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Manifestation of intermediate meson loop effects in charmonium decays*

ZHANG Yuan-Jiang(张远江)[1;1)] LI Gang(李刚)[1,3;2)] ZHAO Qiang(赵强)[1,2;3)]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2] Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China
[3] Department of Physics, Qufu Normal University, Qufu 273165, China

Abstract We report the progress on understanding some of those existing puzzles in charmonium decays. We show that the intermediate meson loops (IML) as a long-distance transition mechanism will provide novel insights into these issues. In particular, we show that the IML mechanism would be essentially important for understanding the $\psi(3770)$ non-$D\bar{D}$ decays. We also comment that such a mechanism is correlated with the Okubo-Zweig-Iizuka (OZI) rule evasions in charmonium hadronic decays.

Key words charmonium decay, intermediate meson loop, $\psi(3770)$ non $D\bar{D}$ decay

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1 Introduction

The energy region of charmonium masses contains rich information about both perturbative and non-perturbative QCD dynamics. Charmonium decays serve an ideal probe for studying their interferences from which insights into the strong QCD properties can be gained. In this proceeding, we report a recent progress on understanding several long-standing puzzles in the vector charmonium sector [1, 2] which include the $\psi(3770)$ non-$D\bar{D}$ decay, $\rho\pi$ puzzle and the M1 transition puzzle in $J/\psi\to\gamma\eta_c$ and $\psi'\to\gamma\eta_c(\eta_c')$. We will show that the intermediate meson loops will play an important role in understanding all these problems in a self-consistent way.

First, we briefly review the problems. The vector charmonium states can be directly produced in e^+e^- annihilation, and then detected in their exclusive decays into final state particles. As shown by the charmonium spectrum, the charmonia below the open charm threshold $D\bar{D}$ generally have narrow widths such as J/ψ and ψ', while states above the $D\bar{D}$ threshold are broad. This is an indication of the so-called OZI rule [3] as a recognition of the pQCD feature (i.e. $\alpha_s < 1$). In contrast, the broad $\psi(3770)$ decay is dominated by the $D\bar{D}$ decay while its non-$D\bar{D}$ branching ratios were expected to be negligible. However, the empirical OZI rule must be violated as manifested by the hadronic decays of J/ψ and ψ' into light hadrons.

An interesting and nontrivial question here is whether the $\psi(3770)$ decay is totally saturated by $D\bar{D}$, or whether there exist significant non-$D\bar{D}$ decay channels [1, 2, 4–8]. Unfortunately, a definite answer from either experiment or theory is unavailable. CLEO collaboration measured the exclusive cross sections for $\psi(3770)\to D\bar{D}$ [9, 10] and inclusive cross sections for $\psi(3770)\to$ hadrons [11]. These results lead to $BR_{\psi(3770)\to D\bar{D}} = (103.0\pm1.4^{+5.1}_{-6.8})\%$, of which the lower bound suggests the maximum non-$D\bar{D}$ branching ratio is about 6.8%.

The $D\bar{D}$ production cross sections measured by BES [12] are consistent with CLEO [10]. However, the analyses lead to much larger non-$D\bar{D}$ branching ratios of $\sim 15\%$. Such a significant discrepancy makes the experimental status quite puzzling, and also revives the theoretical interests in this problem [13–15].

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1) E-mail: yjzhang@ihep.ac.cn

2) E-mail: gli@ihep.ac.cn

3) E-mail: zhaoq@ihep.ac.cn

As follows, we first briefly introduce the effective Lagrangian model and then report the theoretical results with discussions. A summary will be given in the last section.

2 Intermediate meson loop transitions in $\psi(3770)$ non-$D\bar{D}$ decays

In Fig. 1, the intermediate meson loops recognized as t- and s-channel transitions are illustrated. The following effective Lagrangians are adopted to evaluate the transition amplitudes,

$$\begin{aligned}
\mathcal{L}_{\psi D\bar{D}} &= g_{\psi D\bar{D}}\{D\partial_\mu\bar{D}-\partial_\mu D\bar{D}\}\psi^\mu,\\
\mathcal{L}_{\mathcal{V}D\bar{D}^*} &= -ig_{\mathcal{V}D\bar{D}^*}\epsilon_{\alpha\beta\mu\nu}\partial^\alpha\mathcal{V}^\beta\partial^\mu\bar{D}^{*\nu}D+\text{H.c.},\\
\mathcal{L}_{\mathcal{P}D^*\bar{D}^*} &= -ig_{\mathcal{P}D^*\bar{D}^*}\epsilon_{\alpha\beta\mu\nu}\partial^\alpha D^{*\beta}\partial^\mu\bar{D}^{*\nu}\mathcal{P}+\text{H.c.},\\
\mathcal{L}_{\mathcal{P}\bar{D}D^*} &= g_{D^*\mathcal{P}\bar{D}}\{\bar{D}\partial_\mu\mathcal{P}-\partial_\mu\bar{D}\mathcal{P}\}D^{*\mu}+\text{H.c.},
\end{aligned}\tag{1}$$

