Hindawi Publishing Corporation
Advances in High Energy Physics
Volume 2015, Article ID 918231, 8 pages
http://dx.doi.org/10.1155/2015/918231

Research Article

Discovery Potential for the Neutral Charmonium-Like $Z^0(4200)$ by $\bar{p}p$ Annihilation

Xiao-Yun Wang[1,2,3] **and Xu-Rong Chen**[1,3]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China*

Correspondence should be addressed to Xiao-Yun Wang; xywang@impcas.ac.cn

Received 7 March 2015; Accepted 12 May 2015

Academic Editor: George Siopsis

Inspired by the observation of charmonium-like $Z(4200)$, we explore the discovery potential of the neutral $Z^0(4200)$ production by antiproton-proton annihilation with an effective Lagrangian approach. By investigating the $\bar{p}p \rightarrow J/\psi\pi^0$ process including the $Z^0(4200)$ signal and background contributions, it is found that the center of mass energy $E_{\text{c.m.}} \simeq 4.0$–$4.5$ GeV is the best energy window for searching the neutral $Z^0(4200)$, where the signal can be clearly distinguished from background. The relevant calculations not only are helpful to search for the neutral $Z^0(4200)$ in the future experiment but also will promote the understanding of the nature and production mechanism of neutral $Z^0(4200)$ better.

1. Introduction

In the conventional constituent quark model (CQM), all mesons can be described as quark-antiquark ($q\bar{q}$) states. Such as the charmonium state J/ψ, it is composed of a $c\bar{c}$ quark pair. However, a series of charmonium-like states (including $X(3872)$, $Y(4260)$, $Y(4008)$, $Z(3900)$, $Z(4025)$, $Z(4020)$, $Z(4050)$, $Z(4250)$, $Z(4430)$, and $Z(4200)$) have been observed in experiments [1–5], many of which do not fit into the $q\bar{q}$ meson spectrum in the classical CQM. In particular, some charged charmonium-like Z states are considered to have a minimal quark content of $|c\bar{c}u\bar{d}\rangle$ (Z^+) or $|c\bar{c}\bar{u}d\rangle$ (Z^-), which have attracted great interest in experimental and theoretical aspect [1–11]. These charmonium-like Z states are interpreted as a tetraquark, a hadron molecule or just a cusp effect, and so on [1, 7–11]. In addition, a series of hidden-charm baryons also have been investigated in [12–14], which were considered as the pentaquark candidates and composed of $|c\bar{c}qqq\rangle$. On the one hand, these studies enriched the picture of exotic states. On the other hand, it should be noted that our understanding of these exotic states is far from being sufficient. Thus, more theoretical and experimental works are needed.

Recently, a new charged charmonium-like $Z^+(4200)$ decaying to $J/\psi\pi^+$ has been observed by the Belle Collaboration with a significance of 6.2σ [5]. The relevant experiment results show that the spin-parity quantum number of $Z^+(4200)$ favors 1^+. Furthermore, its mass and width are measured to be [5]

$$M = 4196^{+31+17}_{-29-13}\ \text{MeV}/c^2,$$
$$\Gamma = 370^{+70+70}_{-70-132}\ \text{MeV}. \qquad (1)$$

It is noticed that the $Z^+(4200)$ has the largest width among those charmonium-like Z states which have been observed in experiment. In [7], by analyzing all the available experimental information about charmonium-like states within the framework of the color-magnetic interaction, the $Z(4200)$ was supposed to be a very promising candidate of the lowest axial-vector hidden-charm tetraquark state and its dominant decay should be $J/\psi\pi$. In [8–10], the relevant results also support the tetraquark interpretation of $Z(4200)$ in the frame of QCD sum rule. Moreover, with QCD sum rule approach, the $Z(4200)$ was described as the molecule-like state in [11]. These experimental and theoretical results indicate that the $Z(4200)$

is an ideal candidate for investigating and understanding the nature of exotic charmonium-like states.

As of now, the charmonium-like states are only observed in four ways including the $\gamma\gamma$ fusion process, e^+e^- annihilation, B meson decay, and hidden-charm dipion decays of higher charmonia or charmonium-like states. Obviously, it is an important topic to study the production of the charmonium-like state in different processes. As mentioned above, $Z(4200)$ was only observed in the B meson decay. It is natural to ask whether $Z(4200)$ can be found in other processes.

In addition, we note that searching for the neutral partner of the charmonium-like or bottomonium-like state also aroused the great interest in both experiment and theory. The first observation of neutral $Z_c(3900)$ has been reported by CLEO-c [15]. Later, the neutral bottomonium-like $Z_b^0(10610)$ and charmonium-like $Z_c^0(4020)$ have been observed by Belle and BESIII [16, 17], respectively. In theory, the production of the neutral $Z^0(4430)$ in $\bar{p}p \rightarrow \psi'(2s)\pi^0$ reaction was investigated in our previous work [18]. These studies not only help in confirming these charmonium-like states, but also open a window to investigate the nature and production mechanism of exotic state beyond the conventional $q\bar{q}$ states.

Since the $Z(4200)$ was observed in $J/\psi\pi$ channel [5] and its dominant decay mode is very likely to be $J/\psi\pi$ [7], the neutral $Z^0(4200)$ should has a coupling with $J/\psi\pi^0$. Besides, the tetraquark or molecule-like state can be regard as a general four-quark state [10], which means that the neutral $Z^0(4200)$ probably is composed of $|c\bar{c}u\bar{u}\rangle$ or $|c\bar{c}d\bar{d}\rangle$. According to the OZI rule [19–21], one can speculate that the partial decay width of $Z^0(4200) \rightarrow \bar{p}p$ may be larger than that of $J/\psi \rightarrow \bar{p}p$. Therefore, the $\bar{p}p \rightarrow J/\psi\pi^0$ reaction is probably an ideal channel for searching and studying the neutral $Z^0(4200)$.

In this work, with an effective Lagrangian approach, the production of neutral $Z^0(4200)$ in $\bar{p}p \rightarrow J/\psi\pi^0$ reaction is investigated for the first time. Furthermore, in light of the situations of PANDA detector at FAIR@GSI [22–24], the feasibility of searching the neutral $Z^0(4200)$ by $\bar{p}p$ annihilation is discussed, which can provide valuable information to future experimental exploration of neutral $Z^0(4200)$.

