A SCREENED LINEAR POTENTIAL MODEL AND SPIN STRUCTURE OF P-STATE HEAVY QUARKONIA

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A SCREENED LINEAR POTENTIAL MODEL AND SPIN STRUCTURE OF P-STATE HEAVY QUARKONIA

Masanobu HIRANO and Yasuo MATSUDA*)

Hokkaido University of Education, Sapporo, 002
*) Hokkaido Automotive Engineering College, Sapporo, 062

遮蔽されたリニアーポテンシャル模型と重いP状態クォーコニアのスピン構造

平 野 雅 宣・松 田 康 夫*)

北海道教育大学札幌分校物理学教室
*) 北海道自動車短期大学

Abstract

It has been considered that a simple Lorentz vector confining potential favored by dynamical chiral symmetry breaking does not work in the spin dependent structure of the hadron mass spectrum. This article proposes a model where the nonperturbative potential of Lorentz vector property is screened due to the light quark vacuum polarization effect at large quark-antiquark seperations and where the perturbative QCD radiative corrections are taken into account. We show that the controversial spin structure within the L=1 states of heavy quarkonia are explained by this model.

§ 1 Introduction

The gross features of heavy quark systems are well described by the static potential. Usually this potential has been assumed to be the sum of a short-range and a long range part. These have been considered related to the asymptotic behavior of QCD: the former due to the perturbative QCD and the latter due to the non-perturbative region of the interaction, which may possibly be responsible for the confinement. In initial analyses, the long-range (linear) confining potential was assumed to originate in an effective Lorentz vector exchange[1] (referred to as the "Vector" model). Later, mainly for phenomenological reasons[2~8] it was assumed that it is a Lorentz scalar or that it has a large Lorentz scalar component (referred to as the

"Scalar" monel).

One important feature of hadron phenomena is the approximate chiral symmetry. The breaking may be described properly as due to dynamic consequences[9,10] of the long range confining interaction. This Lorentz vector confining potential is known not to work well in the phenomenology of the hadron mass spectrum, especially due to a large spin-spin interaction. Kogut & Susskind[11] have suggested that the light quark-antiquark pair creation effect may play an important role in the hadron spectrum. They examined the effect in a coupled channel formalism, and showed that the confining linear potential will be screened at large quark-antiquark seperations.

The radiative corrections of perturbative QCD are known not to be small even for charm quarks. There have been some mass splitting analyses incluing radiative corrections, but there is no good agreement between data and approximations in estimating the radiative corrections.

We have proposed a "Vector" model, in which we consider a screened linear potential and the radiative corrections[12,13] of perturbative QCD. The screened form of the nonperturbative part of the static potential is due to the light quark vacuum polarization effect at large distances and it is assumed to be of Lorentz vector natume. In the first step of the study the QCD radiative correction uses the numerical results of one loop calculations by Pantaleone and Tye[13]. We examine the P wave heavy quarkonia mass splitting quantitatively by the model and will show that it explains features of both data of hyperfine splittings and the long debated fine splittings of heavy quarkonia.

In § 2, we briefly review a coupled channel formalism and see how the screening of the confining potential occurs. In § 3, we present the screened linear potential model. The spin dependent potentials are calculated whith the model in § 4 and general expressions for the hyperfine and fine splittings of p-wave heavy quarkonia are shown and the results are compared with the "Scalar" model. Numerical estimates are performed in § 5, and § 6 contains the discussion and conclusions.

§ 2 A coupled channel formalism and screening of a linear potential

We first review the vacuum polarization effect of light quarks at large $Q\bar{Q}$ distances in a coupled channel formalim as discussed by Kogut and Susskind[11]: the S-wave state of a heavy quark(Q) and heavy antiquark($\bar{Q}$) pair in a coupled channel Ψ^{CP} (r) consists of a quark-antiquark channel Ψ(r) and a meson-antimeson channel Φ(r). The coupling mixing two channels, is caused by the creation of a light-quark pair in a spin triplet and in the relative S-wave which is generated by a vector gluon. The radial equation of motion for $r\Psi^{CP}(r)=\Psi_{CP}(r)=\begin{pmatrix}\psi\\ \phi\end{pmatrix}r$ is

$$(T+V)\Psi_{CP}(r)=E\Psi_{CP}(r) \tag{2-1}$$

with

$$T=\begin{pmatrix} -\frac{1}{2m_C}\frac{d^2}{dr^2} & 0 \\ 0 & -\frac{1}{2m_D}\frac{d^2}{dr^2} \end{pmatrix} \tag{2-2}$$

$$V(r)=\begin{pmatrix} G(r) & f(r) \\ f(r) & Y(r)+\frac{1}{\mu_D r^2} \end{pmatrix} \tag{2-3}$$

