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THE INITIAL SINGLE CHIRAL PARTICLE EMISSION MECHANISM AND THE PREDICTIONS OF CHARGED CHARMONIUM-LIKE STRUCTURES*

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In this paper, we introduce our theoretical progress on the initial single chiral particle emission mechanism and the predictions of charged charmonium-like structures.

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1. Introduction

There have been abundant observations of charmonium-like states XYZ in the past decade, which were reported by BaBar, Belle, CLEO-c, CDF, D0, CMS, LHCb and BESIII. These experimental observations have stimulated theorists' extensive interest (see recent review [1] for more details).

In this paper, we introduce an important mechanism existing in the hidden-bottom/charm decays of higher bottomonia/charmonia, which is named the initial single chiral particle emission (ISChE) mechanism. Under

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this mechanism, we have given plentiful novel phenomena relevant to charmonium-like and bottomonium-like structures, which can be accessible by experiments.

2. Lessons from studying hidden-bottom dipion decays of $\Upsilon(5S)$

In 2011, the Belle Collaboration reported two charged bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$ in the $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ ($m = 1,2$) and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$) decay processes [2]. The typical properties of these two Z_b states are that $Z_b(10610)$ and $Z_b(10650)$ have charged structures and are near the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively. Before this observation, Belle once studied the hidden-bottom dipion decays of $\Upsilon(5S)$ and indicated that the branching ratios of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$) are larger than the dipion transition rates between the lower members of the Υ family by two orders of magnitude [3], which is a puzzle of $\Upsilon(5S)$ decays. For solving this puzzle, the rescattering mechanism [4] and tetraquark state Y_b near $\Upsilon(5S)$ [5] were proposed. Although these two mechanisms can explain why the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays have larger decay rates, they failed to describe the experimental data of the $\Upsilon(2S)\pi$ and $\pi\pi$ invariant mass spectra of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ [6, 7]. Thus, the authors of Ref. [7] indicated that there exists a new puzzle in $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay.

Later, Chen, Liu and Zhu realized the relation of two experiments mentioned above, which is crucial to solving this new puzzle in $\Upsilon(5S) \to \Upsilon(2S)$ $\pi^+\pi^-$ decay [8]. By introducing the contribution from two Z_b structures in $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ and considering the interference effects of different mechanisms, the $\Upsilon(2S)\pi$ and $\pi\pi$ invariant mass spectra of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ can be well understood [8], which shows that two observed Z_b structures play an important role to solve a new puzzle in $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. However, we must answer what is the source to generate $Z_b(10610)$ and $Z_b(10650)$.

Due to the peculiar properties of $Z_b(10610)$ and $Z_b(10650)$, the explanations of the exotic state including molecular state were proposed in Refs. [9, 10]. In addition, the cusp effect resulted from the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds was given by Bugg in Ref. [11]. After these theoretical work, we were seeking other mechanisms to explain the $Z_b(10610)$ and $Z_b(10650)$ structures. In Ref. [12], Chen and Liu first proposed a new decay mechanism existing in $\Upsilon(5S)$ decay, which is named the initial single pion emission (ISPE) mechanism. With $\Upsilon(5S) \to \Upsilon(mS)\pi^+\pi^-$ as an example, we illustrate the ISPE mechanism, where the emitted pion with continuous energy distribution makes the intermediate $B^{(*)}$ and $\bar{B}^{(*)}$ have low momenta. Hence, $B^{(*)}$ and $\bar{B}^{(*)}$ easily interact with each other to transit into final states $\Upsilon(mS)\pi$.

By calculating these $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ processes by introducing the ISPE mechanism, we explain why the charged structures near the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds can be found in the hidden-bottom dipion decays of $\Upsilon(5S)$. We also indicated that we cannot find the sharp peak close to the $B\bar{B}$ threshold [12].

3. Novel charged charmonium-like structures existing in the hidden-charm dipion decays of higher charmonia or charmonium-like states

If the ISPE mechanism is a universal mechanism in heavy quarkonium dipion decays, we naturally extend the ISPE mechanism to study the hidden-charm dipion decays of higher charmonia because of the similarity between charmonium and bottomnium families. We would like to give more predictions for future experiments, which can be an important test for the ISPE mechanism proposed in Ref. [12].

In reference [13], the hidden-charm dipion decays of higher charmonia $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ and charmonium-like state $Y(4260)$ were calculated by introducing the ISPE mechanism. Here, we predicted the charged charmonium-like structures near the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds in the $J/\psi\pi$, $\psi(2S)\pi$ and $h_c(1P)\pi$ invariant mass spectra. We found that our obtained $h_c(1P)\pi^+$ distribution of $\psi(4160) \to h_c(1P)\pi^+\pi^-$ can depict the CLEO-c measurement of the $h_c(1P)\pi^\pm$ mass distribution from $e^+e^- \to h_c(1P)\pi^+\pi^-$ at $E_{\rm CM} = 4170$ MeV [14]. Later, Yuan, who represented the Belle Collaboration, gave a talk in "Hadron Structure and Interaction 2011" conference. The comparison between the Belle data and our result of $Y(4260) \to J/\psi\pi^+\pi^-$ was presented, which shows that there is the evidence of enhancement structures in the $J/\psi\pi^\pm$ invariant mass spectrum as predicted by us in Ref. [13].