This paper is organized as follows. After an introduction, we present the investigated method and formalism for $Z^0(4200)$ production. In Section 3, the background contributions to the $J/\psi\pi^0$ final states are discussed. The numerical results are given in Section 4. Finally, This paper ends with the discussion and conclusion.

2. The $Z^0(4200)$ Yield by the Antiproton-Proton Scattering

It will be difficult to study $Z^0(4200)$ at quark-gluon level in the now energy range. Therefore, the effective Lagrangian method in terms of hadrons will be used in our research.

2.1. Feynman Diagrams and Effective Interaction Lagrangian Densities. The basic tree level Feynman diagram for the production of $Z^0(4200)$ in $\bar{p}p \rightarrow J/\psi\pi^0$ reaction through s-channel is depicted in Figure 1. For the $Z(4200)$, its quantum number of spin-parities has been determined by Belle Collaboration to be $J^P = 1^+$ [5]. Therefore, the relevant effective Lagrangian for the vertices of $Z\bar{p}p$ and $Z\psi\pi$ (for simplicity, we use Z and ψ to denote $Z^0(4200)$ and $J\psi$, resp.) read as [25]:

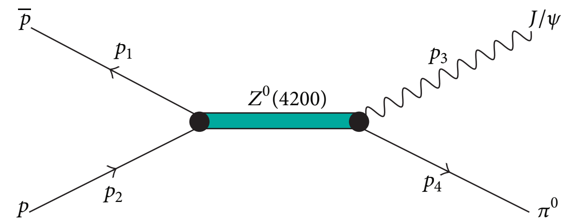


FIGURE 1: The production of $Z^0(4200)$ through $p\bar{p}$ collision.

$$\mathcal{L}_{Z\bar{p}p} = g_{Z\bar{p}p}\bar{\phi}_{\bar{p}}\gamma^{\mu}\gamma_5\phi_p Z_{\mu},$$
$$\mathcal{L}_{Z\psi\pi} = \frac{g_{Z\psi\pi}}{M_Z}\left(\partial^{\mu}\psi^{\nu}\partial_{\mu}\pi Z_{\nu} - \partial^{\mu}\psi^{\nu}\partial_{\nu}\pi Z_{\mu}\right), \quad (2)$$

where Z, ψ, and ϕ denote the fields of $Z(4200)$, J/ψ, and nucleon, respectively. The $g_{Z\bar{p}p}$ and $g_{Z\psi\pi}$ are the coupling constants. Considering the size of the hadrons, we introduce the general form factor for the intermediate $Z^0(4200)$ as used in [26–28]:

$$\mathcal{F}_Z\left(q^2\right) = \frac{\Lambda_Z^4}{\Lambda_Z^4 + \left(q^2 - M_Z^2\right)^2}, \quad (3)$$

where q, M_Z, and Λ_Z are the 4-momentum, mass, and cut-off parameters for the intermediate $Z^0(4200)$, respectively.

2.2. Coupling Constants and the OZI Analysis in the Process of $Z^0(4200) \rightarrow \bar{p}p$. With the effective Lagrangians above, the coupling constants $g_{Z\bar{p}p}$ and $g_{Z\psi\pi}$ can be determined by the partial decay widths $\Gamma_{Z^0(4200)\rightarrow\bar{p}p}$ and $\Gamma_{Z^0(4200)\rightarrow J/\psi\pi^0}$, respectively:

$$\Gamma_{Z^0(4200)\rightarrow\bar{p}p} = \left(g_{Z\bar{p}p}\right)^2 \frac{2}{3\pi M_Z^2}\left|\vec{p}_N^{\,\mathrm{c.m.}}\right|^3,$$
$$\Gamma_{Z^0(4200)\rightarrow J/\psi\pi^0} = \left(\frac{g_{Z\psi\pi}}{M_Z}\right)^2 \frac{\left|\vec{p}_\pi^{\,\mathrm{c.m.}}\right|}{24\pi M_Z^2} \cdot \left[\frac{\left(M_Z^2 - m_\psi^2 - m_\pi^2\right)^2}{2} + m_\psi^2 E_\pi^2\right], \quad (4)$$

with

$$\left|\vec{p}_N^{\,\mathrm{c.m.}}\right| = \frac{\lambda^{1/2}\left(M_Z^2, m_{\bar{p}}^2, m_p^2\right)}{2M_Z},$$
$$\left|\vec{p}_\pi^{\,\mathrm{c.m.}}\right| = \frac{\lambda^{1/2}\left(M_Z^2, m_\psi^2, m_\pi^2\right)}{2M_Z}, \quad (5)$$
$$E_\pi = \sqrt{\left|\vec{p}_\pi^{\,\mathrm{c.m.}}\right|^2 + m_\pi^2},$$

where λ is the Källen function with $\lambda(x,y,z) = (x-y-z)^2 - 4yz$.

As of now, no relevant experiment data about $\Gamma_{Z(4200)\to\overline{p}p}$ and $\Gamma_{Z(4200)\to J/\psi\pi}$ are available [29]. However, in [10, 11] the decay widths $\Gamma_{Z(4200)\to J/\psi\pi} = 87.3 \pm 47.1$ MeV or $\Gamma_{Z_c(4200)\to J/\psi\pi} = 24.6$ MeV were obtained with QCD sum rule by assuming that the $Z(4200)$ is a tetraquark state or molecule-like state, respectively. Thus we get the coupling constants $g_{Z\psi\pi}/M_z = 1.73, 0.918\ \mathrm{GeV}^{-1}$, which correspond to the partial decay width $\Gamma_{Z(4200)\to J/\psi\pi} = 87.3, 24.6$ MeV.

