BOTTOMONIUM VECTOR RESONANCES AND THRESHOLD EFFECTS*

Eef van Beveren†

Centro de Física da UC, Departamento de Física, Universidade de Coimbra
3004-516 Coimbra, Portugal

George Rupp

Centro de Física e Engenharia de Materiais Avançados
Instituto Superior Técnico, Universidade de Lisboa, 1000-043 Lisboa, Portugal

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The bottomonium spectrum is the perfect testing ground for the confining potential and unitarisation effects. The bottom quark is about three times heavier than the charm quark, so that $b\bar{b}$ systems probe primarily the short-range part of that potential. Also, the much smaller colour-hyperfine interaction in the B mesons makes the $B\bar{B}$ threshold lie significantly higher than the $D\bar{D}$ threshold in charmonium, on a relative scale of course. A further complicating circumstance is that none of the experimentally observed vector $b\bar{b}$ mesons has been positively identified as a ${}^3D_1$ state, contrary to the situation in charmonium. This makes definite conclusions about level splittings very problematic. Finally, there are compelling indications that the $\Upsilon(10580)$ is not the $\Upsilon(4S)$ state, as is generally assumed. Here, we review an analysis of experimental bottomonium data which show indications of the two lowest and so far unlisted ${}^3D_1$ states below the $B\bar{B}$ threshold. Next, an empirical modelling of vector $b\bar{b}$ resonances above the open-bottom threshold is revisited, based on the Resonance-Spectrum-Expansion production formalism applied to other experimental data. A recent effective-Lagrangian study supporting our non-resonant assignment of the $\Upsilon(10580)$ is briefly discussed as well.

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1. Introduction: radial spectra of light and heavy mesons

One of the principal goals of meson spectroscopy [1] is to learn more about the confining potential, in particular its behaviour as a function of

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† Deceased on 6 December, 2022.

constituent quark masses ranging from about 300–400 MeV (u, d) to roughly 5 GeV (b). Now, since this potential is generally assumed to be flavour-independent, on the basis of perturbative-QCD arguments, one would naively expect smaller radial mass splittings for larger quark masses. However, systems made of u, d quark mostly probe the linear part of the commonly accepted Coulomb-plus-linear (or "funnel") confining potential, whereas $b\bar{b}$ states almost exclusively feel the Coulombic part. Therefore, there is a delicate balance of two different mechanisms that will ultimately give rise to the observed mass splittings. When the first two bottomonium states Υ and Υ' were observed, their mass splitting differing less than 5% from that in charmonium [2] came as quite a surprise. While this could indeed be the accidental result of the mentioned balance, in Ref. [3], an alternative confining potential was proposed, namely with a logarithmic r dependence. This choice trivially leads to a radial spectrum that is independent of mass. Nevertheless, the authors showed [3] that the funnel potential is also capable of fitting both the first two $c\bar{c}$ and $b\bar{b}$ states, provided that the coupling constant of the Coulombic part is strongly increased from its fitted value in Ref. [4]. In Fig. 1, the resulting $c\bar{c}$ and $b\bar{b}$ spectra are displayed for the logarithmic and so-called "Modified Coulomb" potential, together with the then [3] available data. Note that, for higher excitations, the predictions of the two potentials clearly diverge. Moreover, the $\psi(4415)$, already observed in 1976 [2] yet not mentioned in Ref. [3], conflicts with the logarithmic potential, if it is indeed the $\psi(4S)$ state.

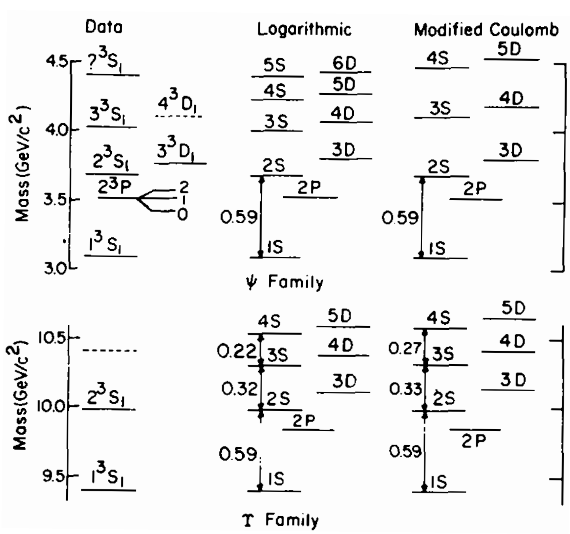

Fig. 1. Charmonium and bottomonium spectra for the logarithmic and "Modified Coulomb" potentials, from Fig. 2 in Ref. [3]. Also, see the text.

