Production of charmed baryon $Λ_c(2940)^+$ at PANDA

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In this work we evaluate the production rate of the charmed baryon $Λ_c(2940)^+$ at PANDA. For possible assignments of $Λ_c(2940)^+$: $J^P = 1/2^+$, 3/2$^+$ and 5/2$^+$, the total cross section of $p\bar{p} \rightarrow \Lambda_c, \Lambda_c(2940)^+$ is estimated, which may exceed 1 nb. With the designed luminosity ($2 \times 10^{32}$ cm$^{-2}$/s) of PANDA, our estimate indicates that ten thousand events per day if $Λ_c(2940)^+$ is of $J^P = 1/2^+$ or 5/2$^+$ per day if it is of $J^P = 5/2^+$ can be expected. Those values actually set the lower and upper limits of the $Λ_c(2940)^+$ production. In addition, we present the Dalitz plot and carry out a rough background analysis of the $Λ_c(2940)^+$ production in the $p\bar{p} \rightarrow D^0 p \Lambda_c$ and $p\bar{p} \rightarrow \Sigma^{0,+,−}\pi^+\Lambda_c$ processes, which would provide valuable information for accurate determination of the $Λ_c(2940)^+$ identity.

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I. INTRODUCTION

The charmed baryon $Λ_c(2940)^+$ with mass $m = 2939.8 \pm 1.3$ (stat) $\pm 1.0$ (syst) MeV and width $\Gamma = 17.5 \pm 5.2$ (stat) $\pm 5.9$ (syst) MeV was first observed in the $D^0 p$ invariant mass spectrum by the BaBar Collaboration [1]. Later, $Λ_c(2940)^+$ was confirmed by the Belle Collaboration in the $J^P = 1/2^+$ channels $[2]$, where the obtained mass and width are $m = 2938.0 \pm 1.3^{+2.0}_{−2.0}$ MeV and $\Gamma = 13^{+8}_{−5} - 7$ MeV respectively. Obviously the values achieved by the two collaborations are consistent with each other within the error tolerance [1].

Actually, comparing with the meson case, the structure of baryons is more intriguing from both theoretical and experimental aspects. Recently, along with the experimental progress at the BaBar, Belle and BES, a great number of new states of mesons have been observed and some of them are identified as exotic, i.e., these states cannot be categorized into the regular $q\bar{q}$ structure. It is natural to conjecture that the possibility also exists for the baryons. However, this situation is much more complicated than the meson case. By the regular structure, the baryon is composed of three quarks, so the exotic configuration of baryons would be much more difficult to be identified. On the other side, this study can enrich our knowledge on the fundamental structure of hadrons; namely, it will answer the long-standing question that the $SU(3)$ theory indeed allows existence of the non $q\bar{q}$ and $qq\bar{q}$ configurations, and, if yes, where do we search for them? That is the job of theorists of high energy physics.

Experimentally, some peculiar phenomena have been observed. Before we can attribute them to new physics or new hadronic configuration, a thorough study of whether they can be interpreted by the regular quark structure and the standard model (SM) must be carried out.

The observation of $Λ_c(2940)^+$ has stimulated theorists’ extensive interest in understanding its structure. Since the observed charmed baryon $Λ_c(2940)^+$ is close to the production threshold of $D^0 p$, a conjecture that $Λ_c(2940)^+$ may be a $D^*N$ molecular state, was naturally proposed [3]. The masses of $D^*N$ molecular states were calculated in the potential model, and the results support the statement that $Λ_c(2940)^+$ is an $S$-wave $D^0 p$ molecular state with spin parity $J^P = 1/2^+$ or $3/2^+$ [3]. Recently, the authors of Ref. [4] systematically studied the interaction between $D^*$ and the nucleon, and concluded that the $D^*N$ systems may behave as $J^P = 1/2^+$, $3/2^+$ baryon states. With the $J^P = 1/2^+$ and $J^P = 3/2^+$ assignments, the strong decays of $Λ_c(2940)^+$ have been investigated by the authors of Ref. [5], but their result determines that the assignment of $Λ_c(2940)^+$ as a $D^*N$ molecular state with $J^P = 1/2^+$ should be excluded. Later, the radiative and strong three-body decays of $Λ_c(2940)^+$ were explored in Refs. [6, 7], where $Λ_c(2940)^+$ was assigned as a $D^*N$ molecular state of $J^P = 1/2^+$.

