A first estimate of hunting charmed baryon $\Lambda_c(2880)$ at $\overline{\text{PANDA}}$

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In the present work we explore the production potential of $\Lambda_c(2880)^+$ at $\overline{\text{PANDA}}$. With the $J^P = \frac{1}{2}^+$ assignment to $\Lambda_c(2880)^+$, we calculate the differential and total cross sections of $p\bar{p} \to \Lambda_c pD^0$, where the signal and background contributions are considered. Our numerical results indicate that the production of $\Lambda_c(2880)^+$ may reach up to 1 mb, where about $10^7$ events can be accumulated per day if taking the designed luminosity ($2 \times 10^{22}$ cm$^{-2}$s$^{-1}$) of $\overline{\text{PANDA}}$.

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I. INTRODUCTION

As the higher orbital excitation of $\Lambda_c$ baryon family, $\Lambda_c(2880)$ was first announced by the CLOE Collaboration through analyzing the $M(\Lambda_c^+ \pi^+ \pi^-) - M(\Lambda_c^+) \; \text{mass difference plot}$ [1]. In 2007, Belle carried out the study of $\Lambda_c(2880)$, where $\Lambda_c(2880)$ decay into $\Sigma_c(2455)^{0,+,\pi^+\pi^-}$ was observed. What is more important is that the measurement of its spin-parity assignment is given, i.e., its $J^P$ favors 5/2$^+$ [2]. In Ref. [3], $\Lambda_c(2880) \to D^0 p$ was reported by the BaBar Collaboration. The resonance parameters of $\Lambda_c(2880)$ include [2–4]

| Experiment | $M$ (MeV) | $\Gamma$ (MeV) |
|------------|-----------|---------------|
| Belle      | 2881.2 ± 0.2 ± 0.4 MeV, | 5.8 ± 0.7 ± 1.1 MeV, |
| BaBar      | 2881.9 ± 0.1 ± 0.5 MeV, | 5.8 ± 1.5 ± 1.1 MeV. |

The above experimental phenomena show that the experimental information of $\Lambda_c(2880)$ is quite abundant among all observed charmed baryons [4].

After the observation of $\Lambda_c(2880)$, different theoretical groups have performed the theoretical studies of $\Lambda_c(2880)$. The most of theoretical studies of $\Lambda_c(2880)$ mainly focus on the decay behavior of $\Lambda_c(2880)$ as we are going to introduce. By the quark pair creation model, the strong decay behaviors of charmed baryons are investigated systematically [5]. The results indicate that $\Lambda_c(2880)$ favor $\Lambda_{c2}^+(5/2^+)$ (the notation of charmed baryon can be found in Fig. 3 of Ref. [5]) since the corresponding total decay width and the ratio $\Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2455)\pi)$ are consistent with the experimental data of $\Lambda_c(2880)$ given by Belle [2]. In Ref. [6], Cheng and Chua calculated the strong decays of $\Lambda_c(2880)$ by the heavy hadron chiral perturbation theory, where $\Lambda_c(2880)$ can be an mixture of $L = 2$ charmed baryons $\Lambda_{c2}^+(5/2^+)$ and $\Lambda_{c3}^+(5/2^+)$ [6]. Later, Zhong and Zhao also studied the charmed baryon strong decays via a chiral quark model, which contain the $\Lambda_c(2880)$ two-body strong decay [7].

Although studying the decay behavior of $\Lambda_c(2880)$ is helpful to reveal the inner structure of $\Lambda_c(2880)$, exploring the production of $\Lambda_c(2880)$ is also an important and intriguing research topic. Until now, all experimental observations of $\Lambda_c(2880)$ have been from the $B$ meson weak decays [1–3]. Thus, it is natural to ask whether $\Lambda_c(2880)$ can be produced by other processes. For answering this question, in this work we will carry out the study of the $\Lambda_c(2880)$ production. We notice that $\Lambda_c(2880)$ can decay into $D^0 p$ [3], which shows that there exists the strong coupling between $\Lambda_c(2880)$ and $D^0 p$. In addition, searching for charmed baryon is one of physical aims at $\overline{\text{PANDA}}$ [8]. Considering the above reasons, we study the discovery potential of $\Lambda_c(2880)$ at $\overline{\text{PANDA}}$, which can provide valuable information to future experimental exploration of $\Lambda_c(2880)$ at $\overline{\text{PANDA}}$.

This work is organized as follows. After introduction, we present the selected process of $\Lambda_c(2880)$ produced at $\overline{\text{PANDA}}$ and the corresponding calculation detail. In Sec. II, the Dalitz plot and the $pD^0$ invariant mass spectrum are given, which contains the analysis of the signal and background contributions. Finally, this paper ends with the summary in Sec. IV.

