Possible effects of color screening and large string tension in heavy quarkonium spectra

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Possible effects of the color-screened confinement potential are investigated. A color-screened linear potential with a large string tension $T = (0.26\text{–}0.32)$ GeV^2 is suggested by a study of the $c\bar{c}$ and $b\bar{b}$ spectra. The $\psi(4160)$ and $\psi(4415)$ are, respectively, assigned as the $\psi(4S)$-dominated and the $\psi(5S)$ $c\bar{c}$ states. Satisfactory results for the masses and leptonic widths (with QCD radiative corrections) of $c\bar{c}$ and $b\bar{b}$ states are obtained.

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String tension is the most fundamental physical quantity in quark confinement. It is argued based on a rotating string picture that the string tension T is related to the Regge slope α' by [1]

$$T = \frac{1}{2\pi\alpha'} = 0.18 \text{ GeV}^2, \tag{1}$$

with the experimental value for $\alpha' = 0.9$ (GeV)$^{-2}$. This result is supported phenomenologically by the heavy quarkonium spectrum when identifying the string tension with the slope of the linear confinement potential between a heavy-quark–antiquark ($Q\overline{Q}$) pair [2]. Lattice QCD calculations for the string tension are not conclusive, because one needs to estimate the lattice scale Λ_L in physical units, even if one has obtained from lattice calculations the value for c which is related to T via

$$c = \frac{\Lambda_L}{\sqrt{T}}. \tag{2}$$

In Ref. [3] the string tension is estimated (though with some theoretical uncertainty) to be

$$T = (0.33^{+0.82}_{-0.23}) \text{ GeV}^2 \tag{3}$$

with typical values

$$c = (7.5 \pm 0.5) \times 10^{-2},$$
$$\Lambda_{\overline{\rm MS}} = (200^{+150}_{-80}) \text{ MeV}, \tag{4}$$

where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme, although this estimate has some uncertainties; e.g., the value of c is calculated in the quenched approximation while the experimental value of $\Lambda_{\overline{\rm MS}}$ is obtained with dynamical fermions [the more recent data give $\Lambda^{(5)}_{\overline{\rm MS}} = (195 + 65 - 50)$ MeV [4]]. The central value in Eq. (3) is significantly larger than that given in Eq. (1), but they may be still consistent with each other when the large error involved is reduced.

On the other hand, while the potential model, which assumes a linear confinement potential plus a one-gluon exchange potential, is generally successful for $c\bar{c}$ and $b\bar{b}$ spectroscopy, some problems may remain. One of them is concerned with the assignment of $\psi(4160)$ and $\psi(4415)$. With the linear confinement potential, $\psi(4160)$ and $\psi(4415)$ are usually assigned as the $2D$ and $4S$ states, respectively. However, experimentally the $\psi(4160)$ has a quite large leptonic width [4] $\Gamma_{ee} = 0.77 \pm 0.23$ keV, comparable to that for the $3S$ state $\psi(4040)$, but in the nonrelativistic limit the $2D$ state will be forbidden to decay to e^+e^-. Neither the S-D mixing nor the coupled channel models can consistently solve this problem [5]. Moreover, for $\psi(4415)$, with the linear potential the leptonic width of $4S$ state is usually predicted to be larger by more than a factor of 2 than the observed value of $\psi(4415)$, hence the assignment of $\psi(4415)$ as $4S$ state is also problematic. The way to solve this problem is probably to assign the $\psi(4160)$ and $\psi(4415)$ as the $4S$ and $5S$ states, respectively, but this must require the linear potential to be softened at large distances. In addition, with the linearly rising potential the calculated masses and leptonic widths for highly excited $b\bar{b}$ states (e.g., the $6S$ state) usually are also larger than their observed values. It is clear that for a pure linear potential all the wave functions (S wave) at origin take the same value. Therefore, if the $Q\bar{Q}$ potential keeps linearly rising at large distances the leptonic widths for highly excited states will gradually approach to a constant value when the linear potential becomes dominant over the short-ranged

Coulomb potential. However, the experimental data for both $c\bar{c}$ and $b\bar{b}$ do not show this tendency at all. On the contrary, as argued above the data strongly indicate a softening effect on the linear potential.

Indeed, it is expected (e.g., in the color flux tube picture for confinement) that at large distances the creation of a light quark pair will screen the static color sources of $Q\overline{Q}$, and will therefore flatten the linear potential [6]. Some recent lattice QCD calculations with dynamical fermions seem to indicate that the color-screening effects on the linear potential do exist at large distances [7].

