The quark potential model for vector mesons and their decay constants.

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The relativistic quark potential model (QPM) is developed for describing vector mesons and their leptonic decays. The new representation Salpeter equation for vector mesons is proposed. Studying the $\tau \rightarrow \rho \nu$ decay the expression for $\rho$-meson leptonic decay constant $f_\rho$ is obtained. It is shown that quark model describes on a satisfactory level both the constant $f_\rho$ and the masses of other charged vector mesons. The values for the leptonic decay constants of $K^*, D^*, D_{s}^*, B^*, B_{s}^*$ mesons are predicted.

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I. INTRODUCTION

The basic idea of our quark potential model is simple. First, we consider Schwinger-Dayson equation which described one-particle quark "inside" hadron [1]. The solutions of Schwinger-Dayson (SDE) we used in case bound state of quark antiquark pair. Second step, we consider Salpeter equation sometimes called the Bethe-Salpeter equation, which describe the spectra mass of mesons as bound state of quark antiquark. Using the spectra masses, wave functions which we have found and then we will calculate the leptonic decay constant of mesons.

At present a reliable experimental information on leptonic decay constants of heavy pseudoscalar and vector mesons does not exist. However, these constants play an important role in phenomenological describing of heavy mesons physics: the $B - B_0$-splitting, mass difference and life time, violation of $CP$-parity and rare decays.

In the last time the mass spectrum of these mesons and their leptonic decay constants is mainly described in the framework of phenomenological models based on the ideas of the quantum chromodynamics (QCD) [8]-[10]. The relativistic quark potential model [1], on the basis of which there are two principles – the minimal quantization of gauge fields and a choice of the quantization axis [1], also belongs to this kind of models.

In papers [8][9][10] within this model the description of spectroscopy of pseudoscalar mesons including pion had been obtained on a satisfactorily level with their experimental values. However, the estimates for the leptonic decay constant of pion $f_\pi$ were considerably smaller than its experimental value [8][10]. The mass and decay
constant of pion are calculated in the framework of the quark potential model in paper [11]. Radial excitation of $\pi', K', D'$ mesons and their decay of constant was calculated in [12] communication. In paper [13] the value of constant $f_\pi$ also could be reproduced by means of modification of the SDE in this model.

Using decomposition of the vector meson wave function over its structure components in papers [6,8] the Salpeter equation (SE) for vector mesons had been obtained. Then it was considered that the vector meson is a bound state consisting of quark and antiquark and its polarization vectors $c_\mu^\lambda$ ($\lambda = 1, 2, 3$ are the polarization indices) depend on relative momentum $q$.

However, it is known that the vector particle with nonzero mass having internal structure is described by three orthogonal spacelike vectors $\xim$, which depend on total momentum $P$ and obey to orthogonality condition $P^\mu c_\mu^\lambda = 0$. Hence it follows that $P^\mu$ plays role of the vector giving some distinguished direction to which the vector fields are referred [13].

In the present paper we proceed from that $c_\mu^\lambda$ are the functions of $P^\mu$ and propose new representation SE which describes mass spectrum and wave functions of vector mesons. The $\tau \rightarrow \rho \nu$ decay is considered and the expression for leptonic decay constant of $\rho$ meson $f_\rho$ is given. Choosing the interquark interaction potential as sum of the oscillator and Coulomb type potentials and using solutions of the SDE and SE proposed we obtain both constant $f_\rho$ and masses of other charged vector mesons consisting of "up" and "down" quarks with different flavours on qualitative level. The values for their leptonic decay constants are predicted as well.

This paper is organized as follows. In Section II we obtain the new representation of SE for vector mesons from the effective action of QCD for bilocal meson fields and compare with its previous versions. In Section III we consider the $\tau \rightarrow \rho \nu$ decay and representation for constant $f_\rho$, which can be generalized also for the leptonic decay constants of other charged vector mesons too is received. In Section IV we present the results of calculation of the masses and leptonic decay constants of charged vector mesons and give an outlook.

