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A.B.Govorkov, S.B.Drenska

RADIATION DECAYS OF VECTOR MESONS IN THE MODEL OF RELATIVISTIC HARMONIC OSCILLATOR

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Говорков А.Б., Дренска С.Б. E2 - 10078

Радиационные распады векторных мезонов в модели релятивистского гармонического осциллятора с цветными кварками

Магнитные дипольные распады векторных мезонов в псевдоскалярные рассмотрены в рамках четырехмерного гармонического осциллятора. Приводятся результаты расчетов как для обычных векторных мезонов ω, ρ^0, k^{0*}, так и для новых мезонов J/ψ и ψ', которые интерпретируются в рамках "цветной" модели как состояния аналогичные ω и ϕ мезонам, соответственно. Для новых мезонов за счет релятивистских эффектов получается существенное подавление радиационных распадов. Попутно выясняется, что размеры новых мезонов должны быть существенно меньше размеров обычных мезонов.

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Govorkov A.B., Drenska S.B. E2 - 10078

Radiation Decays of Vector Mesons in the Model of Relativistic Harmonic Oscillator

The magnetic dipole decays of vector mesons in pseudoscalar ones are considered in the framework of a four-dimensional harmonic oscillator. The results of the calculations are given both for the usual vector mesons ω, ρ^0, k^{0*} and for the new mesons J/ψ and ψ' that are interpreted in the framework of the "colored" model as states analogous to ω and ϕ mesons, respectively. For the new mesons due to the relativistic effects the essential suppression of the radiative decays is obtained. In passing it is found out that the dimensions of the new mesons should be essentially smaller than those of the usual mesons.

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1. INTRODUCTION

In the present paper the radiation decays of vector mesons (V) in pseudoscalar mesons (Π):

$$V \to \Pi + \gamma \qquad (1.1)$$

are considered in the framework of the four-dimensional harmonic oscillator model. The meson states are interpreted in the three-triplet ("colored") model with integral charges [1,2].

We would like to investigate the extent of importance of the role of the relativistic effects by examining the transition from the successful phenomenological nonrelativistic quark model [3] to the phenomenological relativistic oscillator [4]. We think that such an investigation can be interesting both in general and particularly in connection with the attempts to interpret the new discovered J/ψ -mesons in the framework of a colored model. Actually an objection to this interpretation is the necessity of explaining the absence of considerable radiation decays of the new vector J/ψ -mesons in usual hadrons.

The estimates based on the "naive" quark model give for the widths of these transitions more than 10 MeV! A lot many of authors [5] have shown that the account of the form factors may give a considerable suppression of these decays. The empirical expressions for the form factors have been used as an illustration.

In this paper we should like to obtain these form factors consistently on the basis of the four-dimensional oscillator model that has already been used for an explanation of the behaviour of the nucleon form factor [4,6-8]. The only arbitrary parameter of the model - the frequency of the oscillator, we fix using the data for the leptonic decays:

$$V \to \ell^+ \ell^- . \quad (1.2)$$

Our main approximation is the assumption for the factorisation of the inner unitary, spin and space variables, and the meson state-vectors can be represented by the direct product of the corresponding wave functions.

2. FOUR-DIMENSIONAL HARMONIC OSCILLATOR

We describe the motion of the quark and antiquark, which we suppose to compose all mesons, by a wave function of the 4-coordinate x_1 of the quark and x_2 of the antiquark that satisfies the equation

$$[2(\Box_1 + \Box_2) - \frac{1}{16}\Omega^2 (x_1 - x_2)^2 + m_0^2]\Psi(x_1, x_2) = 0, \quad (2.1)$$

where $\Box \equiv \partial_\mu \partial^\mu$, ($\partial_\mu \equiv \partial / \partial^\mu$). Introducing the coordinates of the mass center and the relative coordinates

$$X = (x_1 + x_2)/2, \quad (2.2)$$
$$\xi = (x_1 - x_2)/2\sqrt{2},$$

we may divide the variables and represent the wave function in the form

$$\Psi(X, \xi) = \exp(-iPX)\Phi(P, \xi), \quad (2.3)$$

where P is the complete four-momentum of the system ($P = p_1 + p_2$). The wave function of the inner motion of the quarks is determined by the equation for the eigen-values

