PRODUCTION OF THE SPIN-2 PARTNER OF $X(3872)$ IN e^+e^- COLLISIONS*

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A narrow structure, reported by the Belle Collaboration in the $\gamma\psi(2S)$ channel, is an excellent candidate for the spin-2 partner of $X(3872)$ in the hadronic molecular picture. This paper explores the decay processes of $X_2 \to \gamma\psi$ ($\psi = J/\psi,\ \psi(2S)$) and $X_2 \to e^+e^-$, evaluating the direct production of X_2 in e^+e^- collisions. Our results indicate that the ratio $\Gamma[X_2 \to \gamma\psi(2S)]/\Gamma[X_2 \to \gamma J/\psi]$ is less than 1.0. Additionally, based on the estimation of the process $X_2 \to e^+e^-$, we expect that the planned Super τ-Charm Facility provides an opportunity to search for this new state in $\gamma J/\psi$ and $\gamma\psi(2S)$ final states.

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1. Introduction

In 2021, the Belle Collaboration reported on a hint of the existence of an isoscalar structure in the $\psi(2S)\gamma$ invariant mass distribution through the two-photon fusion process [1]. The measured mass and decay width of this structure are

$$\begin{aligned} M_{\mathrm{R}} &= (4014.3 \pm 4.0 \pm 1.5)\ \mathrm{MeV}\,, \\ \Gamma_{\mathrm{R}} &= (4 \pm 11 \pm 6)\ \mathrm{MeV}\,, \end{aligned} \tag{1}$$

and its global significance is 2.8σ. Assuming $J^{PC} = 2^{++}$ for its quantum numbers, the experiment provides

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$$\Gamma_{\rm R}^{\gamma\gamma}{\rm Br}(R \to \psi(2S)\gamma) = (1.2 \pm 0.4 \pm 0.2)\ {\rm eV}\,. \tag{2}$$

Here, $\Gamma_{\rm R}^{\gamma\gamma}$ is the two-photon decay width of this resonance.

The new structure is a perfect candidate for an isoscalar $D^*\bar{D}^*$ molecule, labeled X_2, with quantum numbers 2^{++}: The detection in the $\gamma\gamma$ fusion process suggests possible quantum numbers of 0^{++} or 2^{++}. In Ref. [2], the calculations within the hidden gauge approach indicate that the interaction between $D^*\bar{D}^*$ and the 2^{++} molecule is more attractive compared to the 0^{++} molecule[1]. This suggests that the formation of the 2^{++} molecule is more favorable than that of the 0^{++} molecule. Moreover, the experimental mass of the X_2 aligns with the predictions of the Heavy Quark Spin Symmetry (HQSS) [3, 4], since the mass splitting between X_2 and $X(3872)$ is approximately equal to that between the vector and pseudoscalar charmed mesons, *i.e.* $M_{X_2} - M_{X(3872)} \sim m_{D^*} - m_D \sim 140$ MeV. This implies that the interaction of $D\bar{D}^*$ is close to that of 2^{++} $D^*\bar{D}^*$, consistent with HQSS, where, at Leading Order (LO), the potentials for the $X(3872)$ and the 2^{++} $D^*\bar{D}^*$ channels are identical [3, 4]. In addition, the width of X_2 has the same order of magnitude as predicted in Refs. [5, 6]. In summary, the collected evidence strongly supports the interpretation of this new structure as the 2^{++} $D^*\bar{D}^*$ molecule.

In this presentation, we investigate the direct production of X_2 in e^+e^- collisions through a two-photon process $e^+e^- \to \gamma^*\gamma^* \to \gamma\psi \to X_2$ with $\psi = J/\psi,\ \psi(2S)$. The decay channel for $X_2 \to \gamma\psi$ is explored based on the HQSS in our previous work [7]. Based on the results of the $X_2 \to \gamma\psi$ decay and the partial width $X_2 \to \gamma\gamma$ in Ref. [8], we estimate the direct production rate of X_2 with the vector-meson dominance (VMD) model. This estimation is intended to provide insights into the search for X_2 in e^+e^- collisions, especially at the upcoming high-luminosity Super τ-Charm Facility (STCF) [9].

