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Abstract: We review masses and leptonic decay widths of all $^3S_1$ bound states below the strong decay threshold for $32 \leqslant 2m_Q \leqslant 60$ GeV, in a potential model which incorporates the QCD scaling violations to the short distance Coulomb potential between heavy quarks.

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I. INTRODUCTORY SURVEY.

In their classical paper, Appelquist and Politzer [1)] described the J/ψ [2)] as a $c\bar{c}$ system bound by a one-gluon exchange potential, $V(R) = -4/3\alpha_s/R$. After the discovery of ψ' [3)] it became clear that charmonium is not a Coulombic system. Eichten, Gottfried, Kinoshita, Lane and Yan [4)] proposed the 'standard charmonium model' by adding a constant confinement force at large distances, $V(R) = -4/3\alpha_s/R + a\cdot R$. They successfully fitted and predicted the gross features of the spectrum, leptonic and radiative widths in charmonium. Eichten and Gottfried [5)] extrapolated this model up to $2m_Q = 12$ GeV. The discovery of the Υ family around 10 GeV at FNAL [6)] showed that the predicted energy levels were too close. Quigg and Rosner [7)] subsequently proposed a simple potential model which has the special property of quark mass independent level spacings, $V(R) = b\cdot\log(R/c)$. However, the more precise measurement of $M_{\Upsilon'} - M_\Upsilon$ at DORIS [8,9)] showed that $M_{\Upsilon'} - M_\Upsilon < M_{\psi'} - M_{J/\psi}$. Furthermore, the leptonic decay widths of $^3S_1$ states, calculated according to the nonrelativistic quark model formula of Matveev, Struminskii and Tavkhelidze [10)]

$$W(V \to e^+ + e^-) = \frac{16\pi}{3m_V^2}\cdot Q_V^2\cdot \alpha^2 \left|\psi(0)\right|^2 \tag{1}$$

$(W = \Gamma,\ m_V = M)$,

decrease in the log potential like $\Gamma \propto Q_V^2\cdot M^{-1/2}$, unlike the experimental observation [8,9,11)] : $\Gamma(\Upsilon \to e^+e^-) \approx 1/4\, \Gamma(J/\psi \to e^+e^-)$.

A more refined model, proposed by Bhanot and Rudaz [12)], uses the $b\cdot\log(R/c)$ term at intermediate distances only in order to interpolate between the short distance Coulomb and the long distance linear potential, and predicted the $\Upsilon' - \Upsilon$ mass difference successfully [8,9)].

This intermediate potential region (between 0.2 and 0.8 fm) is the most important one for charmonium and bottonium. The exact form of the potential in this region cannot be 'derived' from QCD but must remain subject to guesses and/or fits.

For shorter distances or systems heavier than bottonium respectively one may 'derive' a potential from QCD, incorporating the scaling violations to the Coulomb potential as suggested by asymptotic freedom [13] :

$$V(R) \overset{R\to 0}{=} -8\pi/25(R\cdot\log(\mu/R))^{-1} \qquad (2)$$

Such a softened short distance Coulomb potential has been considered by Celmaster, Georgi and Machacek [14], Billoire and Morel [15], Richardson [16], Rafelski and Viollier [17], and has been added to the successful potential of Bhanot and Rudaz by two of us [18] in order to study quarkonia up to $2m_Q \approx 200$ GeV. It was found that for $2m_Q \gtrsim 25$ GeV drastic differences to models without asymptotic freedom [4,12] start to show up. The 1^3S_1 ground state in those models becomes purely Coulombic: $E(1S) = -(4/3\alpha_s)^2 m_Q/4$, $\Gamma_{e^+e^-}(1^3S_1) = \alpha^2 \cdot e_Q^2 \cdot (4/3\alpha_s)^3 m_Q/2$, $(\alpha_s = 0.3 - 0.4)$. For the 'softened' singularity, on the other hand, the mysterious regularity, first pointed out by Yennie [19], : $2\Gamma^{\rho}_{e^+e^-} \approx 9\Gamma^{\phi}_{e^+e^-} \approx 9/4\Gamma^{J/\psi}_{e^+e^-} \overset{!}{\approx} 9\Gamma^{\Upsilon}_{e^+e^-}$ continues to hold, $\overset{!}{\approx} e_Q^{-2}\Gamma^{Q\bar{Q}}_{e^+e^-}(1^3S_1)$, up to $2m_Q \approx 60$ GeV. One of us [20] has shown that the validity of this relationship at low masses is eventually understandable in potential models, too.