II. THE PRODUCTION OF $\Lambda_c(2880)$

Since $\Lambda_c(2880)$ can couple with $pD^0$ [3], $\Lambda_c(2880)$ can be produced in the proton and antiproton collision process $p\bar{p} \to \Lambda_c^-\Lambda_c(2880)^+$ by exchanging a $D^0$ meson, which is shown in Fig. 1. In the present work, we don't consider the contribution from the direct $p\bar{p}$ annihilation, which is suppressed by the Okubo-Zweig-Iizuka rule [9–12].

Since the initial state interaction (ISI) effect is regarded to play an important role in nucleon-nucleon collisions when the transition occurs near the threshold [13–18], thus the ISI effect should be considered here when studying the production of $\Lambda_c(2880)$ via the meson exchanged in the nucleon-nucleon collision. The ISI effect is not calculable since the ISI effect is governed by the non-perturbative QCD effects. Just suggested

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in Refs. [19, 20], an overall factor can be introduced to reflect the ISI effect, which may reduce the cross section by a factor 10. In this work, we also adopt the same consideration.

In the following, we calculate the total production probability of $\Lambda_c(2880)$ in the process $p\bar{p} \rightarrow \Lambda_c^+\Lambda_c(2880)^+$ by the effective Lagrangian approach, where the differential and total cross sections are discussed.

\[
\begin{align*}
p & \quad p_2 \quad p_4 \quad \Lambda_c(2880)^+ \\
p_i & \quad p_3 \quad \Lambda_c^- \\
\theta & \quad D^0 \quad \bar{p} \quad p_1
\end{align*}
\]

FIG. 1: The diagram describing the $p\bar{p} \rightarrow \Lambda_c^-\Lambda_c(2880)^+$ process.

A. The Lagrangians and the coupling constants

As measured by Belle [2], we take the quantum number of $\Lambda_c(2880)^+$ to be $J^{PC} = \frac{3}{2}^-$. For depicting the coupling of the meson with the charmed meson and the charmed baryon, we adopt the effective Lagrangians [21–23]

\[
\begin{align*}
\mathcal{L}_{DN_{\Lambda_c}} &= -\frac{g_{\Lambda_cN}}{m_N + m_{\Lambda_c}} \gamma_5 \gamma^\mu \partial_\mu DN + h.c., \\
\mathcal{L}_{DN_{\Lambda_c}} &= -\frac{g_{\Lambda_cN}}{m_R + m_{\Lambda_c}} \gamma_5 \gamma^\mu \gamma^\nu \partial_\mu \partial_\nu DN + h.c.,
\end{align*}
\]

where $N$, $R$ and $D$ are the isodoublet nucleon field, the $\Lambda_c(2880)$ field and the isodoublet meson field, respectively, with the definitions $N = (\rho, \eta)^T$, $N = (\bar{p}, \bar{n})$, $D = (D^0, D^\star)$, and $\mathcal{T} = (D^0, D^\star)^T$. In the following formulae, we take $g_{\Lambda_cN} = g_{\Lambda_cDN}$, and $g_{\Lambda_cN} = g_{\Lambda_cDN}$ for convenience sake.

The propagators for the fermion with $J = 1/2$, 5/2 are expressed as [22, 24–26]

\[
G_F^{(1/2)}(p) = \frac{\bar{p}p}{p^2 - m_F^2 + i m_F \Gamma_F} \quad G_F^{(5/2)}(p) = \frac{\bar{p}p}{p^2 - m_F^2 + i m_F \Gamma_F}
\]

with

\[
\begin{align*}
\bar{p}^{(1/2)}(p) &= \frac{p + m_F}{2m_F}, \\
\bar{p}^{(5/2)}(p) &= \frac{p + m_F}{2m_F} G_{\mu\nu} \sigma(p).
\end{align*}
\]

where $g_{\mu\nu} = -g_{\mu\nu} + p_\mu p_\nu / p^2$ and $\gamma_\mu = -\gamma_\mu + p_\mu p / p^2$. In addition, $p$ and $m_F$ are the momentum and the mass of the fermion, respectively.