For the partial decay width of $Z^0(4200) \to \overline{p}p$, we try to obtain it by analyzing and comparing with the OZI suppressed process of $J/\psi \to \overline{p}p$. According to constituent quark model, the traditional charmonium J/ψ is regarded as a pure $c\overline{c}$ state, while there are only up and down quarks (antiquarks) in the proton (antiproton). Thus the $J/\psi \to \overline{p}p$ decay is actually a disconnected process and at least needs three gluons to connect it (as shown in Figure 2(a)). In the frame of the Okubo-Zweig-Iizuka (OZI) rule [19–21], the incidence of $J/\psi \to \overline{p}p$ process is greatly suppressed. With the total decay width and branch ratios of J/ψ listed in PDG [29], one get the partial decay width $\Gamma_{J/\psi\to\overline{p}p} \simeq 0.2$ keV, which is indeed a small value and consistent with the prediction by OZI rule [19–21]. Since the neutral $Z^0(4200)$ may have minimal quark content of $(c\overline{c}u\overline{u})$ or $(c\overline{c}d\overline{d})$, as seen in Figure 2(b), the $Z^0(4200) \to \overline{p}p$ reaction is a connected whole and it is an OZI allowed process [19–21]. Therefore, in principle, the probability of $Z^0(4200)$ decay to $\overline{p}p$ should be higher than $J/\psi \to \overline{p}p$, which may be part of reason that the total decay width of $Z(4200)$ is 3 orders larger than the total width of J/ψ. Accordingly we speculate that the partial width $\Gamma_{Z^0(4200)\to\overline{p}p}$ may well be at least three magnitudes larger than $\Gamma_{J/\psi\to\overline{p}p}$. Then we get $g_{Z\overline{p}p} \simeq 0.05$ by taking $\Gamma_{Z^0(4200)\to\overline{p}p} = 200$ keV.

2.3. Amplitude. Following the Feynman rules and using the above Lagrangian densities, we can obtain the invariant amplitude $\mathscr{M}_Z^{\text{signal}}$ for the $\overline{p}(p_1)p(p_2) \to J/\psi(p_3)\pi^0(p_4)$ reaction through s-channel as shown in Figure 1:

$$\begin{aligned}\mathscr{M}_Z^{\text{signal}} = {} & \frac{g_{Z\overline{p}p}g_{Z\psi\pi}\mathscr{F}_Z(q^2)}{M_z}\varepsilon^{\nu}(p_3) \\ & \cdot\left(p_3\cdot p_4 g_{\mu\nu} - p_{3\mu}p_{4\nu}\right) \\ & \cdot G_Z^{\mu\alpha}(q)\,\overline{v}(p_1)\,\gamma_\alpha\gamma_5 u(p_2),\end{aligned} \tag{6}$$

where $G_Z^{\mu\alpha}$ are the propagators of the $Z^0(4200)$, taking the Breit-Wigner form [30]:

$$G_Z^{\mu\alpha}(q) = i\frac{\mathscr{P}^{(1)}}{q^2 - M_Z^2 + iM_Z\Gamma_Z}. \tag{7}$$

Here

$$\mathscr{P}^{(1)} = \sum_{\text{spins}} \varepsilon^{\mu}\cdot\varepsilon_\alpha^{*} = \tilde{g}^{\mu\alpha}(q) = -g^{\mu\alpha} + \frac{q^{\mu}q^{\alpha}}{q^2} \tag{8}$$

is the projection operator for the state with spin-1.

3. The Background Analysis and Cross Section

Figure 3 shows the $\overline{p}(p_1)p(p_2) \to J/\psi(p_3)\pi^0(p_4)$ process through t-channel (a) and u-channel (b) by exchanging a proton, which can be regarded as the main background contributions for the production of $Z^0(4200)$ as described in Figure 1.

The Lagrangian densities for the vertices of $\overline{p}p\pi^0$ and $J/\psi\overline{p}p$ read as [31]

$$\begin{aligned}\mathscr{L}_{\overline{p}p\pi^0} &= -ig_{\overline{p}p\pi}\overline{\phi}_{\overline{p}}\gamma_5\tau\cdot\pi\phi_p, \\ \mathscr{L}_{\overline{p}p\psi} &= -g_{\overline{p}p\psi}\overline{\phi}_{\overline{p}}\gamma^{\mu}\phi_p\psi_\mu,\end{aligned} \tag{9}$$

where ψ and ϕ denote the fields of J/ψ and nucleon, respectively, while τ is Pauli matrix.

The coupling constant $g_{\overline{p}p\pi} = 13.5$ is adopted [32], while coupling constant $g_{\overline{p}p\psi}$ is determined by partial decay widths:

$$\Gamma_{\psi\to\overline{p}p} = \left(g_{\overline{p}p\psi}\right)^2\frac{\left|\vec{p}_{\text{c.m.}}\right|}{6\pi m_\psi^2}\left(m_\psi^2 + 2m_p^2\right) \tag{10}$$

with

$$\vec{p}_{\text{c.m.}} = \frac{\sqrt{m_\psi^2 - 4m_p^2}}{2}. \tag{11}$$

Thus we get $g_{\overline{p}p\psi} \simeq 1.6\times10^{-3}$, which is calculated by the measured branching fractions and total widths of J/ψ ($m_\psi = 3096.916$ MeV and $\Gamma_\psi = 92.9$ keV) [29].

The monopole form factors for the $\overline{p}p\pi^0$ and $J/\psi\overline{p}p$ vertices are introduced as the same as Bonn potential model [33]:

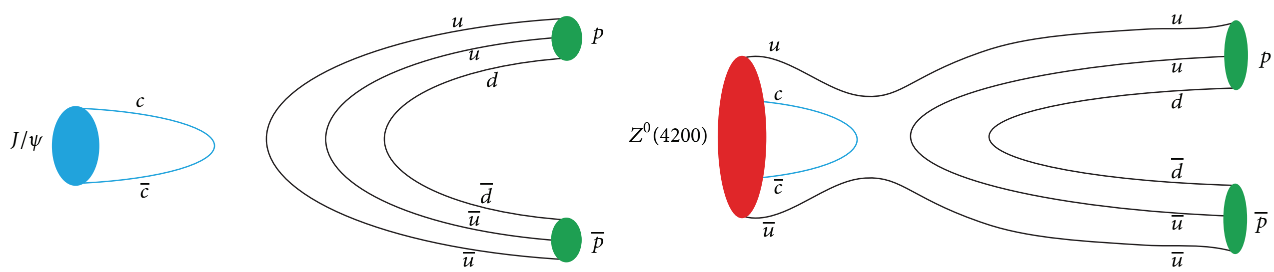
$$\mathscr{F}\left(q_i^2\right) = \frac{\Lambda_N^2 - m_p^2}{\Lambda_N^2 - q_i^2}, \quad i = t, u, \tag{12}$$

where Λ_N, m_p, and q_i ($q_t = (p_3 - p_1)$ and $q_u = (p_4 - p_1)$) are the cut-off parameter, mass, and four momentums of the exchanged proton, respectively.

