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Single eta production in heavy quarkonia: Breakdown of multipole expansion

Yu.A. Simonov, A.I. Veselov *

State Research Center, Institute of Theoretical and Experimental Physics, Moscow 117218, Russia

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ABSTRACT

The η production in the (n,n') bottomonium transitions $\Upsilon(n) \to \Upsilon(n')\eta$, is studied in the method used before for dipion heavy quarkonia transitions. The widths $\Gamma_\eta(n,n')$ are calculated without fitting parameters for $n = 2,3,4,5$, $n' = 1$. Resulting $\Gamma_\eta(4,1)$ is found to be large in agreement with recent data. Multipole expansion method is shown to be inadequate for large size systems considered.

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1. Introduction

The η and π^0 production in heavy quarkonia transitions is attracting attention of experimentalists for a long time [1]. The first result refers to the $\psi(2S) \to J/\psi(1S)\eta$ process (to be denoted as $\psi(2,1)\eta$ in what follows, similarly for Υ) with $\frac{\Gamma_\eta}{\Gamma_{\text{tot}}} = (3.09 \pm 0.08)\%$ [1], $\Gamma_{\text{tot}} = 337 \pm 13\text{keV}$.

For the $\Upsilon(2,1)\eta$ and $\Upsilon(3,1)\eta$ transitions only upper limits $B < 2 \times 10^{-3}$ and $B < 2.2 \times 10^{-3}$ were obtained in [2] and [3] correspondingly and preliminary results appeared recently in [4], $B(\Upsilon(2,1)\eta) = (2.5 \pm 0.7 \pm 0.5)10^{-4}$, $B(\Upsilon(2,1)\pi^0) < 2.1 \times 10^{-4}$(90% c.l.) and $B(\Upsilon(3,1)\eta) < 2.9 \times 10^{-4}$ in [5].

On theoretical side the dominant approach for both dipion and single η and π production is the Multipole Expansion Method (MEM) (see [6,7] and references therein), where it is assumed that heavy quarks emit two gluons and the latter are converted into meson(s) by a not clarified mechanism. An essential requirement for this mechanism in QED is the smallness of the source size r_0 as compared to the wavelength, so that $r_0 k \ll 1$.

In reality both for charmonium and bottomonium transitions $r_0 k \gtrsim 1$, but it is not this parameter which invalidates MEM for heavy quarkonia. It appears, that in QCD there is another important length parameter, the QCD vacuum correlation length λ, which makes it impossible to emit freely gluons at points separated by distance $r, r > \lambda$.

The value of λ was found on the lattice and analytically, $\lambda \lesssim 0.2$ fm [8]. Since r.m.s. radii of all excited $c\bar{c}, b\bar{b}$ states are larger than 0.5 fm[1] all vacuum gluons there are correlated forming the QCD string and emission of additional gluons (if any) implies formation of heavy hybrids. All this is considered in detail in Field Correlator Method (FCM) [9].

Table 1
Predicted splittings, between spin-averaged levels, and experiment.

Splitting	MEM [11]	FCM [12]	exp [1]
$2S$–$1S(b\bar{b})$	479	557	558 MeV
$2S$–$1P(b\bar{b})$	181	122	123 MeV
$3S$–$2S(b\bar{b})$	4570	348	332 MeV
$2S$–$1S(c\bar{c})$	9733	610	606 MeV

One can make an independent check of MEM in application to the bottomonium level calculation. Here MEM yields nonperturbative correction to the levels expressed via gluonic condensate [10]. Comparison to the experimental data shows (see [11] and Table 1) that for all level splittings except $(2S$–$1S)$ in bottomonium, MEM prediction is more than 50% off, while for charmonium MEM does not work at all. Thus one concludes that only at distances below or equal 0.2 fm, MEM can give reasonable results, while for all states of charmonium and all excited states of bottomonium (where sizes are much larger than vacuum correlation length λ) the application of MEM is unjustifiable.

A similar failure of MEM is found in applications to dipion bottomonium transitions, where using MEM one can fit dipion spectra in $\Upsilon(2,1)\pi\pi$, but not in $\Upsilon(3,1)\pi\pi$ and $\Upsilon(4,2)\pi\pi$ [6,7]. In contrast to that, FCM as will be discussed below explains both spectra and $\cos\theta$ dependence for all dipion transitions in universal approach with two fixed parameters.

In FCM large distances are under control and not single gluons but combined effect of all gluons in the string defines the dynamics.