Besides supposing $Λ_c(2940)^+$ to be a molecular state, the alternative theoretical explanation that $Λ_c(2940)^+$ is just a conventional charmed baryon has also been widely discussed. The calculation in terms of the potential model shows that the masses of the conventional charmed baryons of $J^P = 2/3^−, 3/2^−$ and $J^P = 3/2^+$ are 2900 MeV and 2910 MeV, respectively [8, 9], which are close to the mass of $Λ_c(2940)^+$. In Ref. [10], the authors suggested that $Λ_c(2940)^+$ is the first radial excitation of the $Σ_c(2520)$ of $J^P = 3/2^+$ and possesses the quantum number of $J^P = 3/2^−$. In their calculations of the mass spectrum the relativistic quark-diquark model was used. In addition, $Λ_c(2940)^+$ as the first radial excitation of the $Σ_c$ was also suggested via solving the Faddeev equations for three-body systems in the momentum space [11]. In the heavy hadron chiral perturbation theory, the ratio $\Gamma(Λ_c(2940)^+ → Σ_cπ)/Γ(Λ_c(2940)^+ → Σ_cπ)$ was obtained if the spin-parity of $Λ_c(2940)^+$ is $J^P = 3/2^−$.

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or \(J^P = \frac{3}{2}^+\) [13]. These ratios will be applied to distinguish different \(J^P\) assignments of \(\Lambda_c(2940)^+\) [12]. In Ref. [13], the authors calculated the strong decays of newly observed charmed hadrons in the \(\frac{3}{2}^+\) model. Here, \(\Lambda_c(2940)^+\) could only be a D-wave charmed baryon \(\Lambda_c^0(\frac{5}{2}^+)\) or \(\Lambda_c^0(\frac{3}{2}^+)\) while \(\Lambda_c(2940)^+\) as the first radial excitation of \(\Lambda_c(2286)^+\) is completely excluded since \(\Lambda_c(2940)^+ \rightarrow D^0 p\) was observed by the BaBar Collaboration [11]. The result obtained in terms of the chiral quark model indicates that \(\Lambda_c(2940)^+\) could be a D-wave charmed baryon \(\Lambda_c^0 \frac{3}{2} D_{33} \frac{5}{2}^+\) [12].

TABLE I: The possible \(J^P\) assignments to the \(\Lambda_c(2940)^+\) in the literature [3–15]. Here, we use "\(\sqrt{\gamma}\)" or "\(\times\)" to denote that the corresponding studies suggest or exclude that \(J^P\) assignment for \(\Lambda_c(2940)^+\). Additionally, the upper and lower values in the bracket denote the decay widths (MeV) for its \(D^0 p\) and \(\Sigma^0 \pi^+\) channels obtained in the literature corresponding to the quantum number assignments.

| Authors        | \(J^P\) | \(\frac{3}{2}^+\) | \(\frac{1}{2}^+\) | \(\frac{3}{2}^+\) | \(\frac{1}{2}^+\) | \(\frac{5}{2}^+\) | \(\frac{5}{2}^+\) |
|----------------|--------|----------------|----------------|----------------|----------------|----------------|----------------|
| He et al.      | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Dong et al.    | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Dong et al.    | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| He et al.      | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Capstick et al.| ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Cheng et al.   | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Zhong et al.   | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Chen et al.    | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Ebert et al.   | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Valcarce et al.| ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |
| Chen et al.    | ✓      | ✓              | ✓              | ✓              | ✓              | ✓              | ✓              |

As summarized in Table I, a great deal of theoretical ansatz for the structure \(\Lambda_c(2940)^+\) was proposed, by which its spectrum was calculated, and the results are quite model dependent. At present the properties of \(\Lambda_c(2940)^+\) are still unclear, the fact means that more work is needed to determine its real structure, especially investigating from different angles.

