\mu'\rho\rho'\sigma\sigma'}(2^+) = \Pi_{\mu\mu'}D_{\rho\rho'}D_{\sigma\sigma'},\]
\[d^V_{\mu\mu'\rho\rho'\sigma\sigma'}(2^-) = d^V_{\mu\mu'\rho\rho'}(1^{++})D_{\sigma\sigma'},\]
\[d_{\mu\mu'\rho\rho'\sigma\sigma'}(3^-) = d^V_{\mu\mu'\rho\rho'}(2^{++})D_{\sigma\sigma'},\]
\[d^V_{\mu\mu'\rho\rho'}(1^{++}) = \frac{1}{2}D_{\mu\mu'}D_{\rho\rho'} - \frac{1}{2}D_{\mu\rho}D_{\rho'\mu},\]
\[d^V_{\mu\mu'\rho\rho'}(2^{++}) = \frac{1}{2}D_{\mu\mu'}D_{\rho\rho'} - \frac{1}{3}D_{\mu\rho}D_{\rho'\mu} + \frac{1}{2}D_{\mu\rho'}D_{\rho'\mu}.\]

Here one use the projectors of P-wave states: \(d^V_{\mu\mu'\rho\rho'}(1^{++})\) and \(d^V_{\mu\mu'\rho\rho'}(2^{++})\), \(\Pi_{\mu\mu'} = P_\mu P_{\mu'}/P^2\), \(D_{\mu\mu'} = \delta_{\mu\mu'} - \Pi_{\mu\mu'}\), \(P\) is the total momentum of quark pair.

The interaction amplitude can be written as N/D-relation. The expression for the amplitude expanded into the eigenstates have the following form:

\[A^i_D(t, J^{PC}) = N^i_D(t) \frac{\overline{D}^i_D(t, J^{PC})}{\det D(t, J^{PC})},\]

where \(\overline{D}_D\) is the co-factor matrix \(D_D\). To obtain unitarized amplitude the elastic-unitarity condition is used, which provides us with an imaginary part of the D-wave amplitude of the loop diagram:

\[16\pi \sum_{j^{PC}} \text{Im} D^i_D(t, J^{PC}) M^i_{i\rho\rho'\sigma\sigma'}(J^{PC}) = -\frac{[\{t - (m_1^* + m_2^*)\}^2(t - (m_1^* - m_2^*)^2)]^{1/2}}{t} \times \int \frac{d\Omega}{4\pi} \text{Tr}(O^i(\overline{p}_1 + m_1^*)O^j(-\overline{p}_2 + m_2^*))n_{\rho\rho'}n_{\sigma\sigma'}N^i_{D}(t)M^j_i,\]

\[m_1^*\text{ and } m_2^*\text{ are the effective quark and antiquark masses respectively. Using the equation (A10) we can extract the eigenstates for the D-wave amplitude:}\]

\[\text{Im} D^i_D(t, J^{PC}) = -\rho^i_D(t, J^{PC})N^i_D(t)\]

There one introduce the two-particle phase space for the unequal quark masses:

\[\rho^i_D(t, J^{PC}) = \left(\alpha^i_D(J^{PC}) \frac{t}{(m_1^* + m_2^*)^2} + \beta^i_D(J^{PC}) + \frac{(m_1^* - m_2^*)^2}{t}\right) \times \delta^i_D(J^{PC})\times\]
\[
\times \frac{[(t - (m_1^* + m_2^*)^2)(t - (m_1^* - m_2^*)^2)]^{1/2}}{t}
\]

(A12)

The coefficients \(\alpha_D^i(J^{PC})\), \(\beta_D^i(J^{PC})\), \(\gamma_D^i(J^{PC})\) are given in Table VI. Using the dispersion relation with the cut-off, we define the Chew-Mandelstam function [29]:

\[
D_D^i(t, J^{PC}) = 1 + \frac{1}{\pi} \int_{(m_1^* + m_2^*)^2}^{A} dt' \frac{\text{Im} D_D^i(t', J^{PC})}{t' - t}
\]

(A13)

