PHYSICAL REVIEW D **102,** 116014 (2020)

Discovery potential for the LHCb fully charm tetraquark $X(6900)$ state via $\bar{p}p$ annihilation reaction

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(Received 2 August 2020; accepted 16 November 2020; published 18 December 2020)

Inspired by the observation of the fully-charm tetraquark $X(6900)$ state at LHCb, the production of $X(6900)$ in $\bar{p}p \to J/\psi J/\psi$ reaction is studied within an effective Lagrangian approach and Breit-Wigner formula. The numerical results show that the cross section of $X(6900)$ at the c.m. energy of 6.9 GeV is much larger than that from the background contribution. Moreover, we estimate dozens of signal events can be detected by the D0 experiment, which indicates that searching for the $X(6900)$ via antiproton-proton scattering may be a very important and promising way. Therefore, related experiments are suggested to be carried out.

DOI: 10.1103/PhysRevD.102.116014

I. INTRODUCTION

In recent decades, more and more exotic hadron states have been observed [1]. These exotic hadron states are not only conducive to the development of the hadron spectrum but also provide an important opportunity for us to better understand the multiquark states and strong interactions [2,3]. In the past years, the experimental explorations focus on the multiquark states composed of light and heavy quarks, while studies for the states composed entirely of heavy quarks are still very limited [1–3].

Very recently, the LHCb experiment reported a narrow structure, named $X(6900)$, in the J/ψ pair invariant mass spectrum with a significance level of more than 5σ [4]. Based on the simple model with interference, the mass and width of the $X(6900)$ resonance are measured to be

$$M = 6886 \pm 11 \pm 11 \text{ MeV}, \tag{1}$$

$$\Gamma = 168 \pm 33 \pm 69 \text{ MeV}, \tag{2}$$

respectively. Actually, based on various theoretical models, a lot of studies have been conducted on fully-heavy tetraquark states [5–32], which are important to reveal the structure and properties of the fully-heavy tetraquark states. After its observation, $X(6900)$ has inspired extensive studies on its underlying properties, where it is interpreted as a P-wave tetraquark state in a nonrelativistic quark model [27], the first radial excitation of $cc\bar{c}\,\bar{c}$ in an extended relativized quark model [28]. Besides, in the QCD sum rule framework, the narrow structure $X(6900)$ can be interpreted as a second radial excited S-wave tetraquark state [29] with $J^{PC} = 0^{-+}$ or a P-wave state [30] with 1^{-+}, respectively. In Refs. [31,32], the theoretical results indicate that there may exist the resonance states, with masses ranging between 6.3 to 7.4 GeV, and the quantum numbers $J^P = 0^+, 1^+$, and 2^+. In Ref. [33], the spin parity of the state formed by the two-vector system was discussed, and a possible method for determining its quantum number was given. In Refs. [34–36], the spectrum or mass of fully-heavy tetraquarks was discussed in diquark model with different approaches.

In addition to the study of the mass spectrum and the decay behavior of $X(6900)$, studying the production of $X(6900)$ through different scattering reactions is also very important and will help us to understand its nature as genuine states. For example, in Ref. [37], the production of

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the ground $cc\bar{c}\,\bar{c}$ with $J^{PC}=0^{++}, 2^{++}$ in pp collisions was calculated, and the upper limit of the cross section is about 40 fb for the four muons channel. In addition to pp collisions, determining the tetraquark states via the annihilation of positive and negative protons is usually an important and effective way [38–44]. In this work, the discovery potential for the tetraquark state $X(6900)$ via $\bar{p}p$ annihilation reaction will be investigated. One will estimate the cross section of $X(6900)$ production via $\bar{p}p\to J/\psi J/\psi$ reaction and analyze the corresponding background contribution. The theoretical results obtained will be an important theoretical basis for the $\bar{p}p$ annihilation experiment.

This paper is organized as follows. After the Introduction, we present the formalism for the production of $X(6900)$ in Sec. II. The numerical results of the $X(6900)$ production follow in Sec. III. Finally, the paper ends with a brief summary.

II. FORMALISM

A. $X(6900)$ production in $\bar{p}p$ annihilation

The Feynman diagram of the $\bar{p}p\to J/\psi J/\psi$ reaction via the s channel $X(6900)$ exchange is depicted in Fig. 1(a). For convenience, $X(6900)$ and J/ψ will be abbreviated as X and ψ, respectively.