By taking into account the color-screening effect, the $Q\overline{Q}$ potential may be modified and take the form

$$V(r) = -\frac{4\alpha_s}{3r} + Tr\left(\frac{1-e^{-\mu r}}{\mu r}\right), \tag{5}$$

where the first term on the right-hand side is the usual one gluon exchange Coulomb potential, and the second term is the screened confining potential with a screening parameter μ. The potential will keep linearly rising up to a distance $r \le \mu^{-1}[r \le (1-2)$ fm for $\mu = (0.2-0.1)$ GeV] and then gradually become flattened and eventually reach a constant value $\frac{T}{\mu}$.

Since the presence of the Cornell potential [8], many improved potentials have been suggested. In particular, the running coupling constant α_s (see, e.g., Ref. [9]) and one loop QCD radiative corrections [10] have been successfully incorporated into the $Q\bar{Q}$ potential. On the other hand, however, the understanding of the confining potential is still poor, though some phenomenological confining potentials have been considered to improve the fit to the heavy quarkonium spectra including that of the higher lying states [11,12]. Since color confinement is the most important part of dynamics in hadron physics, it is necessary to have further studies regarding the confining potential together with the $Q\bar{Q}$ spectroscopy. In this connection the screened confining potential expressed in (5), i.e., $V_{\rm sc}(r) = Tr(\frac{1-e^{-\mu r}}{\mu r})$ may differ from many other phenomenological potentials (e.g., various power law potentials, see Refs. [11,12] and references therein) in the following respects.

(i) It is indicated by some lattice QCD calculations with dynamical fermions (see, e.g., Ref. [7]).

(ii) It keeps linearly rising up to about 1 fm and then gradualy becomes a constant at large distances, and therefore it incorporates the large distance asymptotic behavior of color screening into the linear confinement in a natural manner. This is well motivated theoretically.

(iii) As noted previously [13], the inclusion of color screening is connected to the removal of the infrared divergences of the $Q\bar{Q}$ interaction kernel in the momentum space. In fact, in momentum space the screened confining potential reads [13]

$$V_{\rm sc}(\mathbf{p}) = -\frac{T}{\mu}\delta^3(\mathbf{p}) + \frac{T}{\pi^2}\frac{1}{(\mathbf{p}^2+\mu^2)^2}. \tag{6}$$

In view of the regularization of the linear potential in momentum space, the form of (6) and hence (5) seem to be quite natural and unique. The nonvanishing value of the cutoff μ is expected to be related to the polarization of dynamical light quark pairs.

Although the exact form of confinement interaction has not been analytically derived from the first principles of QCD, we believe that the screened confining potential $V_{\rm sc}$ expressed in (5) should be a better candidate for describing confinement than many other potentials. Potential (5) may have phenomenological implications and it has been used in the study of heavy flavor mesons [13]. It will be interesting to have further phenomenological investigations regarding this potential.

In the following we will use potential (5) to calculate the $c\bar{c}$ and $b\bar{b}$ mass spectra, and then find the possible phenomenological values for the string tension T. As the first trial in a previous paper [14], we used

$$\begin{aligned} &T = 0.21\ \text{GeV}^2,\ \alpha_s = 0.51, \\ &\mu = 0.11\ \text{GeV},\ m_c = 1.4\ \text{GeV}, \end{aligned} \tag{7}$$

as inputed parameters to solve the nonrelativistic Schrödinger equation with potential (5). The obtained mass spectrum is satisfactory with $\psi(4160)$ and $\psi(4415)$ assigned as $\psi(4S)$ and $\psi(5S)$, respectively. However, there are two problems for (7). The first one is that with the same value for T and μ and a smaller value for α_s, we cannot find good result for the $b\bar{b}$ mass spectrum. The second is that the value of α_s in (7) seems too large, not compatible with the present value of QCD scale parameter (see below).