\(N_{J^{PC}}(t)\)-function for the D-wave quark-quark amplitudes are defined by (eq.(2)):

\[
N_{1-}(t) = N^S(t)
\]

\[
N_{2-}(t) = N^V(t)
\]

\[
N_{3-}(t) = N^V(t)
\]

\[
N_{2+}(t) = N^P(t) + \frac{(m_1^* + m_2^*)^2}{t} N^A(t)
\]

(A14)

By analogy with (A6)-(A14) one can consider the F-wave amplitudes.
TABLE I. Masses of lowest meson multiplets (GeV)

| $J^{PC}$ | Masses | $J^{PC}$ | Masses | $J^{PC}$ | Masses |
|-----------|--------|-----------|--------|-----------|--------|
| $0^{-+}$  | $\pi$  | 0.14(0.14)| $\rho$ | 0.77(0.77)| $a_0$  | 0.78(0.98)|
| $1^{++}$  | $\eta$ | 0.48(0.55)| $\omega$ | 0.77(0.78)| $f_0$  | 0.87(0.98)|
| $0^{++}$  | $K$    | 0.50(0.50)| $K^*$  | 0.89(0.89)| $K^*_0$| 0.88(1.35)|
|           | $\eta'$| 1.00(0.96)| $\Phi$ | 1.00(1.02)|        |        |

Parameters of model: cut-off $\Lambda=17.3$, gluon constant $g_V=0.226$, four-fermion interaction induced by instantons constant $g_I=-0.081$, quark masses $m_{u,d}=0.385$ GeV, $m_s=0.501$ GeV, parameter of quark mass shift $\Delta_s=0$. Experimental values are given in parentheses [21].

TABLE II. Masses of three P-wave meson multiplets (GeV)

| $J^{PC}$ | Masses | $J^{PC}$ | Masses | $J^{PC}$ | Masses |
|-----------|--------|-----------|--------|-----------|--------|
| $1^{++}$  | $a_1$  | 1.273(1.260)| $b_1$  | 1.203(1.235)| $a_2$  | 1.320(1.320)|
|           | $f_1$  | 1.273(1.285)| $h_1$  | 1.203(1.170)| $f_2$  | 1.320(1.270)|
| $2^{++}$  | $K_1^*$| 1.385(1.400)| $K_1$  | 1.308(1.270)| $K_2$  | 1.436(1.430)|
|           | $f_1$  | 1.497(1.420)| $h'_1$ | 1.414( - ) | $f_2$  | 1.552(1.525)|

Parameters of model: cut-off $\Lambda=17.3$, gluon constant $g_V=0.226$, quark masses $m_{u,d}=0.385$ GeV, $m_s=0.501$ GeV, parameter of quark mass shift $\Delta_P=0.275$ GeV. Experimental values are given in parentheses [21].
### TABLE III. Masses of D-wave meson multiplets (GeV)

| $J^{PC}$ | Masses          | $J^{PC}$ | Masses          |
|---------|-----------------|---------|-----------------|
| $1^{--}$ |                 | $2^{--}$ |                 |
| $\rho_1$ | 1.590(1.700)    | $\pi_2$ | 1.620(1.670)    |
| $\omega_1$ | 1.590(1.600) | $\eta_2$ | 1.620(−)        |
| $K_1^*$ | 1.690(1.680)    | $K_2$  | 1.720(1.770)    |
| $\Phi_1$ | 1.800(1.680)    | $\eta_2$ | 1.840(−)        |

| $J^{PC}$ | Masses          | $J^{PC}$ | Masses          |
|---------|-----------------|---------|-----------------|
| $2^{--}$ |                 | $3^{--}$ |                 |
| $\rho_2$ | 1.670(−)        | $\rho_3$ | 1.690(1.690)    |
| $\omega_2$ | 1.670(−)      | $\omega_3$ | 1.690(1.670)    |
| $K_2^*$ | 1.780(1.820)    | $K_3^*$ | 1.800(1.780)    |
| $\Phi_2$ | 1.900(−)        | $\Phi_3$ | 1.920(1.850)    |

Parameters of model are analogous Table II, except of the quark mass shift $\Delta_D=0.460$ GeV.