For the production of the resonance $X(6900)$ in the s channel of $\bar{p}p\to\psi\psi$ reaction, the cross section can be calculated by the standard Breit-Wigner formula [1]

$$\sigma_X=\frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k_{\mathrm{in}}^2}\frac{\Gamma^2}{4}\left[\frac{\mathrm{Br}(X\to\bar{p}p)\mathrm{Br}(X\to\psi\psi)}{(W-W_0)^2+\Gamma^2/4}\right], \tag{3}$$

where W is the c.m. energy, J is the spin of the resonance $X(6900)$, and S_1 and S_2 are the spins of the initial antiproton and proton, respectively. Moreover, k_{in} is the c.m. momentum in the initial state, W_0 is the c.m. energy corresponding to the mass threshold of $X(6900)$, and Γ is the full width of $X(6900)$.

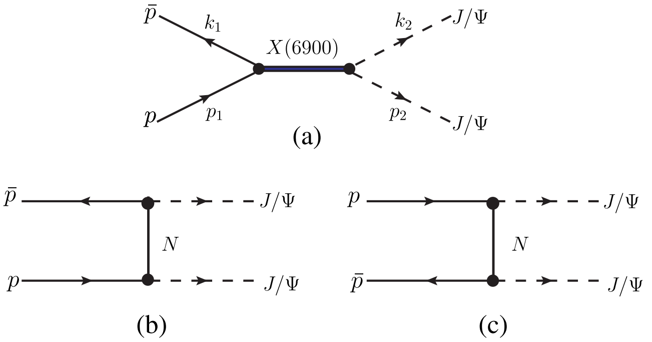

FIG. 1. Feynman diagrams for the reaction $\bar{p}p\to X(6900)\to\psi\psi$.

The production cross section of $X(6900)$ structure relative to that of all J/ψ pair, times the branching fraction $\mathrm{Br}(X\to\psi\psi)$, $\mathcal{R}$, is determined as $[2.6\pm0.6\,(\mathrm{stat})\pm0.8\,(\mathrm{syst})]\%$ by the LHCb experiment [4]. Therefore, in this work, we roughly take the value of the branching ratio $\mathrm{Br}(X\to\psi\psi)\simeq2\%$.

Having fixed the branch ratio $\mathrm{Br}(X\to\psi\psi)$, we turn to the value of $\mathrm{Br}(X\to\bar{p}p)$, which is indispensable in Eq. (3). However, it has never been determined in experiments. Meanwhile, we notice in Refs. [39,40] that the branching fractions of $\mathrm{Br}(Y(4260)\to\bar{p}p)$ and $\mathrm{Br}(\psi(4040)\to\bar{p}p)$ were estimated using the branching ratio of J/ψ state, multiplying by the ratio of the width of the $Y(4260)$ or $\psi(4040)$ to the width of J/ψ. Thus, in this work, we will adopt the same method as in Refs. [39,40] to naively determine the branching ratio of X decaying into $\bar{p}p$. Due to the lack of deep understanding of the fully-charm tetraquark $X(6900)$, its inner structure and quantum numbers are still unknown. Different J^{PC} assignments were assumed to evaluate the mass of a full-charm tetraquark, as discussed in Sec. I. To carry out the estimation of the cross section of the s channel, we assume that the quantum number J^{PC} of $X(6900)$ is 0^{++} or 2^{++}, the same as the assumption in Ref. [37]. In the known charmonium family, the spin parities of χ_{c0} and χ_{c2} are 0^{++} and 2^{++}, respectively. Therefore, we plan to simply replace J/ψ with χ_{c0} and χ_{c2} to estimate the branching ratio of $X\to\bar{p}p$, namely,

$$\mathrm{Br}(X\to\bar{p}p)\simeq\mathrm{Br}(\chi_{c0}\to\bar{p}p)\times\frac{\Gamma_{\chi_{c0}}}{\Gamma_X},\quad \text{for } X \quad \text{with} \quad J^{PC}=0^{++} \tag{4}$$

and

$$\mathrm{Br}(X\to\bar{p}p)\simeq\mathrm{Br}(\chi_{c2}\to\bar{p}p)\times\frac{\Gamma_{\chi_{c2}}}{\Gamma_X},\quad \text{for } X \quad \text{with} \quad J^{PC}=2^{++}, \tag{5}$$

where $\Gamma_{\chi_{c0}}=10.8$ MeV, $\Gamma_{\chi_{c2}}=1.97$ MeV, and $\Gamma_X=168$ MeV are the total width of χ_{c0}, χ_{c2}, and $X(6900)$ states, respectively. By taking the branching ratio $\mathrm{Br}(\chi_{c0}\to\bar{p}p)=2.24\times10^{-4}$ and $\mathrm{Br}(\chi_{c2}\to\bar{p}p)=7.33\times10^{-5}$, one gets $\mathrm{Br}(X\to\bar{p}p)=1.44\times10^{-5}$ for X with $J^{PC}=0^{++}$ and $\mathrm{Br}(X\to\bar{p}p)=8.6\times10^{-7}$ for X with $J^{PC}=2^{++}$. Here, it must be noted that if we use the branching ratio of J/ψ for estimation $\mathrm{Br}(X\to\bar{p}p)=1.17\times10^{-6}$ is obtained, which is just between the value estimated by the branching ratio of χ_{c0} and χ_{c2}.

