PHYSICAL REVIEW D **92,** 094032 (2015)

$\Lambda_c^*(2940)^+$ photoproduction off the neutron

Xiao-Yun Wang,[1,2,3,*] Alexey Guskov,[4,†] 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
[4]*Joint Institute for Nuclear Research, Dubna 141980, Russia*

(Received 9 September 2015; published 25 November 2015)

By assuming that the $\Lambda_c^*(2940)$ is a pD^{*0} molecular state with spin-parity $J^P=\frac{1}{2}^+$ and $J^P=\frac{1}{2}^-$, the photoproduction of charmed $\Lambda_c^*(2940)$ baryon in the $\gamma n\to D^-\Lambda_c^*(2940)^+$ process is investigated with an effective Lagrangian approach. It is found that the contributions from the t-channel with D^* exchange are dominant, while those from the s-channel with nucleon pole exchange give a sizeable contribution around the threshold. The contributions from the u-channel and contact term are very small. The total cross section of the $\gamma n\to D^-\Lambda_c^*(2940)^+$ reaction is estimated, which indicate it is feasible to searching for the charmed $\Lambda_c^*(2940)$ baryon at the COMPASS experiment.

DOI: 10.1103/PhysRevD.92.094032 PACS numbers: 14.20.Lq, 13.60.Rj, 13.30.Eg

I. INTRODUCTION

Searching for and explaining the exotic states, which may consist of the non $q\bar{q}$ and qqq configurations, has become a very interesting topic in hadron physics. Actually, the structure of the baryon is more intriguing than that of the meson. Recently, some charmed baryons have been experimentally identified [1,2], which provide an ideal place to investigate the dynamics of the light quarks in the environment of a heavy quark. For example, the charmed baryon $\Lambda_c^*(2940)$ has aroused intensive studies on its nature.

The charmed baryon $\Lambda_c^*(2940)$ was first announced by the *BABAR* Collaboration [3] by analyzing the pD^0 invariant mass spectrum. Later, the Belle Collaboration [4] confirmed it as a resonant structure in the final state $\Sigma_c(2455)^{0,++}\pi^\pm\to\Lambda_c^+\pi^+\pi^-$. The values for the mass and width of the $\Lambda_c^*(2940)$ state were reported by both collaborations [3,4], which are consistent with each other:

$$\begin{aligned} BABAR\colon\ M &= 2939.8\pm1.3\pm1.0\ \text{MeV},\\ \Gamma &= 17.5\pm5.2\pm5.9\ \text{MeV},\\ \text{Belle}\colon\ M &= 2938.0\pm1.3^{+2.0}_{-4.0}\ \text{MeV},\\ \Gamma &= 13^{+8+27}_{-5-7}\ \text{MeV}. \end{aligned}$$

However, the spin-parity of the $\Lambda_c^*(2940)$ state has still not been determined in experiment. Different theoretical groups [5–19] have performed theoretical studies of $\Lambda_c^*(2940)$ by assuming different assignments for its spin-parity $J^P=\frac{1}{2}^\pm,\ \frac{3}{2}^\pm,\ \frac{5}{2}^\pm$. For example, by assuming the $\Lambda_c^*(2940)$ as a pD^{*0} molecular state, the spin-parity of $\Lambda_c^*(2940)$ was assigned to be $\frac{1}{2}^\pm$ in Refs. [6,7,18]. Besides supposing $\Lambda_c^*(2940)$ to be a hadronic molecular state, the $\Lambda_c^*(2940)$ also is explained as a conventional charmed baryon [9] with $J^P=\frac{3}{2}^+$ or $J^P=\frac{5}{2}^-$. Since the nature of $\Lambda_c^*(2940)$ is still unclear, more work is needed to determine its real inner structure.