The current information of \(\Lambda_c(2940)^+\) is extracted from the \(e^+e^-\) collision [1]. Thus, it is interesting to investigate the \(\Lambda_c(2940)^+\) production in other processes. The PANDA experiment [10] at the Facility for Antiproton and Ion Research (FAIR) will be carried out in the near future, which will definitely provide valuable data for understanding of non-perturbative QCD. Study of the charmed baryon is one of the main physics goals of PANDA since its beam momentum \(p = 5 \sim 15\) GeV just covers the production threshold of charmed hadron. Encouraged by the prospect, in this work, we study the \(\Lambda_c(2940)^+\) production at PANDA. Some parallel theoretical investigations of the production of the charmonium-like states \(X(3872), Z^0(4430)\) at PANDA [17, 18] were also carried out.

This paper is organized as follows. After the Introduction, we will present the effective Lagrangian and the corresponding coupling constants used in this work. The formulation and the numerical result of the \(\Lambda_c(2940)^+\) productions at PANDA will be given in Sec. III. In Sec. IV considering the sequential decay \(\Lambda_c(2940)^+ \rightarrow D^0 p\), we make the Dalitz plot analysis on \(p \bar{p} \rightarrow \Lambda_c \Lambda_c(2940)^+ \rightarrow \Lambda_c D^0 p\), where \(p \bar{p} \rightarrow \Lambda_c \Lambda_c \rightarrow \Lambda_c D^0 p\) forms the background. Finally the paper ends with our discussion and conclusion.

II. EFFECTIVE LAGRANGIANS AND COUPLING CONSTANT

Associated with a \(\Lambda_c\) production, \(\Lambda_c(2940)^+\) could be produced in the proton and antiproton collision by exchanging a \(D^0\) meson, as shown in the Fig. 1. It is noted that direct \(p \bar{p}\) annihilation into \(\Lambda_c \Lambda_c(2940)^+\) is negligible in comparison with the mechanism shown in Fig. 1 because the annihilation channel is Okubo-Zweig-Iizuka (OZI) suppressed. Thus, in this work we do not consider its contribution at all.

For being at most model-independent, we apply the effective Lagrangian approach to study the \(p \bar{p} \rightarrow \Lambda_c \Lambda_c(2940)^+\) process. In our calculation, we consider the production rates of \(\Lambda_c(2940)^+\) whose \(J^P\) assignments are priori assumed. The following Lagrangians describe the interaction of \(\Lambda_c(2940)^+\) with \(D^0 p\) for different \(J^P\) assignments to \(\Lambda_c(2940)^+\) [19–22]:

\[
\begin{align*}
L_{\Lambda_c}^{1+} &= g_{\Lambda_c}^1 \Lambda_c(2940)^+ \gamma_5 p D^0, \\
L_{\Lambda_c}^{2+} &= g_{\Lambda_c}^2 \Lambda_c(2940)^+ p D^0, \\
L_{\Lambda_c}^{3+} &= g_{\Lambda_c}^3 \Lambda_c(2940)^+ p \bar{D}^0, \\
L_{\Lambda_c}^{4+} &= g_{\Lambda_c}^4 \Lambda_c(2940)^+ \bar{D} \Lambda_c D^0, \\
L_{\Lambda_c}^{5+} &= g_{\Lambda_c}^5 \Lambda_c(2940)^+ \bar{D} \Lambda_c D^0,
\end{align*}
\]

where we use the subscripts \(\frac{1}{2}, \frac{3}{2}, \frac{5}{2}\) and \(\frac{3}{2}\) to distinguish possible \(J^P\) quantum numbers of \(\Lambda_c(2940)^+\). The Lagrangian for the interaction of \(\Lambda_c\) and \(\bar{D}^0 p\) can be easily obtained by replacing \(\Lambda_c(2940)^+\) \((p, D^0)\) in Eq. (1) with \(\Lambda_c\) \((\bar{p}, \bar{D}^0)\). In the above Lagrangians, the coupling constants \(g_{\Lambda_c}\) are given by fitting the partial width of \(\Lambda_c(2940)^+ \rightarrow D^0 p\) decay, i.e.,

