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SPIN EFFECTS IN QUARKONIA

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The spin-spin mass splitting and leptonic decays of heavy and mixed mesons are described within a good accuracy in the potential model with screened potential. We conclude that the long-distance part of the potential cannot be pure scalar and that a vector-scalar mixture is favoured. With the same parameters which give correct average mass spectrum excellent spin-spin splittings of heavy quarkonia is obtained. The results are obtained by going beyond usually used perturbation method, namely using "configuration interaction approach" (CIA). It is known that the first term of CIA method is in fact just a perturbative method result. CIA expansion better takes into account the interaction between particles. The suggested method is of considerable interest, since the perturbation method is still used as the practical method. We turned to use realistic potential, namely, screened potential.

The problem of hyperfine splitting in mesons still attracts wide interest. It is widely acceptable that quark potential model gives a rather good description of spin-average mass spectrum of hadrons, considered as composite system of quarks [1]. However, the question of explaining the influence of spin, namely spin-orbit ("fine"), spin-spin ("hyperfine") interaction, is not solved yet. The problem of mass splitting is due to spin structure and it is closely connected with the Lorentz – structure of the quark potential. These effects are far from being solved yet.

Following many authors we assume admixture vector-scalar potential ("soft model"). We consider vector and scalar parts of static potential [1]

$$V(r)=V_V(r)+V_S(r) \quad (1)$$

where

$$V_V=-\frac{\alpha_S}{r}+\varepsilon\frac{g^2}{6\pi\mu}\left(1-e^{-\mu r}\right)$$

$$V_S=(1-\varepsilon)\frac{g^2}{6\pi\mu}\left(1-e^{-\mu r}\right) \quad (2)$$

and ε is the mixing constant.

The Hamiltonian can be written as

$$H=H_0+H_{SS} \quad (3)$$

for screened potential:

$$H_0=-\frac{1}{2m}\Delta-\frac{\alpha_S}{r}+\frac{g^2}{6\pi\mu}\left(1-e^{-\mu r}\right) \quad (4)$$

where m is the reduced mass of qq–system and $\hbar=c=1$ units are used. In (3) only H_{SS} is taken into account, because we calculate hyperfine splitting in S-waves. Then all terms which contain the orbital quantum number ℓ are absent. The concrete form of such screened potential was previously suggested in [2]. We choose screened potential, because it gives excellent description of mass-spectrum in nonrelativistic potential models for heavy mesons. As Gerasimov pointed out [3] the QCD calculations on lattice indicates that the spin-spin forces are rather short range. Exactly the screened potential satisfies this condition. In this case even the basic solutions for unperturbed Hamiltonian can not be found in analitic form. We found these solutions numerically and evaluated the matrix elements numerically too. Final results for hyperfine splitting for screened potential are given in Tables 1,2. The following parameters were used in screened potential $g^2/6\pi = 0.224$ GeV^2, $\mu = 0.054$ GeV. All parameters were taken from [4] and the experimental data were taken from [5].

The main problem of our work is to clarify some aspects of hyperfine interaction in the framework of configuration interaction approach (CI approximation, or CIA[6]).

In the frame of Breit-Fermi approach the spin-spin interaction term is

$$H_{SS} = \frac{2}{3m_{q_1}m_{q_2}}\vec{S}_1\vec{S}_2\Delta V_V \quad ,(5)$$

where $S_{1,2}$ are the spins of the particles. $\vec{S}_1 \cdot \vec{S}_2 = -3/4$ for pseudoscalar mesons and $\vec{S}_1 \cdot \vec{S}_2 = 1/4$ for vector mesons.

Now we consider Shroedinger equation

$$(H_0 + H_{SS})\Psi(\vec{r}) = E\Psi(\vec{r}) \qquad (6)$$

Here we suggest to use CI approach, which was previously very successfully applied in atomic physics [6] . The essence of this approximation is that wave function Ψ(r) is expanded in a set of eigenfunctions φ_n of the Hamiltonian H_0:

$$\Psi(\vec{r}) = \sum_n a_n\varphi_n(\vec{r}) \qquad (7)$$

Substituting (7) into (6) and using eigenvalues E_n^0, we obtain homogeneous system of linear equations for a_n

$$a_n\left(E_m^0 - E\right) = -\sum_n a_n \langle\varphi_m|H_{SS}|\varphi_n\rangle \quad ,(8)$$

which have to be truncated for reasonable large n. In (8) E_m^0 is the eigenvalue of the nonperturbative Hamiltonian:

$$H_0\varphi_m = E_m^0\varphi_m \qquad (9)$$

The solution of the system (8) exists if its determinant is equal to zero. The diagonalization of this determinant gives the values of energies we are looking for. This is a good method to find the eigenvalues E_n. This procedure goes far outside of perturbative method.