We now find that with

$$\begin{aligned} &T = 0.32\ \text{GeV}^2,\ \alpha_s = 0.306, \\ &\mu = 0.156\ \text{GeV},\ m_c = 1.6\ \text{GeV} \end{aligned} \tag{8}$$

for $c\bar{c}$, and

$$\begin{aligned} &T = 0.32\ \text{GeV}^2,\ \alpha_s = 0.275, \\ &\mu = 0.132\ \text{GeV},\ m_b = 4.8\ \text{GeV} \end{aligned} \tag{9}$$

for $b\bar{b}$, as the the parameters in potential (5) to solve the Schrödinger equation, good results for both $c\bar{c}$ and $b\bar{b}$ can be obtained. The calculated masses and leptonic widths for $c\bar{c}$ states are shown in Table I, and for $b\bar{b}$ states in Table II. The experimental data are given by the Particle Data Group [4]. The leptonic widths are calculated using the nonrelativistic expressions without QCD radiative corrections (Γ^0_{ee}) and with QCD radiative corrections (Γ_{ee})(see, e.g., Refs. [8,15,16])

$$\Gamma^0_{ee} = 16\pi\alpha^2 e_Q^2 \frac{|\Psi(0)|^2}{M^2}, \tag{10}$$

$$\Gamma_{ee} = \Gamma^0_{ee}\left(1 - \frac{16}{3\pi}\alpha_s(m_Q)\right), \tag{11}$$

where $\alpha_s(m_Q)$ stands for the coupling constant at the heavy quark mass scale, and it can be determined in the timelike processes of heavy quarkonium decays. Here we use $\alpha_s(m_c) = 0.28$ for $c\bar{c}$ and $\alpha_s(m_b) = 0.19$ for $b\bar{b}$ [16]. These values of the running coupling constant are consistent with the QCD scale parameter $\Lambda_{\overline{\rm MS}} \approx 200$ MeV [16].

From Table I we can see that the $\psi(4160)$ and $\psi(4415)$ are assigned as the $4S$ and $5S$ states. The predicted leptonic widths for these two states are in excellent agreement with data, whereas in the usual potential mod-

TABLE I. Calculated masses and leptonic widths for charmonium states with the screened potential (5) and parameters (8), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_c)]$ with $\alpha_s(m_c) = 0.28$ [16].

States	Mass (MeV)	Γ^0_{ee} (keV)	Γ_{ee} (keV)	$\Gamma^{\text{expt}}_{ee}$ (keV)	Candidate
$1S$	3097	10.18	5.34	5.26 ± 0.37	$\psi(3097)$
$2S$	3686	4.13	2.17	2.14 ± 0.21	$\psi(3686)$
$3S$	4033	2.35	1.23	0.75 ± 0.15	$\psi(4040)$
$4S$	4262	1.46	0.77	0.77 ± 0.23	$\psi(4160)$
$5S$	4415	0.91	0.48	0.47 ± 0.10	$\psi(4415)$
$1P$	3526				$\chi(3526)_{\text{c.o.g.}}$
$1D$	3805				$\psi(3770)$
$2D$	4105				

els without the color-screening effects the $\psi(4160)$ and $\psi(4415)$ are assigned as $2D$ and $4S$ states and then $\psi(4160)$ would have a zero leptonic width (in the nonrelativistic limit) and $\psi(4415)$ would have a leptonic width of, say 1.1 keV [8], too large by more than a factor of 2 than the observed value (0.47 ± 0.10) keV. As for the mass of the $4S$ state, the predicted value is higher than $\psi(4160)$ by 100 MeV, and this could be due to the neglect of S-D mixing and coupled channel effects. In any case, if $\psi(4415)$ is the $5S$ state, the $\psi(4160)$ must be a $4S$-dominated state with possibly some mixed components of $2D$ and virtual charmed meson pairs. It might be interesting to note that in these assignments the $c\bar{c}$ would have an anomalous mass relation that $m(4S)$-$m(3S)$ is smaller than $m(5S)$-$m(4S)$. Exactly the same anomalous mass relation is also observed for the $b\bar{b}$ states [4]. These anomalous mass relations may imply that in the energy region just above thresholds of many opened channels (e.g., in $3.8 - 4.3$ GeV for $c\bar{c}$) the masses of resonances can be significantly distorted. Of course, in explaining these difficulties there could be other possibilities such as the $c\bar{c}q\bar{q}$ states [17] or $c\bar{c}g$ states [18]. However, these states in general do not seem to have large enough leptonic widths to be the $\psi(4160)$, because their couplings to the photon are expected to be suppressed. In Table I the predicted mass for $\psi(3S)$ is now 4.03 GeV, much closer to its observed value than 4.11 GeV [8] predicted by usual potential models. Moreover, in Table I the predicted leptonic widths for $\psi(1S)$ and $\psi(2S)$ also agree with data.