\[
\Gamma(\Lambda_c(2940)^+ \rightarrow D^0 p) = \frac{m_N}{4(2J + 1)\pi} \frac{2|k|}{\sqrt{S}} B_{\text{eff}} A^2 J
\]

with \(B_{\text{eff}} = \frac{E_{m_N}}{m_N} + S\) and \(S = P(1)^{J + 1/2}\), where \(J\) is the spin of \(\Lambda_c(2940)\), \(E_N(m_N)\) denotes the energy (mass) of proton. \(A^2 J = \frac{N}{2J}|k|^{2J - 1}\) with \(N = 1, 2, 2\) corresponds to

\[
\begin{align*}
\text{FIG. 1: The diagram for the process } p \bar{p} \rightarrow \Lambda_c \Lambda_c(2940)^+ \text{ by exchanging the } D^0 \text{ meson.}
\end{align*}
\]
$J = 1/2, 3/2, 5/2$, respectively. $k$ is the three-momentum of the daughter mesons in the center of mass frame of $p\bar{p}$. From $BR(\Lambda_c(2940)^+ \rightarrow D^0 p)$, we extract the coupling constant $g_\rho$. However, the BaBar and Belle experiments only measured the total width of $\Lambda_c(2940)^+$, and have not given the partial decay width of $\Lambda_c(2940)^+ \rightarrow D^0 p$ so far. Thus, to obtain $g_\rho$, one needs to invoke theoretical calculations. In terms of different theoretical models to estimate, different groups have obtained different values of the decay width of $\Lambda_c(2940)^+$ which are listed in Table. I. Since the cross section of $D^0$ is theoretical models to estimate, different groups have obtained different values of the decay width of $\Lambda_c(2940)^+$ which are listed in Table. I. Since the cross section of $\Lambda_c(2940)^+ \rightarrow D^0 p$ which are listed in Table. I. Since the cross section of $p\bar{p} \rightarrow \Lambda_c(2940)^+$ is proportional to $g_\rho^2$, the line shape of the cross section of $p\bar{p} \rightarrow \Lambda_c(2940)^+\Lambda_c$ depends on the c.m. energy $\sqrt{s}$, but does not depend on the $g_\rho$ value. In this work, we choose a concrete $g_\rho$ value to calculate the cross section of $p\bar{p} \rightarrow \Lambda_c(2940)^+$. Concretely, we set the partial decay width to be $\Gamma(\Lambda_c(2940)^+ \rightarrow D^0 p) = 1.5$ MeV and then determine the coupling constant $g_\rho$ as $g_\rho^+ = 0.26$; $g_\rho^- = 1.25$; $g_\rho\perp = 5.26$ GeV$^{-1}$; $g_\rho\parallel = 1.10$ GeV$^{-1}$; $g_\rho\times = 4.23$ GeV$^{-2}$ and $g_\rho\gamma = 20.19$ GeV$^{-3}$. By an approximate $SU(4)$ flavor symmetry, the coupling constant $g_{\Lambda_c pD}$ is equal to $g_{\Lambda c N K} = 13.2$ [23,26], which is larger than $g_{\Lambda c N K} = 6.7 \pm 2.1$ estimated via the QCD sum rules [27,28].

The propagators for a fermion of $J = 1/2, 3/2, 5/2$ are written as [22,29]  

$$G^{\mp,\pm}(q) = \frac{p^{\mp,\pm}}{2MR} \frac{2M_R}{q^2 - M_R^2 + imRF_R} \quad (8)$$

with  

$$p^{\pm}(q) = \frac{\beta R + M_R}{2MR}, \quad (9)$$

$$p_{\mu\nu}^{\pm}(q) = \frac{\beta R + M_R}{2MR} \left[ -g_{\mu\nu} + \frac{1}{3} \gamma_\mu \gamma_\nu + \frac{1}{3M_R}(\gamma_\mu q_\nu - \gamma_\nu q_\mu) + \frac{2}{3M_R}q_\mu q_\nu \right], \quad (10)$$

$$P_{\mu\nu\lambda\gamma\rho\tau}(q) = \frac{\beta R + M_R}{2MR} \left[ \frac{1}{2} (\bar{g}_{\mu\nu\lambda} \bar{g}_{\mu\nu\rho\tau} + \bar{g}_{\mu\nu\rho\tau} \bar{g}_{\mu\nu\lambda}) - \frac{1}{5} \bar{g}_{\mu\nu\lambda} \bar{g}_{\mu\nu\rho\tau} \bar{g}_{\mu\nu\lambda} \right], \quad (11)$$

where $\gamma_\nu = \gamma_\nu - q_\nu q / q^2$ and $\bar{g}_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu / q^2$. $q$ and $M_R$ are the momentum and the mass of the fermion particle, respectively.