### TABLE IV. Masses of F-wave meson multiplets (GeV)

| $J^{PC}$ | Masses          | $J^{PC}$ | Masses          |
|---------|-----------------|---------|-----------------|
| $2^{++}$ |                 | $3^{--}$ |                 |
| $a_2$   | 1.930(−)        | $b_3$  | 1.950(−)        |
| $f_2$   | 1.930(2.010)    | $h_3$  | 1.950(−)        |
| $K_2^*$ | 2.030(−)        | $K_3$  | 2.060(−)        |
| $f_3$   | 2.140(−)        | $h_3$  | 2.170(−)        |

| $J^{PC}$ | Masses          | $J^{PC}$ | Masses          |
|---------|-----------------|---------|-----------------|
| $3^{++}$ |                 | $4^{++}$ |                 |
| $a_3$   | 1.960(−)        | $a_4$  | 2.050(−)        |
| $f_3$   | 1.960(−)        | $f_4$  | 2.050(2.050)    |
| $K_3^*$ | 2.070(−)        | $K_4^*$ | 2.160(2.045)    |
| $f_3$   | 2.180(−)        | $f_4$  | 2.280(−)        |

Parameters of model are analogous Table II, except of the quark mass shift $\Delta_F=0.640$ GeV.
TABLE V. Regge trajectories $q\bar{q}$-mesons

| Regge trajectories | $\alpha(0)$ | $\alpha'$ |
|--------------------|-------------|-----------|
| $\alpha_{p,\omega}$ | 0.5(0.5)    | 0.9(0.9)  |
| $\alpha_{K^*}$     | 0.4(0.4)    | 0.8(0.8)  |
| $\alpha_{\phi}$    | 0.2(0.1)    | 0.8(0.9)  |
| $\alpha_{\pi}$     |              | 0.8(0.8)  |
| $\alpha_{K}$       | -0.3(-0.3)  | 0.7(0.7)  |
| $\alpha_{\eta}$    | -0.2(-0.2)  | 0.8(0.8)  |
| $\alpha_{\eta'}$   | -0.6( - )   | 0.8( - )  |
| $\alpha_{a_0,f_0}$ | -0.3(-0.5)  | 0.6(0.6)  |
| $\alpha_{K_0^*}$   | -0.4( - )   | 0.6( - )  |
| $\alpha_{\tilde{f}_0}$ | -0.6( - ) | 0.6( - )  |
| $\alpha_{a_1,f_1}$ | -0.4( - )   | 0.8( - )  |
| $\alpha_{K_1}$     | -0.5(-0.5)  | 0.7(0.7)  |
| $\alpha_{\tilde{f}_1}$ | -0.6( - ) | 0.7( - )  |

Experimental values of the parameters Regge trajectories are given in parentheses [21].

TABLE VI. Coefficients of Chew-Mandelstam functions

| $J^P C$ | $\alpha_D$ | $\beta_D$ | $\gamma_D$ |
|---------|------------|-----------|------------|
| 1--     | $-\frac{1}{2}$ | $\frac{1}{2}$ | 0          |
| 2++     | $\frac{1}{2}$  | $-\frac{1}{2}e$ | 0          |
| 2--     | $\frac{4}{7}$  | $-\frac{1}{14} - \frac{3}{7}e$ | $\frac{1}{14}$ |
| 3--     | $\frac{2}{7}$  | $\frac{3}{14} - \frac{10}{7}e$ | $-\frac{3}{14}$ |

| $J^P C$ | $\alpha_F$ | $\beta_F$ | $\gamma_F$ |
|---------|------------|-----------|------------|
| 2++     | $-\frac{1}{2}$ | $\frac{1}{2}$ | 0          |
| 3--     | $\frac{1}{2}$  | $-\frac{1}{2}e$ | 0          |
| 3++     | $\frac{11}{18}$ | $-\frac{1}{9} - \frac{7}{18}e$ | $\frac{1}{9}$ |
| 4++     | $\frac{5}{18}$ | $\frac{2}{9} - \frac{13}{18}e$ | $-\frac{2}{9}$ |

Here is $e = (m_1^* - m_2^*)^2/(m_1^* + m_2^*)^2$
Fig. 1 a) Diagram of gluonic exchange defines the short-range component of quark interactions.

Fig. 1 b) box-diagram of meson M takes into account the long-range interaction component of the quark forces.
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