By an approximate SU(4) flavor symmetry, the coupling constant $g_{\Lambda_cN}$ is equal to $g_{\Lambda_cN} = 13.2$ [27–30], which is larger than $g_{\Lambda cK} = 6.7 \pm 2.1$ estimated by the QCD sum rules [31, 32]. The former one is adopted in this work. Additionally, the coupling constant $g_{\Lambda_cN}$ can be obtained by fitting the measured partial width of the $\Lambda_c(2800)^+\to D^0(K)p(p)$ decay, where the partial decay width is

\[
d\Gamma_i = \frac{m_{\Lambda_cN}}{8\pi^2} |\mathcal{M}_i|^2 \frac{d\Omega}{m_R} \\
\end{align*}
\]

with

\[
E_K = \frac{m_R^2 - m_N^2 + m_D^2}{2m_R}, \\
|\mathcal{K}| = \frac{\left(\sqrt{(n_\mu - (m_D - m_N)^2)}\right)}{2m_R}.
\]

Here, $E_K$ and $|\mathcal{K}|$ are the energy and the three-momentum of the daughter $D^0$ meson, respectively. $m_N$ and $m_D$ are the masses of proton and $D^0$ meson, respectively. Furthermore, the concrete expression of the corresponding decay width is

\[
\Gamma_i = \frac{m_{\Lambda_cN}}{2\pi m_R^2} \left|\mathcal{K}\right|^2 \sum_{ji} \left|T_{ji}\right|^2 \\
= \frac{g_{\Lambda_cN}^2 m_{\Lambda_cN}}{12\pi m_R^2} \sum_{ji} T_{ji} \left(\bar{u}(P)\gamma_\mu u(P)\gamma_\nu \gamma_\rho \gamma_\sigma \mathcal{K} \times K_\mu K_\nu K_\rho K_\sigma\right) \\
= \frac{g_{\Lambda_cN}^2 |\mathcal{K}|}{24\pi m_R(m_N + m_D)^2} \sum_{ji} T_{ji} \left(\bar{u}(P + m_N)\gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma \mathcal{K} \times K_\mu K_\nu K_\rho K_\sigma\right),
\]

where $\mathcal{P}^{(1/2)}(Q)$ is the projection operator for a fermion with $J = 5/2$ as defined in Eq. (5). Since the measurement of the branching ratio of $\Lambda_c(2880)^+ \to D^0 p$ is still absent, thus we can determine the coupling constant $g_{\Lambda_cN}$ by the theoretical result of the branching ratio of $\Lambda_c(2880)^+ \to D^0 p$. In Refs. [5], the estimated branching fraction $BR(\Lambda_c(2880)^+ \to D^0 p)$ is around 20%, where the quark pair creation model is adopted. The corresponding partial decay width is 1.2 MeV. Considering the above situation, in this work we take typical value $\Gamma(\Lambda_c(2880)^+ \to D^0 p) = 1$ MeV to extract $g_{\Lambda cK} = 40.69$ GeV$^{-2}$, which will be applied to the following calculation.

Before carrying out the study of the cross section of $p\bar{p} \to \Lambda_c^-\Lambda_c(2880)^+$, we display the kinematically allowed region of square of the transfer momentum $q^2$ (see Fig. 2), which is the function of $\sqrt{s}$. In Fig. 2, the maximum of $q^2$ is negative and less than the mass square of the exchanged $D^0$ meson in the energy range of our interest.
B. The production of $\Lambda_c(2880)$

The transition amplitude for the process $p\bar{p} \to \Lambda_c^-\Lambda_c^+(2880)$ shown in Fig. 1 is expressed as

$$i\mathcal{T}_{fi} = \frac{g_N g_R}{(m_N + m_N)(m_N + m_R)} \bar{u}(p_4) C_R(q) u(p_2)$$

$$\times \bar{v}_p(p_1) C(q) v_{\Lambda_c}(p_3) G_D(q^2) F^2(q^2, m^2_{p_3}),$$  \(11\)

where $C(q) = \gamma_5 q$ and $C_R(q) = \gamma_3 q_\mu q_\nu$ describe the Lorentz structures of the vertices of $D^0$ interacting with $p\Lambda_c$ and $p\Lambda_c(2880)^*$, respectively. $G_D(q^2) = i/(q^2 - m^2_{p_3})$ is the propagator of the exchanged meson. In addition, the monopole form factor $F(q^2, m^2_{p_3}) = (\Lambda^2 - m^2_{p_3})/(\Lambda^2 - q^2)$ is also introduced. The transition amplitude of $p\bar{p} \to \Lambda_c^-\Lambda_c^+$ can be obtained by replacing $C_R(q)$ with $-C(q)$ in Eq. (11). The unpolarized cross section is [4]

$$\frac{d\sigma}{dt} = \frac{m_N m_N m_N m_R}{16\pi s} \left| \mathcal{T}_{fi} \right|^2,$$  \(12\)

where

$$\left| \mathcal{T}_{fi} \right|^2 = \left( \frac{g_N g_R}{(m_N + m_N)(m_N + m_R)} \right)^2 |G_D(q^2)|^2 F^2(q^2, m^2_{p_3})$$

$$\times Tr \left[ \frac{p^{1/2}(p_4) C_R(q)}{2m_N} \gamma^\mu C_R(q)^\dagger \gamma^\nu \right]$$

$$\times Tr \left[ \frac{p_{2/1} - m_N - m_N}{2m_N} C R_{3/1} - m_N - m_N \right].$$  \(13\)