B. Background analysis

Figures 1(b) and 1(c) present the $\bar{p}p\to\psi\psi$ reaction with the t and u channels by exchanging a nucleon, which can be considered as the main background contributions for the production of $X(6900)$. By employing the effective

Lagrangian approach, the cross section of the $\bar{p}p \to \psi\psi$ reaction can be calculated.

The Lagrangian density for the vertex of ψNN is written as [41]

$$\mathcal{L}_{\psi NN} = -g_{\psi NN}\bar{N}\gamma^{\mu}N\psi_{\mu}, \tag{6}$$

where ψ and N denote the fields of J/ψ and the nucleon, respectively.

The values of coupling constant $g_{\psi NN}$ can be derived from the corresponding decay width,

$$\Gamma_{\psi\to\bar{p}p} = (g_{\psi NN})^2 \frac{\sqrt{m_\psi^2 - 4m_N^2}}{12\pi m_\psi^2}(m_\psi^2 + 2m_N^2).$$

Thus, we get $g_{\psi NN} \simeq 1.6 \times 10^{-3}$, which is calculated by the measured branching fractions and total widths of J/ψ ($m_\psi = 3096.916$ MeV and $\Gamma_{\psi\to\bar{p}p} \simeq 0.197$ keV) [1].

Based on the above Lagrangians, the scattering amplitude for the reactions $\bar{p}p \to \psi\psi$ can be constructed as

$$-i\mathcal{M}_{\bar{p}p\to\psi\psi} = \epsilon_\psi^\nu(p_2)\bar{u}(p_1)\mathcal{A}_{\mu\nu}u(k_1)\epsilon_\psi^\mu(k_2), \tag{7}$$

where u is the Dirac spinor of the nucleon and ϵ_γ is the polarization vector of the photon.

The reduced amplitude $\mathcal{A}_{\mu\nu}$ for the t and u channel background reads

$$\mathcal{A}^t_{\mu\nu} = (g_{\psi NN}g_{\psi NN})\gamma_\nu \frac{\not{q}_t + m_N}{q_t^2 - m_N^2}\gamma_\mu \mathcal{F}_t^2(q_t^2), \tag{8}$$

$$\mathcal{A}^u_{\mu\nu} = (g_{\psi NN}g_{\psi NN})\gamma_\mu \frac{\not{q}_u + m_N}{q_u^2 - m_N^2}\gamma_\nu \mathcal{F}_u^2(q_u^2). \tag{9}$$

For two ψNN vertices, a general form factor $\mathcal{F}_t(q_t^2) = \mathcal{F}_u(q_u^2) = (\Lambda_{t/u}^2 - m_N^2)/(\Lambda_{t/u}^2 - q_N^2)$ is taken into account [41,43]. In Refs. [41,43], it can be found that the cross section of $\bar{p}p \to J/\psi\pi$ reaction with nucleon exchange was consistent with the E760 and E835 data by taking $\Lambda_{t/u} = 1.9$ and 3.0 GeV, respectively. In the spirit of estimating the upper limit of background contribution, in this work, we take $\Lambda_t = \Lambda_u = 3$ GeV.

With the preparation in the previous section, the cross section of the reaction $\bar{p}p \to \psi\psi$ can be calculated. The differential cross section in the c.m. frame is written as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{k}_2^{\text{c.m.}}|}{|\vec{k}_1^{\text{c.m.}}|}\left(\frac{1}{4}\sum_\lambda |\mathcal{M}|^2\right). \tag{10}$$

Here, $s = (k_1 + p_1)^2$, and θ denotes the angle of the outgoing J/ψ meson relative to $\bar{p}$ beam direction in the c.m. frame. $\vec{k}_1^{\text{c.m.}}$ and $\vec{k}_2^{\text{c.m.}}$ are the 3-momenta of the initial photon beam and final J/ψ meson, respectively.