2. Radiative decay of X_2

The mechanism of the radiative $X_2 \to \gamma\psi$ decay can occur via loops with charmed mesons as the intermediate states. We construct the gauge-invariant amplitudes within the framework of HQSS, see Ref. [7] for details. To handle the loop integrals, we employ dimensional regularization. In particular, we adopt the $\overline{\rm MS}$ subtraction scheme. Due to the unknown strength of short-range interaction, we cannot directly estimate the contribution of the counterterms. To address this, we adopt a strategy outlined in Ref. [10], where the finite part of the counterterms is set to zero. To explore the scale

[1] Note that, in Ref. [2], the pole position of the 2^{++} molecule is significantly below the $D^*\bar{D}^*$ threshold.

dependence, we vary the renormalization scale μ within a broad range, from 1.5 GeV up to $2M_{X_2}$, where M_{X_2} denotes the mass of X_2. This allows us to observe how counterterms adapt to changes in μ, ensuring that our results remain independent of the specific choice of the renormalization scale. At the same time, the method is believed to provide an order of magnitude estimate for the finite parts of the counterterms.

Our calculations indicate that the partial width is significantly influenced by the energy scale μ, detailed in Ref. [7]. To explore the physical predictions, which should be independent of μ, we estimate the ratio for the partial widths of the $X_2 \to \gamma\psi(2S)$ and $X_2 \to \gamma J/\psi$ processes

$$R_{X_2} \equiv \frac{\mathrm{Br}\,(X_2 \to \gamma\psi(2S))}{\mathrm{Br}\,(X_2 \to \gamma J/\psi)}\,. \tag{3}$$

The ratio R_{X_2} as a function of μ is shown in Fig. 1. Two methods are used to determine the value of g_2'/g_2, where g_2' (g_2) denotes the coupling constant between charmed mesons and the charmonium $\psi(2S)$ (J/ψ). In the first approach, we directly set $g_2'/g_2 = 1.67$ based on the VMD model [11]. Alternatively, the value g_2'/g_2 can be constrained by the upper limit of the ratio $R_{X(3872)}$ reported by the BESIII Collaboration [12], where the $X(3872)$ is assumed to also be a molecular state. With $\mu = 1.5$ GeV, the upper limit for this ratio is $g_2'/g_2 < 2.34$. Remarkably, the ratio R_{X_2} in Fig. 1 exhibits barely any dependence on μ. Additionally, the flat variation of the double ratio $R_{X_2}/R_{X(3872)}$, as depicted in the right panel of Fig. 1, indicates that we can set any value of μ and estimate the upper limit of R_{X_2}. When we set $\mu = 1.5$ GeV, the upper limit of R_{X_2} is $R_{X_2} \lesssim 1.0$.

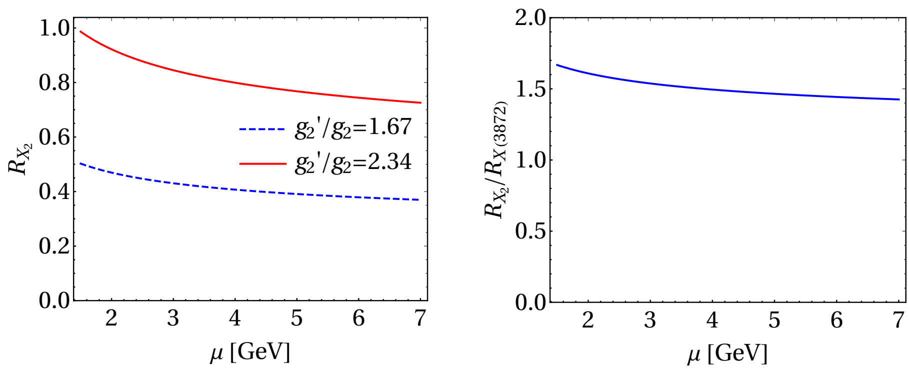

Fig. 1. The ratios for R_{X_2} and $R_{X_2}/R_{X(3872)}$ as a function of the energy scale μ.

Utilizing the upper limit of R_{X_2}, we can predict the signal yield of X_2 in the $\gamma J/\psi$ invariant mass distribution. Assuming equal efficiency and total integrated luminosity as the Belle data sample, the signal yield of X_2 in the

$\gamma J\psi$ final states is given by

$$N(X_2 \to \gamma J/\psi) = \frac{N(X_2 \to \gamma\psi(2S))}{R_{X_2}\mathrm{Br}[\psi(2S) \to \pi^+\pi^- J/\psi]}\,, \tag{4}$$

where the signal yield of X_2 in the $\gamma\psi(2S)$ channel is $N(X_2 \to \gamma\psi(2S)) = 19 \pm 7$ [12]. Considering the branching fraction for $\psi(2S) \to \pi^+\pi^- J/\psi$ as $(34.68 \pm 0.30)\%$ [13] and the upper limit of $R_{X_2} \lesssim 1.0$, the yield of X_2 is

$$N\,(X_2 \to \gamma J/\psi) \gtrsim 35\,. \tag{5}$$

Consequently, we estimate that at least 35 events of X_2 can be observed in the $\gamma J/\psi$ invariant mass distribution for the two-photon collision at Belle.