$$(\Box_\xi - \Omega^2 \xi^2)\Phi_n(P, \xi) = 2\Lambda_n \Phi_n(P, \xi), \quad (2.4)$$

and by the mass of the system

$$M^2 = P^2 = m_0^2 + \Lambda_n . \quad (2.5)$$

We have not discussed the difficulties of this model connected with the time excitations [7]. We have considered only the ground state and its wave function

$$\Phi_0(P, \xi) = \frac{\Omega}{\pi} \exp\{-\frac{\Omega}{2}[2(\frac{P\xi}{M})^2 - \xi^2]\}. \quad (2.6)$$

A lot many of authors have shown that it is just this type of solution of equation (2.4) that describes well the asymptotic behaviour of the elastic nucleon form factor [6-8].

Now, we take into account the spinor structure of the wave function $\Psi(x_1, x_2)$, that is 4x4-spinor, and following Lipes [6], we introduce the electromagnetic current in a minimal way (writing $\Box_i = \gamma_\mu \partial_i^\mu \gamma_\nu \partial_i^\nu$ $(i=1,2)$ and making the change $\partial_\mu^i \to \partial_\mu^i + i Q_i \mathcal{A}_\mu$)*.

The current matrix element of the transition $i \to f$, normalized to one final and one initial meson in unit volume has the form

$$J^\mu(P_i, P_f) = -\frac{\bar{\chi}_f(P_f) Q_q (\sigma_q^{\mu\nu} - \sigma_{\bar{q}}^{\mu\nu}) k_\nu I \chi_i(P_i)}{[E_i E_f (\bar{\chi}_i \chi_i)(\bar{\chi}_f \chi_f)]^{1/2}}, \qquad (2.7)$$

where $\chi(P)$ is the spin-unitary-spin part of the meson wave function; P_i, P_f and k are the four-momenta of the initial (i), final (f) mesons and photon, respectively; Q_q and $Q_{\bar{q}}$ are the quark and antiquark charges; $\sigma_q^{\mu\nu}$ and $\sigma_{\bar{q}}^{\mu\nu}$ are matrices acting on the spin quark and antiquark wave functions.

The integral I is defined by

$$I = \int d^4\xi \exp(ik\xi\sqrt{2}) \Phi_f^*(P_f, \xi) \Phi_i(P_i, \xi), \qquad (2.8)$$

where the star means complex conjugation. We have also taken into account the fact that the initial vector and the final pseudoscalar mesons are related to the ground state of the oscillator, and that $Q_{\bar{q}} = -Q_q$.

3. SPINOR WAVE FUNCTIONS

We suppose that quarks are quasi-independent and consider that their masses and four-momenta are just equal to half mass and four-momentum of the meson in the structure of which they take part. Then, in accordance with de' Broglie's fusion theory [9] we may represent the wave function of the composite particle as the matrix

$$\phi_{\alpha\beta}(P) = u_\alpha(P) \times \bar{v}_\beta(P), \qquad (3.1)$$

where u(P) and v(P) are plus and minus frequent spinor of the Dirac equation. The matrix ϕ satisfies the equation

$$(\hat{P} - M)\phi = 0, \qquad \bar{\phi}(\hat{P} + M) = 0, \qquad (3.2)$$

where $\hat{P} = P_\mu \gamma^\mu$ and M is the mass of the composed particle. The action of the matrices to the spinor quark and antiquark wave functions is replaced by a matrix multiplication

$$\Gamma_q \phi = \Gamma\phi, \qquad \Gamma_{\bar{q}}\phi = \phi C \Gamma^T C^{-1}, \qquad (3.3)$$

where Γ is an arbitrary element of the Dirac matrix algebra, and the matrix C realizes a unitary transformation of the transposed matrices

$$C\gamma_\mu^T C^{-1} = -\gamma_\mu, \quad C^+ = C^{-1}, \quad C^T = -C. \qquad (3.4)$$

