

**Exotic four quark matter:  $Z_1(4475)$** Li Ma,<sup>1,\*</sup> Xiao-Hai Liu,<sup>1,†</sup> Xiang Liu,<sup>2,3,‡</sup> and Shi-Lin Zhu<sup>4,§</sup><sup>1</sup>*Department of Physics and State Key Laboratory of Nuclear Physics and Technology and Center of High Energy Physics, Peking University, Beijing 100871, China*<sup>2</sup>*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*<sup>3</sup>*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*<sup>4</sup>*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*

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Motivated by the LHCb's recent confirmation of  $Z_1(4475)$  as the  $J^P = 1^+$  resonance, we investigate various exotic interpretations of  $Z_1(4475)$ , which may be an axial vector tetraquark state, the P-wave excitation of the S-wave  $D_1\bar{D}^*$  or  $D_2\bar{D}^*$  molecule, the S-wave molecule composed of a  $D$  or  $D^*$  meson and a D-wave vector  $D$  meson, or the cousin molecular state of  $Z_c(3900)$  and  $Z_c(4020)$  composed of a  $D$  or  $D^*$  meson and their radial excitations. With the help of the heavy quark symmetry, we predict the typical radiative and hidden-charm and open-charm strong decay patterns of  $Z_1(4475)$ , which are crucial to further identify the molecular state assignment of  $Z_1(4475)$ .

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**I. INTRODUCTION**

As a great achievement in the understanding of matter, quantum chromodynamics (QCD) is established as the theory of the strong interaction. However, QCD is highly nonperturbative in the infrared region and the color confinement issue remains one of the most challenging problems in 21st century science. It is well known that a nucleon is composed of three quarks and a meson is composed of a pair of quark and anti-quark. Besides the above conventional hadrons, QCD may allow the existence of the subatomic particles with the other quark/gluon configurations such as hybrid hadrons, hadronic molecules or tetraquarks, etc. The experimental and theoretical investigations of these exotic states will shed light on the nonperturbative dynamics of QCD.

Very recently, the LHCb experiment has confirmed the existence of the exotic hadrons [1].  $Z_1(4475)$  is the first charged charmoniumlike state discovered by the Belle Collaboration in the  $\psi'\pi$  mode in the  $B$  decays [2]. Later, the measurement indicates that the spin parity  $1^+$  was favored over other assignments  $0^-$ ,  $1^-$ ,  $2^-$  and  $2^+$  by  $3.4\sigma$ ,  $3.7\sigma$ ,  $4.7\sigma$  and  $5.1\sigma$ , respectively [3]. Recently, the LHCb Collaborations confirmed  $Z_1(4475)$  as the  $J^P = 1^+$  state with a significance of  $13.9\sigma$  and ruled out the other quantum numbers with less significance [1]. Its mass and width are measured to be 4475 and 172 MeV, respectively. From now on, we will denote this charged state as  $Z_1(4475)$ . The obtained Argand diagram for the  $Z_1(4475)$  amplitude is consistent with the resonance behavior. Moreover, LHCb observed a second charged

state  $Z_0(4239)$  with  $J^P = 0^-$  with a significance of  $6\sigma$  and a width around 220 MeV.

Since its observation,  $Z_1(4475)$  was first considered to be a good candidate of the loosely bound S-wave molecular state composed of the  $D_1^{(\prime)}\bar{D}^*$  meson pair [4–9]. In particular, it was pointed out in Ref. [7] that there exists only the  $J^P = 0^-$  molecule for the S-wave  $D_1\bar{D}^*$  system. However, there exists the S-wave  $D_1'\bar{D}^*$  molecule with  $J^P = 0^-, 1^-, 2^-$  [7]. The authors pointed out that the broad width of  $D_1'$  seems not very compatible with the narrow width of  $Z_1(4475)$  around 45 MeV measured in Belle's discovery paper [2]. LHCb's precise measurement shows that  $Z_1(4475)$  sits exactly on the threshold of  $D_2^*(2460)$  and  $\bar{D}^*(2010)$  and is slightly above the  $D_1(2420)\bar{D}^*$  threshold. The confirmation of its spin parity as  $J^P = 1^+$  leads to very puzzling new challenges, which are also a good opportunity to demystify  $Z_1(4475)$  as the four quark matter.