II. THE SALPETER EQUATION FOR VECTOR MESONS

We proceed from the effective action of QCD for bilocal meson fields $\mathcal{M}(x,y)$ proposed in Refs. [6,8]

$$W_{\text{eff}}(\mathcal{M}) = N_c \left\{ \frac{1}{2} (\mathcal{M}, \mathcal{K}^{-1}\mathcal{M}) - i \text{Tr} \ln \left[ - (i\mathcal{D} - m^0) + \mathcal{M} \right] \right\},$$  \hspace{1cm} (1)

where

$$\mathcal{K}(x,y) = \mathcal{K}(z,X) = \hbar \times \gamma V(z^\perp)\delta(z\eta)$$

$$z = x - y, \quad X = \frac{x + y}{2}, \quad z^\parallel = \eta(z\eta), \quad z^\perp = z - z^\parallel, \quad \hbar = \gamma_\mu \eta^\mu, \quad \eta^\mu = \frac{P^\mu}{\sqrt{P^2}}.$$  \hspace{1cm} (2)

Here $N_c = 3$ is the number of colors, $V(z^\perp)$ is the phenomenological interquark interaction potential which is used for describing of the spectroscopy of mesons, $m^0 = \text{diag}(m_1^0, ..., m_{n_f}^0)$ is the matrix of current quark masses, $n_f$ is the quark flavour number. The symbol $\text{Tr}$ denotes integration over the space-time coordinates and summation over the flavour and Dirac spinor indices.

Expansion of action (1) about the stationary solution ($\Sigma$) in small fluctuations $\mathcal{M}' (\mathcal{M}' = \mathcal{M} - \Sigma)$ leads to the action bilinear in these fluctuations [3]

$$W^{(2)} = N_c \left[ \frac{1}{2} (\mathcal{M}', \mathcal{K}^{-1}\mathcal{M}') + \frac{1}{2} \text{Tr}(G_{\Sigma}\mathcal{M}')^2 \right],$$  \hspace{1cm} (2)

describing the meson spectrum, and to the interaction of these mesons

$$W_{\text{int}} = i N_c \text{Tr} \sum_{n=2}^{n_f} \frac{\prime \sigma^0 (G_{\Sigma}\mathcal{M}')^2}{n},$$  \hspace{1cm} (3)

where $G_{\Sigma}$ is the quark Green function, and prime $'$ denotes absence of the quadratic term over the bilocal fields.
In order to account interaction of the bilocal meson fields between leptons we are to modify $\mathcal{M}(x,y)$ taking the weak interaction into account:

$$\mathcal{M}(x,y) \rightarrow \mathcal{M}(x,y) + \mathcal{L}(x,y),$$

where

$$\mathcal{L}(x,y) = \frac{G_F}{\sqrt{2}} K_{ij} \gamma^\mu (1 + \gamma_5) \lambda \gamma_\mu (1 + \gamma_5) \nu_l (y) \delta (x-y)$$

is the local leptonic current.

Here $K_{ij}$ are the Cabibbo-Kobayashi-Maskawa mixing matrix elements, $G_F$ is the Fermi constant, $l(x) = (e(x), \mu(x), \tau(x))$ and $\nu_l(x) = (\nu_e(x), \nu_\mu(x), \nu_\tau(x))$ are the leptons and their neutrinos wave functions, respectively.