III. NUMERICAL RESULTS

After the above preparations, we calculated the total cross section for the reaction $\bar{p}p \to \psi\psi$ from threshold to 12 GeV of the center of mass energy, as depicted in Fig. 2. As can be seen from the Fig. 2, the cross section from the $X(6900)$ contribution has a distinct peak near the center of mass energy of 6.9 GeV. Whatever J^{PC} assignment (0^{++} or 2^{++}) is chosen, the cross section of X production through the s channel can reach dozens of picobarns, which is much larger than the cross section from the background contribution. In addition, we also calculated the background cross section without the form factor (FF). Although the background cross section without FF is an order of magnitude higher than that with the FF added, it is still much lower than that of the s channel. The main reason for the very small background is that the $g_{\psi NN}$ coupling constant is very small.

The above results indicate that the best energy window for searching for the fully-charm tetraquark state $X(6900)$ via the $\bar{p}p \to \psi\psi$ process is near the c.m. energy 6.9 GeV, in which the signal can be clearly distinguished from background. The D0 [44] and the forthcoming PANDA [39] experiments are ideal platforms to study new hadronic states via $\bar{p}p$ reactions, of which the designed c.m. energy is below the double J/ψ threshold for the latter one. By taking the cross section of $X(6900)$ production calculated above, one finds that the number of events of $X(6900)$ can reach as many as dozens if taking an integrated luminosity of 10.4 fb^{-1} collected with the D0 detector, when a 50% selection efficiency is adopted. Considering that the background is very clean, it should be possible for $X(6900)$ to

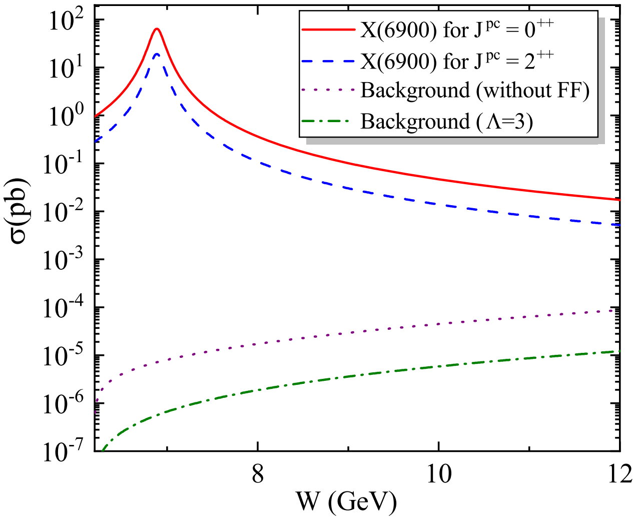

FIG. 2. The total cross section for the $\bar{p}p \to \psi\psi$ reaction. The red solid and blue dashed lines are for the cross section of $X(6900)$ production when the spin parity is $0++$ and $2++$, respectively. Moreover, the green dot-dashed and violet dotted lines are for the contributions from background with and without the form factor, respectively.

be observed by the D0 experiment with a high confidence level. It should be noted that the quantum number of $X(6900)$ has not been identified yet. However, to evaluate the production of $X(6900)$, the J^{PC} assignments of 0^{++} and 2^{++} are adopted in this work. The results indicate that the cross sections are at the same order of magnitude for both cases. It means that it may be an effective way to find $X(6900)$ through the $\bar{p}p$ annihilation.

IV. CONCLUSIONS

In this work, the $X(6900)$ production in the antiproton proton reaction is investigated by employing the effective field theory and the Breit-Wigner formula. We find that $\bar{p}p \to \psi\psi$ can be a suitable process to study the production of $X(6900)$. One finds that the cross section of X production can reach dozens of picobarns at the best energy window $W = 6.9$ GeV, which is much larger than that of the background. It means that the signal can be clearly distinguished from the background. Furthermore, according to our estimation, dozens of $X(6900)$ can be detected with a data sample of 10.4 fb^{-1} collected by the D0 detector, which indicates that it is feasible to find $X(6900)$ through the $\bar{p}p \to \psi\psi$ reaction. The results indicate that it is accessible to search for $X(6900)$ via $\bar{p}p$ annihilation.

It should be noted that the $p\bar{p}$ will be annihilated into gluons first and then those gluons will be converted into the di-J/ψ final state. The production of the fully-charm tetraquarks at LHC was discussed, and the relative cross section for the process $gg \to J/\psi J/\psi$ was estimated [45,46]. The cross sections performed are around 10 pb, which have the same order of magnitude as the results exhibited here.

ACKNOWLEDGMENTS

The authors would like to acknowledge Doctor Liupan An for useful discussions. This project is supported by the National Natural Science Foundation of China (Grants No. 12065014 and No. 11705076) and by the Strategic Priority Research Program of Chinese Academy of Sciences, Grant No. XDB34030301. This work is partly supported by HongLiu Support Funds for Excellent Youth Talents of Lanzhou University of Technology.

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