3. Production of X_2 in e^+e^- collisions

The direct production of the X_2 in e^+e^- collisions proceeds through the two-photon process, $e^+e^- \to \gamma^*\gamma^* \to X_2$. Under the time reversal and P-parity transformations, the same amplitudes appear in both processes $e^+e^- \to X_2$ and $X_2 \to e^+e^-$. Therefore, the difference between the production cross section and decay width is originated from the phase space. We can calculate the decay process $X_2 \to e^+e^-$ and from this also estimate the direct production cross section.

The decay of $X_2 \to e^+e^-$ can occur through intermediate states $\gamma\psi$ and $V\psi$ with $\psi = J/\psi,\ \psi(2S)$, and $V = \rho,\ \omega$. According to the calculation for the $X(3872) \to e^+e^-$ decay process, the contributions from $V\psi$ in the intermediate state are orders of magnitude smaller than those from $\gamma\psi$ [14]. As the spin-2 partner of $X(3872)$, we expect a similar hierarchy in contributions from $V\psi$ and $\gamma\psi$. Therefore, for the purpose of estimating the decay width in the $X_2 \to \gamma\psi \to e^+e^-$ process, we neglect the contributions of the $V\psi$ channels.

For the calculation of the $X_2 \to e^+e^-$ decay [9], the coupling constant for the interaction between $\gamma\psi(2S)$ and X_2 is determined by the partial width $\Gamma[X_2 \to \gamma\gamma] \simeq 0.1$ keV [8] and Eq. (2). Additionally, we use the upper limit of R_{X_2} in the above section to constrain the coupling for X_2 and $\gamma J/\psi$. The dimensional regularization within the $\overline{\mathrm{MS}}$ subtraction scheme is also employed to estimate the branching fraction for $X_2 \to e^+e^-$.

As listed in Table 1, our results exhibit that the branching fraction $X_2 \to e^+e^-$ falls within the range of 10^{-9}–10^{-8}. Considering the total width of X_2 as $\Gamma_{X_2} \sim 1$ MeV, the partial width of $X_2 \to e^+e^-$ is 10^{-3} eV. This value is an order of magnitude smaller than that of genetic charmonium [15, 16]. Alternatively, for $\Gamma_{X_2} \sim 10$ MeV, the partial width of X_2 is compatible with the charmonium picture. This suggests that investigating the electronic width provides valuable insights into the nature of X_2. To further compare the molecular and charmonium pictures for this state, we list their order-of-magnitude branching fractions in Table 2. The branching fractions of $\chi_{c2}(2P)$ are based on the predictions of various models [15–17]. The branching fraction $\chi_{c2}(2P) \to \gamma\psi$ is estimated using the relation in Eq. (2), assuming the charmonium nature of the new structure observed by Belle [1].

Table 1. The branching fraction of the $X_2 \to e^+e^-$ decay for different μ.

μ [GeV]	2.0	4.0	6.0
$\mathrm{Br}_{\mathrm{loop}}[X_2 \to e^+e^-] \times 10^9$	2	7	11

Table 2. The order-of-magnitude estimates for the branching fractions of various decays of the $D^*\bar{D}^*$ molecule and $\chi_{c2}(2P)$. The two values quoted for the two-photon decay of X_2 correspond to $\Gamma_{X_2} = 1$ MeV and $\Gamma_{X_2} = 10$ MeV, respectively.

Channel	$J/\psi\gamma$	$\psi(2S)\gamma$	$\gamma\gamma$	e^+e^-
X_2	10^{-2}	10^{-2}	$10^{-4}/10^{-5}$	10^{-9}
$\chi_{c2}(2P)$	10^{-3}	10^{-3}	10^{-4}	10^{-9}

The direct production rate of X_2 is [18]

$$\sigma_C \simeq \frac{20\pi}{M_{X_2}^2}\mathrm{Br}[X_2 \to e^+e^-] \simeq 7 \text{ pb}\,. \tag{6}$$

Since the expected integrated luminosity of the STCF is around 1 ab^{-1}/year [19], one expects that approximately $7\,\mathrm{pb} \times 1\,\mathrm{ab}^{-1} = 7 \times 10^6$ events will be directly produced in e^+e^- collisions. Considering the interpretations of this structure as either a generic charmonium $\chi_{c2}(2P)$ or a $D^*\bar{D}^*$ molecule, approximately $\mathcal{O}(10^2)$ to $\mathcal{O}(10^3)$ events could be reconstructed in the $J/\psi\gamma$ or $\psi(2S)\gamma$ channel annually, respectively. In conclusion, the STCF offers a promising opportunity for the direct search of X_2 in the $\gamma\psi$ invariant mass distribution.

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