Until now, all experimental observations of $\Lambda_c^*(2940)$ have been from the e^+e^- collision [3,4]. Thus it is interesting to study the production of $\Lambda_c^*(2940)$ in other process. In Refs. [5,20], the production of $\Lambda_c^*(2940)$ by $\bar{p}p$ annihilation is proposed, while the production of $\Lambda_c^*(2940)$ via a π meson induced nucleon is discussed in Ref. [21]. However, one notices that there is no relevant information about the photoproduction of $\Lambda_c^*(2940)$. Thus the studies on the photoproduction of $\Lambda_c^*(2940)$ are highly necessary.

In this work, with an effective Lagrangian approach, the photoproduction of $\Lambda_c^*(2940)$ in the $\gamma n\to D^-\Lambda_c^*(2940)^+$ process is investigated. Moreover, the feasibility of searching for the charmed $\Lambda_c^*(2940)$ resonance is also discussed. It is shown that modern experiments based on energetic lepton beams of high intensity like the COMPASS experiment at CERN [22,23] could be the promising platform to search for photoproduction of the charmed baryon $\Lambda_c^*(2940)$ and study its properties.

This paper is organized as follows. After an Introduction, the formalism and the main ingredients are presented. The numerical results and discussions are given in Sec. III. In Sec. IV, the $\Lambda_c^*(2940)$ production at COMPASS is discussed. Finally, the paper ends with a brief summary.

II. FORMALISM

In the present work, an effective Lagrangian approach in terms of hadrons is adopted, which is an important theoretical method in investigating various processes in the resonance region [5,20,21,24–29].

---

[*] xywang@impcas.ac.cn
[†] avg@jinr.ru

A. Feynman diagrams and effective Lagrangian densities

Figure 1 describes the basic tree level Feynman diagrams for the production of $\Lambda_c^*(2940)$ $(\equiv\Lambda_c^*)$ in $\gamma n \to D^-\Lambda_c^{*+}$ reaction. These include the t-channel with D^+ and D^{*+} exchange, s-channel with nucleon pole exchange, u-channel with Λ_c^* exchange and the contact term. Figure 2 is the Feynman diagrams for the $\gamma n \to D^- D^0 p$ reaction.

In Refs. [6,7], by assuming the $\Lambda_c^*(2940)$ as a molecular $D^{*0}p$ state, the spin-parity (J^P) quantum number of $\Lambda_c^*(2940)$ was assigned to be $\frac{1}{2}^+$, while the quantum number $J^P = \frac{1}{2}^-$ is completely excluded because the calculated partial widths are much larger than the experimental width of the $\Lambda_c^*(2940)$ state. In this present work, two cases of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^\pm$ are calculated for a comparison. Thus we take the normally used effective Lagrangians for $\Lambda_c^* ND$, $\Lambda_c^* ND^*$, and $\gamma\Lambda_c^*\Lambda_c^*$ couplings as [5,21]

$$\mathcal{L}_{ND\Lambda_c^*(\frac{1}{2}^\pm)} = i g^{\pm}_{\Lambda_c^* ND} \bar{\Lambda}_c^* \Gamma^\pm N D + \text{H.c.}, \tag{1}$$

$$\mathcal{L}_{ND^*\Lambda_c^*(\frac{1}{2}^\pm)} = g^{\pm}_{\Lambda_c^* ND^*} \bar{\Lambda}_c^* \Gamma^\pm_\mu N D^*_\mu + \text{H.c.}, \tag{2}$$

$$\mathcal{L}_{\gamma\Lambda_c^*\Lambda_c^*(\frac{1}{2}^\pm)} = -e\bar{\Lambda}_c^* \left(Q_{\Lambda_c^*} A - \frac{\kappa^\pm_{\Lambda_c^*}}{4m_{\Lambda_c^*}} \sigma^{\mu\nu} F^{\mu\nu} \right) \Lambda_c^* + \text{H.c.}, \tag{3}$$

with

$$\Gamma^\pm = \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix}, \qquad \Gamma^\pm_\mu = \begin{pmatrix} \gamma^\mu \\ \gamma_5\gamma^\mu \end{pmatrix}. \tag{4}$$