Here G(r) is a quark-antiquark static potential which may be identified with a Coulomb+linear potential. Y(r) is a meson-antimeson potential which presumably has typical short range characteristics. It is chosen to be a short range Yukawa repulsive potjntial, f(r) is a ϕ-ψ coupling which describes the transition of a heavy quark-antiquark state to a meson-antimeson state by a light quark-antiquark pair creation. They were assumed to be of the form in the ref.11)

$$G(r)=\lambda r+U-\alpha\frac{1}{r} \tag{2-4a}$$

$$Y(r)=3.13e^{-0.20r} \tag{2-4b}$$

$$f(r)=0.16[1+\tanh(1.3r-9.1)] \tag{2- 4 c}$$

By the transformation $\Psi(r)=U(r)\Psi_{CP}(r)$ diagonalizing V(r)

$$U(r)V(r)U^{-1}(r)=V_D(r)$$

the kinetic energy part T transforms to

$$U(r)TU^{-1}(r)=T+C.$$

Supposing that the matrix elements of C are small for a heavy quarkonium, then an iterated solution becomes passible :

$$\Psi=\Psi^{(0)}+\Psi^{(1)}+\cdots\cdots \tag{2-5}$$

we have

$$(T+V)\Psi^{(0)}=E\Psi^{(0)} \tag{2-6a}$$

$$(T+V_D-E)\Psi^{(1)}=-C\Psi^{(0)} \tag{2-6b}$$

etc.

where

$$V_D(r)=\begin{pmatrix} V_-(r) & 0 \\ 0 & V_+(r) \end{pmatrix}$$

with

$$V_\pm(r)=\frac{1}{2}[G(r)+Y(r)+\frac{1}{m_D r^2}]\pm\frac{1}{2}[\{G(r)-Y(r)-\frac{1}{m_D r^2}\}^2+4f^2]^{1/2} \tag{2-7}$$

The zero order equation (2-6a) is diagonal and the upper component of $\Psi^{(0)}$, $\psi_-^{(0)}$ may be called the naive (constituent) quark model state. Accepting the features of Eqs. (2-4a)~(2-4c), the effective potential, $V_\pm(r)$ and the associated eigenfunctions $\Psi_{CP\pm}^{(0)}$ have the following asymptotic behavior is:
At small r, f(r) is negligible so

$$V_-(r) \rightarrow \lambda r + U - \alpha/r, \quad \Psi_{CP-}^{(0)} \sim \begin{pmatrix} 1 \\ 0 \end{pmatrix},$$

$$V_+(r) \rightarrow Y(r) + 1/(mr^2) \text{ and } \Psi_{CP+}^{(0)} \sim \begin{pmatrix} 0 \\ 1 \end{pmatrix},$$

For large r,

$$V_-(r) \rightarrow Y(r) + 1/(mr^2), \quad \Psi_{CP-}^{(0)} \sim \begin{pmatrix} 0 \\ 1 \end{pmatrix},$$

$$V_+(r) \rightarrow \lambda r + U - \alpha/r, \quad \Psi_{CP+}^{(0)} \sim \begin{pmatrix} 1 \\ 0 \end{pmatrix},$$

Showing a screening effect of the original linear+Coulomb potential, G(r).

§3 Screened Linear Potential Model

This reviews the equation of motion to the lowest order of the iteration of Eq. (2-5). It consists of two seperate equations, and this article concerned only with the upper component $\Psi_-^{(0)}$ which may be identified with a mesonic state of this order. The model in this order of approximation should be referred to as a naive constituent quark model. The wave function, $\Psi_-^{(0)}(r)$ is obtained by a Schrodinger equation:

$$\{-\frac{1}{2m_C}\frac{d^2}{dr^2} + \frac{L(L+1)}{r^2} + V_-(r)\}\Psi_-^{(0)}(r) = E\Psi_-^{(0)}(r) \tag{3-1}$$