According to the Feynman rules and the above equations, the full invariant amplitude $\mathscr{M}_N = \mathscr{M}_N^t + \mathscr{M}_N^u$ for the background as depicted in Figure 3 can be obtained:

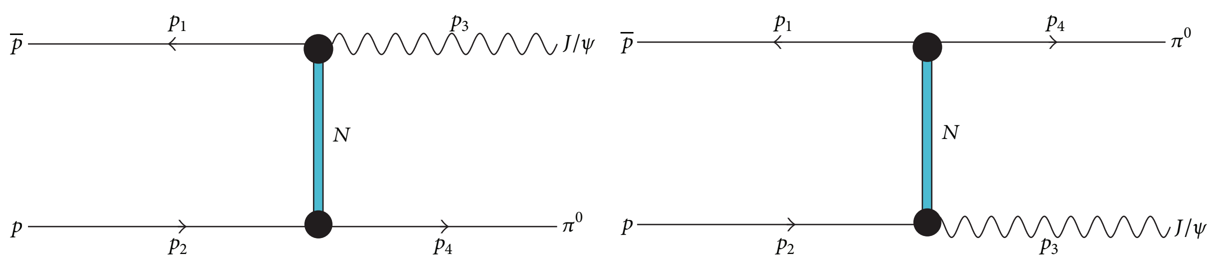
$$\begin{aligned}\mathscr{M}_N = {} & \mathscr{M}_N^t + \mathscr{M}_N^u = g_{\overline{p}p\pi}g_{\overline{p}p\psi}\overline{v}_{\overline{p}}(p_1) \\ & \cdot\left\{\gamma_\mu\varepsilon^{\mu}(p_3)\frac{\not{q}_t + m_p}{q_t^2 - m_p^2}\gamma^5\mathscr{F}^2\left(q_t^2\right)\right. \\ & \left. + \gamma^5\frac{\not{q}_u + m_p}{q_u^2 - m_p^2}\gamma_\mu\varepsilon^{\mu}(p_3)\mathscr{F}^2\left(q_u^2\right)\right\}u_p(p_2).\end{aligned} \tag{13}$$

With the amplitudes listed in (6) and (13), we get the square of the total invariant amplitude (in principle, the interference between amplitudes for the signal and the nonresonant background should be considered; since we do not now have experimental data, we take the relative phase between different amplitudes as zero in the present work; thus the total



(a) (b)

Figure 2: The quark level diagram depicting $J/\psi \to \bar{p}p$ decay (a) and $Z^0(4200) \to \bar{p}p$ decay (b).



(a) (b)

Figure 3: Feynman diagrams for the nucleon exchange in $\bar{p}p \to J/\psi\pi^0$ reaction.

cross section for the $\bar{p}p \to J/\psi\pi^0$ process obtained by us is an upper estimate):

$$|\mathcal{M}|^2 = \sum \left|\mathcal{M}_Z^{\text{signal}} + \mathcal{M}_N\right|^2. \tag{14}$$

We define $s = q^2 = (p_1 + p_2)^2$, and then the unpolarized differential cross section for the reaction $\bar{p}(p_1)p(p_2) \to J/\psi(p_3)\pi^0(p_4)$ at the center of mass (c.m.) frame is as follows:

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{\left|\vec{p}_3^{\text{ c.m.}}\right|}{\left|\vec{p}_1^{\text{ c.m.}}\right|}\left(\frac{1}{4}\sum_{\text{spins}}|\mathcal{M}|^2\right), \tag{15}$$

where $\vec{p}_1^{\text{ c.m.}}$ and $\vec{p}_3^{\text{ c.m.}}$ are the three momentums of initial antiproton and final J/ψ, while θ denotes the angle of the outgoing J/ψ meson relative to the antiproton beam direction in the c.m. frame. The total cross section can be easily obtained by integrating the above equation.

4. Numerical Results and Discussion

With the formalisms and equations determined above, we calculate the total and differential cross section including both signal and background contributions as presented in Figures 4–7.

In these calculations, we note that the cut-off parameter related to the form factor is the only free parameter. Therefore, first we need to discuss the effect of cut-off parameter on cross section of signal and background.

We present the variation of the cross section from the s-channel signal contribution for $\bar{p}p \to J/\psi\pi^0$ reaction with

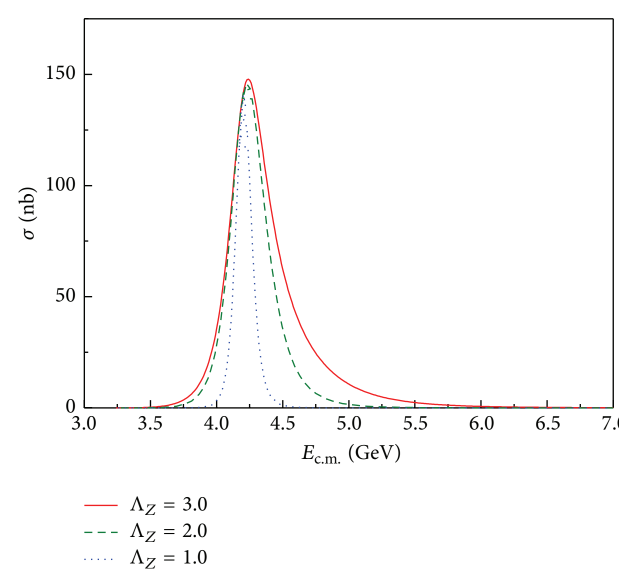


Figure 4: The energy dependence of cross section for the production of $Z^0(4200)$ through s-channel with the different typical cut-off Λ_Z. Here, the partial decay width is taken as $\Gamma_{Z(4200)\to J/\psi\pi} = 87.3$ MeV.

different cut-off parameters Λ_Z as shown in Figure 4, where Λ_Z is taken as 1.0–3.0 GeV with the step of 1.0 GeV.