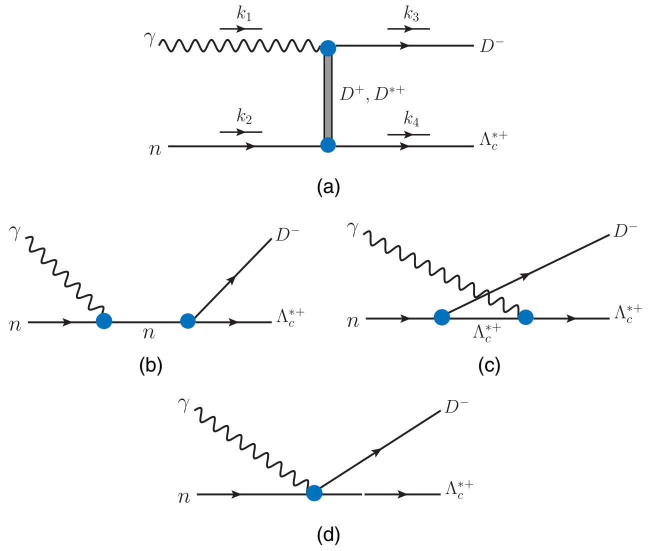

FIG. 1 (color online). Feynman diagrams for the $\gamma n \to D^-\Lambda_c^{*+}$ reaction: (a) t-channel; (b) s-channel; (c) u-channel; (d) contact term.

The $Q_{\Lambda_c^*}$ is the electric charge (in the units of e), while the anomalous magnetic momentum[1] $\kappa^+_{\Lambda_c^*} = 0.38$ for the Λ_c^* with $J^P = \frac{1}{2}^+$ [30]. The anomalous magnetic moment $\kappa^-_{\Lambda_c^*}$ for Λ_c^* with $J^P = \frac{1}{2}^-$ amounts to 0.44 in the SU(3) quark model [31]. We take the coupling constants $g^+_{\Lambda_c^* ND} = -0.45$, $g^-_{\Lambda_c^* ND} = -0.97$, $g^+_{\Lambda_c^* ND^*} = 6.64$, and $g^-_{\Lambda_c^* ND^*} = 3.75$ as used in Refs. [5,21].

Moreover, the effective Lagrangians for the γDD, γDD^*, and γNN couplings are

$$\mathcal{L}_{\gamma DD} = ieA_\mu (D^+\partial^\mu D^- - \partial^\mu D^+ D^-), \tag{5}$$

$$\mathcal{L}_{\gamma DD^*} = g_{\gamma DD^*} \epsilon_{\mu\nu\alpha\beta} (\partial^\mu A^\nu)(\partial^\alpha D^{*\beta}) D + \text{H.c.}, \tag{6}$$

$$\mathcal{L}_{\gamma NN} = -e\bar{N}\left(Q_N A - \frac{\kappa_N}{4m_N} \sigma^{\mu\nu} F^{\mu\nu} \right) N, \tag{7}$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ with A^μ, D, $D^{*\mu}$, and N are the photon, D-meson, D^*-meson, and nucleon fields, respectively. m_D and m_N are the masses of the D-meson and nucleon, while $\epsilon_{\mu\nu\alpha\beta}$ is the Levi-Cività tensor. Q_N is the charge of the hadron in the units of $e = \sqrt{4\pi\alpha}$ with α being the fine-structure constant. The anomalous magnetic moment $\kappa_N = -1.913$ for the neutron [32].

The coupling constant $g_{\gamma DD^*}$ is determined by the radiative decay widths of D^*,

$$\Gamma_{D^{*\pm}\to D^\pm\gamma} = \frac{g^2_{\gamma DD^*}(m^2_{D^*} - m^2_D)^2}{32\pi m^2_{D^*}} |\vec{p}_D^{\,\text{c.m.}}|, \tag{8}$$

where $\vec{p}_D^{\,\text{c.m.}}$ is the three-vector momentum of the D in the D^* meson rest frame. With $m_{D^*} = 2.01$ GeV, $m_D = 1.87$ GeV and $\Gamma_{D^{*\pm}\to D^\pm\gamma} = 1.35$ keV, one obtains $g_{\gamma DD^*} = 0.117\ \text{GeV}^{-1}$.