There are several interesting schemes of the underlying structure of  $Z_1(4475)$ . The first possibility is that  $Z_1(4475)$  may be the  $J^P = 1^+$  hidden-charm tetraquark candidate. The axial-vector charmoniumlike tetraquark mass spectrum are discussed extensively in Ref. [10]. As a tetraquark candidate,  $Z_1(4475)$  should decay into the  $J/\psi\pi$  mode more easily with a larger partial width than that of the discovery mode  $\psi'\pi$ . Moreover,  $Z_1(4475)$  should also decay into the open-charm modes  $\bar{D}D^*$  and  $\bar{D}^*D^*$  very easily via S-wave. Then,  $Z_1(4475)$  should be a very broad state with the total width much larger than 172 MeV, which seems not compatible with the Belle and LHCb's precise measurement of its width.

The second possibility is that  $Z_1(4475)$  is the P-wave excitation of the S-wave  $D_1\bar{D}^*$  or  $D_2\bar{D}^*$  molecule. If so, is  $Z_0(4239)$  the ground state of the  $D_1\bar{D}^*$  molecule? Then, the binding energy of  $Z_0(4239)$  is as large as 190 MeV,

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which is in strong contrast with the tiny binding energy (around 2 MeV) of the deuteron. Generally one would expect that the strong interaction between two color-singlet hadrons leads to a binding energy around a few to several tens MeV instead of hundreds of MeV, although the very deeply bound hadronic molecules may also exist.

The third possibility is that  $Z_1(4475)$  is the S-wave molecule composed of a  $D$  or  $D^*$  meson and a D-wave vector  $D$  meson in the  $(1^-, 2^-)$  multiplet whose mass is around 2700 MeV.

The fourth possibility is that  $Z_1(4475)$  is the S-wave molecule composed of a  $D$  or  $D^*$  meson and their radial excitations whose masses are around 2.6 GeV. In other words,  $Z_1(4475)$  may be the cousin of the charged states  $Z_c(3900)$  and  $Z_c(4025)$  observed by the BESIII Collaborations [11,12], which are speculated to be molecular candidates composed of the  $D$  and  $D^*$  mesons.

The discovery mode  $\psi'\pi$  and nonobservation of  $Z_1(4475)$  in the  $J/\psi\pi$  channel are also serious challenges to the second and third possibilities listed above. However, the situation is quite different for the last scheme. If  $Z_1(4475)$  contains the radial excitation of the  $D$  or  $D^*$  meson as its component, it may decay into the final state containing a radial excitation more easily, i.e., the  $\psi'\pi$  final state may be a more favorable decay mode of  $Z_1(4475)$  than  $J/\psi\pi$  within the fourth scheme.

In this work we will investigate the implications of the Belle and LHCb's determination of the spin parity of  $Z_1(4475)$ . With the help of heavy quark symmetry, we will study the electromagnetic, both hidden-charm and open-charm, strong decay patterns of  $Z_1(4475)$  under various molecular assumptions. Some interesting features can be tested experimentally.

This paper is organized as follows. After the Introduction, we present the formalism and results in Sec. II. Section III is a short summary.

## II. THE DECAY BEHAVIOR OF $Z_1(4475)$

The quantum number of the neutral component of  $Z_1(4475)$  is  $J^{PC} = 1^{+-}$ . As a molecular state candidate, the possible flavor wave functions of  $Z_1(4475)$  are listed in Table I. Here,  $D(\frac{3}{2}, 1)$  is a D-wave charmed meson with the light spin  $S_l = \frac{3}{2}$  and  $J^P = 1^-$ .  $D(2550)$  and  $D^*(2600)$  were reported by *BaBar* [13], which can be good candidates of  $2^1S_0$  and  $2^3S_1$  charmed mesons, respectively [14].  $Z_1(4475)$  can be a P-wave  $D_1\bar{D}^*$  or  $D'_1\bar{D}^*$  molecular state.  $Z_1(4475)$  may also be an S-wave molecular state containing a D-wave meson or a radially excited state.