In Fig. 3, the variation of the total cross section to the different values of the cutoff $\Lambda$ is plotted, where $\Lambda$ is taken as $2.0 \sim 3.25$ GeV with the step of 0.25 GeV. Our results of the $\Lambda_c(2880)^+$ production indicate that the cross section of $p\bar{p} \to \Lambda_c^-\Lambda_c^+(2880)$ strongly depends on the adopted values of cutoff. The cross section of the $\Lambda_c(2880)^+$ production with $\Lambda = 2.0$ GeV is much smaller than that with $\Lambda = 3.25$ GeV. It should be noticed that the meson-exchanged mechanism was used to study the production of $\Lambda_c^-\Lambda_c^+$ and $\Lambda_c^-\Lambda_c^+(2940)$ in the proton and antiproton collision [19, 20], where the cutoff value $\Lambda = 3.0$ GeV was adopted. Due to the similarity of these involved processes in the present work and Refs. [19, 20], in this work we also take typical value $\Lambda = 3.0$ GeV to estimate the cross section of $p\bar{p} \to \Lambda_c^-\Lambda_c^+(2880)$.

In addition, we calculate the total cross section of $p\bar{p} \to \Lambda_c^-\Lambda_c^+$ given in Fig. 4. It is obvious that the cross section for this process is rather smaller than that of $p\bar{p} \to \Lambda_c^-\Lambda_c^+(2880)^*$. We also present the differential cross section of $p\bar{p} \to \Lambda_c^-\Lambda_c^+(2880)$ with different values of center-of-mass energy $\sqrt{s}$, which is shown in Fig. 5.
with the present work, we consider the processes $p\bar{p} \rightarrow \Lambda_c \Lambda_c(2880)^+$ and $\Lambda_c^+ \bar{p} \rightarrow p \bar{\Lambda}_c$, with the intermediate $\Lambda_c(2880)^+$ (a) and $\Lambda_c^+$ (b) contributions.

III. THE BACKGROUND ANALYSIS AND THE DALITZ PLOT

Besides giving the total and differential cross sections of the production of $\Lambda_c(2880)^+$ in the $p\bar{p}$ collision, it is also important to perform the background analysis and the Dalitz plot of the corresponding reaction, which can provide more abundant information of the $\Lambda_c(2880)^+$ production at PANDA. In the present work, we consider the processes $p\bar{p} \rightarrow \Lambda_c^- p D^0$, where $p D^0$ is from the intermediate resonance $\Lambda_c(2880)^+$ or $\Lambda_c^+$ as shown in Fig. 6. The process $p\bar{p} \rightarrow \Lambda_c^- \bar{\Lambda}_c^+ \rightarrow \Lambda_c^- p D^0$ with the off-shell $\Lambda_c^+$ is as the main background contribution.

The transition amplitudes of $p\bar{p} \rightarrow \Lambda_c^- p D^0$ are written as

$$i T_{fi}^\Lambda = \left( \frac{g_{\Lambda_c}}{m_{\Lambda_c} + m_N} \right)^2 \frac{g_{\Lambda}}{m_{\Lambda} + m_N} \bar{u}_p(p_4) \left[ -C_b(p_5) \right]$$

$$\times G_D(q^2) F^2(q^2, M_D^2),$$

(14)

which correspond to Fig. 6 (a) and (b), where the expressions of $C_b$ and $C$ are defined in Sec. II B. The definition of the involved momentums can be found in Fig. 6.

With Eqs. (14)-(15), one obtains the square of the total invariant transition amplitude

$$|M|^2 = \sum |T_{fi}^\Lambda|^2.$$  

(16)

The corresponding total cross section of the process $p\bar{p} \rightarrow \Lambda_c^+ p D^0$ is

$$d\sigma = \frac{m_N^2}{|p_1 \cdot p_2|^2} \frac{|M|^2}{4(2\pi)^4} d\Phi_3(p_1 + p_2; p_3, p_4, p_5)$$

(17)

with the definition of $n$-body phase space [4]

$$d\Phi_n(P^i; k_1, ..., k_n) = \delta^n(P^i) \prod_{i=1}^n \frac{d^3k_i}{(2\pi)^3 2E_i}.$$  