Considering the internal structure of hadrons, a form factor is introduced to describe the possible off-shell effects in the amplitudes. For the exchange baryons, we adopt the following form factors as used in Refs. [5,33,34],

$$\mathcal{F}_B(q^2_{ex}) = \frac{\Lambda^4_B}{\Lambda^4_B + (q^2_{ex} - m^2_{ex})^2}, \tag{9}$$

while for the D and D^* exchange, we take

$$\mathcal{F}_{D/D^*}(q^2_{ex}) = \frac{\Lambda^2_{D/D^*} - m^2_{ex}}{\Lambda^2_{D/D^*} - q^2_{ex}}, \tag{10}$$

---

[1] In Ref. [30], the magnetic moment of lighter state $\Lambda_c(2286)$ is predicted to be 0.38. Since this predicted magnetic moment does not depend on the mass of the Λ_c state, it is reasonable to take $\kappa^+_{\Lambda_c^*} = 0.38$ for the Λ_c^* with $J^P = \frac{1}{2}^+$.

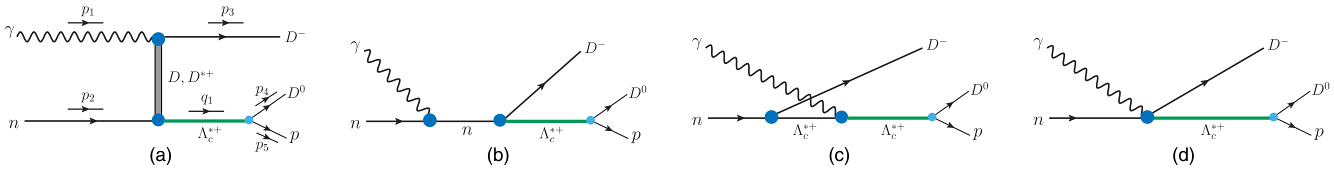

FIG. 2 (color online). Feynman diagrams for the $\gamma n \to D^- D^0 p$ reaction. The contributions from t-channel D^+ and D^{*+} exchange (a), s-channel nucleon pole (b), u-channel Λ_c^{*+} exchange (c), and contact term (d) are included.

where q_{ex} and m_{ex} are the four-momenta and the mass of the exchanged hadron, respectively. The values of cutoff parameters Λ_B and Λ_{D/D^*} will be discussed in the next subsection.

For the propagators of spin-1/2 baryon, we adopt the Breit-Wigner form [5,21]

$$G_{1/2}(q_{ex}) = i\frac{\not{q}_{ex} + m_{ex}}{q_{ex}^2 - M_{ex}^2 + im_{ex}\Gamma}, \tag{11}$$

where Γ is the total decay width of baryon. We take $\Gamma = 17$ MeV [1] for the $\Lambda_c^*(2940)$ state and $\Gamma = 0$ for the other intermediate baryons.

The propagator for D exchange is written as

$$G_D(q_{ex}) = \frac{i}{q_{ex}^2 - m_D^2}. \tag{12}$$

For the D^* exchange, we take the propagator as

$$G_{D^*}^{\mu\nu}(q_{ex}) = i\frac{-g^{\mu\nu} + q_{ex}^\mu q_{ex}^\nu / m_{D^*}^2}{q_{ex}^2 - m_{D^*}^2}, \tag{13}$$

where μ and ν denote the polarization indices of vector meson D^*.

B. Cross section for the $\gamma n \to D^- \Lambda_c^*(2940)^+$ reaction

After the above preparations, the invariant scattering amplitude of the $\gamma(k_1) n(k_2) \to D^-(k_3) \Lambda_c^{*+}(k_4)$ process as shown in Fig. 1 can be constructed as

$$-i\mathcal{M}_j^{\frac{1}{2}^\pm} = \bar{u}(k_4, \lambda_{\Lambda_c^*}) A_j^{\nu(\frac{1}{2}^\pm)} u(k_2, \lambda_n) \epsilon_\nu(k_1, \lambda_\gamma), \tag{14}$$

where j denotes the s-, t-, u-channel or contact term process that contributes to the total amplitude, while ϵ and u are the photon polarization vector and Dirac spinor, respectively. $\lambda_{\Lambda_c^*}$, λ_n, and λ_γ are the helicities for the $\Lambda_c^*(2940)$, the neutron, and the photon, respectively.