The heavy quark spin symmetry [15] is very useful in the study of the heavy hadron properties. In the heavy quark limit, the heavy quark mass  $m_Q \rightarrow \infty$ , the spin-flipping interaction is suppressed. Throughout the decay process, the heavy quark spin  $S_H$  is a conserved quantity, which is named as “heavy spin” for simplicity. The total angular momentum

TABLE I. The flavor wave functions of  $Z_1(4475)$  as a molecular candidate.

States		
P-wave molecules	$^1P_1$	$\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)$ $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)$
	$^3P_1$	$\frac{1}{\sqrt{2}}(D'_1\bar{D}^* + D^*\bar{D}'_1)$
		$\frac{1}{\sqrt{2}}(D_1\bar{D}^* + D^*\bar{D}_1)$
		$\frac{1}{\sqrt{2}}(D_2\bar{D}^* - D^*\bar{D}_2)$
	$^5P_1$	$\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)$
		$\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)$
$\frac{1}{\sqrt{2}}(D_2\bar{D}^* + D^*\bar{D}_2)$		
S-wave molecules	$\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D} - D\bar{D}(\frac{3}{2}, 1))$	
	$\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D}^* + D^*\bar{D}(\frac{3}{2}, 1))$	
	$\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$	
	$\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$	

$J$  of a hadron is also a conserved quantity. We can also define the conserved “light spin”  $\vec{S}_l \equiv \vec{J} - \vec{S}_H$ , which includes both the light quark spin and the orbital angular momenta within a hadron. In the decays of a hadron, the heavy spin, light spin and total angular momentum are all good quantum numbers in the heavy quark limit, which are separately conserved. Therefore we can decompose the total angular momentum of the initial and final states according to their heavy spin and light spin, which was employed to study the radiative decays of  $XYZ$  states extensively in Ref. [16]. We borrow the same notations and formalism from Ref. [16] to study the radiative and strong decay patterns of  $Z_1(4475)$ . Since the charm quark is not very large, the heavy quark symmetry is not exact. In the following, we analyze the hidden-charm molecular systems in the heavy quark symmetry limit. One may naively expect the recoil corrections from the finite charm quark mass will not spoil the qualitative features outlined in this work. We focus on the P-wave  $D_1\bar{D}^*$  or  $D'_1\bar{D}^*$ , S-wave  $D(\frac{3}{2}, 1)\bar{D}$  or  $D(\frac{3}{2}, 1)\bar{D}^*$ , as well as S-wave  $D(2550)\bar{D}^*$  or  $D\bar{D}^*(2600)$  molecular systems in this work.

With the heavy quark spin symmetry [15], the heavy and light spins of the molecular state can be re-coupled separately. We adopt the spin re-coupling formula with  $6-j$  or  $9-j$  symbols in analyzing the general spin structure. In the heavy quark limit, the final state charmonia can also be decomposed into the heavy spin and light spin. For the neutral component of  $Z_1(4475)$ , there exists the radiative decay  $Z_1(4475) \rightarrow (c\bar{c}) + \gamma$ , where the initial state is a hadronic molecule and final state is a charmonium. The photon is from the  $q\bar{q}$  annihilation. We can calculate the rearranged spin structures of the final states in

the  $Z_1(4475) \rightarrow (c\bar{c}) + \gamma$  decays. The general expression is [16]

$$\begin{aligned} & |\text{Charmionia}\rangle \otimes |\gamma\rangle \\ &= [[(c\bar{c})_g \otimes L]_K \otimes Q]_J |(c\bar{c})\rangle |\gamma\rangle \\ &= \sum_{h=|L-Q|}^{L+Q} (-1)^{g+L+Q+J} [(2K+1)(2h+1)]^{1/2} \\ &\quad \times \left\{ \begin{matrix} L & g & K \\ J & Q & h \end{matrix} \right\} [[(c\bar{c})_g \otimes [L \otimes Q]_{h,J}] |(c\bar{c})\rangle |\gamma\rangle, \end{aligned}$$