One notices that there is an obvious peak structure at center-mass energy $E_{\text{c.m.}} \simeq 4.2$ GeV which is near the threshold of $Z(4200)$. Moreover, the cross section of signal increases with the increasing of cut-off parameter Λ_Z, but

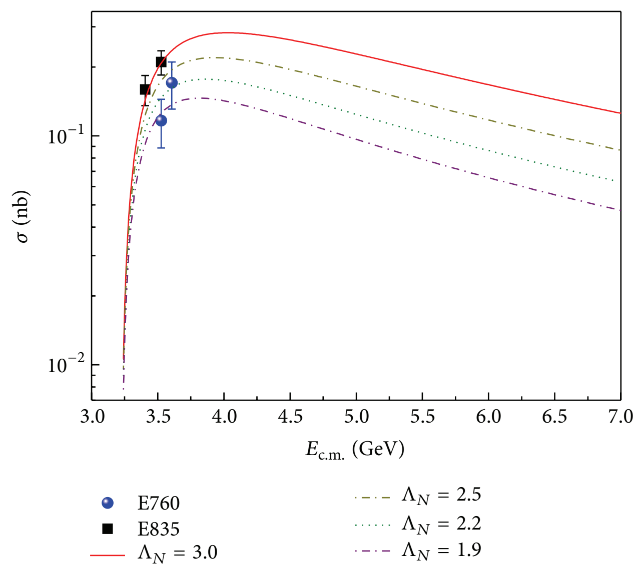


FIGURE 5: The contribution of background from the proton exchange for $\bar{p}p \rightarrow J/\psi\pi^0$ reaction though t-channel and u-channel with different typical cut-off Λ_N. The data are taken from [34–36].

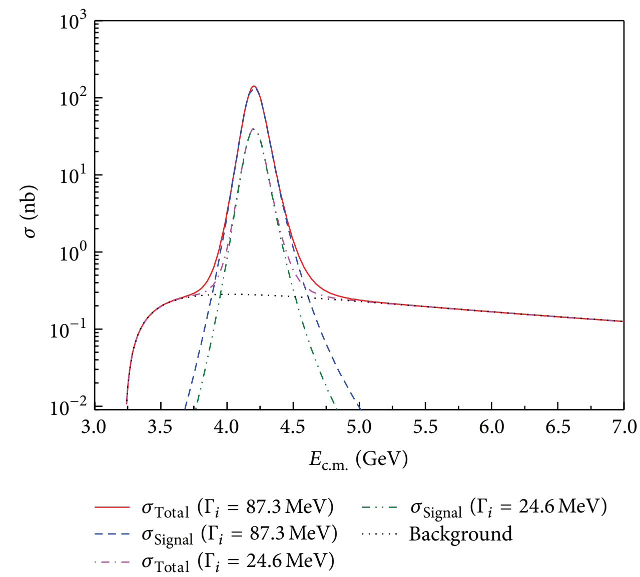


FIGURE 6: The energy dependence of the total cross sections for the process of $\bar{p}p \rightarrow J/\psi\pi^0$ with two typical values of Γ_i, where Γ_i denotes the decay width of $Z(4200) \rightarrow J/\psi$. Here, the σ_{Total} and σ_{Signal} are the total cross section and the cross section of signal, respectively.

at a modest rate. In particular, in the range of $4.0\,\text{GeV} \lesssim E_{\text{c.m.}} \lesssim 4.5\,\text{GeV}$, it is found that the cross sections from signal contributions are not sensitive to the cut-off parameter Λ_Z. We take typical value $\Lambda_Z = 1.0\,\text{GeV}$ in the following, which can ensure the cross sections of signal are limited to a smaller value.

In Figure 5, we illustrate the proton exchange contributions with different cut-off parameters Λ_N, which is obvious that the cross sections from background contributions are sensitive to the values of the cut-off Λ_N. Fortunately, the reaction $\bar{p}p \rightarrow J/\psi\pi^0$ has been measured by the E760 and E835 experiment at low energy [34–36], which can help us to constrain the cut-off parameter Λ_N. From Figure 5 it can be found that the numerical results from the proton exchange contributions are consistent with the E760 and E835 data by taking $\Lambda_N = 1.9$ and $3.0\,\text{GeV}$, respectively. Based on the consideration of seeking a larger limit for the cross section of background, we take $\Lambda_N = 3.0\,\text{GeV}$ in the next calculation. Besides, we notice that the amplitude estimate of $\bar{p}p \rightarrow J/\psi\pi^0$ is about 0.3 nb at $E_{\text{c.m.}} = 3.5$–$3.6\,\text{GeV}$ in [37]. This value is closer to the E835 data [35, 36] if we consider its uncertainty. Thus we taking $\Lambda_N = 3.0\,\text{GeV}$ in our calculation should be reasonable.

Figure 6 shows the total cross sections for $\bar{p}p \rightarrow J/\psi\pi^0$ reaction including both signal and background contributions by taking $\Lambda_Z = 1.0\,\text{GeV}$ and $\Lambda_N = 3.0\,\text{GeV}$. We notice that the cross section of $Z^0(4200)$ production goes up very rapidly and has a peak around $E_{\text{c.m.}} \simeq 4.2\,\text{GeV}$. Besides, it is found that the contributions from the signal are dominant in the region of $4.0\,\text{GeV} \lesssim E_{\text{c.m.}} \lesssim 4.5\,\text{GeV}$. Naturally, we can conclude that $4.0\,\text{GeV} \lesssim E_{\text{c.m.}} \lesssim 4.5\,\text{GeV}$ is the best energy window for searching the neutral charmonium-like $Z^0(4200)$ in experiment, in which the signal can be clearly distinguished from background. Around the center of mass $E_{\text{c.m.}} \simeq 4.2\,\text{GeV}$, the total cross section from signal and background contributions is on the order of $0.14\,\mu\text{b}$ and $0.04\,\mu\text{b}$, which correspond to the decay width $\Gamma_{Z^0(44200) \rightarrow J/\psi\pi^0} = 87.3\,\text{MeV}$ and $\Gamma_{Z^0(44200) \rightarrow J/\psi\pi^0} = 24.6\,\text{MeV}$, respectively.