To numerically calculate the total cross section of $p\bar{p} \rightarrow \Lambda_c^+ p D^0$ including both signal and background contributions, the Mathematica and FOWL codes are utilized. In Fig. 7, the variation of the total cross sections to $\sqrt{s}$ is given, where $\sigma_R$ and $\sigma_{\Lambda_c}$ correspond to the signal and background contributions, respectively. As shown in Fig. 7, the line shape of $\sigma_R$ increases rapidly near the threshold. Since the process can proceed via on-shell intermediate $\Lambda_c(2880)^+$, a steep increase appears at about $\sqrt{s} = 5.17$ GeV and $\sigma_R$ can reach up to about $10^3$ nb at the energy range of our interest. $\sigma_{\Lambda_c}$ has a dominant role at $\sqrt{s} < 5.11$ GeV. However, $\sigma_R$ becomes important when $\sqrt{s}$ increases. And then $\sigma_R$ is much larger than $\sigma_{\Lambda_c}$ when

FIG. 5: (color online). The differential cross section for $p\bar{p} \rightarrow \Lambda_c^- \Lambda_c(2880)^+$ dependent on $-t$ with the fixed center-of-mass energy $\sqrt{s} = 5.2, 5.3, 5.4$ GeV.

FIG. 6: The diagrams for $p\bar{p} \rightarrow D^0 p\Lambda_c$, with the intermediate $\Lambda_c(2880)^+$ (a) and $\Lambda_c^+$ (b) contributions.

FIG. 7: (color online). The obtained total cross section for $p\bar{p} \rightarrow \Lambda_c^- p D^0$. Here, $\sigma_R$ and $\sigma_{\Lambda_c}$ are the results via the exchanged $\Lambda_c(2880)^+$ and $\Lambda_c^+$, respectively, while $\sigma_T$ denotes the total cross section.
For more details).

\[ \sqrt{s} > 5.18 \text{ GeV}, \] which indicates that the signal can be easily distinguished from the background in this energy region.

After giving the total cross section of \( p\bar{p} \rightarrow \Lambda_c pD^0 \), we also carry out the analysis of the Dalitz plot and the \( pD^0 \) invariant mass spectrum for this process, which are useful for studying the production of \( \Lambda_c(2880)^+ \) in the proton-antiproton collision \( p\bar{p} \rightarrow \Lambda_c pD^0 \). In Fig. 8, the Dalitz plot and the corresponding \( pD^0 \) invariant mass spectrum at \( \sqrt{s} = 5.35 \text{ GeV} \) are given. When 10 million events are generated in the Monte Carlo simulation, the signal event can reach up to about \( 10^5 \) Events/0.005 GeV\(^2\). The \( pD^0 \) invariant mass spectrum indicates that the signal can be well distinguished from the background. This is due to the fact that the contribution from the signal is far larger than that from the background at the energy range \( \sqrt{s} > 5.18 \text{ GeV} \) (see Fig. 7 for more details).

IV. SUMMARY

In this work, we investigate the discovery potential of charmed baryon \( \Lambda_c(2880) \) produced at \( \text{PANDA} \), which is different from the \( \Lambda_c(2880) \) production in \( B \) meson decay \[2\]. Thus, this study will be helpful to further experimental search for \( \Lambda_c(2880) \) at the forthcoming \( \text{PANDA} \) experiment, where searching for charmed baryon is one of the most important physical aims of \( \text{PANDA} \) \[8\].

The total and differential cross sections of the \( \Lambda_c(2880)^+ \) production indicate that \( p\bar{p} \rightarrow \Lambda_c^- pD^0 \) is a suitable process to explore the \( \Lambda_c(2880)^+ \) production at \( \text{PANDA} \). What is more important is that the background analysis and the Dalitz plot are given in this work, where the process \( p\bar{p} \rightarrow \Lambda_c^- pD^0 \) are calculated by including the signal and background contributions. We find that the contribution from the signal is much larger than that from the background when \( \sqrt{s} > 5.18 \text{ GeV} \), which is a suitable energy window to study the \( \Lambda_c(2880)^+ \) production at \( \text{PANDA} \). These results also show that the \( \Lambda_c(2880) \) can be easily distinguished from the background.

In summary, we suggest future \( \text{PANDA} \) experiment to perform the search for the charmed baryon \( \Lambda_c(2880)^+ \). This experimental study can not only further confirm \( \Lambda_c(2880)^+ \) by different processes, but also provide more abundant information to \( \Lambda_c(2880)^+ \), which will be valuable to reveal the underlying structure of \( \Lambda_c(2880)^+ \).

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