We should keep in mind that the above quarkonium potentials are very naive, because they ignore the dynamical effects of strong decay. A clear improvement was the coupled-channel calculation of $b\bar{b}$ states in Ref. [5], which also used a slightly smaller coupling in the Coulombic potential, so as to mimic asymptotic-freedom effects. Nevertheless, this and all other funnel-type potentials will inevitably fail [1] to reproduce radial spacings in the light-quark meson sector, because there, the linear part will strongly dominate and so the spacings will come out too large. The only alternative potential that gives rise to radial splittings independent of quark mass and also in agreement with the $\psi(2S)$, $\psi(4040)$, and $\psi(4415)$ charmonium levels is a harmonic oscillator with universal frequency. It was successfully applied to $c\bar{c}$ and $b\bar{b}$ vector states [6], light, heavy–light, and heavy vector and pseudoscalar mesons [7], and light scalar mesons [8]. In Ref. [7], the first three radial states of the vector ρ, ϕ, ψ, and Υ spectra were shown [7, Fig. 1] to have remarkably similar mass splittings, especially the ρ, ψ, and Υ levels. Crucial for the good model results for these mesons is a unitarised framework accounting for non-perturbative strong-decay effects, which yield a downward mass shift of the ground state that is larger than for the excitations, owing to the absence of a node in the corresponding wave function [1]. It is also essential that the first ρ excitation be $\rho(1250)$ and not $\rho(1450)$, as confirmed [10] in a recent multichannel and fully unitary S-matrix analysis with crossing-symmetry constraints.

In the present short note, we review our analyses of data published by the BaBar Collaboration, which we believe contain a wealth of additional information on $b\bar{b}$ vector states. In particular, we revisit varied evidence [11] of the so far unreported $\Upsilon(1D)$ and $\Upsilon(2D)$ states, as well as our analysis [13] of open-bottom vector $b\bar{b}$ resonances, which suggests a non-resonant nature of the $\Upsilon(10580)$. The latter conclusion is supported by an effective model study [16], summarised here in conclusion.

2. Evidence of $\Upsilon(2\,^3D_1)$ and indication of $\Upsilon(1\,^3D_1)$

In Ref. [11], we analysed data published by the BaBar Collaboration [12], thereby focusing on the $e^+e^- \to \pi^+\pi^-\Upsilon(1S) \to \pi^+\pi^-e^+e^-$ process. The chosen method of analysis is to collect data on invariant e^+e^- masses in bins of 10 MeV, for increasingly wide mass windows around the $\Upsilon(1S)$. By looking at the growth rate of events in each bin, fluctuations around a smooth curve as a function of window size, and events in neighbouring bins, clear enhancements with estimated errors and signal-to-background ratios can be identified. For details, see Ref. [11].

In Fig. 2, we show the graphical results of our analysis. The left-hand side plot displays a small enhancement between the two huge $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks, with a statistical significance of 3.0σ, which is in all likelihood the so far undetected [2] $\Upsilon(1D)$ state. The 7 in the enlarged inset just refers to the corresponding data bin's number. We estimate the $\Upsilon(1D)$ mass at 10098 ± 5 MeV. In the right-hand side plot, the energy region between roughly 10.4 and 10.7 GeV is shown, revealing a huge peak just below 10.5 GeV, besides the known $\Upsilon(10580)$. No doubt this amounts to the missing [2] $\Upsilon(2D)$, whose mass we assess at 10495 ± 5 MeV, with statistical significance of 10.7σ.

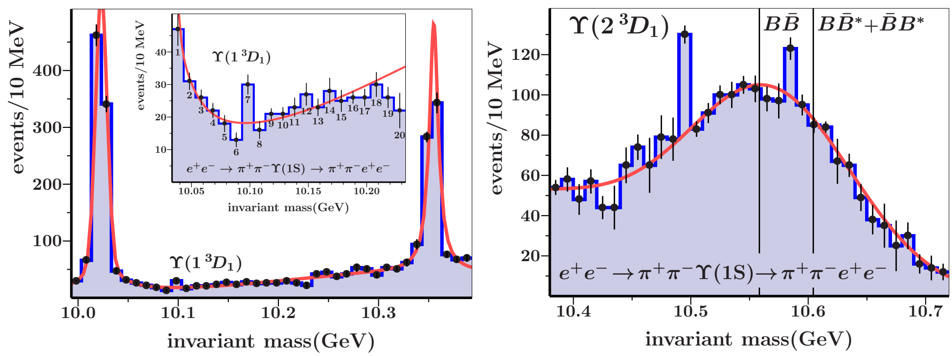

Fig. 2. Analysis [11] of the BaBar data [12]; left: $\Upsilon(1D)$, right: $\Upsilon(2D)$. Also, see the text.