The $V_-(r)$ of Eq. (2-6) is somewhat complicated for an estimate of the spin-dependent forces. For simplicity, $V_-(r)$ is replaced by a "screened linear potential+Coulomb" potential:

$$V_{SC}(r) = (\lambda r + U)e^{-\varepsilon r} - \frac{\alpha}{r} \qquad \text{(3-2)}^{*)}$$

The two potentials, $V_-(r)$ and $V_{SC}(r)$, are compared in Fig. 1, showing that $V_{SC}(r)$ represents the features of $V_-(r)$ reasonably well. The nonperturbative part of $V_{SC}(r)$ corresponds to a kernel used in the previous analysis[14] of the dynamical effects of the "confining interaction". For simplicity, we assume that the $V_{SC}(r)$ is a Lorentz vector and that there is no Lorentz scalar component, and we refer to the model of potential Eq. (3-1) coming from a Lorentz vector type

*) Similar static potentials have been used by Henriques et al.[3] and H. Ito[8]. They chose the nonperturbative potential to be of Lorentz scalar, and used their screened potentials for the convenience of numerical convergence of their calculations.

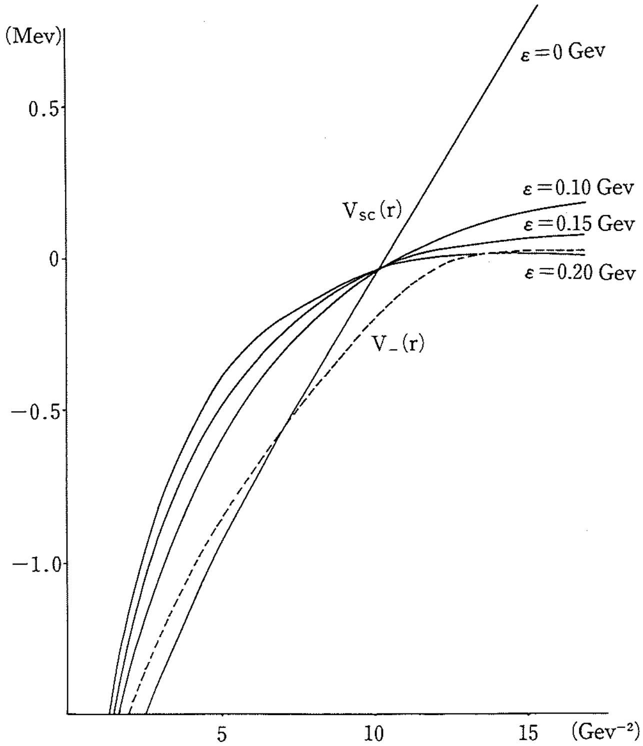

Fig. 1 Comparison of $V_{-}(r)$ and $V_{SC}(r)$ for Kogut & Susskind parametrization ($\lambda=0.16\ Gev^2$, $U=-1.6$ Gev, $\alpha_s=0.28$, $m=1.6$ Gev) with $\varepsilon=0.1$, 0.15 and 0.20 Gev.

of interaction as "A Screened Linear Potential Model".

Other screened potentials have been reported in the literature. Possio and Schnitzer[15] considered the screened effect on the vector part of the confining potential. Here the scalar part of the confining potential is assumed not to be screened. An example of a complete screened static potential is the one confirmed recently by a lattice calculation[16] of the SU(2) color gauge theory including dynamic quarks in the Monte Carlo simulation of the form:

$$V_{LC}(r)=\text{const.}-\frac{\alpha}{r}+\lambda\frac{1-e^{-\mu r}}{\mu}. \tag{3-3}$$

The spin dependent corrections to the Coulombic part of Eq. (3-1) appear from higher order nonrelativistic approximations by a reduction of the Bethe-Salpeter equation and are known to be expressed in terms of a static potential. The spin dependent contribution of the non -perturbative part is assumed to appear similarly and this is related to the static potential also depending on its Lorentz property.

We examined the spin structure of heavy quarkonia masses in terms of a Breit type Hamiltonian. For the spin splittings among L=1 states, this Hamiltonian will be sufficient for heavy quarkonia[6]. It is in general written as

$$H=\Sigma(m_i+\frac{\mathbf{P}_i^2}{m_i^2})+V(r)+\delta V(r)+A(\mathbf{r})\mathbf{L}\cdot\mathbf{S}+B(\mathbf{r})T_{12}+C(\mathbf{r})\mathbf{s}_1\cdot\mathbf{s}_2+D(\mathbf{r})(\mathbf{s}_1-\mathbf{s}_2)\cdot\mathbf{L} \tag{3-4}$$

Where V(r) is the static potential, $\delta V(r)$ is the leading order correction to V(r), T_{12} is the standard tensor operator, and A(**r**), B(**r**), C(**r**), D(**r**) are radial functions. For the self-conjugate mesons (quarkonium) which we deal with, D(**r**) is absent.