As mentioned above, the PANDA detector at FAIR [22–25] is an ideal platform searching for the $Z^0(4200)$ by $\bar{p}p$ collision. With a $\bar{p}$ beam of $15\,\text{GeV}/c$ [22–25] one has $E_{\text{c.m.}} = 5.47\,\text{GeV}$, which allows one to observe charmonium-like $Z^0(4200)$ state in $J/\psi\pi^0$ production up to a mass $M_Z \simeq 4.2\,\text{GeV}$. Assuming the integrated luminosity of PANDA can reach up to $1.5\,\text{fb}^{-1}$ per year [22–25], taking $\sigma_{\text{total}} \approx 0.04$–$0.14\,\mu\text{b}$, one can expect about 6×10^7–2.1×10^8 events per year for the production of $J/\psi\pi^0$ at $E_{\text{c.m.}} \simeq 4.2\,\text{GeV}$, which are enough to meet the requirement of the experiment. At present, except for the $Z(4200)$, other charmonium-like Z states (such as $Z(3900)$, $Z(4025)$, and $Z(4430)$) were also observed in the $J/\psi\pi$ invariant mass. Since all of them have probably the identical quantum numbers $J^P = 1^+$, the interference of each other is possible. The above situation indicates that the contributions from other Z^0 may be significant for the $\bar{p}p \rightarrow J/\psi\pi^0$ process. However, in this work, we focus only on the $Z^0(4200)$ state and do not consider the contributions from other Z^0 states.

Figure 7 shows the differential cross section including both signal and background contributions at the center of mass energy $E_{\text{c.m.}} = 4.0$, 4.2, 4.5, and 5 GeV. We notice that the line shape of total differential cross section is less affected by background and almost coincident with the line shape of signal differential cross section at $E_{\text{c.m.}} = 4.0$–$4.5\,\text{GeV}$, which are consistent with the calculations as presented in Figure 6.

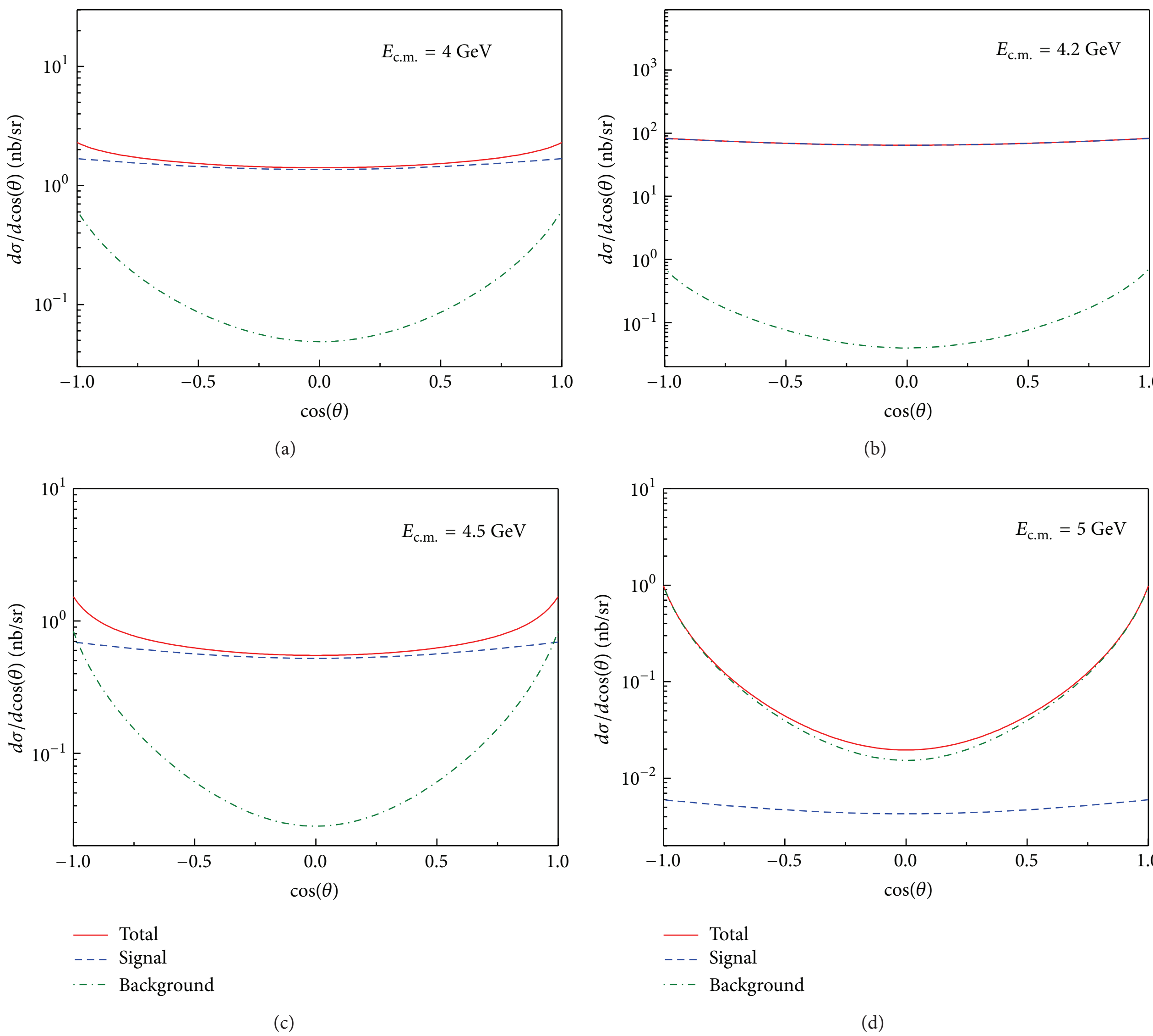


FIGURE 7: The differential cross sections for the process of $\bar{p}p \rightarrow J\psi\pi^0$ at different center of mass energy $E_{c.m.}$ = 4.0, 4.2, 4.5, and 5 GeV, where the "Total" denotes the differential cross section including both signal and background contributions. Here, the partial decay width is taken as $\Gamma_{Z(4200)\rightarrow J/\psi\pi}$ = 87.3 MeV.