III. THE PRODUCTION OF $\Lambda_c(2940)^+$ IN THE PROTON AND ANTIPOTON COLLISION

In this section we calculate the $\Lambda_c(2940)$ production rate in the proton-antiproton collision as shown in Fig. I. For the $p\bar{p} \rightarrow \Lambda_c(2940)^+$ process, the production amplitudes is

$$\mathcal{M} = g_{\Lambda_c pD} g_{\Lambda_c(2940)^+ p\bar{p}} \bar{u}_R(k_2) \mathcal{C}_R(k) u_p(p_2) \times \bar{v}_R(k_1) \mathcal{C}_R(p_1) G_D(k^2) \mathcal{F}^2(k^2), \quad (12)$$

where $\mathcal{C}_R$ or $C$ describe the Lorentz structures of the vertex for $D^0$ interacting with $\Lambda_c(2940)^+$ or $\bar{\Lambda}_c$ $\bar{p}$. They are derived in terms of the Lagrangians in Eqs. (11). $k_1$, $k_2$, $p_1$, $p_2$ and $k$ are the momenta of $\Lambda_c(2940)^+$, $\bar{\Lambda}_c$, $p$, $\bar{p}$ and the exchanged meson $D^0$, respectively. Additionally, the monopole form factor $F(k^2) = (\Lambda^2 - m_{\bar{p}}^2) / (\Lambda^2 - k^2)$ is introduced. As well understood, the concerned hadrons at the effective vertices by no means are point-particles, but have complicated structures, thus the form factor phenomenologically describes the inner structure effect of interaction vertices shown in Fig. I and moreover, it partly compensates for the off-shell effect of the exchanged $D^0$ meson as suggested in Ref. [30]. Indeed the monopole form factor is a phenomenological ansatz and not derivable from the field theory, thus errors are unavoidably brought just like any phenomenological computation. Since the involved parameters are fixed by fitting data, the model-dependence is greatly alleviated, therefore, it is observed that for lower energy reactions, the scenario works well.

Before studying the cross section for the $\Lambda_c(2940)^+$ production at the $p\bar{p}$ collision, let us first calculate the total cross section for the proton-antiproton scattering to the $\Lambda_c$ and anti-$\Lambda_c$ pair in our theoretical frame, which has been experimentally measured and carefully studied in the literature [35,31]. In Fig. 2 the total cross section of $p\bar{p} \rightarrow \Lambda_c$ with different cutoffs is presented, where we restrict the $\Lambda$ value within a reasonable range from 2 GeV to 3.25 GeV.
The cross sections for $\Lambda_c(2940)^+$ production with different spin-parity assignments to $\Lambda_c(2940)^+$ are presented in Fig. 3.

![Graph showing cross section for $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+$ with different J^P assignments.]

FIG. 3: The cross section for the process $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+$ with different J^P assignments of $\Lambda_c(2940)^+$.

Our results of $\Lambda_c(2940)^+$ production indicate that the cross section of $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+$ strongly depends on the J^P assignments of $\Lambda_c(2940)^+$. If $\Lambda_c(2940)^+$ is a $J^P=1/2^-$ state, the cross section of the $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+$ process is much smaller than that if $\Lambda_c(2940)^+$ is a $J^P=5/2^+$ state by a big fraction of $\sim 10^4$.