We want to stress here that the 'softness' of the potential singularity, governed by the parameter μ in eq. (2), which is of the order of 0.5 fm, can only be precisely determined from toponium. The guess $\mu = 0.5$ fm, using the charmonium fine structure and deep inelastic scattering as input, is not as strong as one would wish (turning the argument around, is saying, that measuring $t\bar{t}$ level differences will tell us a lot about the QCD scale parameter). Throughout this paper, however, we will use $\mu = 0.5$ fm as in ref. 18. Moreover, once non-perturbative gluonic degrees of freedom are taken into consideration, they ultimately can never be absorbed into an 'interaction potential' between quarks, as discussed by Voloshin [21].

There are now new data on bottonium, especially Υ'', from CESR [22,23]. Υ''' seems to lie already above the strong decay threshold [24]. This nicely confirms the original prediction of three narrow $^3S_1$ states below threshold [5]. That this is a rather model independent statement was shown by Quigg and Rosner [25].

The nodes in the wave function of radially excited states strongly influence the Zweig allowed decay widths [26]. This effect and $^3S_1 - {}^3D_1$ mixing have been studied in detail for charmonium by Eichten, Gottfried, Kinoshita, Lane and Yan [27]. Based on the quark pair creation model of Le Yaouanc, Oliver, Pène and Raynal [28], a similar investigation for bottonium has been made by one of us [29]. Again the results are very sensitive to the exact locations of the various thresholds. The experimental situation of the node structure is, however, not yet clear, even for charmonium.

A top quark t should exist, as proposed by Kobayashi and Maskawa [30], and required as the weak isospin partner of b. The predictions of its mass are not very unique: $2m_t$(in GeV) = 20-22 [31], 22 [32], 23.8 [33], 26 [32], 26-28 [34], 27.2 [35], 28 [36], 28 [37], 37.6±2.0 [38], 40±5 [39], 40 [40], 40 [41], 42 [42], 44 [35], 52 [43], 54 [44], 54 [45], 70 [40], 80 [46], 100 [32], 150 [37].....

Some of the numbers are based on the same formula, but differ by the numerical input. In a recent paper [47] the 'running masses' of u, d, s, c and b quarks have been estimated and used in formulae which were proposed previously to determine m_t. As a result of this numerical analysis, the toponium tends to become of lower mass than estimated in original papers [45,43]. The present limit for the 1^3S_1 ground state of toponium is $M_{t\bar{t}} > 31.46$ GeV. It results from the energy scan performed at PETRA [48] between 29.90 and 31.46 GeV, where an upper limit for $\Gamma_{e^+e^-}$ has been obtained and where the average value$\langle R \rangle$ is consistent with the u, d, s, c and b flavors only.

In this paper we shall compare the model of ref. 18 with the presently known properties of bottonium, in the next section. As mentioned before, the model has been extrapolated already to large quark masses: energy levels up to 4S, 3D, $^3S_1$ leptonic decay widths, ^3P fine structure and 1S hyperfine structure. Here we persue a simple pragmatic point of view: we concentrate on those bound state properties which are measured most directly in an e^+e^- storage ring experiment: i) the masses of the $^3S_1$ states by energy scan and ii) their e^+e^- decay width by integrating the resonance cross section: $\int_{res} \sigma(e^+e^- \to res \to all)dM = 6\pi^2 \Gamma_{e^+e^-}/M^2$. Much in the spirit of ref. 5 we do this for all states up to the threshold. The range considered will be $32 \lesssim 2m_Q \lesssim 60$ GeV. Finally we shall consider the correction of eq. (1) due to the Z^o boson of the Salam-Weinberg theory. It is relevant for quarks with charge $e_Q = -1/3$ and is of the order of $\lessdot 40\%$ at $2m_Q = 60$ GeV.