As predicted in Ref. [13], there exists a charged charmonium-like structure near the $D\bar{D}^*$ threshold announced by three experimental analyses. In 2013, the BESIII Collaboration observed a charged charmonium-like structure $Z_c(3900)$ in the $J/\psi\pi^\pm$ invariant mass spectrum of $Y(4260) \to J/\psi\pi^+\pi^-$, which is near the $D\bar{D}^*$ threshold [15]. Belle independently studied the same decay process and claimed the observation of $Z_c(3900)$ [16]. In Ref. [17], Xiao *et al.* analyzed the CLEO-c data of $e^+e^- \to \psi(4160) \to J/\psi\pi^+\pi^-$, and found $Z_c(3900)$ single.

The observation of $Z_c(3900)$ provides a direct support for the prediction given by the ISPE mechanism. After the observation of $Z_c(3900)$, we carried our further study of $Z_c(3900)$ by combining with the ISPE mechanism in Ref. [18], where we considered the interference effects among different mechanisms. Our calculation shows that the $Z_c(3900)$ structure can be well reproduced by analyzing the $J/\psi\pi^+$ and $\pi^+\pi^-$ invariant mass spectra of $Y(4260) \to J/\psi\pi^+\pi^-$.

4. More novel phenomena of charged charmonium-like structures

Under the ISPE mechanism, we studied the hidden-charm dipion decays of charmonium-like state $Y(4360)$, where $Y(4360) \to J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$, and $h_c(1P)\pi^+\pi^-$ [19] were considered. We also predicted the enhancement structure near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds existing in $J/\psi\pi$, $\psi\pi$ and $h_c(1P)\pi$ invariant mass spectra [19].

As an extension of the ISPE mechanism, the initial single chiral particle emission (ISChE) mechanism was proposed in Ref. [20]. Since the pion and kaon can be categorized into chiral particles, we explored the hidden-charm dikaon decays of higher charmonia, which are intriguing processes, where the ISChE mechanism can play an important role in these discussed decays. Via the ISChE mechanism, we have studied the processes $\psi(4415) \to J/\psi K^+K^-$, $Y(4660) \to J/\psi K^+K^-$, and $\psi(4790) \to J/\psi K^+K^-$, where $Y(4660)$ is a charmonium-like state observed in $e^+e^- \to \psi(2S)\pi^+\pi^-$ [21], while $\psi(4790)$ is a predicted higher charmonium with quantum number $5S$ in Ref. [22]. By this study, we predicted charged charmonium-like structures with the hidden-charm and open-strange. Our result indicates that there is no charged charmonium-like structure near the $D_s\bar{D}$ threshold with hidden-charm and hidden-strange in the $J/\psi K^+$ invariant mass distribution of $\psi(4415) \to J/\psi K^+K^-$. However, for $Y(4660) \to J/\psi K^+K^-$, and $\psi(4790) \to J/\psi K^+K^-$ decays, there exist enhancement structures with both hidden-charm and open-strange. These predicted charged charmonium-like structures can be accessible by future experiments, especially BESIII and forthcoming BelleII.

5. Summary

In this paper, we have introduced how we have proposed the ISPE mechanism existing in the hidden-bottom/charm dipion decays of higher bottomonia/charmonia, which is due to the lesson in the study of the hidden-bottom dipion decays of $\Upsilon(5S)$, where the Z_b structures can be understood via the ISPE mechanism. Considering the similarity between the J/ψ and Υ families, the ISPE mechanism was applied to investigate the hidden-charm dipion decays of higher charmonia or charmonium-like states, we also predicted the charged charmonium-like structures near the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds, and introduced the comparison of these results with the experimental measurements. The $Z_c(3900)$ observation by BESIII and Belle confirmed our prediction, which is an important test of the ISPE mechanism. For further testing the ISPE mechanism, we applied the ISEP mechanism to hidden-charm dipion decays of charmonium-like state $Y(4360)$, where the charged charmonium-like structures near the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds were predicted. As an important extension of the ISPE mechanism, we proposed the ISChE mechanism to study the hidden-charm dikaon decays of higher charmonia. Some predictions of charged enhancement structures with both hidden-charm and open-strange were also given.

Under the ISEP and ISChE mechanisms, we have predicted abundant novel phenomena, which are waiting for the test from further experiments, especially from BESIII and BelleII. We believe that this serves a good opportunitiy for experimentalists to study charmonium-like states. We expect more experimental progress on this research field that has full of challenges.

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