Taking expression (4) into account from action (3) we get

$$W_{int} = i N_c \sum_{n=2}^{\infty} \frac{1}{n} |G_{\Sigma}(\mathcal{M} + L)|^n.$$  

In order to calculate the matrix elements of the processes with presence of a vector meson as a $q\bar{q}$-bound state, which is described by effective QCD action (5) we decompose $\mathcal{M}(x,y)$ over the creation and annihilation operators of mesons, $a_i^+(\mathcal{P})$, with eigenvalues, $\sqrt{\mathcal{P}}^2 = M$ and $\omega = (\mathcal{P}^2 + M^2)^{1/2}$ ($M$ is the meson mass)

$$\mathcal{M}(x,y) = \mathcal{M}(z|X) = \frac{3}{\lambda^2} \int d^3 \mathcal{P} \frac{d^4 q}{(2\pi)^4} \exp (iqz) \exp (iP \mathcal{X}) \Gamma^\lambda (q|\mathcal{P}) a_i^+(\mathcal{P})$$

$$+ \exp (-iP \mathcal{X}) \Gamma^\lambda (q|\mathcal{P}) a_i^-(\mathcal{P}),$$

where $\Gamma^\lambda (q|\mathcal{P})$ and $\Gamma^\lambda (q|\mathcal{P})$ are the vector meson vertex functions.

In expression (6) operators $a_i^+(\mathcal{P})$ and $a_i^-(\mathcal{P})$ satisfy to commutative relations

$$[a_i^-(\mathcal{P}), a_i^+(\mathcal{P})]_\pm = \delta_{i,i'} \delta (\mathcal{P} - \mathcal{P}')$$

Variation of action (2) about of $\mathcal{M}'$ taking into account expression (6) leads to the Bethe-Salpeter equation

$$\Gamma^\lambda (a,b)(q|\mathcal{P}) = -\frac{i}{(2\pi)^4} V(p^q - q^q) \eta G_{\Sigma_a} \left( q + \frac{P}{2} \right) \Gamma^\lambda (a,b)(q|\mathcal{P}) G_{\Sigma_a} \left( q - \frac{P}{2} \right) \eta,$$

where $a, b$ are the quark and antiquark flavours.

Integrating equation (7) over the longitudinal momentum $q^\parallel = \eta_p(q\eta)$ and introducing the ”dressed” vector meson wave function $\Psi^\lambda (a,b)(q^\perp|\mathcal{P})$

$$\Psi^\lambda (a,b)(q^\perp|\mathcal{P}) = S_a(q^\perp) \Psi^\lambda (a,b) (q^\perp|\mathcal{P}) S_b(q^\perp) = \int \frac{dq^\parallel}{2\pi} G_{\Sigma_a} \left( q + \frac{P}{2} \right) \Gamma^\lambda (a,b)(q^\perp|\mathcal{P}) G_{\Sigma_a} \left( q - \frac{P}{2} \right),$$

where

$$S_a,b(q^\perp) = \exp \left[ \frac{q^\perp \eta_p(q^\parallel)}{q^\parallel} \right]$$

is the Foldy-Wouthuysen type transformation matrix [4],

$$\Psi^\lambda (a,b)(q^\perp|\mathcal{P}) = \phi^\lambda (\mathcal{P})(N_1(q^\perp) - \eta N_2(q^\perp))$$

is the ”undressed” vector meson wave function, we obtain the SE for vector mesons in the following form

$$MN^\lambda (a,b) (p^\perp) = E_q(p^\perp) N^\lambda (a,b) (p^\perp) - \frac{1}{3} \int \frac{d^3 q^{\perp}}{(2\pi)^3} V(p^\perp - q^\perp) [c^+_p c_q + c^+_p c_q + c^+_p c_q]$$
\[-\xi(2s_p^+s_q^- + s_p^+s_q^+) + \xi^2(c_p^-c_q^- + c_p^+c_q^- + c_p^-c_q^+ + c_p^+c_q^+)N(\xi)(q^\perp), \tag{11}\]

where

\[c_p^\pm = \cos[\vartheta_a(p^\perp) \pm \vartheta_b(p^\perp)], \quad s_p^\pm = \sin[\vartheta_a(p^\perp) \pm \vartheta_b(p^\perp)], \quad \xi = \frac{p^\perp q^\perp}{|p^\perp||q^\perp|}, \]

\[E_i(p^\perp) = E_a(p^\perp) + E_b(p^\perp). \]