The Dirac conjugation spin wave function is the matrix

$$\bar{\phi}_{\alpha\beta}(P) = -\bar{u}_\beta(P) \times v_\alpha(P) \qquad (3.5)$$

and it is defined by the relation

$$\bar{\phi}(P) = -\gamma^0 \phi^+(P) \gamma^0, \qquad (3.6)$$

where ϕ^+ is the matrix Hermitian conjugated

*We use the metric $g_{00} = -g_{11} = -g_{22} = -g_{33} = 1$, $g_{\mu\nu} = 0$ when $\mu \neq \nu$, and the significations $\sigma^{\mu\nu} = \frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$, $\sigma_5^\mu = \gamma^\mu\gamma_5$, $\gamma_5 = \gamma^0\gamma^1\gamma^2\gamma^3$.

to ϕ. To obtain the norm, we must take the trace

$$Sp\bar{\phi}\,\phi = -(\bar{u}u)(\bar{v}v) = 1. \qquad (3.7)$$

The matrix

$$\phi_V(P) = \frac{1}{2\sqrt{2}}[V_\mu(P)\gamma^\mu + \frac{1}{2}F_{\mu\nu}(P)\sigma^{\mu\nu}],$$
$$\bar{\phi}_V(P) = \frac{1}{2\sqrt{2}}[V^*_\mu(P)\gamma^\mu + \frac{1}{2}F^*_{\mu\nu}(P)\sigma^{\mu\nu}], \qquad (3.8)$$

corresponds to a vector composite particle. (In (3.8) we put $\bar{\phi} = +\gamma^0\phi^+\gamma^0$ for convenience). The three states that are responsible for the three projections of the spin on the axis z, that we direct along the momentum of the particle, are defined by the three vectors

$$V_\mu(s_z = \pm 1) = \frac{1}{\sqrt{2}}(0,1,\pm 1,0),$$
$$V_\mu(s_z = 0) = (P/M, 0, 0, -E/M). \qquad (3.9)$$

The components of the tensor $F_{\mu\nu}$ are given by equations

$$F_{\mu\nu} = \frac{1}{M}(V_\mu P_\nu - V_\nu P_\mu). \qquad (3.10)$$

The norm is

$$Sp\,\bar{\phi}_V\phi_V = V^*_\mu V^\mu . \qquad (3.11)$$

The matrix

$$\phi_\Pi(P) = \frac{1}{2\sqrt{2}}[\Pi_5(P)\gamma_5 + \mathcal{A}_{\mu 5}(P)\sigma^\mu{}_5],$$
$$\bar{\phi}(P) = \frac{1}{2\sqrt{2}}[-\Pi^*_5(P)\gamma_5 + \mathcal{A}^*_{\mu 5}\sigma^\mu{}_5], \qquad (3.12)$$

corresponds to a pseudoscalar composite particle. In (3.12)

$$\mathcal{A}_{\mu 5}(P) = \frac{P_\mu}{M}\Pi_5(P), \qquad (3.13)$$

the norm is

$$Sp\,\bar{\phi}_\Pi\phi_\Pi = \Pi^*_5\Pi^5. \qquad (3.14)$$

Using the relation (3.3), it is possible to prove that for the antiquark

$$Sp\bar{\phi}_\Pi\sigma^{\mu\nu}_q\,\phi_V = -Sp\,\bar{\phi}_\Pi\sigma^{\mu\nu}\,\phi_V . \qquad (3.15)$$

Hence, the antiquark part in the relation (2.7) gives the same contribution as the quark one, and the last must double.