From Table II we see that in general the calculated masses and leptonic widths for the $b\bar{b}$ states are also in good agreement with data. As a result, using potential (5) with parameters (8) and (9), the obtained $c\bar{c}$ and $b\bar{b}$ spectra are remarkably improved.

We have also tried to fit the spin-averaged mass spectrum using potential (5). Here the spin-averaged masses for the S wave states mean the masses before hyperfine splittings, e.g., for $c\bar{c}$ $m(1S) = \frac{1}{4}[3m(J/\psi) + m(\eta_c)]$. For other S wave states, because of the lack of observed values for the 0^- mesons, we use calculated hyperfine splittings [see (12)] and observed 1^- meson masses to determine the spin-averaged masses. We find that with slightly adjusted parameters (e.g., a slightly smaller string tension and a slightly larger α_s) we can get good fit for the spin-averaged $c\bar{c}$ mass spectrum and leptonic widths. Again, the assignments of $\psi(4160)$ and $\psi(4415)$ as the $4S$ and $5S$ $c\bar{c}$ states seem to require a screened confining potential with a large string tension.

We have also used a modified Coulomb potential [with a running coupling constant $\alpha_s(r)$] and the screened confining potential to fit the heavy quarkonium spectra, and the obtained results are similar to that obtained with the fixed coupling constant α_s. Namely, a large string tension with color screening is still needed if a good fit for the higher excited states is required. In another words, taking a running α_s does not change the basic feature of our observation on the screened string tension, though a slightly smaller value, say $T = (0.28 - 0.30)$ GeV^2 is found.

These studies might indicate that the color screened quasiconfinement potential with a large string tension, say, $T = (0.26$–$0.32)$ GeV^2 should be an interesting possibility.

The following observations might be in order.

(1) In order to get better results for higher excited $Q\bar{Q}$

TABLE II. Calculated masses and leptonic widths for bottomonium states with the screened potential (5) and parameters (9), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_b)]$ with $\alpha_s(m_b) = 0.19$ [16].

States	Mass (MeV)	Γ^0_{ee} (keV)	Γ_{ee} (keV)	$\Gamma^{\text{expt}}_{ee}$ (keV)	Candidate
$1S$	9460	1.94	1.31	1.32 ± 0.03	$\Upsilon(9460)$
$2S$	10023	0.90	0.61	0.58 ± 0.10	$\Upsilon(10023)$
$3S$	10368	0.62	0.42	0.47 ± 0.06	$\Upsilon(10355)$
$4S$	10627	0.47	0.32	0.24 ± 0.05	$\Upsilon(10580)$
$5S$	10833	0.37	0.25	0.31 ± 0.07	$\Upsilon(10860)$
$6S$	11002	0.30	0.20	0.13 ± 0.03	$\Upsilon(11020)$
$1P$	9894				$\chi_b(9900)_{\text{c.o.g.}}$
$2P$	10267				$\chi_b(10261)_{\text{c.o.g.}}$
$1D$	10152				
$2D$	10451				

states [e.g., $\psi(4160)$ and $\psi(4415)$], a screened confining potential plus a Coulomb potential (with fixed or running α_s) seem to work well, whereas the unscreened linear potential gives too large level spacings and leptonic widths. While a large α_s with a normal string tension [e.g., as shown in (7)] is possible, a smaller α_s, which is more consistent with the value of QCD scale parameter, with a larger string tension [e.g., as shown in (8) and (9)] seem to work better for both $c\bar{c}$ and $b\bar{b}$ states. (Note that the value of α_s in (5) is at the scale of the inverse of the $Q\bar{Q}$ meson's size.) The screening parameter μ is found to be (0.14 ± 0.03) GeV. This value is consistent with lattice QCD calculations [7].

