Spectroscopy of the J/ψ family including charmoniumlike Y states

Takayuki Matsuki

in collaboration with J.-Z. Wang, D.-Y. Chen, and X. Liu

Tokyo Kasei University RIKEN @ Wako

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based on our paper: Phys Rev D99, 114003 (2019)

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- 5 Conclusions and summary

Motivation: Observed charmonia with first observed year



Figure: The observed charmonia with the corresponding first observed year. Here, the $D\bar{D}$ threshold is also given.

Motivation: Structure at 4.22 GeV



Figure: The measured resonance parameters of Y(4220) in hidden-charm processes $e^+e^- \rightarrow J/\psi\pi^+\pi^-$, $e^+e^- \rightarrow h_c\pi^+\pi^-$, $e^+e^- \rightarrow \chi_{c0}\omega$, and $e^+e^- \rightarrow \psi(3686)\pi^+\pi^-$ BESIII.

We consider spectrum of $\psi(1^{--})$ states above 4.2 GeV. There is one at 4415 MeV. (Yuping Guo (Sat morning) mentioned complexity of charmonium spectrum.)

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Formulation: modified GI model

How to obtain mass spectrum of $\psi(1^{--})$ is as follows.

The interaction between charm quark and anti-charm quark can be expressed by the Hamiltonian:

$$ilde{H} = \left(p^2 + m_c^2
ight)^{1/2} + \left(p^2 + m_{ar{c}}^2
ight)^{1/2} + ilde{V}_{
m eff} \left({f p}, {f r}
ight),$$

with $V_{ ext{eff}}(r) = H_{qar{q}}^{ ext{conf}} + H_{qar{q}}^{ ext{hyp}} + H_{qar{q}}^{ ext{SO}}$

Smearing potentials:

$$\tilde{S}(r)/\tilde{G}(r) = \int d^3 \mathbf{r}' \rho(\mathbf{r} - \mathbf{r}') S(r')/G(r').$$
(1)

Further relativistic effects on V_{eff}

$$ilde{V}_i(r)
ightarrow \left(rac{m_c m_{ar{c}}}{E_c E_{ar{c}}}
ight)^{1/2+arepsilon_i} ilde{V}_i(r) \left(rac{m_c m_{ar{c}}}{E_c E_{ar{c}}}
ight)^{1/2+arepsilon_i},$$

Motivation: Numerical values of $\psi(nS, nD)$

State	Mass	Expt. [9]	State	Mass	Expt. [9]
$\eta_c(1^1S_0)$	2981	2983.9±0.5	$\psi(1^3D_1)$	3830	3778.1±1.2
$\psi(1^3S_1)$	3096	3096.9 ± 0.006	$\psi_2(1^3D_2)$	3848	3822.2±1.2
$\eta_c(2^1S_0)$	3642	3637.6 ± 1.2	$\psi_3(1^3D_3)$	3859	
$\psi(2^3S_1)$	3683	3686.097 ± 0.01	$\eta_{c2}(2^1D_2)$	4137	
$\eta_c(3^1S_0)$	4013		$\psi(2^3D_1)$	4125	4159 ± 20
$\psi(3^3S_1)$	4035	4039 ± 1	$\psi_2(2^3D_2)$	4137	
$\eta_c(4^1S_0)$	4260		$\psi_3(2^3D_3)$	4144	
$\psi(4^3S_1)$	4274	4230±8	$\eta_{c2}(3^1D_2)$	4343	
$\eta_c(5^1S_0)$	4433		$\psi(3^3D_1)$	4334	
$\psi(5^{3}S_{1})$	4443		$\psi_2(3^3D_2)$	4343	
$h_c(1^1P_1)$	3538	3525.38 ± 0.11	$\psi_3(3^3D_3)$	4348	
$\chi_{c0}(1^3P_0)$	3464	3414.71 ± 0.3	$\eta_{c2}(4^1D_2)$	4490	
$\chi_{c1}(1^3P_1)$	3530	3510.67 ± 0.05	$\psi(4^3D_1)$	4484	

Figure: 4S-3D mixing in red and 5S-4D mixing in green.

Validity: Y(4220)

• Mass spectrum: $\psi(4^3S_1)$ 4274 MeV via modified GI model. Difference of mass from 4220 is due to mixing with $\psi(3D)$

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- Branching ratios:

$$\begin{array}{rcl} \mathcal{B}[\psi(4S) \to D\bar{D}] &=& 9.39\%, \\ \mathcal{B}[\psi(4S) \to DD^*] &=& 0.347\%, \\ \mathcal{B}[\psi(4S) \to D^*\bar{D}^*] &=& 87.7\%, \\ \mathcal{B}[\psi(4S) \to D_s\bar{D}_s] &=& 7.13 \times 10^{-2}\%, \\ \mathcal{B}[\psi(4S) \to D_sD^*_s] &=& 2.50\%, \\ \mathcal{B}[\psi(4S) \to D^*_s\bar{D}^*_s] &=& 3.38 \times 10^{-2}\% \end{array}$$

Validity: partner of Y(4220): $\psi(3D) = \psi(4334)$

Branching ratios: $D\overline{D}$ is dominant for decays of $\psi(3D)$

$$\begin{array}{rcl} \mathcal{B}[\psi(3D) \to D\bar{D}] &=& 36.8\%, \\ \mathcal{B}[\psi(3D) \to DD^*] &=& 4.68\%, \\ \mathcal{B}[\psi(3D) \to D^*\bar{D}^*] &=& 32\%, \\ \mathcal{B}[\psi(3D) \to D_s\bar{D}_s] &=& 3.33 \times 10^{-2}\%, \\ \mathcal{B}[\psi(3D) \to D_s\bar{D}_s^*] &=& 1.22\%, \\ \mathcal{B}[\psi(3D) \to D_s\bar{D}_s^*] &=& 0.583\%, \\ \mathcal{B}[\psi(3D) \to DD_1(2420)] &=& 7.65\%, \\ \mathcal{B}[\psi(3D) \to DD_1(2430)] &=& 16.4\%, \\ \mathcal{B}[\psi(3D) \to DD_2^*(2460)] &=& 0.235\%, \\ \mathcal{B}[\psi(3D) \to D^*D_0(2400)] &=& 0.408\%. \end{array}$$

No validity: ψ (4334)



Figure: The experimental data of the open-charm channels $e^+e^- \rightarrow D\bar{D}_2^* \rightarrow D^0D^-\pi^+$ (upper panel) and $e^+e^- \rightarrow D^0D^{*-}\pi^+$ (lower panel). T. Matsuki (Tokyo Kasei University) Spectroscopy of the J/ψ family including che Aug. 18, 2019 10 / 14

Validity: $\psi(4S) - \psi(3D)$ mixing

Mixing solves all the problems.



Figure: The yellow for Y(4220) and the cyan for $\psi(4380)$, respectively, where the dashed horizontal lines in bands corresponds to each average value.

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Validity: 4*R* fit to $e^+e^- \rightarrow \psi(3686)\pi^+\pi^-$



Figure: Hint of existence of $\psi(4380)$ Fit to $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ reaction in the Fano-like interference picture under 3R and 4R ($\psi(4160)$, Y(4220), $\psi(4380)$, and $\psi(4415)$) fit schemes. Matsuki (Tokyo Kasei University) Spectroscopy of the J/ψ family including che Aug. 18, 2019 12 / 14

Construct J/ψ family above 4.2 GeV with S - D mixing

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Other results:

• Predict $\psi(3D)$ as $\psi(4380)$

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- Predict $M(\psi(4D)) = 4500$ MeV

Thanks for your attention

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Guilin