4. THE WIDTH OF THE RADIATION DECAYS

The current matrix element (2.7) of the transition is determined by the expression

$$J^\mu(P_V, P_\Pi) = -\frac{2Q_{V\Pi}|Sp\,|\bar{\phi}_\Pi(P_\Pi)\sigma^{\mu\nu}k_\nu\phi_V(P_V)|}{[E_\Pi E_V(V^*_\mu V^\mu)(\Pi^*_5\Pi^5)]^{1/2}}, \qquad (4.1)$$

where

$$Q_{V\Pi} = \sum_q Q_q c_V^q c_\Pi^q \qquad (4.2)$$

is the sum of the quark charges Q_q taken by the corresponding coefficients c_V^q and c_Π^q with which the qiarks take part in the SU(3)-wave functions of the vector and pseudoscalar mesons, respectively (see the next chapter). After standard calculations, we have obtained for the width of the radiation transition the expression

$$\Gamma(V \to \Pi + \gamma) = \frac{4}{3\pi} Q^2_{V\Pi} \mu^2 I^2 \omega^3, \qquad (4.3)$$

where μ is the effective magnetic momentum of the transition:

$$\mu = \frac{e}{2}\left(\frac{1}{M_V} + \frac{1}{M_\Pi}\right), \quad (e^2/4\pi \cong 1/137). \qquad (4.4)$$

In the "naive" quark model the form factor $I = 1$ and the effective magnetic momentum of the quark has been put equal to magnetic momentum of the proton $\mu = \mu p = 2{,}79 e/2Mp$. In our case substituting (2.6) in (2.8), we obtain for the form factor the expression:

$$I(\omega) = \Omega \frac{\Omega_V \Omega_\Pi}{\Omega^2} \left(1 + \frac{\Omega_V \Omega_\Pi}{\Omega^2} \kappa^2\right)^{-1/2} \times$$

$$\times \exp\left\{ - \frac{M^2_\Pi}{\Omega} \cdot \frac{\kappa^2}{1 + \frac{\Omega_\Pi}{\Omega} \kappa \left(\kappa - \sqrt{1+\kappa^2}\right)} \right\}, \qquad (4.5)$$

where $\Omega = (\Omega_V + \Omega_\Pi)/2$, Ω_V and Ω_Π are the frequencies of the oscillators corresponding to the vector and pseudoscalar mesons; $\kappa = \omega / M_\Pi = (M^2_V - M^2_\Pi)/2 M_V M_\Pi$. We notice that in the non-relativistic harmonic oscillator model the form factor is

$$I_{NR}(\omega) = \left(\frac{\Omega_V \Omega_\Pi}{\Omega}\right)^{3/4} \exp\left\{ - \frac{M^2_\Pi}{\Omega} \frac{\kappa^2}{2} \right\}. \qquad (4.6)$$

The relation (4.5) does not coincide with the non-relativistic one (4.6) in the limit $\kappa \to 0$. This is the specific peculiarity of the four-dimensional harmonic oscillator - Gaussian distribution of the wave function in the relative time even in the rest system of the composite meson.

5. DECAY OF VECTOR MESONS IN A LEPTONIC PAIR AND OSCILLATOR PARAMETERS

To estimate the values of the oscillator parameters (Ω_V and Ω_Π) we use the experimental data for the decays of vector mesons in a leptonic pair (1.2). The width of this decay realized through one intermediate state is obtained by the equation

$$\Gamma(V \to \ell^+ \ell^-) = \frac{4\pi}{3} \alpha^2 M_V f_V^{-2}, \quad \alpha = e^2/4\pi, \qquad (5.1)$$

where the constant $f_V^2/4\pi$ defines the virtual transition "vector meson-photon". These quantities are obtained from the experimental data [11-14] and are given in Table 1. On the other hand if we consider the process of annihilation of the quark and antiquark in one photon intermediate state, we obtain

$$\frac{4\pi}{f_V^2} = \frac{16\pi}{M_V^3} |\Phi_V(0)|^2 Q_V^2, \qquad (5.2)$$

where $Q_V = \sum_q Q_q c_V^q$, and $\Phi_V(0)$ is the value of the wave function of the relative quark-antiquark motion at the zero point. In order to determine the latter value, we must pass from the four dimensional function (2.6) to the three-dimensional one. For this purpose we consider the meson in its rest system and we integrate the corresponding expression by the relative time. We normalize the wave function so that the condition

$$\int d^3x_1 \int d^3x_2 \, \Phi^*_{\vec{P}'}(\vec{x}_1, \vec{x}_2) \Phi_{\vec{P}}(\vec{x}_1, \vec{x}_2) = \delta^{(3)}(\vec{P} - \vec{P}') \qquad (5.3)$$

is satisfied.