II. BOTTONIUM.

The masses of $\Upsilon, \Upsilon', \Upsilon''$ and the leptonic decay widths have been determined by various experiments. In table I we summarize these informations and compare them with the model predictions. The input for the model is charmonium, for historical reasons. $m_b = 4.5$ GeV is used, in accord with the estimate by Bertlmann and Martin [49], $m_b - m_c = 3.4$ GeV, while $M_\Upsilon = 9.46$ GeV.

Experiment	Data	Model	Data	Model	Data	Model	Model
	$M_{\Upsilon'} - M_\Upsilon$ [MeV]		$\Gamma^\Upsilon_{e^+e^-}$ [keV]		$\Gamma^{\Upsilon'}_{e^+e^-}/\Gamma^\Upsilon_{e^+e^-}$		$R_i \equiv \frac{9\pi}{2\alpha^2} \cdot \frac{\Gamma_{e^+e^-}(M_i)}{M_{i+1} - M_i}$
PLUTO [11]	-		1.3 ± 0.4		-		
DASP II [8]	555 ± 11		1.3 ± 0.4		0.23 ± 0.08		
DESY-Heidelberg II [9]	560 ± 10	555	$1.04 \pm 0.28 \times \frac{1}{B_h}$	1.04	0.31 ± 0.09	0.45	0.55
CLEO [22]	$560.7 \pm 0.8 \pm 3$				$0.44 \pm 0.06 \pm 0.04$		
CUSB [23]	$559 \pm 1 \pm 3$				0.39 ± 0.06		
	$M_{\Upsilon''} - M_\Upsilon$ [MeV]				$\Gamma^{\Upsilon''}_{e^+e^-}/\Gamma^\Upsilon_{e^+e^-}$		
CLEO [22]	$891.1 \pm 0.7 \pm 3$				$0.35 \pm 0.04 \pm 0.03$		
CUSB [23]	$889 \pm 1 \pm 5$	868			0.32 ± 0.04	0.31	0.44
	$M_{\Upsilon'''} - M_\Upsilon$ [MeV]						
		1115				0.27	0.38

Table I: Comparison of experimental mass differences and leptonic decay widths with the model [18]. Model input is charmonium (compare text).

The discrepancy between experimental mass differences and model numbers might be gauged away by fine tuning the potential parameters. That we have not done because it does not affect the scaling behaviour and therefore would give us no new insights. It should be done, however, if the location of the P states is found and $\Gamma^T_{e^+e^-}$ is known with better accuracy. At this point we would like to mention that a low value for $\Gamma^T_{e^+e^-}$ is also favourable in the analysis by Voloshin. [50)]

In the last column of table I we also give the 'smoothened' step in R,

$R \equiv \frac{1}{\Delta M} \int_{res} \sigma(e^+e^- \rightarrow res)dM/\sigma^{QED}_{e^+e^-\rightarrow\mu^+\mu^-}(q^2 = M^2_{res})$, where the interval ΔM has been chosen to be the mass difference of two neighbouring resonances, for simplicity. Within the errors, R_{model} coincides with R_{exp}. It is seen that R approaches to $3(-1/3)^2$ from above.

III. MASSES AND LEPTONIC DECAY WIDTHS OF $^3S_1$ STATES BELOW THRESHOLD.

The potential model [18)] is defined as

$$V(R) = \begin{cases} -\frac{8\pi}{25}\frac{1}{R\cdot\log(\mu/R)} + c_1 & R < R_1 \\ b\cdot\log(R/c) \quad ; & R_1 \leq R \leq R_2 \\ a\cdot R & R_2 < R \end{cases} \quad (3)$$

where $\mu = 0.5$ fm, $a = 0.787$ GeV/fm. R_2 and b are such that V(R) is continuously differentiable at R_2 with $c = \sqrt{4/3\cdot 0.31/a}$ as determined in the model ref.12, while R_1 and c_1 are such that V(R) is continuously differentiable at R_1: $R_1 = 0.07192$ fm, $R_2 = c\cdot\exp(1) = 0.8745$ fm, $b = a\cdot R_2/c$.