We may then write the radial functions as

$$\begin{aligned} A(\mathbf{r}) &= \frac{3}{2m^2}(\frac{U'(r)}{r}-\frac{S'(r)}{3r})+\delta_A \\ B(\mathbf{r}) &= \frac{1}{12m^2}(-U''(r)+\frac{U'(r)}{r})+\delta_B \\ C(\mathbf{r}) &= \frac{2}{3m^2}\nabla^2 U(r)+\delta_C \end{aligned} \tag{3-5}$$

with a general static potential V(r)=U(r)+S(r) where U(r) and S(r) are of Lorentz vector and Lorentz scalar nature respectively, and δ's are possible rediative contributions[13].

§ 4 Spin-dependent Forces

The radial functions for a screened linear potential model are given by substituting Eq. (3-2) into U(r) and putting S(r)=0 in Eq. (3-5). The expressions for them are:

$$\begin{aligned} A(\mathbf{r}) &= \frac{2}{m^2r^3}\alpha_s+\frac{3}{2m^2r}\{\lambda(1-\varepsilon r)-U\varepsilon\}e^{-\varepsilon r} \\ B(\mathbf{r}) &= \frac{1}{3m^2r^3}\alpha_s+\frac{1}{12m^2r}\{\lambda(1+\varepsilon r-\varepsilon^2r^2)-U\varepsilon(1+\varepsilon r)\}e^{-\varepsilon r} \\ C(\mathbf{r}) &= \frac{32\pi}{9m^2}\sigma(\mathbf{r})\alpha_s+\frac{2}{3m^2r}\{\lambda(2-4\varepsilon r+\varepsilon^2r^2)-U\varepsilon(2-\varepsilon r)\}e^{-\varepsilon r} \end{aligned} \tag{4-1}$$

And for the Scalar model:

$$\begin{aligned} A^s(\mathbf{r}) &= \frac{2}{m^2r^3}\alpha_s-\frac{1}{2m^2r}\lambda \\ B(\mathbf{r}) &= \frac{1}{3m^2r^3}\alpha_s \\ C^s(\mathbf{r}) &= \frac{32\pi}{9m^2}\sigma(\mathbf{r})\alpha_s \end{aligned} \tag{4-2}$$

For the evaluation of hyperfine and fine splittings of L=1 heavy quarkonium states, we treat the spin-dependent terms in the Hamiltonian, Eq. (3-4) as small perturbations. The unperturbed Hamiltonlam H_0 is spin independent as specified in § 5. From Eq. (3-4), a sum rule is derived for the mass of the L=1 states:

$$P_{cog}-{}^1P_1=\langle C(\mathbf{r})\rangle \tag{4-3}$$

$$^3P_2 - {}^3P_1 = 2\langle A\rangle - \frac{12}{5}\langle B\rangle \tag{4-4}$$

$$^3P_1 - {}^3P_0 = \langle A\rangle + 6\langle B\rangle \tag{4-5}$$

$$\underline{P} - {}^1P_1 = -\frac{4}{3}\langle A\rangle + 8\langle B\rangle + \langle C\rangle = -\frac{4}{3}\delta_A + 8\delta_B + \delta_C \tag{4-6}$$

Where $P_{cog} = \frac{5^3 P_2 + 3^3 P_1 + {}^3P_0}{9}$, $\underline{P} = \frac{-5^3 P_2 + 21^3 P_2 - 7^3 P_0}{9}$, and the bracket represents the expected value of the lowest L=1 eigenstate of H_0. The so called R ratio

$$R = ({}^3P_2 - {}^3P_2)/({}^3P_1 - {}^3P_0) \tag{4-7}$$

has been a controversial matter in the analysis of heavy quarkonium spin dependent mass splittings.