Notice that these inferred masses of the $\Upsilon(1D)$ and $\Upsilon(2D)$ states are close to the very old coupled-channel model [6] predictions 10.14 and 10.48 GeV, respectively, and even closer [11] to the values of the bare states at 10.113 and 10.493 GeV, respectively, as resulting from our (with two co-authors) more general multichannel model fit in Ref. [7]. Note that mass shifts of ${}^3D_1$ states from unitarisation are small [11] as compared to those of ${}^3S_1$ states.

3. Production analysis of excited Υ resonances

In Ref. [13], we reanalysed another BaBar publication [14] with a wealth of data on $b\bar{b}$ states, now above the open-bottom threshold. In order to deal with the several partly overlapping resonances and decay thresholds, we carried out an empirical analysis loosely based on our multichannel production formalism [15]. Its non-standard features are: non-resonant and purely kinematical complex coefficients relating the production amplitude to the scattering T-matrix while satisfying extended unitarity, with an also kinematical, real inhomogeneous term in that relation. For the derivation of this approach to production processes and further details, see Ref. [15]. The results of our fit, with 16 adjustable parameters — comparable to a standard Breit–Wigner (BW) analysis — are displayed in Fig. 3 (see Ref. [13] for details of the model fit). Note that we have not included any BW pa-

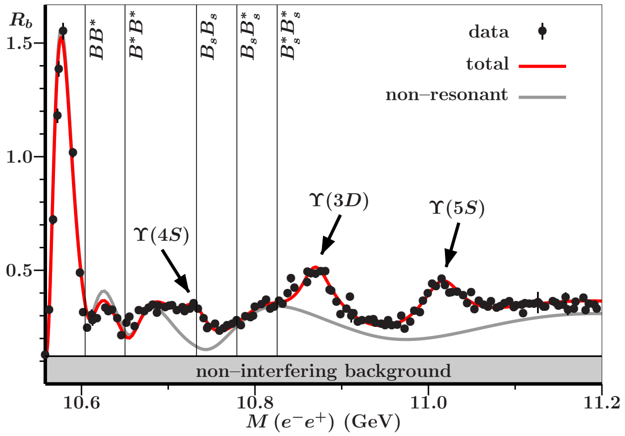

Fig. 3. Model [13] fit of the BaBar data [14] for vector $b\bar{b}$ resonances. Also, see the text.

rameters for the $\Upsilon(10580)$, whose large peak is the result of the mentioned non-resonant lead term in our production formalism due to the opening of the $B\bar{B}$ decay channel, further enhanced [13] by the nearby subthreshold $\Upsilon(2D)$ pole at 10.495 GeV [11]. From the fit, we extract the true resonances $\Upsilon(10735)$ ($\Gamma = 38$ MeV), $\Upsilon(10867)$ ($\Gamma = 42$ MeV), and $\Upsilon(11017)$ ($\Gamma = 59$ MeV), which we interpret as $\Upsilon(4S)$, $\Upsilon(3D)$, and $\Upsilon(5S)$, respectively. The PDG [2] lists these states with the following masses and widths: $\Upsilon(10753)$ ($M = 10753$ MeV), $\Gamma = 35.5$ MeV; $\Upsilon(10860)$ ($M = 10885$ MeV), $\Gamma = 37$ MeV; $\Upsilon(11020)$ ($M = 11000$ MeV), $\Gamma = 24$ MeV.

4. Other work on Υ resonances and conclusions

In Ref. [16], a simple effective model based on the $^3P_0$ mechanism was employed to study Υ resonances above the open-bottom threshold, from the wave-function renormalisation constant Z for a propagator dressed with loops of pairs of B, $B^\star$, B_s, and $B_s^\star$ mesons. The authors concluded from the results that only the $\Upsilon(10580)$ has an abnormally large meson–meson component in its wave function. Moreover, the high peak and relatively large width of this state were argued to be incompatible with a vector $b\bar{b}$ resonance decaying only into $B\bar{B}$ and with little phase space. These observations lend further support to our non-resonant assignment of $\Upsilon(10580)$.

In conclusion, let us once more stress the importance for meson spectroscopy and low-energy QCD to observe and correctly interpret the unlisted [2] states in the bottomonium spectrum. Another interesting approach [17] is to extract static quark–antiquark, meson–meson, and transition potentials from lattice simulations and then use these in a coupled-channel calculation. However, difficulties remain on predicting the precise $\Upsilon(n\,^3D_1)$ masses.

In Memoriam

My longtime collaborator Eef van Beveren passed away due to a sudden illness on December 6$^{\mathrm{th}}$, 2022. I will always be indebted to his brilliance in physics and unconditional friendship.

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