(2) In our calculation we have simply focused on the spin-independent solutions of the Schrödinger equation including the mass spectra and the leptonic widths, and ignored the coupled channel effects and relativistic corrections. In fact, the coupled channel effects (see, e.g., Refs. [5,8]) and the relativistic corrections (see, e.g., Refs. [15,19–22]) within the linear potential model seem to be unable to solve the puzzle regarding $\psi(4160)$ and $\psi(4415)$, as well as some other highly excited states. For instance, in the linear confinement model of Ref. [21], with relativistic corrections the masses are found to be (in units of MeV) 3097, 3527, 3681, 3846, 4108, and 4446, for $1S$, $1P$, $2S$, $1D$, $3S$, and $4S$ $c\bar{c}$ states, respectively. We see that although relativistic corrections for $c\bar{c}$ are important (the energy shifts due to relativistic corrections ranging from -61 MeV to -219 MeV from $1S$ to $4S$ states), the energy spacings with relativistic corrections can be very similar to that obtained without relativistic corrections, e.g., in the Cornell model [8] (the model in Ref. [21] will of course have different parameters from that in Ref. [8]). This may imply that as far as the energy spacings are concerned the relativistic effects may be largely absorbed by the readjustment of potential parameters (e.g., the value of string tension takes $T = 0.22$ GeV^2 in Ref. [21] while $T = 0.18$ GeV^2 in Ref. [8]) and therefore the relativistic effects appear to be small in practice. Although this result is seen specifically in the model of Ref. [21], the conclusion here can be quite general and similar observations have also been made by other authors (see, e.g., Ref. [22]). Hence the relativistic corrections with unscreened confining potential are expected to be not very helpful in solving the difficulties associated with, e.g., $\psi(4160)$ and $\psi(4415)$. So it is very likely that in order to improve the fit to the higher excited states the screened confining potential is still needed even with these coupled channel and relativistic effects taken into consideration.

(3) We have tried to calculate the spin-dependent splittings of these heavy quarkonium states in a very simple version. If the spin-spin force is entirely due to the lowest-order perturbative one-gluon exchange, the 0^-–1^- meson mass splitting Δ will be given by

$$\Delta = \frac{32\pi\alpha_s}{9m_Q^2}\,|\Psi(0)|^2\,. \tag{12}$$

Then for the J/ψ and η_c, with $\alpha_s = 0.306, m_c = 1.6$ GeV as given in (8), and the Schrödinger wave functions obtained by using (8), we get a mass spliting $\Delta = 110$ MeV, slightly smaller than its experimental value (118 ± 2) MeV. As for the fine splittings the situation is more complicated, since the long-range nonperturbative forces may contribute. It is argued [23] based on a consistent condition due to Lorentz invariance that the confining potential should transform as a Lorentz scalar and therefore induce a spin-orbit term which then compensates the short-ranged spin-orbit force caused by one-gluon exchange. On the other hand, in many studies regarding chiral symmetry breaking, in order to preserve chiral invariance the vector (or at least the time component of a four-vector) confining force has to be chosen [24]. In the phenomenological studies of heavy quarkonium spectra (see, e.g., Refs. [15,19,20,21,25,26]), though the scalar confining is favored, a vector-scalar mixture for the confining potential may work even better. For instance, the vector-scalar mixed confining potential in some models can give an excellent fit to the low-lying $c\bar{c}$ and $b\bar{b}$ spectra [25]. It is also argued that the observed tiny mass difference (about -0.9 MeV) [4] between the center of gravity of triplet $1P$ and the singlet $1P$ charmonium states may not necessarily mean the short-ranged perturbative hyperfine splitting is dominant because nonperturbative and other effects could be also important [25,26]. Although there are uncertainties for the spin-dependent splittings and the Lorentz-transformed structure of the confining potential especially the color screened quasi-confining potential, we believe it should be dominated by the scalar with possibly a small mixture of the vector component. We find for the P-wave mass splittings, if the screened confining potential is a pure scalar, then with (5), (8), and (9) the obtained splittings are too small. If it is a vector-scalar mixture with a weight factor being about 3:7 then a fairly good fit can be obtained. However, we would like to emphasize that to calculate the spin-dependent splittings the naive calculation given here with a Coulomb potential of fixed α_s in (5) with (8) and (9) should not be a good one, and a more refined calculation with higher-order perturbative corrections and nonperturbative effects is apparently better. Therefore our calculation for the spin-dependent splittings is not conclusive, and we will leave this to a more refined work.

To conclude, by studying the heavy quarkonium spectra especially for the higher excited states, e.g., $\psi(4160)$, $\psi(4415)$, and $\Upsilon(11020)$, we find some evidence for the color-screened confining potential, which is expected theoretically when the creation of dynamical light quark pairs at large distances is taken into consideration. A large string tension, say $T = (0.26$–$0.32)$ GeV^2, is favored by an overall fit to the mass spectra and leptonic widths. The existing calculations with the coupled channel effects and relativistic corrections based on the unscreened linear potential model seem to be unable to solve the difficulties associated with those higher excited states. Therefore the color-screened linear confining potential with a large string tension should be an interesting possibility and deserves further investigations.

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