IV. THE DALITZ PLOT AND THE BACKGROUND ANALYSIS

As shown in the above section, considerable events of $\Lambda_c(2940)^+$ can be produced in the proton and antiproton collision. In this section, we present the Dalitz plot of $p\bar{p}\rightarrow\Lambda_cD^0p$, where $\Lambda_c(2940)$ or $\Lambda_c$ is an intermediate state just shown in Fig. 4. A comparison of Fig. 2 with Fig. 3 indicates that the cross section of $p\bar{p}\rightarrow\Lambda_c\Lambda_c$ is comparable with that of $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+$. Thus, $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$ where $\Lambda_c$ is off-shell, becomes a main background contribution when we analyze the $\Lambda_c(2940)^+$ production in the $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\rightarrow\Lambda_cD^0p$ process.

![Diagram showing diagrams for $p\bar{p}\rightarrow\Lambda_cD^0p$; the left and right diagrams occur via the intermediate $\Lambda_c(2940)^+$ and $\Lambda_c^*$, respectively.]

FIG. 4: The diagrams for the $p\bar{p}\rightarrow\Lambda_cD^0p$; the left and right diagrams occur via the intermediate $\Lambda_c(2940)^+$ and $\Lambda_c^*$, respectively.

The amplitude of $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\rightarrow\Lambda_cD^0p$ where $\Lambda_c(2940)$ can be an on-shell baryon, reads as

\[
\mathcal{M} = g_{A_c\rho\rho}^2 g_{\Lambda_c(2940)^+\rho D^0} \bar{u}(k_2)1\Gamma_R(k_1)G_R^{\rho\rho+}(q)\Gamma_R(k)p_\rho(p_2) \\
\times\bar{u}_L(k_1)\Gamma_{\rho\rho}(p_1)G_D(k_2)^F(k_2),
\]

where $q$, $k_2$, and $k_3$ are the four-momenta of the intermediate state $\Lambda_c(2940)^+$ and final states $p$ and $D^0$, respectively. We can easily obtain the amplitude of $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$ by Eq. 13, where we only need to replace the relevant parameter of $\Lambda_c(2940)^+(J^P=1/2^-)$ with that of $\Lambda_c$.

In Fig. 5 we present the cross section of $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\rightarrow\Lambda_cD^0p$, which is dependent on $\sqrt{s}$. As shown in Fig. 5 there exists a steep increase at about $\sqrt{s} = 5.2$ GeV, where $\Lambda_c(2940)^+$ approaches its mass-shell, so its propagator contributes a cusp.

![Graph showing the dependence of the cross section for the process $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\rightarrow\Lambda_cD^0p$.]

FIG. 5: The dependence of the cross section for the process $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\rightarrow\Lambda_cD^0p$ process on $\sqrt{s}$. Here, we consider different J^P assignments to $\Lambda_c(2940)^+$.

Taking the background contribution into account, the dependence of the cross section of $p\bar{p}\rightarrow\Lambda_cD^0p$ on $\sqrt{s}$ is shown in Fig. 6. Our calculation also indicates that the order of magnitude of the cross section of $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$ is about 10 nb, which is far larger than that of $p\bar{p}\rightarrow\Lambda_c\Lambda_c(2940)^+\Lambda_c\rightarrow\Lambda_cD^0p$ as $\Lambda_c(2940)^+$ is a $J^P=1/2^-$ state. To some extent, the contribution of the intermediate $\Lambda_c(2940)^+$ of $J^P=1/2^-$ to $p\bar{p}\rightarrow\Lambda_cD^0p$ is immersed in the background.

The Dalitz plot is a very useful tool for the data analysis since much information is exposed by the plot. With the help of the FOWL code, we present the Dalitz plot for the $p\bar{p}\rightarrow\Lambda_cD^0p$ process and the $pD^0$ invariant mass spectrum $m^2_{pD^0}$ in Figs. 7-9.

Just as shown in Fig. 7, the shape of the distributions, where peaks appear at certain locations, are not the Breit-Wigner types. This is mainly due to an interference between the amplitudes of $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$ and $p\bar{p}\rightarrow\Lambda_c(2940)^+\Lambda_c\rightarrow\Lambda_cD^0p$, which also implies that $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$ forms the dominant background for $p\bar{p}\rightarrow\Lambda_cD^0p$.