where $\epsilon_{\alpha\beta\mu\nu}$ is the Levi-Civita tensor; $\mathcal{P}$ and $\mathcal{V}^\beta$ are the pseudoscalar and vector meson fields, respectively.

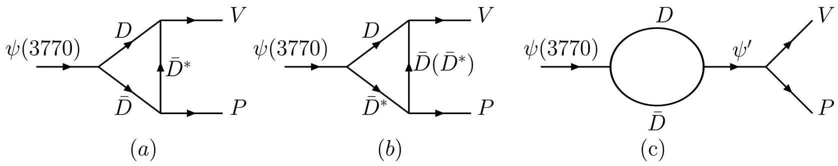

Fig. 1. The t [(a) and (b)] and s-channel (c) meson loops in $\psi(3770)\to VP$.

The charmed meson couplings to light meson are obtained in the chiral and heavy quark limits [16],

$$\begin{aligned}
g_{D^*D\pi} &= \frac{2}{f_\pi}g\sqrt{m_D m_{D^*}}, \quad g_{D^*D^*\pi}=\frac{g_{D^*D\pi}}{\tilde{M}_D},\\
g_{D^*D\rho} &= \sqrt{2}\lambda g_\rho, \quad g_{DD\rho}=g_{D^*D\rho}\tilde{M}_D,
\end{aligned}\tag{2}$$

where $f_\pi = 132$ MeV is the pion decay constant, and $\tilde{M}_D \equiv \sqrt{m_D m_{D^*}}$ sets a mass scale. The parameters g_ρ respects the relation $g_\rho = m_\rho/f_\pi$ [17]. We take $\lambda=0.56\ \text{GeV}^{-1}$ and $g=0.59$ [18, 19].

Note that the t-channel loops suffer from divergence [20]. A dipole form factor is thus introduced to kill the divergence and also compensate the off-shell effects arising from virtual particle exchanges:

$$\mathcal{F}(q^2)=\left(\frac{\Lambda^2-m_{\text{ex}}^2}{\Lambda^2-q^2}\right)^2 , \tag{3}$$

where $\Lambda\equiv m_{\text{ex}}+\alpha\Lambda_{\text{QCD}}$, with $\Lambda_{\text{QCD}}=0.22$ GeV; m_{ex} is the mass of the exchanged meson and α is a parameter to be determined by experimental data for $\psi(3770)\to J/\psi\eta$.

The detailed formulae, which we will skip here, can be found in Ref. [14]. As follows, we will clarify those points which are essential for constraining the model and quantifying the contributions from different mechanisms.

1) We use the measured $\psi(3770)\to J/\psi\eta$ to constrain the form factor parameter α. Note that the momentum carried by the final state mesons is rather small. This is an indication that the gluon exchanges are very soft. We hence assume that the short-distance pQCD processes are strongly suppressed, and the transition is dominated by the long-distance transition mechanism via intermediate meson loops. With $BR^{\text{exp}}_{J/\psi\eta}=(9.0\pm4)\times10^{-4}$ [21], $\alpha=1.73$ can be determined and the exclusive t-channel contributes 8.44×10^{-4}.

2) For light meson final states, we expect that the short-distance transitions will still contribute since much larger momentum transfers are involved. We then argue that this amplitude will approximately respect the $SU(3)$ flavor symmetry, and introduce a coupling strength g_S to describe the production of two pairs of $q\bar{q}$ in the final VP via OZI singly disconnected (SOZI) transitions. One can easily obtain the following relation:

$$\begin{aligned}
&g_S^{\rho^0\pi^0}:g_S^{K^{*+}K^-}:g_S^{\omega\eta}:g_S^{\omega\eta'}:g_S^{\phi\eta}:g_S^{\phi\eta'}=\\
&1:1:\cos\alpha_P:\sin\alpha_P:(-\sin\alpha_P):\cos\alpha_P\ ,
\end{aligned}\tag{4}$$

with the other isospin channels implicated. The angle $\alpha_P\equiv=\theta_P+\arctan(\sqrt{2})$ is η and η' mixing angle.