In figure 1 we have plotted the S wave binding energies up to the threshold. The threshold energy $E_{Q\bar{Q}}(\text{threshold}) = 2m_q + 2E_{Q\bar{q}}(1S)$ is essentially independent of m_Q since $E_{Q\bar{q}}(\mu_{reduced}) \approx E_{Q\bar{q}}(m_q)$. Thus it is fixed already by

charmonium and bottonium.

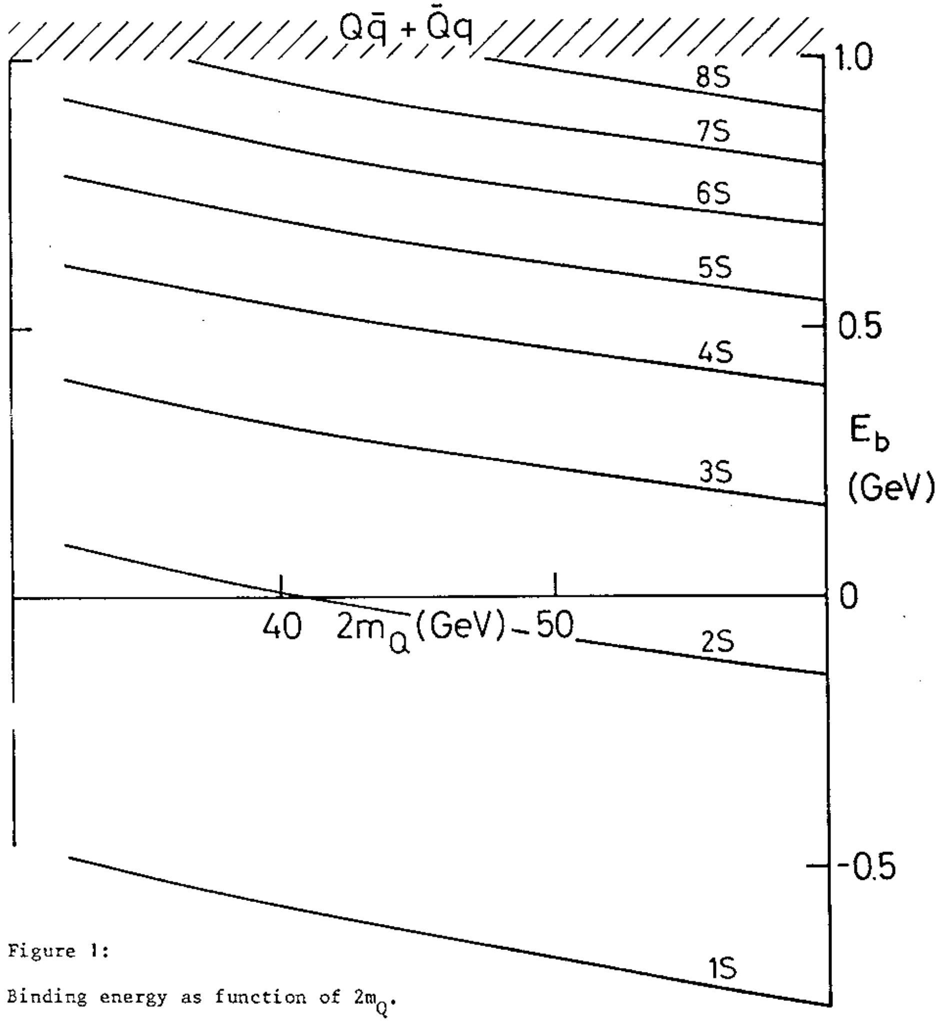

Figure 1:

Binding energy as function of $2m_Q$.

From the figure it is seen that the spacings are essentially independent of m_Q, but with increasing m_Q the states fall deeper into the potential well. The number N of bound states below threshold checks with the WKB approximation [25)]: $N \approx 1/4 + \text{const}\ m_Q^{1/2}$. The mass of a bound state is obtained by

$$M_{Q\bar{Q}}(nS) = 2m_Q + E_b(nS) \qquad (4)$$

Figure 2 shows the leptonic decay widths for the states below threshold, using the nonrelativistic, uncorrected formula (1). Again there is only a rather weak m_Q dependence.