Here \(\vartheta_{a,b}(p^\perp)\) and \(E_{a,b}(p^\perp)\) are the single-particle phase functions and energies of quark and antiquark inside the meson, which are found by solving the SDE [6]

\[E_{a,b}(p^\perp) \cos 2\vartheta_{a,b}(p^\perp) = m^0 + \frac{1}{2} \int \frac{d^3q^\perp}{(2\pi)^3} V(p^\perp - q^\perp) \cos 2\vartheta_{a,b}(q^\perp), \tag{12}\]

\[E_{a,b}(p^\perp) \sin 2\vartheta_{a,b}(p^\perp) = |p^\perp| + \frac{1}{2} \int \frac{d^3q^\perp}{(2\pi)^3} V(p^\perp - q^\perp) \xi \sin 2\vartheta_{a,b}(q^\perp). \tag{13}\]

In expression (10) \(N_1(q^\perp)\) and \(N_2(q^\perp)\) are the structure formfactors of the vector meson, \(\epsilon^\mu_\lambda(P)\) are its polarization vectors, which satisfy the following conditions, respectively:

\[
\frac{4N_c}{M} \int \frac{d^3q^\perp}{(2\pi)^3} N_1(q^\perp)N_2(q^\perp) = 1,
\]

\[
\sum_{\lambda=1}^3 \epsilon^\mu_\lambda(P)e^\lambda_\beta(P) = - \left( g_{\alpha\beta} - \frac{P_\alpha P_\beta}{M^2} \right).
\]

It is to be noted that unlike the works [6,8], where \(N_1\) and \(N_2\) are the vector quantities, in our scheme they are divided to the polarization vectors matrix and structure scalar formfactors (see, expression (10)), which are decomposed over the spherical functions. This circumstance simplifies to find the mass spectrum and wave functions of vector mesons, and leads to the only leptonic decay constant.

### III. \(\tau \to \rho \nu\) DECAY AND LEPTONIC DECAY CONSTANTS OF VECTOR MESONS

Now we consider \(\tau \to \rho \nu\) decay, studying of which gives an information about of hadronization of the intermediate charged weak vector \(W\) boson to the vector meson, that allows to calculate the constant \(f_\rho\).

The matrix element of the decay is

\[
< \rho|W_{int}|\tau> = -N_c \text{Tr} \int d^4x_1d^4y_1d^4x_2d^4y_2 < \nu|L(x_1, y_2)|\tau> <\rho|G_\Sigma(x_1 - x_2)M(x_2, y_1)G_\Sigma(y_1 - y_2)|0>, \tag{14}\]

where

\[
G_\Sigma(x - y) = \begin{pmatrix} G_{\Sigma_\alpha}(x - y) & 0 \\ 0 & G_{\Sigma_\beta}(x - y) \end{pmatrix}
\]

is the Green functions matrix of \(u\) and \(d\) quarks;
\[ M(x, y) = \left( \frac{M_{\rho^+}(x, y)}{\sqrt{2}} \quad \frac{M_{\rho^0}(x, y)}{\sqrt{2}} \right) \]

is the matrix of bilocal meson fields;

\[ L(x, y) = \tau^{-} \gamma_{\alpha}(1 - \gamma_5) \delta^4(x - y) L^\alpha(x), \]

is the local leptonic current.

Here

\[ L^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ F = \frac{G_F}{\sqrt{2}} \bar{\psi}(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ r^\alpha = (r_1 - r_2)/2, \]

\[ F = \frac{G_F}{\sqrt{2}} \bar{\psi}(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

is the matrix of bilocal meson fields;

\[ \mathcal{L}(x, y) = \tau^{-} \gamma_{\alpha}(1 - \gamma_5) \delta^4(x - y) \mathcal{L}^\alpha(x), \]

is the local leptonic current.