The reduced $A_j^{v(\frac{1}{2}^\pm)}$ amplitudes read as

$$A_s^{\nu(\frac{1}{2}^\pm)} = -ie\frac{g_{\Lambda_c^* ND}^\pm}{2m_N}\frac{\kappa_N}{s - m_N^2}\Gamma^\pm(\not{q}_n + m_N)\gamma^\nu \not{k}_1 \mathcal{F}_B, \tag{15}$$

$$A_{t,D}^{\nu(\frac{1}{2}^\pm)} = -eg_{\Lambda_c^* ND}^\pm \Gamma^\pm \frac{(2k_3 - k_1)^\nu}{t - m_D^2}\mathcal{F}_D^2, \tag{16}$$

$$A_{t,D^*}^{\nu(\frac{1}{2}^\pm)} = \frac{g_{\gamma DD^*} g_{\Lambda_c^* ND^*}^\pm}{t - m_{D^*}^2}\epsilon_{\mu\alpha\nu\beta} k_1^\alpha q_{D^*}^\beta \Gamma_\mu^\pm \mathcal{F}_{D^*}^2, \tag{17}$$

$$\begin{aligned} A_u^{\nu(\frac{1}{2}^\pm)} = {} & -ie\frac{g_{\Lambda_c^* ND}^\pm}{u - m_{\Lambda_c^*}^2}\Gamma^\pm[Q_{\Lambda_c^*}(\not{q}_{\Lambda_c^*} + m_{\Lambda_c^*})\gamma^\nu \\ & + \frac{\kappa_{\Lambda_c^*}}{2m_{\Lambda_c^*}}(\not{q}_{\Lambda_c^*} + m_{\Lambda_c^*})\gamma^\nu \not{k}_1]\mathcal{F}_B, \end{aligned} \tag{18}$$

where $s = q_n^2 = (k_1 + k_2)^2 \equiv W^2$, $t = q_{D/D^*}^2 = (k_1 - k_3)^2$, and $u = q_{\Lambda_c^*}^2 = (k_2 - k_3)^2$ are the Mandelstam variables.

To restor the gauge invariance, a generalized contact term is introduced as [35,36]

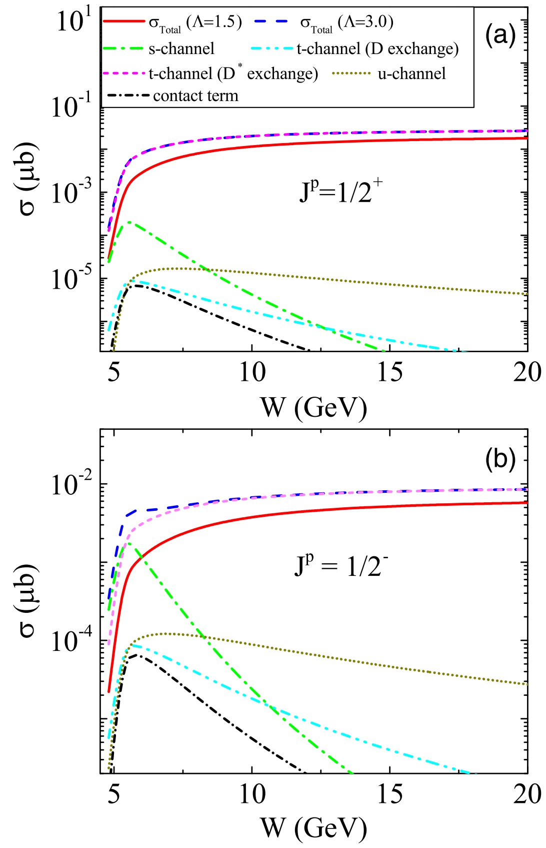

FIG. 3 (color online). (a): The total cross section for the $\gamma n \to D^- \Lambda_c^{*+}$ reaction as a function of the center-of-mass energy W for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^+$. Here, the s-, t-, u-channel and contact term are calculated with $\Lambda = 3.0$ GeV. (b): The same as (a), but for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^-$.