If we make a change of the variables according to (2.2), we obtain for the three-di-

Table 1. The Constants of the Transitions "Vector Meson-Photon" and the Parameters of the Oscillators

Particles / Characteristics	ρ^0 (770)	ω (784)	ϕ (1019)	J/ψ (3095)	ψ' (3684)
$f_V^2/4\pi$	2.56 ±0.24 a)	18.4 ± 2.	12.2 ± 1. a)	11.5 ± 1.5	30. ± 4.
Q_V	$\frac{3}{\sqrt{6}}$	$\frac{\cos\delta+\sqrt{2}\sin\delta}{\sqrt{6}}$ b)	$\frac{-\sin\delta+\sqrt{2}\cos\delta}{\sqrt{6}}$ b)	$-\frac{2}{\sqrt{3}}$	$\frac{2}{\sqrt{6}}$
Ω_V $(GeV)^2$	0.446±0.028	0.471±0.034	0.813±0.044	2.86 ± 0.25	3.40 ± 0.30
$<r^2>^{1/2}_{cm}$ Fm	0.677±0.016	0.662±0.014	0.506±0.008	0.230±0.008	0.207±0.007

a) It is introduced a correction of finite width of the meson.

b) $\delta = 4°20'$.

mensional wave function of the relative motion the expression

$$\Phi_0(\vec{\xi}) = \frac{1}{2\sqrt{2}}\left(\frac{\Omega}{2\pi}\right)^{3/4} \exp\left(-\frac{\Omega_V \vec{\xi}^{\,2}}{2}\right). \quad (5.4)$$

Using (5.4) and (5.2) we find

$$\frac{f_V^2}{4\pi} = \frac{\sqrt{2\pi}\, M_V^3}{\Omega_V^{3/2} Q_V^2}. \quad (5.5)$$

According to the color interpretation of the new vector mesons [2,15], J/ψ (3095) and ψ' (3684) mesons are considered as analogs of ω and ϕ ones, respectively, and we denote these states by $\tilde{\omega}$ and $\tilde{\phi}$.

In Table 1 the coefficients Q_V determined on the basis of the color model are represented in the second line. For the usual ω and ϕ mesons we take into account a slight deviation from the ideal singlet-octet mixing (according to the squared mass formulae [16] the angle of the deviation is $\delta = 4°20'$). We suppose that the mixing for the new mesons is ideal.

In the third line of Table 1 we give the oscillator frequencies Ω_V, computed according to (5.5), with the help of the experimental data. In the fourth line the mean squared electromagnetic radius of mesons

$$<r^2>^{1/2} = \left\{3\left(\frac{1}{\Omega_V} + \frac{1}{M_V}\right)\right\}^{1/2} \quad (5.6)$$

is given. The expression (5.6) is obtained by the decomposition of the elastic form factor

$$G(q^2) = \frac{2M_V^2}{2M_V^2 - q^2} \exp\left\{\frac{1}{\Omega_V}\frac{M_V^2 q^2}{2M_V^2 - q^2}\right\}, \; q^2 = (P_f - P_i)^2 \quad (5.7)$$

into q^2.

We remark that for the new J/ψ and ψ′ mesons the oscillator frequency is almost identical, just so it is identical for ρ° and ω mesons (it is a little larger for the φ - meson), but for the new and usual mesons the frequencies are strongly different. Therefore, the dimensions of the new mesons must be essentially less than the dimensions of the usual mesons. An additional confirmation of this fact is the observed decrease of the slope of the differential cone for the photoproduction of the new mesons [17], in comparison with the usual mesons. We notice that the electromagnetic radius for ρ° and ω mesons in this model is almost equal to the experimental value of the pion radius: (0.68 ± 0.05) Fm [18].