Here

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

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\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

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\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]

\[ \mathcal{L}^\alpha(x) = \frac{G_F \cos \theta_c}{\sqrt{2}} \bar{\psi}_\nu(x) \gamma^\alpha(1 - \gamma_5) \psi_{\tau}(x), \]

\[ \tau^- = (\tau_1 - \tau_2)/2, \]
where $V_0$ and $\alpha_s$ are the parameters of their potentials.

As a rule SDE (12), (13) and SE (11) with such kind of potentials are solved using numerical methods. In order to remove ultraviolet divergences in the SDE, arising because of Coulomb part of the potential we use the standard renormalization scheme, proposed in Refs. [5].

In paper [2] mass spectrum of mesons had been calculated by solving the SDE and SE with pure oscillator potential ($\alpha_s = 0$). Then it was considered that the current quark mass equals to zero ($m^0 = 0$) and pion is the pseudo Goldstone particle with zero mass. Fitting only parameter $V_0$ by the $\rho$ meson mass for it was obtained $(4V_0/3)^{1/3} = 289$ MeV, which allows to describe on a satisfactory level the mass spectrum of light mesons.

However, the spectroscopy of heavy mesons and also leptonic decay constants of pseudoscalar mesons could not been reproduced with oscillator potential. Taking into account availability of the current masses $u$ and $d$ quarks, values of which were defined fitting by pion mass ($m^0_u = m^0_d = 2$ MeV), does not resolve this problem either [9].

Complication of the potential by means of adding to potential of the Coulomb type term ($\alpha_s \neq 0$), which is due to one gluon exchange between quarks and also taking into account other quark ($s$, $c$ and $b$) flavours, of course, leads to redefinition of values of input parameters $V_0$ and $m^0$. After fitting them by masses of $\pi$, $\rho$, $K$, $D$ and $B$ mesons we receive

$$(4V_0/3)^{1/3} = 299$ MeV, $\alpha_s = 0.2$, $m^0_{u,d} = 2.3$ MeV,

$$m^0_s = 68$ MeV, $m^0_u = 1273$ MeV, $m^0_d = 4720$ MeV.

Solving equation (11) with potential (20) numerically by Continuous Analogy of Newton Methods [18] using of shown solutions of the SDE from expression (19) we obtain the following value for constant $f_\rho$ $f_\rho = 1.03 \cdot 10^5$ MeV$^2$,

which is closer to available experimental data $f_\rho^{exp} \approx 1.57 \pm 0.09 \cdot 10^5$ MeV$^2$.

As for the values of masses of other charged vector mesons and their leptonic decay constants calculated within QPM with potential (20), they are listed in Table 1.

| Vector meson | Masses, (MeV) | Decays, $\times 10^4$ MeV$^2$ |
|--------------|---------------|------------------------------|
| $\rho$       | 770           | Model 770, Experiment [20]   |
| $K^*$        | 807           | 1.17                         |
| $D^*$        | 1880          | 3.21                         |
| $D_s^*$      | 1894          | 3.51                         |
| $B^*$        | 5281          | 6.61                         |
| $B_{cs}^*$   | 6203          | 15.28                        |

It is seen from the Table 1 that QPM with potential (20) can reproduce in satisfactory level the masses of charged vector mesons.

Thus, we would like to note that calculation of the leptonic decay constants both pseudoscalar and vector mesons is important for extraction from experimental data of corresponding Cabibbo-Kobayashi-Maskawa matrix elements, which are input parameters of standard model of interaction of elementary particles. We have the only charged lepton and its neutrino in the end of leptonic decays of mesons and then effect of strong interactions in the initial state is parametrized to the only constant. Consequently, these constants within QPM with SDE for the quark phase function and SE for the bound state of quarks describe hadronization of the $W$ boson to the charged bilocal vector meson, and vice versa, annihilation of the vector meson to charged weak boson.
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