To obrerve the qualitative features of the screened confining potential, we examined expressions in the order $O(\varepsilon)$, neglecting radiative corrections δ's. The expressions for Eqs. (4-3)~(4-6) are given by

$$P_{cog} - {}^1P_1 \sim \frac{4}{3m^2}\{(\lambda - U\varepsilon)\langle\frac{1}{r}\rangle - 2\varepsilon\lambda\}. \tag{4-3'}$$

$$^3P_2 - {}^3P_1 \sim 2\langle A_0\rangle - \frac{12}{5}\langle B_0\rangle - \langle\Delta_1\rangle \tag{4-4'}$$

$$^3P_1 - {}^3P_0 \sim \langle A_0\rangle + 6\langle B_0\rangle - \langle\Delta_0\rangle, \tag{4-5'}$$

where $A_0(B_0)$ is A(B) of Eq. (3-3) when $\varepsilon=0$, and $\Delta_1 = (30\lambda r + 14U)/(5m^2 r)$, $\Delta_2 = (3\lambda r + 2U)/(m^2 r)$.

We understand from Eq. (4-3′) that while the spin-spin force is quite a lot larger than that implied by the data for an unscreened vector confining potential, it may be smaller in a screened confining potential where an appropriate value of ε has been set*⁾. For the scalar linear confining potential, it is zero for all quarkonia independent of quark flavor.

Of fine splittings, if the nonperturbative potential is Lorentz vector and linear ($\varepsilon=0$), it is difficult to fit the data. The predicted values are quite a lot larger than the data of fine splittings and the R ratio. In the present model $\langle\Delta_1\rangle$ and $\langle\Delta_2\rangle$ are positive for parameters used and $\langle\Delta_1\rangle$ is larger than $\langle\Delta_2\rangle$. By increaing ε above zero, we get smaller predictions for both fine splittings and R than for the case with $\varepsilon=0$, thus improving the results.

§ 5 Numerical estimates of spin dependent splittings

This section, examines the hyperfine and finecsplittings of heavy L=1 quarkonium states numerically, with first order perturbation theory. For the unperturbed Hamiltonian H_0 of Eq. (3-4), we set

*⁾ See Fig. 2 in § 5.

$$H_0=2m+\frac{p^2}{m^2}+\lambda r+U \tag{5-1}$$

and consider the rest of the Hamiltonian a perturbation. We can then write down the analytical expressions for the expectation values with a complete set of harmonic osilator functions*). The L=1 radial wave function of the above H^0 is excellently approximated, in terms of a single oscillator wave function by using a variational principle to select the optimal oscillator interaction strength. Thus we have approximate expressions[17] for the expected values of the 1P state

$$\langle\frac{1}{r}\rangle=\frac{8}{8}\{\frac{\lambda m}{15\pi^2}\}^{1/3} \tag{5-2}$$

$$\langle\frac{1}{r^3}\rangle=\frac{32}{45\pi}\lambda m.$$

which are neccesary to evaluate expected values of the radial functions of Eq. (4-1).

Two sets of parameters used here,[A]and[B], are shown in Table 1.

For contribution of the radiative corrections of radial funcoions are from Pantaleone and Tye's estimates which are tabulated in Table 2.

Table 1 Three sets of model parameters. The two values of m (and α_S) for each set are for the charm and bottom quarks. [A]and[B]are used for estimating the Vector model prediction, vhile[S][6] is for the Scalar model.

	λ (Gev²)	(U (Gev)	m (Gev)	α_S	ε (Gev)
[A]	0.33	0.0	1.4 4.7	0.42 0.38	0.19
[B]	0.36	0.0	1.4 4.7	0.36 0.32	0.19
[S]	0.153	0.0	1.484 4.865	0.53 0.49	

Table 2 Magnitude (in Mev) of radiative correction contribution for the radial functions used in ref. 13).

quark flavor	δ_A	δ_B	δ_C
charm	−18.0	2.5875	−3.6
bottom	− 8.311	−0.22	−0.4

*) Schnitzer[1] has obtained the expected value<1/r>for the L=0 state and Henriques[7] analyses ($t\bar{t}$) and ($t\bar{u}$) states using this method.

The numerical results to all orders of ε are shown in Table 3 togather with their data. To observe the screening effect of the non-perturbative part of the static potential, we plot $^3P_2-{}^3P_1$, $^3P_1-{}^3P_0$, $P_{cog}-{}^1P_1$ against ε for the parameter set[A]in Fig. 2.