In this work we obtained hyperfine splitting for heavy and mixed mesons using the configuration interaction approach. For example, as a first step, we calculate the hyperfine splitting in J/Ψ and η mesons with using screened potential.

Table 1. Hyperfine splitting in charmonia with the used CI approach.

	1 approach	2 approach	3 approach	4 approach	5 approach	Experimental value
E_{SING}, MeV	2996.1	2991.537	2989.827	2988.831	2988.153	2980
E_{TRIPL}, MeV	3097.1	3096.577	3096.328	3096.161	3096.041	3096
ΔE_{SS}, MeV	101	105.04	106.501	107.33	107.888	117
$\Delta E_{SS}(n+1) - \Delta E_{SS}(n)$	------	4.04	1.46	0.829	0.55	

Our calculations shown that the next terms of CIA method give contribution of order of 10% for heavy mesons and 35% for mixed mesons. Let us stress that the first term of CIA method is in fact just a perturbative method result. CIA expansion better takes into account the interaction between particles. A similar approach was suggested in paper [7], where expansion was carried into basic functions of the oscillator potential. The suggested method is of considerable interest, since the perturbation method is still used as a practical method [8, 9, 10].

Table 2. Hyperfine splitting for heavy quark systems.

	[7] ΔM_{THEOR}, MeV	[10] ΔM_{THEOR}, MeV	[11] ΔM_{THEOR}, MeV	our results ΔM_{THEOR}, MeV	$\Delta M_{EXP.}$, MeV
$\Delta M_{Ds^{*}-Ds}$	87	190	128	163	144
$\Delta M_{Ds^{*\prime}-Ds'}$	----	----	----	100	----
$\Delta M_{Bs^{*}-Bs}$	----	----	----	50	47
$\Delta M_{Bs^{*\prime}-Bs'}$	----	----	----	33	----
$\Delta M_{Bc^{*}-Bc}$	----	----	----	49	----
$\Delta M_{Bc^{*\prime}-Bc'}$	----	----	----	31	----
$\Delta M_{\Upsilon-\eta_b}$	31	39	82	46	----
$\Delta M_{\Upsilon'-\eta_b'}$	9	----	----	26	----
$\Delta M_{J/\psi-\eta_c}$	65	100	112	108	117
$\Delta M_{\psi'-\eta_c'}$	32	54	----	67	95

In Table 2 we present the results of hyperfine splitting calculation in heavy-quark systems. Namely exactly for these systems our Breit-Fermi approach must be true with maximum extent. The obtained results for the hyperfine splittings of the S-wave states agree with the measured splittings. As it is seen, most of our results have mainly predictive character. In the Table 2 it is shown that for 2S-states we obtain somewhat worse results in hyperfine splitting than in 1S-states. This can be a result of mixing of S and D waves. In 2S state, as it is shown in work [12], the mixing can give contribution of the order of 10%, while in the case of 1S-states the correction for mixing is near 1%.

We compare our results with the results obtained in the works [7,10,11]. In the paper [7] good results are obtained, but the authors introduced additional parameters r_0. In [10] hyperfine splitting is calculated in the first order of perturbation theory. It is shown that the first order perturbation theory gives a good description of the experimental data. The best results are obtained in [11], but only one-gluon exchange is taken into account for spin-spin forces. In all these works there is one common fault as they are restricted to viewing limited number of mesons.

We suggest that the potential consists of a sum of vector and scalar parts. This idea of scalar-vector mixing was discussed in [13,14-16]. The authors of these papers also came to the conclusion that its mixing parameter must be different from zero. Franzinis et al. [13] shown, that V_{conf} must be totally scalar, while V_{oge} must be totally vector, but nevertheless they cannot give an adequate description of the fine splitting data. In a series of papers [14-16] Deoghuria and Chakrabarty had chosen the confining potential in the form

$$V = \varepsilon V_{OGE} + (1-\varepsilon)V_{CONF}$$

and found $\varepsilon = 0.2$, treating ε as an adjustable parameter. In this paper we have used the same approach for CJP-type potential and found $\varepsilon = 0.5$. With this value of ε we described the hyperfine splitting of all mesons from heave to light ones.

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СПІНОВІ ЕФЕКТИ В КВАРКОНІЯХ

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У роботі описано спін-спінове розщеплення у важких і змішаних мезонах у рамках потенціальної моделі з екранованим потенціалом. Показано, що конфайнментна частина потенціалу має змішану Лоренц-структуру. Для розрахунків використано ті ж параметри, з якими було розраховано усереднений спектр мас частинок. Розрахунки проведено з допомогою методу накладання конфігурацій.