3) Between the short- and long-distance transition amplitudes, one relative phase is possible. We then introduce a phase angle δ as follows:

$$\begin{aligned}
\mathcal{M}_{fi} \equiv\ & i(g_L+e^{i\delta}g_S\mathcal{F}_S(\vec{p}_V))\times\\
& \varepsilon_{\alpha\beta\mu\nu}P_\psi^\alpha\epsilon_\psi^\beta P_V^\mu\epsilon_V^{*\nu}/M_{\psi(3770)}
\end{aligned}\tag{5}$$

where g_L denotes the loop amplitude, and the property of antisymmetric tensor is applied to factorize out the effective couplings in the second line. A conventional form factor, $\mathcal{F}_S^2(\vec{P}_V)\equiv\exp(-\vec{P}_V^2/8\beta^2)$ with $\beta=0.5$ GeV, is applied for the SOZI transition with $\vec{P}_V$ the final three momentum in the $\psi(3770)$ rest frame [22, 23]

4) By applying the experimental data, $BR_{\phi\eta}=$

$(3.1\pm0.7)\times10^{-4}$ [21] and $BR_{\rho\pi}<0.24\%$ with C.L. of 90% [24], we can constrain the coupling $g_{\rm S}$ and phase angle δ. Other channels can then be predicted [14].

In Table 1, the results for all VP channels are listed. The exclusive branching ratios given by the t- and s-channels, and SOZI transitions are also presented. Remember that the input channels are $\psi(3770)\to J/\psi\eta$, $\phi\eta$ and $\rho\pi$, where the experimental upper limit for $\rho\pi$ suggests a correlation between the SOZI transition coupling $g_{\rm S}$ and the phase angle δ. By varying δ, but keeping the $\phi\eta$ rate unchanged (i.e. $g_{\rm S}$ will be changed), we obtain a bound for the sum of branching ratios, $\simeq(0.41-0.64)\%$.

Table 1. Branching ratios for $\psi(3770)\to$ VP calculated for different mechanisms. The values for $J/\psi\eta$ and $\phi\eta$ are fixed at the central values of the experimental data [21], and the experimental upper limit is taken for $\rho\pi$ [24].

$BR(\times10^{-4})$	t-channel	s-channel	SOZI	total
$J/\psi\eta$	8.44	0.13	–	9.0
$J/\psi\pi^0$	0.1	2.58×10^{-2}	–	4.4×10^{-2}
$\rho\pi$	34.45	7.69×10^{-5}	8.53	24.0
$K^{*+}K^-+$c.c	10.97	6.83×10^{-6}	5.72	8.91
$K^{*0}\bar{K}^0+$c.c	11.80	4.38×10^{-5}	5.72	9.90
$\phi\eta$	1.25	1.13×10^{-5}	1.16	3.1
$\phi\eta'$	0.87	2.53×10^{-5}	1.86	3.78
$\omega\eta$	6.83	9.64×10^{-6}	1.88	4.69
$\omega\eta'$	0.58	2.87×10^{-5}	0.97	0.39
$\rho\eta$	1.88×10^{-2}	1.77×10^{-5}	–	1.8×10^{-2}
$\rho\eta'$	1.08×10^{-2}	1.54×10^{-5}	–	1.0×10^{-2}
$\omega\pi^0$	2.57×10^{-2}	1.82×10^{-5}	–	2.5×10^{-2}
Sum	75.34	0.16	25.84	63.87

Several interesting points can be learned from Table 1:

(i) It shows that the t-channel transitions are much more important in $\psi(3770)\to$ VP, while the s-channel contributions are generally small and even negligible in light VP channels. This is mainly due to the small partial widths for ψ' decays into light VP. The only non-negligible s-channel is in $\psi(3770)\to J/\psi\eta$, which adds to the t-channel constructively. In contrast, the isospin violating channel $J/\psi\pi^0$ experiences a destructive interference between the t and s-channel.

(ii) The s-channel manifests the $\psi(2S)$-$\psi(1D)$ mixing via a meson loop. With an on-shell approximation, the mixing angle $\phi\simeq4.57°$ in the convention of Ref. [6] can be extracted.