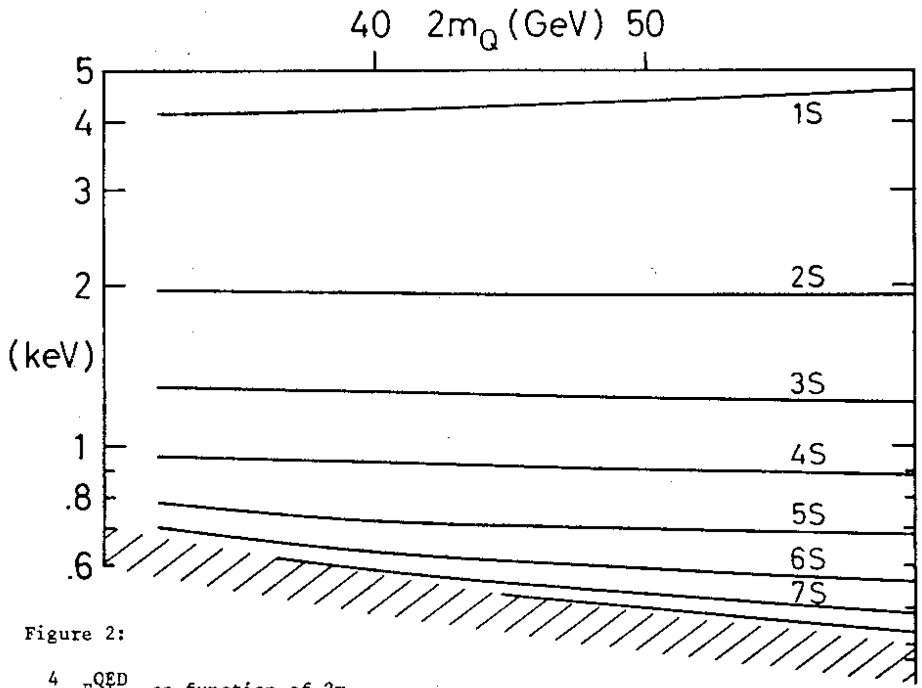

Figure 2:

$\frac{4}{9e_Q^2} \cdot \Gamma^{QED}_{e^+e^-}$ as function of $2m_Q$.

If we apply the smoothening procedure

$$R_i \equiv \frac{9\pi}{2\alpha^2} \frac{\Gamma^{M_i}_{e^+e^-}}{M_{i+1} - M_i} \equiv 3 \cdot e_Q^2 \cdot c_i \qquad (5)$$

we obtain around $2m_Q = 36$ GeV, where there should be already 6 states below threshold, for the coefficients c_i : $c_1=1.30$, $c_2=1.25$, $c_3=1.19$, $c_4=1.13$, $c_5=1.07$, $c_6=1.0$. These numbers might be relevant for a toponium scan, if it

starts above the prominent low lying resonance.

Sofar we have neglected the effect of the Z^o boson of the Salam-Weinberg theory. We incorporate it via

$$\Gamma^{S.W.\ s \neq M_{Z^o}^2}_{e^+e^-} \Rightarrow \Gamma^{QED}_{e^+e^-} \left[1 - \frac{2 \cdot v_e \cdot v_Q}{e_Q \cdot 4 \cdot \sin^2 2\theta} \cdot \frac{s}{s - M_{Z^o}^2} + \frac{(v_e^2 + a_e^2) \cdot v_Q^2}{e_Q^2 (4 \sin^2 2\theta)^2} \cdot \frac{s^2}{(s - M_{Z^o}^2)^2} \right]$$

where

$v_e = -1 + 4 \cdot \sin^2\theta$, $v_{e_Q=-1/3} = -1 + 4/3 \cdot \sin^2\theta$, $v_{e_Q=2/3} = 1 - 8/3 \cdot \sin^2\theta$,

$a_e = -1$, $M_{Z^o} \approx 74.8$ GeV/sin2θ.

The correction is important at large $s \approx (2m_Q)^2$ and for $e_Q = -1/3$. At $s = (60\ \text{GeV})^2$ and for $e_Q = -1/3$ it is: $[\ ] = 1.28 \pm 0.05$ for $\sin^2\theta = 0.23 \pm 0.01$.

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