In comparison, it is found that the shapes of total angular distributions are different from the shapes of signal angular distributions at $E_{c.m.}$ = 5 GeV, which due to the background has a strong effect on the total cross section at $E_{c.m.}$ = 5 GeV. These predictions can be checked by the future experiment.

5. Discussion and Conclusion

In this work, we investigate the neutral $Z^0(4200)$ production in $\bar{p}p \rightarrow J/\psi\pi^0$ reaction with an effective Lagrangian approach. Our numerical result indicates that the $\bar{p}p \rightarrow J/\psi\pi^0$ is very likely an ideal channel to study and search for the neutral hidden-charm $Z^0(4200)$. Furthermore, it is found that the center of mass energy $E_{c.m.} \simeq$ 4.0–4.5 GeV is the best energy window for searching the neutral $Z^0(4200)$, in which the signal can be easily distinguished from background. Moreover, according to our estimation, enough $Z^0(4200)$ events near $E_{c.m.} \simeq$ 4.2 GeV can be produced at PANDA, which indicate that searching for the neutral $Z^0(4200)$ by $\bar{p}p$ annihilation at PANDA is feasible. Besides, since our calculations are carried out in the premise of assuming that the $Z^0(4200)$ has a coupling with $\bar{p}p$ and $J/\psi\pi^0$, the near future experiments at LHC and BelleII will be able to check our predictions on the respective coupling strengths of the $Z^0(4200)$.

It should be mentioned that the value of coupling constant $g_{Z\bar{p}p}$ is determined by analyzing and comparing the degree of OZI suppressed in the process of $Z^0(4200) \rightarrow \bar{p}p$ and $J/\psi \rightarrow \bar{p}p$, which is based on the assumption of the neutral $Z^0(4200)$ which may be composed of $|c\bar{c}u\bar{u}\rangle$ or $|c\bar{c}d\bar{d}\rangle$. According our estimate, even if taking $\Gamma_{Z^0(4200)\rightarrow\bar{p}p}$ = 20 keV (this value is one order smaller than that which we used in the above calculations) and $\Gamma_{Z^0(44200)\to J/\psi\pi^0} = 24.6$ MeV, the cross section from signal $Z^0(4200)$ contributions by $\bar{p}p$ annihilation at $E_{\mathrm{c.m.}} \simeq 4.2$ GeV could still reach up to the level of 4 nb which is at least one order higher than that of background. This means that an obvious bump at $E_{\mathrm{c.m.}} \simeq 4.2$ GeV can be expected to appear in the $\bar{p}p \to J/\psi\pi^0$ process. Thus, we strongly suggest that the relevant experiment can be carried out, which will not only be conducive to verify the existence of $Z(4200)$ but also enable us to have a more comprehensive understanding of the nature of exotic states and OZI rule.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge Ju-Jun Xie for useful comments. Xiao-Yun Wang is grateful to Dr. Qing-yong Lin for valuable discussions and help. This project is partially supported by the National Basic Research Program (973 Program Grant no. 2014CB845406), the National Natural Science Foundation of China (Grant no. 11175220), and the One Hundred Person Project of Chinese Academy of Sciences (Grant no. Y101020BR0).

References

[1] X. Liu, "An overview of *XYZ* new particles," *Chinese Science Bulletin*, vol. 59, no. 29-30, pp. 3815–3830, 2014.

[2] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Measurement of the X(3872) production cross section via decays to $J/\psi\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV," *Journal of High Energy Physics*, vol. 1304, article 154, 2013.

[3] K. Chilikin, R. Mizuk, I. Adachi et al., "Experimental constraints on the spin and parity of the $Z(4430)^+$," *Physical Review D*, vol. 88, Article ID 074026, 2013.

[4] R. Aaij, B. Adeva, M. Adinolfi et al., "Observation of the resonant character of the $Z(4430)^-$ state," *Physical Review Letters*, vol. 112, Article ID 222002, 2014.

[5] K. Chilikin, R. Mizuk, I. Adachi et al., "Observation of a new charged charmoniumlike state in $\bar{B}^0 \to J/\psi K^-\pi^+$ decays," *Physical Review D*, vol. 90, Article ID 112009, 2014.

[6] T. M. Aliev, H. Özşahin, and M. Savcı, "More about the mass of the new charmonium states," *Advances in High Energy Physics*, vol. 2015, Article ID 728098, 7 pages, 2015.

[7] L. Zhao, W. Z. Deng, and S. L. Zhu, "Hidden-charm tetraquarks and charged Z_c states," *Physical Review D*, vol. 90, Article ID 094031, 2014.

[8] W. Chen and S. L. Zhu, "Vector and axial-vector charmonium-like states," *Physical Review D*, vol. 83, no. 3, Article ID 034010, 18 pages, 2011.

[9] W. Chen and S. L. Zhu, "Spin-1 charmonium-like states in QCD sum rule," *The European Physical Journal Conferences*, vol. 20, Article ID 01003, 2012.

[10] W. Chen, T. G. Steele, H.-X. Chen, and S.-L. Zhu, "$Z_c(4200)^+$ decay width as a charmonium-like tetraquark state," http://arxiv.org/abs/1501.03863.

[11] Z. G. Wang, "Analysis of the $Z_c(4200)$ as axial-vector molecule-like state," http://arxiv.org/abs/1502.01459.

[12] J. J. Wu, R. Molina, E. Oset, and B. S. Zou, "Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV," *Physical Review Letters*, vol. 105, no. 23, Article ID 232001, 4 pages, 2010.