With $J^P=3/2^+$ or $5/2^+$ assignments to $\Lambda_c(2940)^+$, we find that there exist explicit cusp structures corresponding to $\Lambda_c(2940)^+$ in the $pD^0$ invariant mass spectrum, which can be described by the Breit-Wigner formalism. The Dalitz plot analysis indicates that $\Lambda_c(2940)^+$ signal can be well distinguished from the background in the $p\bar{p}\rightarrow\Lambda_cD^0p$ process. That is due to the fact that the contribution of $p\bar{p}\rightarrow\Lambda_c\Lambda_c\rightarrow\Lambda_cD^0p$
FIG. 6: The cross section of $p\bar{p} \rightarrow \Lambda_c D^0 p$. Here, we include the background contribution to $p\bar{p} \rightarrow \Lambda_c D^0 p$.

FIG. 7: The Dalitz plot and invariant mass spectra for $p\bar{p} \rightarrow \Lambda_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 3/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

FIG. 8: The Dalitz plot and invariant mass spectra for $p\bar{p} \rightarrow \Lambda_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 3/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

FIG. 9: The Dalitz plot and invariant mass spectra for $p\bar{p} \rightarrow \Lambda_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 5/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

\[ \Lambda_c D^0 p \] is far smaller than that of $p\bar{p} \rightarrow \Lambda_c(2940)^+ \Lambda_c \rightarrow \Lambda_c D^0 p$ as shown in Figs. [3][6]

V. DISCUSSION AND CONCLUSION

In this work we investigate the production rate of $\Lambda_c(2940)^+$ in the future experiments at PANDA. We find if the branching ratio of $\Lambda_c(2940)^+$ decaying into $D^0 p$ is at the order $10^{-1}$, at least $10^4$ events of $\Lambda_c(2940)^+$ per day can be produced at PANDA.

Here, let us briefly discuss dependence of the numerical result on the phenomenologically introduced parameter $\Lambda$ used in this work. The cutoff $\Lambda = 3$ GeV is adopted as suggested in Ref. [30]. If the cutoff $\Lambda$ decreases to 2.5 GeV, both the production rate of $\Lambda_c(2940)^+$ and the background would increase about one order. The number of events is still large enough for investigating behaviors of $\Lambda_c(2940)^+$ in the proton and antiproton collision. In our numerical computations we adopt the same cutoff $\Lambda$ value as that in Ref. [30].

We would like to specify an important issue, which was discussed in literature and may affect our theoretical estimate of the production rate. It is noted that the initial state interaction (ISI) effect is included in the numerical result pre-
represented in Secs. [III and IV]. The ISI is an important effect for studying meson production in nucleon-nucleon collisions as the transition occurs near the threshold. That effect was first observed by the authors of Refs. [32, 33] that the ISI makes the cross section to be reduced by an overall factor, which is slightly energy-dependent. In studying \( p\bar{p} \to \Lambda_c \Lambda_c \), the authors of Ref. [32] also took into account the ISI effect, which reduces the cross section of \( p\bar{p} \to \Lambda_c \Lambda_c \) by a factor 10. The ISI may be induced by complicated interaction processes among the ingredients inside the colliding \( p \) and \( \bar{p} \), which may be valence quarks or even gluons and sea quarks. It is believed that such processes are governed by the non-perturbative QCD effects, thus not calculable so far. Interests to note that for high energy \( p\bar{p} \) or \( pp \) collisions, one can use the parton distribution function (PDF) due to the asymptotic freedom of QCD, but for lower energy collisions, we do not know how to correctly deal with the ISI effects. Therefore, as suggested by previous research [32, 33], we would retain a phenomenological factor in the numerical estimate of the production rate to take care of the ISI effect on \( p\bar{p} \to \Lambda_c \Lambda_c (2940)^+ \). Thus, an extra factor is introduced to reflect the ISI effect, which makes the cross section of \( p\bar{p} \to \Lambda_c \Lambda_c (2940)^+ \) corresponding to Eq. (12) suppressed by one order of magnitude (the ISI effect is considered in the numerical results presented in Figs. 4 and 10).