6. CALCULATION OF THE WIDTHS OF THE RADIATION DECAY OF THE VECTOR MESONS

We compute the widths of the radiation transitions (1.1) on the basis of formulae (4.3-4.5). In our calculations we use the ideal singlet-octet mixing for all mesons (here a little deviation is not essentially). We suppose the parameter Ω_{Π} for the pseudoscalar mesons to be equal to the parameter Ω_V of the corresponding vector meson. We compute these parameters using the data from Table 1, average them by the squares of the coefficients with which the neutral and strange quarks take part in the corresponding composite meson state. The results are given in Table 2. We compare the widths obtained on the basis of three different models: a "naive" quark, nonrelativistic model (I=1 ,

Table 2

The Widths of the Radiation Decays of Vector Mesons

$V \to \Pi + \gamma$	Ω_V Ω_Π GeV²	$Q_{V\Pi}$	$\Gamma_{theor.}$ "naive" model	$\Gamma_{theor.}$ nonrelat. model	$\Gamma_{theor.}$ relat. model	Γ_{exp}
$\omega \to \pi^{\circ} + \gamma$	0.46	1/2	1.18 MeV	0.86 MeV	0.33 MeV	0.87±0.07 MeV [16]
$\rho^{\circ} \to \pi^{\circ} + \gamma$	0.45	1/6	124 keV	91.6 keV	38 keV	35±10 keV [20]
$K^{\circ *} \to K^{\circ} + \gamma$	0.64	−1/3	200 keV	172 keV	141 keV	75±35 keV [21]
$\rho^{\circ} \to \eta + \gamma$	0.45 0.70	$\sqrt{3}/6$	49 keV	43 keV	37 keV	<160 keV [22]
$J/\psi \to \eta + \gamma$	2.9 0.70	$-\sqrt{6}/9$	21.5 MeV	3 MeV	34.4 keV	~0.1 keV [23]
$\psi' \to \eta + \gamma$	3.4 2.70	$-2\sqrt{3}/9$	74.5 MeV	6.4 MeV	37.0 keV	-

$\mu=\mu_p$ and for strange quarks have been supposed $\mu = 0.7\mu_p$ [19]), a nonrelativistic quark model with an oscillator form factor (4.6); and a relativistic model of the four-dimensional oscillator (I is determined by (4.5), μ - by (4.4) with the masses M_V and M_Π).

7. CONCLUSION

The results of our calculations show that the relativistic effects might have already manifested themselves in the radiation decays of the usual mesons. However, we remark that for a decay with a big defect such as $\omega \to \pi^0 + \gamma$ the model of four-dimensional oscillator gives results that agree poorly with experimental data unlike the non-relativistic model. Probably the reason for this fact is in our main approximation for the factorisation of the spin and space parts of the wave function of the quark-antiquark system. So we obtain that the effective mass of the quarks is just half mass of the composite meson. For instance it is only ~70 MeV for the quarks that compose π^0-meson. Possibly, the non-relativistic model with identical effective quark masses is more adjacent than the four-dimensional harmonic oscillator with different effective quark masses that has been used here.

The relativistic effects play the main role in suppression of the radiation decays of the new J/ψ and ψ' mesons from several scores of the MeV to several scores of the keV. But this suppression of the widths is not enough because the experimental width of the decay $J/\psi \to \eta + \gamma$ is a little part of keV [23]. A possible way of explaining the suppression of the widths is given in [15]. The radiation decays of the new mesons are usually connected with an essential change of the oscillator parameter (Ω and m_0 in equation (2.1)). Therefore, the change of the effective quark mass is a real one and it is not connected with our main approximation. But the current (2.7) obtained here is gauge invariant only when the oscillator parameters are the same for the initial and final states. Therefore the transition connected with the change of the quark mass cannot be realized by means of the Dirac magnetic momentum, it may be realized only by means of the abnormal transition magnetic momentum of the quasiindependent quarks. Our estimates show that it must be a little part, ~0.05, of the Dirac magnetic momentum. The last corresponds to the "point-like quarks".

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