[13] J. J. Wu, R. Molina, E. Oset, and B. S. Zou, "Dynamically generated N^* and Λ^* resonances in the hidden charm sector around 4.3 GeV," *Physical Review C*, vol. 84, Article ID 015202, 2011.

[14] X. Y. Wang and X. R. Chen, "The production of hidden charm baryon $N^*(4261)$ from $\pi^- p \to \eta_c n$ reaction," *Europhysics Letters*, vol. 109, p. 41001, 2015.

[15] T. Xiao, S. Dobbs, A. Tomaradze, and K. K. Seth, "Observation of the charged hadron $Z_c^\pm(3900)$ and evidence for the neutral $Z_c^0(3900)$ in $e^+e^- \to \pi\pi J/\psi$ at $\sqrt{s} = 4170$ MeV," *Physics Letters B*, vol. 727, no. 4-5, pp. 366–370, 2013.

[16] P. Krokovny, A. Bondar, I. Adachi et al., "First observation of the $Z_b^0(10610)$ in a Dalitz analysis of $\Upsilon(10860) \to \Upsilon(nS)\pi^0\pi^0$," *Physical Review D*, vol. 88, Article ID 052016, 2013.

[17] M. Ablikim, M. N. Achasov, X. C. Ai et al., "Observation of $e^+e^- \to \pi^0\pi^0 h_c$ and a neutral charmoniumlike structure $Z_c(4020)^0$," *Physical Review Letters*, vol. 113, no. 21, Article ID 212002, 8 pages, 2014.

[18] X. Y. Wang, J. J. Xie, and X. R. Chen, "Production of the neutral $Z^0(4430)$ in $\bar{p}p \to \psi'\pi^0$ reaction," *Physical Review D*, vol. 91, Article ID 014032, 2015.

[19] S. Okubo, "Some consequences of unitary symmetry model," *Physics Letters B*, vol. 4, pp. 14–16, 1963.

[20] G. Zweig, CERN Reports No. 8419/TH412, 1964.

[21] J. Iizuku, "A systematics and phenomenology of meson family," *Progress of Theoretical Physics Supplement*, vol. 38, p. 21, 1966.

[22] W. Erni, I. Keshelashvili, B. Krusche et al., "Physics performance report for PANDA: strong interaction studies with antiprotons," http://arxiv.org/abs/0903.3905.

[23] U. Wiedner, "Future prospects for hadron physics at PANDA," *Progress in Particle and Nuclear Physics*, vol. 66, no. 3, pp. 477–518, 2011.

[24] C. Schwarz, "The PANDA experiment at FAIR," *Journal of Physics: Conference Series*, vol. 374, no. 1, Article ID 012003, 2012.

[25] G. Y. Chen and J. P. Ma, "Production of $X(3872)$ at PANDA," *Physical Review D*, vol. 77, Article ID 097501, 2008.

[26] T. Feuster and U. Mosel, "Unitary model for meson-nucleon scattering," *Physical Review C*, vol. 58, no. 1, pp. 457–488, 1998.

[27] T. Feuster and U. Mosel, "Photon- and meson-induced reactions on the nucleon," *Physical Review C—Nuclear Physics*, vol. 59, no. 1, pp. 460–491, 1999.

[28] V. Shklyar, H. Lenske, and U. Mosel, "Coupled-channel analysis of $K\Lambda$ production in the nucleon resonance region," *Physical Review C*, vol. 72, no. 1, Article ID 015210, 2005.

[29] K. A. Olive, K. Agashe, C. Amsler et al., "Review of particle physics," *Chinese Physics C*, vol. 38, no. 9, Article ID 090001, 2014.

[30] W. H. Liang, P. N. Shen, J. X. Wang, and B. S. Zou, "Theoretical formalism and Monte Carlo study of partial wave analysis for $J/\Psi \to p\bar{p}\omega$," *Journal of Physics G: Nuclear and Particle Physics*, vol. 28, no. 2, pp. 333–343, 2002.

[31] C. Downum, T. Barnes, J. R. Stone, and E. S. Swanson, "Nucleon-meson coupling constants and form factors in the quark model," *Physics Letters B*, vol. 638, no. 5-6, pp. 455–460, 2006.

[32] Z. W. Lin, C. M. Ko, and B. Zhang, "Hadronic scattering of charmed mesons," *Physical Review C*, vol. 61, no. 2, Article ID 024904, 7 pages, 2000.

[33] R. Machleidt, K. Holinde, and C. Elster, "The bonn meson-exchange model for the nucleon-nucleon interaction," *Physics Reports*, vol. 149, no. 1, pp. 1–89, 1987.

[34] T. A. Armstrong, C. Cawlfield, B. I. Eisenstein et al., "Observation of the $^1P_1$ state of charmonium," *Physical Review Letters*, vol. 69, p. 2337, 1992.

[35] M. Andreotti, "Results of a search for the h_c ($^1P_1$) state of charmonium in the $\eta_c\gamma$ and $J/\psi\pi^0$ decay modes," *Physical Review D*, vol. 72, Article ID 032001, 2005.

[36] D. Joffe, "A search for the singlet-P state hc(1 1P1) of charmonium in proton-antiproton annihilations at fermilab experiment E835p," http://arxiv.org/abs/hep-ex/0505007.

[37] A. Lundborg, T. Barnes, and U. Wiedner, "Charmonium production in $p\overline{p}$ annihilation: estimating cross sections from decay widths," *Physical Review D*, vol. 73, no. 9, Article ID 096003, 6 pages, 2006.


Journal of Gravity
Journal of Photonics
The Scientific World Journal
Journal of Soft Matter
Advances in Condensed Matter Physics
Journal of Fluids
Journal of Aerodynamics
Hindawi
Submit your manuscripts at
http://www.hindawi.com
International Journal of Statistical Mechanics
International Journal of Optics
Journal of Computational Methods in Physics
Advances in High Energy Physics
Journal of Thermodynamics
Physics Research International
Advances in Astronomy
Journal of Solid State Physics
Journal of Astrophysics
International Journal of Superconductivity
Journal of Biophysics
Journal of Atomic and Molecular Physics