With above consideration, we can roughly estimate the production events of \( \Lambda_c (2940)^+ \) at PANDA and the results are presented in Fig. 4. The designed luminosity of PANDA is about \( 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \), so the integrated luminosity in one day run is about \( 10^4 \text{ nb}^{-1} \). Assuming we have a 50% overall efficiency, we may expect \( 10^7 \sim 10^8 \) events of \( \Lambda_c (2940)^+ \) per day produced at PANDA. In addition, we also would like to emphasize that the qualitative conclusion, which is made via the background analysis and Dalitz plot, is not affected by whether including the ISI effect.

Furthermore, the line shape of the cross section and invariant mass spectrum without taking in the background is independent of the coupling constant \( g_{\Lambda_c (2940)^+D^0\bar{p}} \). If the branching ratio of \( \Lambda_c (2940)^+ \to D^0\bar{p} \) is about 10%, there is a large final-state phase space for the production of \( p\bar{p} \to \Lambda_c \bar{\Lambda}_c \to \Lambda_c D^0\bar{p} \). As \( 10^4 \sim 10^5 \), \( \Lambda_c (2940)^+ \) per day can be produced, one can carefully study the properties of \( \Lambda_c (2940)^+ \) via the channel of \( p\bar{p} \to \Lambda_c (2940)^+ \Lambda_c \to D^0\bar{p} + D^0\bar{p} \) in the future PANDA experiments. In the second sub-process, \( \Lambda_c \) decays into \( D^0 + \bar{p} \) which is easy to be experimentally observed and the constructed invariant mass can accurately identify \( \Lambda_c \).

Since the Belle Collaboration confirmed \( \Lambda_c (2940)^+ \) in the \( \Sigma_c (2455)^{0+} \) channel [2], we also study the \( \Lambda_c (2940)^+ \) production in \( p\bar{p} \to \pi^+ \Sigma_c^+ \bar{\Lambda}_c \), where \( p\bar{p} \to \Lambda_c \bar{\Lambda}_c \to \Lambda_c \pi^+ \Sigma_c^+ \) and \( p\bar{p} \to \Lambda_c \Lambda_c (2940)^+ \to \Lambda_c \pi^+ \Sigma_c^+ \) compose the background and signal for the \( \Lambda_c (2940)^+ \) production respectively. In the former channel, because of constraint from the phase space, the \( \Lambda_c \) can only be an off-shell intermediate state for the final state \( \pi^+ \Sigma_c^+ \), so due to the Breit-Wigner structure, such sub-process is relatively suppressed in comparison with the "signal". The cross section and the invariant mass spectrum of \( p\bar{p} \to \bar{\Lambda}_c \pi^- \Sigma^+ \) with \( \sqrt{s} = 5.35 \text{ GeV} \) and \( B(\Lambda_c (2940)^+ \to \pi^- \Sigma_c^+) \sim 10\% \) is presented in Fig. 10. Here, we take the coupling constant as \( g_{\Lambda_c \pi \Sigma} = 3.9 \), which results in a weaker background. The signals of \( \Lambda_c (2940)^+ \) can be distinguished from the background easily as shown in Fig. 10. Thus, one can conclude that the channel \( p\bar{p} \to \pi^- \Sigma_c^+ \bar{\Lambda}_c \) is also a suitable channel to study \( \Lambda_c (2940)^+ \).

![Graph](image)

**FIG. 10:** The total cross section and invariant mass spectrum for \( p\bar{p} \to \pi^- \Sigma_c^+ \bar{\Lambda}_c \) at \( \sqrt{s} = 5.35 \text{ GeV} \). Here, we consider the ISI effect just discussed in Sec. [V].

Based on the analysis above, it is optimistic to investigate \( \Lambda_c (2940)^+ \) in the future experiment of PANDA, even though the cross section is not as large as for the charmonium-like states, such as \( X(3872) \) [17].

In addition, it is very interesting to notice the observation potential at BelleII [34, 35] and the SuperB factory [36], which will produce a large database of \( \Upsilon (4S) \). As \( \Upsilon (4S) \) may have a sizable branching ratio to decay into \( \Lambda_c (2940)^+ \Lambda_c (2940)^- \Lambda_c \), thus comparing the data obtained at PANDA with that from the \( B \)-factory would make more sense and help eventually to pin down the spin-parity assignment of \( \Lambda_c (2940)^+ \).

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