where the  $g$  and  $L$  denote the heavy and light spins of the charmonium, respectively.  $Q$  stands for the light spin of the photon. The indices  $c$ ,  $\bar{c}$  and  $\gamma$  in the square brackets represent the corresponding spin wave functions. Similarly, we present the rearranged spin structures of the final states in the  $Z_1(4475) \rightarrow (c\bar{c}) + \text{light meson}$  decays [16], i.e.,

$$\begin{aligned} & |\text{Charmionia}\rangle \otimes |\text{lightmeson}\rangle \\ &= [[(c\bar{c})_g \otimes L]_K \otimes Q]_J |(c\bar{c})\rangle |(q\bar{q})\rangle \\ &= \sum_{h=|L-Q|}^{L+Q} (-1)^{g+L+Q+J} [(2K+1)(2h+1)]^{1/2} \\ &\quad \times \left\{ \begin{matrix} L & g & K \\ J & Q & h \end{matrix} \right\} [[(c\bar{c})_g \otimes [L \otimes Q]_{h,J}] |(c\bar{c})\rangle |(q\bar{q})\rangle, \end{aligned}$$

With the above preparation, we obtain the typical decay behavior of  $Z_1(4475)$  under different molecular state assignments, where these properties follow from the heavy quark symmetry and the presumed nature without employing a particular model, which is crucial to test and establish the exotic four quark matter.

### A. $Z_1(4475)$ as a P-wave molecular candidate

The decay pattern of  $Z_1(4475)$  as a candidate of the  ${}^3P_1$  or  ${}^5P_1$   $D_2\bar{D}^*$  molecular state is very similar to that of the  ${}^3P_1$  or  ${}^5P_1$   $D_1\bar{D}^*$  state. We focus on the latter. As a P-wave  $D_1\bar{D}^*$  or  $D_1'\bar{D}^*$  molecular state,  $Z_1(4475)$  has three possible spin structures, corresponding to  ${}^1P_1$ ,  ${}^3P_1$  and  ${}^5P_1$ , respectively. Its neutral component can decay into  $\chi_{cJ}$  ( $J = 0, 1, 2$ ) via the  $M1$  transition. Except the  ${}^3P_1$  state  $\frac{1}{\sqrt{2}}(D_1'\bar{D}^* + D^*\bar{D}'_1)$ , the other five  $D_1\bar{D}^*$  or  $D_1'\bar{D}^*$  molecular states share the same reduced matrix elements for the  $M1$  transition. These reduced matrix elements depend on the spin configuration  $(1_{\bar{H}}^- \otimes 0_{\bar{L}}^-)_{J=1}^{+-}$ ,  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$  and  $(1_{\bar{H}}^- \otimes 2_{\bar{L}}^-)_{J=1}^{+-}$ .

We notice that both the  ${}^3P_1$  states  $D_1'\bar{D}^*$  and  $D^*\bar{D}'_1$  molecular states with  $R = 1$  contain the spin configurations  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{++}$ ,  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$  and  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{++}$ . The recoupled final state  $\chi_{cJ}({}^1P_J)\gamma(M1)$  with the total angular momentum equal to 1 contains the component of

$(1_{\bar{H}}^- \otimes 0_{\bar{L}}^-)_{J=1}^{+-}$ ,  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$  and  $(1_{\bar{H}}^- \otimes 2_{\bar{L}}^-)_{J=1}^{+-}$ . So both  $D_1'\bar{D}^*$  and  $D^*\bar{D}'_1$  components with  $R = 1$  can independently decay into  $\chi_{cJ}({}^1P_J)\gamma(M1)$ . Unfortunately, these two components have the opposite relative phase for the component of  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ . When they constitute the C-parity eigenstate  $\frac{1}{\sqrt{2}}(D_1'\bar{D}^* + D^*\bar{D}'_1)$ , the radiative decay into  $\chi_{cJ}({}^1P_J)\gamma(M1)$  is suppressed in the heavy quark limit.