In particular, single eta emission in heavy quarkonia proceeds via string breaking due to $q\bar{q}$ pair creation with simultaneous emission of π or η. The flavor SU(3) violation in η production then resides in difference of threshold positions and wave functions for $B\bar{B}$ and $B_s\bar{B}_s$ ($D\bar{D}$ and $D_s\bar{D}_s$) intermediate states.

* Corresponding author.
E-mail address: veselov@itep.ru (A.I. Veselov).

[1] In reality the r.m.s. radius r_0 of heavy quarkonia is not small, e.g. for $\Upsilon(nS)$ it is equal to 0.2 fm, 0.5 fm, 0.7 fm, 0.9 fm, for $n = 1,2,3,4,5$, and for charmonium this radius is even larger: 0.4 fm and 0.8 fm for $n = 1$ and 2, respectively.

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As it is clear, the dynamics of FCM for η emission does not depend strongly on heavy quark mass, and only sizes of initial and final heavy quarkonia states and intermediate heavy–light mesons enter in the form of overlap matrix elements.

In contrast to that, MEM predicts a strong dependence on the heavy quark mass, $\Gamma_\eta(n,n') = O(\frac{1}{m_Q^2})$. In addition in [7] a strong suppression of the ratio $\Gamma_\eta/\Gamma_{\pi\pi}$ with the growth of the energy release $\Delta M = M(n) - M(n')$, $\Gamma_\eta/\Gamma_{\pi\pi} \sim \frac{p_\eta^3}{(\Delta M)^7}$ is predicted for higher excited states of quarkonia and bottomonia, which does not agree with experiment (see below).

Using models based on MEM in [6] small ratios of widths

$$\frac{\Gamma(\Upsilon(2,1)\eta)}{\Gamma(\psi(2,1)\eta)} \cong 2.5 \times 10^{-3} \quad \text{and} \quad \frac{\Gamma(\Upsilon(3,1)\eta)}{\Gamma(\psi(2,1)\eta)} = 1.3 \times 10^{-3} \qquad (1)$$

have been predicted, with the model property that the bottomonium yields of η would be smaller than those of charmonium; specifically in the method of [6], the width is proportional to p^3/m_Q^2, so that for $\Upsilon(4,1)\eta$ the ratio $\frac{\Gamma(\Upsilon(4,1)\eta)}{\Gamma(\psi(2,1)\eta)} \approx 3.3 \times 10^{-3}$.

However recently [13] new BaBar data have been published on $\Upsilon(4,1)\eta$ with the branching ratio

$$B\big(\Upsilon(4,1)\eta\big) = (1.96 \pm 0.06 \pm 0.09)10^{-4} \qquad (2)$$

and [13]

$$\frac{\Gamma(\Upsilon(4,1)\eta)}{\Gamma(\Upsilon(4,1)\pi^+\pi^-)} = 2.41 \pm 0.40 \pm 0.12. \qquad (3)$$

This latter result is very large, indeed the corresponding ratio $\frac{\Gamma(\Upsilon(4,1)\eta)}{\Gamma(\psi(2,1)\eta)}$ is ≈ 0.4 and theoretical estimates (1) from [6] for a similar ratio yields 3.3×10^{-3}. Thus, the experimental ratio is very large as compared to MEM predictions [6,7]. All this suggests that another mechanism can be at work in single η production and below we exploit the approach based on the Field Correlator Method (FCM) recently applied to $\Upsilon(n,n')\pi\pi$ transitions with $n \leqslant 3$ in [14,15], $n \leqslant 4$ in [16] and $n = 5$ in [17,18].

In this Letter we confront MEM and FCM and show that recent experimental data on single η production in $\Upsilon(4S)$–$\Upsilon(1S)$ transition give a strong support to the FCM result and cannot be explained in the framework of MEM.

The method essentially exploits the mechanism of Internal Loop Radiation (ILR) with light quark loop inside heavy quarkonium and has two fundamental parameters — mass vertices in chiral light quark pair $q\bar{q}$ creation $M_{br} \approx f_\pi$ and pair creation vertex without pseudoscalars, $M_\omega \approx 2\omega$, where $\omega(\omega_s)$ is the average energy of the light (strange) quark in the $B(B_s)$ meson. Those are calculated with relativistic Hamiltonian [12] and considered as fixed for all types of transitions $\omega = 0.587$ GeV, $\omega_s = 0.639$ GeV (see Appendix 1 of [14] for details).

Any process of heavy quarkonium transition with emission of any number of Nambu–Goldstone (NG) mesons is considered in ILR as proceeding via intermediate states of $B\bar{B}$, $B\bar{B}^* +$ c.c., $B_s\bar{B}_s$, etc. (or equivalently $D\bar{D}$, etc.) with NG mesons emitted at vertices.