For heavy quarkonia like charmonium and bottonium, the screening effect of the nonperturbative interaction is still effective as the confining interaction is effective. The screening

Table 3 Comparison between predictions with the model and data in Mev. Parameter sets[A]and[B]are used for the Vector model, while[S]is for the Scalar model.

		data	[A]	[B]	[S]
	$P_{cog}-{}^1P_1$	0.0±1.0	7.5	9.8	0
charm*)	$^3P_2-{}^3P_1$	45.6	40.6	37.2	51
	$^3P_1-{}^3P_0$	95.8	96.0	90.7	83
	$P_{cog}-{}^1P_1$	5.4±1.7	3.5	4.1	0
bottom**)	$^3P_2-{}^3P_1$	21.4	10.3	10.4	31
	$^3P_1-{}^3P_0$	32.1	20.4	20.2	41

*) Data due to R704 collaboration[18].
**) Data due to Bowcock et al.[19].

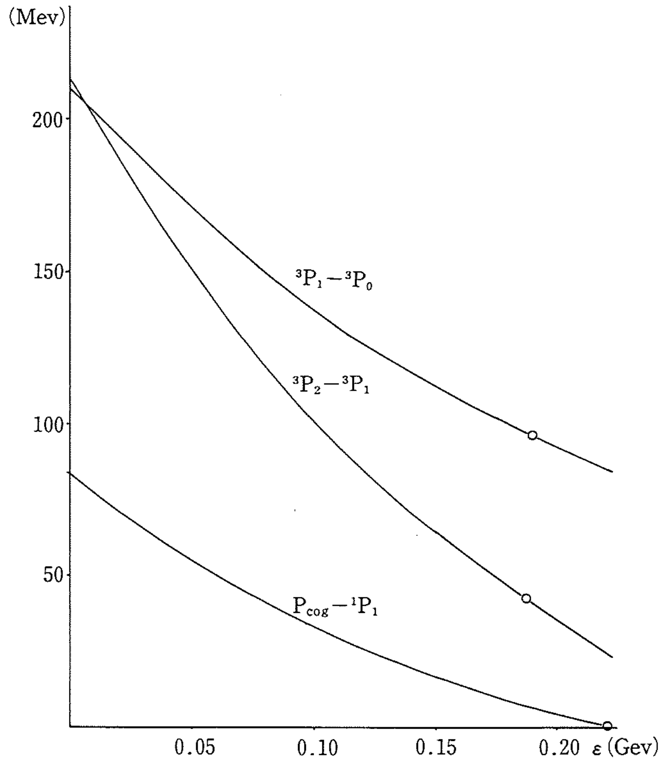

Fig. 2 The model predictions for $P_{cog}-{}^1P_1$, $^3P_2-{}^3P_1$ and $^3P_1-{}^3P_0$ against ε. The circles show the data.

effect becomes smaller as the quark mass gets larger. The role of the effect for the top quark will be smaller.

§ 6 Discussion and conclusion

We have shown that with appropriate parameter values the "Vector" model with a screened linear potential gives nearly as good predictions as the "Scalar" model, for hyperfine splittings and fine splittings of heavy quarkonia. A characteristic of the Scalar model is that the tensor and spin-spin forces coming from the nonperturbative interaction are negligible. This spin-orbit dominance of the nonperturbative component over the other spin dependent forces, is observed in lattice calculations[20] too, and this characteristic is realized in our Vector model either.

Another reason why the "Vector" model has been disregarded so far is the problem of the so-called Klein Paradox. In the present model, however, this does not exist, because the tunnelling solution at large distances is not for the quark-antiquark channel but for meson -antimeson channel.

It was pointed out that chiral symmetry breaking may successfully be described to be caused dynamically due to the linear potential, and if ε is reasonably small, the result is unlikely to change much when the screened linear potential is used. Based on this, we examined[14] the dynamic effects of the screened potential on heavy quarkonia. We found that it is small for heavy quarkonia like charmonium and bottomoniums, and so this article neglects the quark anomalous magnetic moment both for the one-gluon exchange part and for the non -perturbative part.

The Lorentz vector non-perturbative interaction model is restored by considering by the screening effect due to vacuum polarization of light quarks, and allows an understanding of the 1P spin structure of heavy quarkonia like charmonium and bottonium. The present model must be applied to other level splittings between different radial nodes of heavy quarkonia, like 2S-1S.

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