The discussed  $E1$  transitions include  $\eta_c\gamma(E1)$  and  $\eta_{c2}({}^1D_2)\gamma(E1)$ . The states  $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}'_1)({}^1P_1)$  and  $\frac{1}{\sqrt{2}}(D_1'\bar{D}^* - D^*\bar{D}'_1)({}^5P_1)$  don't contain the spin configuration  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ . These  $\eta_c\gamma(E1)$  and  $\eta_{c2}({}^1D_2)\gamma(E1)$  modes are suppressed due to heavy quark symmetry. All the other configurations of  $Z_1(4475)$  can decay into  $\eta_c\gamma(E1)$  and  $\eta_{c2}({}^1D_2)\gamma(E1)$  through the spin configuration  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ .

The  $E2$  decay of  $\frac{1}{\sqrt{2}}(D_1'\bar{D}^* + D^*\bar{D}'_1)({}^3P_1)$  is suppressed in the heavy quark symmetry limit. Both the  $D_1'\bar{D}^*$  and  $D^*\bar{D}'_1$  molecular states with  $J = 1$  contain three spin configurations  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{++}$ ,  $(0_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$  and  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ . The spin-rearranged final states  $\chi_{c1}({}^3P_1)\gamma(E2)$  and  $\chi_{c2}({}^3P_2)\gamma(E2)$  contain the components  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$  and  $(1_{\bar{H}}^- \otimes 2_{\bar{L}}^-)_{J=1}^{+-}$ . Both  $D_1'\bar{D}^*$  and  $D^*\bar{D}'_1$  with  $R = 1$  can independently decay into  $\chi_{c1}({}^3P_1)\gamma(E2)$  or  $\chi_{c2}({}^3P_2)\gamma(E2)$ . But these two contributions have the opposite relative phase for the component  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ . When they constitute the C-parity eigenstate  $\frac{1}{\sqrt{2}}(D_1'\bar{D}^* + D^*\bar{D}'_1)({}^3P_1)$ , the radiative decay into  $\chi_{c1}({}^3P_1)\gamma(E2)$  or  $\chi_{c2}({}^3P_2)\gamma(E2)$  is suppressed in the heavy quark limit. All the other states can decay into  $\chi_{c1}({}^3P_1)$  or  $\chi_{c2}({}^3P_2)$  via the  $E2$  transition.

### B. $Z_1(4475)$ as a S-wave molecular candidate

The  $M1$  decays of both  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D} - D\bar{D}(\frac{3}{2}, 1))$  and  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D}^* + D^*\bar{D}(\frac{3}{2}, 1))$  state occur through the spin configuration  $(1_{\bar{H}}^- \otimes 0_{\bar{L}}^-)_{J=1}^{+-}$ . If  $Z_1(4475)$  is the  $\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$  or  $\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$  molecule, their  $M1$  transitions depend on the spin configuration  $(1_{\bar{H}}^- \otimes 0_{\bar{L}}^-)_{J=1}^{+-}$ . The S-wave states  $\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$  and  $\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$  do not contain the spin configuration  $(1_{\bar{H}}^- \otimes 1_{\bar{L}}^-)_{J=1}^{+-}$ . Thus, their  $E2$  decays into  $\chi_{c1}({}^3P_1)\gamma(E2)$  and  $\chi_{c2}({}^3P_2)\gamma(E2)$  are suppressed in the heavy quark symmetry limit.

We obtain some typical  $M1$  transition ratios  $\Gamma(\chi_{c0}\gamma(M1)) : \Gamma(\chi_{c1}\gamma(M1)) : \Gamma(\chi_{c2}\gamma(M1))$  and  $\Gamma(\chi_{c0}\gamma(E2)) : \Gamma(\chi_{c1}\gamma(E2)) : \Gamma(\chi_{c2}\gamma(E2))$ . If  $Z_1(4475)$  is an S-wave molecular state  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D} - D\bar{D}(\frac{3}{2}, 1))$  or  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D}^* + D^*\bar{D}(\frac{3}{2}, 1))$ , the above  $M1$  decay width ratio is 20:15:1 ignoring the phase space difference. These decays are only governed by the spin configuration  $(1_{\bar{H}}^- \otimes 2_{\bar{L}}^-)_{J=1}^{+-}$ .

If  $Z_1(4475)$  is the S-wave molecular candidate with the configurations  $\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$  and  $\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$ , the above  $M1$  decay width ratio is 1:3:5.