For one η or π^0 emission one has diagrams shown in Fig. 1, where dashed line is for the NG meson. As shown in [14–16], based on the chiral Lagrangian derived in [19], the meson emission vertex has the structure

$$\mathcal{L}_{\mathrm{CDL}} = -i \int d^4x\, \bar{\psi}(x) M_{br} \hat{U}(x) \psi(x), \qquad (4)$$

$$\hat{U} = \exp\left(i\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi}\right),$$

$$\varphi_a\lambda_a = \sqrt{2}\begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}. \qquad (5)$$

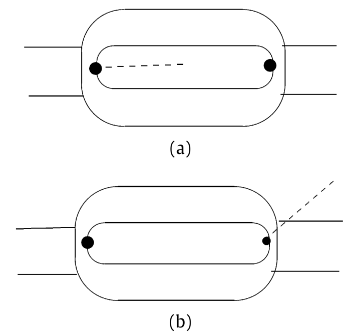

Fig. 1. Single eta production (dashed line) from $\Upsilon(n)BB^*$ vertex (a), and $BB^*\Upsilon(n')$ vertex (b).

The lines $(1,2,3)$ in the $\hat{U}$ matrix (2) refer to u, d, s quarks and hence to the channels B^+B^-, $B^0\bar{B}^0$, $B_s^0\bar{B}_s^0$ (and to the corresponding channels with B^* instead of B). Therefore the emission of a single η in heavy quarkonia transitions requires the flavour SU(3) violation and resides in our approach in the difference of channel contribution $B\bar{B}^*$ and $B_s\bar{B}_s^*$, while the π^0 emission is due the difference of $B^0\bar{B}^{0*}$ and B^+B^{-*} channels (with $B \to D$ for charmonia).

The Letter is devoted to the explicit calculation of single η emission widths in bottomonium $\Upsilon(n,1)\eta$ transitions with $n = 2,3,4,5$. Since theory has no fitting parameters (the only ones, M_ω and M_{br} are fixed by dipion transitions) our predictions depend only on the overlap matrix elements, containing wave functions of $\Upsilon(nS)$, B, B_s, B^*, B_s^*. The latter have been computed previously in relativistic Hamiltonian technic in [12] and used extensively in dipion transitions in [16–18].

The Letter is organized as follows. In Section 2 general expressions for process amplitudes are given; in Section 3 results of calculations are presented and discussed and a short summary and prospectives are given.

2. General formalism

The process of single NG boson emission in bottomonium transition is described by two diagrams depicted in Fig. 1(a) and (b) which can be written according to the general formalism of FCM [14,16,17] as (we consider η emission), see Appendix A for more detail,

$$\mathcal{M} = \mathcal{M}_\eta^{(1)} + \mathcal{M}_\eta^{(2)}, \qquad \mathcal{M}_\eta^{(i)} = \mathcal{M}_{B_sB_s^*}^{(i)} - \mathcal{M}_{BB^*}^{(i)}, \quad i = 1,2. \qquad (6)$$

For the diagram of Fig. 1(a) the amplitude for intermediate BB^* or $B_sB_s^*$ state can be written as

$$\mathcal{M}_\eta^{(1)} = \int \frac{J_n^{(1)}(\mathbf{p},\mathbf{k}) J_{n'}(\mathbf{p})}{E - E(\mathbf{p})} \frac{d^3\mathbf{p}}{(2\pi)^3}, \qquad (7)$$

while $\mathcal{M}_\eta^{(2)}$, corresponding to the diagram of Fig. 1(b), has the same form, but without NG boson energy in the denominator of (7). The overlap integrals of $\Upsilon(nS)$ and BB^* wave functions with emission of η with momentum $\mathbf{k}$ are denoted by $J_n^{(i)}(\mathbf{p},\mathbf{k})$, the corresponding integrals without η emission are given by $J_{n'}(\mathbf{p})$.

Finally we define all quantities in the denominator of (7); in $\mathcal{M}_{BB^*}^{(1)}$ the denominator is

$$E - E(\mathbf{p}) = M\big(\Upsilon(nS)\big) - \left(\omega_\eta + M_B + M_B^* + \frac{\mathbf{p}^2}{2M_B} + \frac{(\mathbf{p}-\mathbf{k})^2}{2M_B^*}\right)$$
$$\equiv -\Delta M^* - \omega_\eta - E(\mathbf{p},\mathbf{k}). \qquad (8)$$

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