(iii) It shows that the meson loop and SOZI amplitudes have constructive interferences in $\phi\eta$ and $\phi\eta'$, but have destructive interferences in $\rho\pi$, $K^*\bar{K}+$c.c., and $\omega\eta(\eta')$, which are automatically given by the $SU(3)$ flavor symmetry. These interference features will be a strong constraint for our model parameters.

(iv) It is interesting to see that the intermediate D meson loop transitions indeed account for some deficit for the non-$D\bar{D}$ decay. In order to clarify this puzzling problem, it is essential to have precise data for $\rho\pi$ and $K^*\bar{K}+$c.c. A search for these decays at BES-III [25] is thus strongly recommended. Theoretical investigation of other channels such as $\psi(3770)\to$ VS, VT, etc is also needed as a prediction and test of the proposed mechanism.

3 The intermediate meson loops in J/ψ and $\psi'\to$ VP and $\gamma\eta_c^{(\prime)}$

Further evidence for the intermediate meson loops can be investigated in other charmonium decays. In particular, it is natural to expect that the ψ' will experience relatively significant influences since it is close to the $D\bar{D}$ open channel. Our studies suggests that the intermediate meson loop transitions would be a key for understanding the long-standing "$\rho\pi$ puzzle" as well as the M1 transition puzzle in J/ψ and ψ' radiative decays. Since the detailed results will be reported independently, we only summarize the main points here:

1) In the VVP transition, all mechanisms contribute to this transition will appear as corrections to a single anti-symmetric tensor coupling. This allows a simple factorization for different transition amplitudes as illustrated by Eq. (5). This can be applied to $J/\psi(\psi')$ decays into VP by which the contributing mechanisms can be isolated and constrained. For instance, in $J/\psi(\psi')\to$ VP, we find that the isospin-violating channels are dominated by the EM transitions via VMD. By fixing the EM transition parameters in the isospin-violating channels, we can then determine the EM amplitudes in those isospin conserved channels [23, 26].

2) The strong transitions can be decomposed into two parts. One is the short-distance amplitude and the other is the long-distance amplitude. We argue that the short-distance amplitude is attributed to the charmonium wavefunction at the origin, while the long-distance amplitude is given by the non-perturbative intermediate meson loop transitions. This scenario explains that the strong amplitude in the $\psi'\to$ VP suffers from an overall suppression due to the destructive interferences between the short-distance and long-distance amplitudes. In comparison, the decay of $J/\psi\to$ VP will have much less contributions from the intermediate meson loops since J/ψ is located rather far away from the open

$D\bar{D}$ threshold [26].

3) The same mechanism also explains the discrepancies between the NRQCD and experimental results for $J/\psi(\psi') \to \gamma\eta_c$. Although the recent CLEO-c results reduce the discrepancies significantly, it shows that the nearly one order-of-magnitude difference between theory and experiment in $\psi' \to \gamma\eta_c$ is still uncompensated. As shown in Ref. [27], the interferences between the short-distance amplitudes from NRQCD and long-distance amplitudes from the intermediate meson loops converge to reduce the discrepancies coherently.

4) The intermediate meson loops play a role as "unquenching" the simple $c\bar{c}$ picture in the quark model. It can be easily understood since we know that the charm quark is somehow not heavy enough. The failure of the heavy quark limit approximation will then exhibit itself in some exclusive transitions, such as the problems tackled in this work. We point out that the recent Lattice QCD calculations of $J/\psi(\psi') \to \gamma\eta_c$ [28] still suffer from large uncertainties. In order to investigate the intermediate meson loop contributions, an "unquenched" calculation is strongly required.

4 Summary

In this proceeding, we illustrate the dynamic role played by intermediate meson loops in charmonium decays by studying the long-standing $\psi(3770)$ non-$D\bar{D}$ decays, "$\rho\pi$ puzzle" and the M1 transition problems. We show that these anomalous phenomena may have the same origin from the long-distance transition mechanisms. In particular, we find that the charmonium states with masses close to charmed meson open channels will suffer from significant interferences, thus some of their properties will deviate from naive expectations by the simple $c\bar{c}$ picture. Nevertheless, the obvious OZI-rule violations observed in many exclusive decays would be a clear signal for the presence of non-perturbative mechanisms.

It should be pointed out that it is non-trivial to provide a quantification of such a non-perturbative mechanism. As we have already emphasized many times in the context, the effective Lagrangian approach lacks fundamental constraints, thus model-dependence will be inevitable. In this sense, one should explore various processes in order to gain better insights into such a non-perturbative mechanism. It is also essential to examine the theoretical predictions in future experiment as a further support of such a scenario [29].

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