### III. STRONG DECAYS OF $Z_1(4475)$

$G$ -parity conservation constrains the hidden-charm decay modes of  $Z_1(4475)$ :  $J/\psi\pi$  ( $\psi'\pi$ ),  $\psi(1^3D_1)\pi$ ,  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$ . Since the radial excitation has the same spin decomposition as the ground state, their decay patterns are the same. For example, it's understood throughout our discussions that the  $J/\psi\pi$  and  $\psi'\pi$  modes are the same in our symmetry analysis.

For the  $^1P_1$  case, all the four hidden-charm decay modes are allowed if  $Z_1(4475)$  is a  $D'_1\bar{D}^*$  molecule. For example, the  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$  modes arise from the spin configuration  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$ . In contrast, the  $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)(^1P_1)$  molecular state doesn't contain the spin configuration  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$ . Hence, its decays into  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$  are suppressed. Both the  $D'_1\bar{D}^*(^1P_1)$  and  $D_1\bar{D}^*(^1P_1)$  states allow the decay modes  $J/\psi\pi$  and  $\psi(1^3D_1)\pi$ , which depend on the spin configurations  $(1_{\bar{H}} \otimes 0_{\bar{I}})_{J=1}^{+-}$  and  $(1_{\bar{H}} \otimes 2_{\bar{I}})_{J=1}^{+-}$ , respectively.

Since neither  $D'_1\bar{D}^*$  nor  $D^*\bar{D}'_1$  in the  $^3P_1$  state contains the component  $(1_{\bar{H}} \otimes 0_{\bar{I}})_{J=1}^{+-}$ , the decays of  $\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)(^3P_1)$  into  $J/\psi\pi$  and  $\psi(1^3D_1)\pi$  are suppressed. For the  $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)(^3P_1)$  state, both  $J/\psi\pi$  and  $\psi(1^3D_1)\pi$  are allowed while they depend on the  $(1_{\bar{H}} \otimes 0_{\bar{I}})_{J=1}^{+-}$  and  $(1_{\bar{H}} \otimes 2_{\bar{I}})_{J=1}^{+-}$  components, respectively. Similar conclusions hold for the  $^3P_1 D_2\bar{D}^*$  molecular state. Both  $\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)(^3P_1)$  and  $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)(^3P_1)$  can decay into  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$  through the spin configuration  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$ .

For  $\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)(^5P_1)$ ,  $\frac{1}{\sqrt{2}}(D_1\bar{D}^* - D^*\bar{D}_1)(^5P_1)$  and  $\frac{1}{\sqrt{2}}(D_2\bar{D}^* + D^*\bar{D}_2)(^5P_1)$ , their  $J/\psi\pi$  and  $\psi(1^3D_1)\pi$  modes are similar to the  $^1P_1$  case. However, these  $^5P_1$  states can also decay into  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$ . Since neither  $D'_1\bar{D}^*$  nor  $D^*\bar{D}'_1$  contains the component  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$ , the  $\eta_c\rho$  and  $\eta_{c2}(1^1D_2)\rho$  modes of  $\frac{1}{\sqrt{2}}(D'_1\bar{D}^* - D^*\bar{D}'_1)(^5P_1)$  are suppressed in the heavy quark symmetry limit.

The S-wave states  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D} - D\bar{D}(\frac{3}{2}, 1))$  and  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D}^* + D^*\bar{D}(\frac{3}{2}, 1))$ , can decay into  $\psi(1^3D_1)\pi$ ,  $\eta_c\rho$  or  $\eta_{c2}(1^1D_2)\rho$  through the components  $(1_{\bar{H}} \otimes 2_{\bar{I}})_{J=1}^{+-}$ ,  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$  and  $(0_{\bar{H}} \otimes 1_{\bar{I}})_{J=1}^{+-}$ , respectively. However, neither  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D} - D\bar{D}(\frac{3}{2}, 1))$  nor  $\frac{1}{\sqrt{2}}(D(\frac{3}{2}, 1)\bar{D}^* + D^*\bar{D}(\frac{3}{2}, 1))$  contains the spin configuration  $(1_{\bar{H}} \otimes 0_{\bar{I}})_{J=1}^{+-}$ . Therefore, the  $J/\psi\pi$  or  $\psi'\pi$  modes are suppressed in the heavy quark symmetry limit.

The S-wave states  $\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$  and  $\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$  can decay into  $J/\psi\pi$ ,  $\eta_c\rho$  or  $\eta_{c2}(1^1D_2)\rho$ . However, neither  $\frac{1}{\sqrt{2}}(D(2550)\bar{D}^* - D^*\bar{D}(2550))$  nor  $\frac{1}{\sqrt{2}}(D\bar{D}^*(2600) - D^*(2600)\bar{D})$  contains the spin configuration  $(1_{\bar{H}} \otimes 2_{\bar{I}})_{J=1}^{+-}$ . The  $\psi(1^3D_1)\pi$  mode is suppressed.

In addition, we notice that all the  $D'_1\bar{D}^*(^1P_1, ^3P_1, ^5P_1)$  and  $D_1\bar{D}^*(^1P_1, ^3P_1, ^5P_1)$  states can decay into  $\bar{D}D^*$  and  $\bar{D}^*D^*$  through either S-wave or D-wave. The S-wave molecule containing the radiation excitation can decay into the  $\bar{D}D^*$  and  $\bar{D}^*D^*$  modes. Thus,  $e^+e^- \rightarrow Y(4660)$  (or  $\gamma^*$  or higher resonances)  $\rightarrow Z_1(4475)\pi \rightarrow D^{(*)}\bar{D}^{(*)}\pi$  is a suitable processes to search for  $Z_1(4475)$ .

### IV. SUMMARY

Motivated by LHCb's confirmation of the spin parity of  $Z_1(4475)$  [1], we have investigated the implications of this measurement. Under the molecular assumption, we have considered three cases: (1)  $Z_1(4475)$  as the P-wave excitation of the S-wave  $D_1\bar{D}^*$  or  $D_2\bar{D}^*$  molecule, (2)  $Z_1(4475)$  as the S-wave molecule composed of a  $D$  or  $D^*$  meson and a D-wave vector  $D$  meson, or (3)  $Z_1(4475)$  as the cousin molecular state of  $Z_c(3900)$  and  $Z_c(4020)$  composed of a  $D$  or  $D^*$  meson and their radial excitations. With the help of the heavy quark symmetry, we have studied the radiative and strong decay patterns of  $Z_1(4475)$ .

In the heavy quark symmetry limit, the S-wave molecule composed of a  $D$  or  $D^*$  meson and a D-wave vector  $D$  meson does not decay into the  $\psi'\pi$  final state, which is the discovery mode of  $Z_1(4475)$ . Therefore, this molecule scheme seems unfavorable.

If  $Z_1(4475)$  could be the P-wave excitation of the  $D_1\bar{D}^*$  or  $D_2\bar{D}^*$  molecule, we can study their radiative and strong decay patterns together with their S-wave molecular ground states simultaneously, the radiative decays of which are presented in Ref. [16]. Within this scheme, the nonobservation of  $Z_1(4475)$  in the  $J/\psi\pi$  mode is always a serious challenge. There exists no manifest symmetry forbidding this mode. The same challenge holds for the tetraquark interpretation. Moreover, if  $Z_1(4475)$  is the P-wave molecule, where is the ground state? Is it  $Z_0(4239)$ ? If so, can we find a natural framework to explain its large binding energy around 190 MeV?

If  $Z_1(4475)$  happens to be the molecular cousin of  $Z_c(3900)$  and  $Z_c(4020)$  composed of a  $D$  or  $D^*$  meson and their radial excitations, it decays into  $J/\psi\pi$  and  $\psi'\pi$  easily. However, it will not decay into  $\psi(1^3D_1)\pi$  in the heavy quark symmetry limit. The neutral component will also decay into  $\chi_{cJ}$  through the  $M1$  transition. The resulting decay width ratio is 1:3:5. Since  $Z_1(4475)$  contains one radial excitation as its molecular component, one may expect that  $Z_1(4475)$  may decay into the final state containing a radial excitation more easily. Up to now,

the puzzling charged state  $Z_1(4475)$  remains very mysterious. Hopefully the present work will help us to understand its underlying structure better.

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