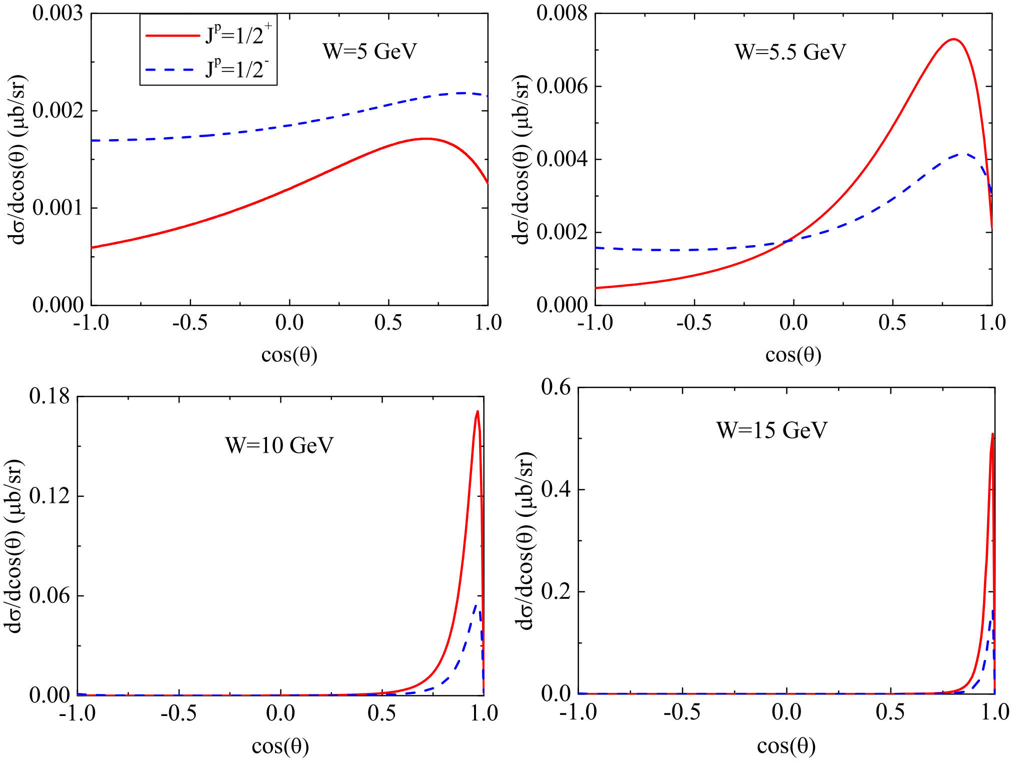

FIG. 4 (color online). Differential cross section $d\sigma/d\cos\theta$ as a function of $\cos\theta$ for the $\gamma n \to D^- \Lambda_c^{*+}$ reaction at $W = 5, 5.5, 10, 15$ GeV.

$$A_{\rm cont}^{\nu(\frac{1}{2}^{\pm})} = ieg^{\pm}_{\Lambda_c^* ND}\Gamma^{\pm}C^{\nu}, \tag{19}$$

with

$$\begin{aligned} C^{\nu} &= (2k_3 - k_1)^{\nu}\frac{\mathcal{F}_D - 1}{t - m_D^2}(1 - h(1 - \mathcal{F}_B)) \\ &\quad + (2k_4 - k_1)^{\nu}\frac{\mathcal{F}_B - 1}{u - m_{\Lambda_c^*}^2}(1 - h(1 - \mathcal{F}_D)), \end{aligned} \tag{20}$$

where $h = 1$ is taken [35].

Thus the unpolarized differential cross section for the $\gamma n \to D^- \Lambda_c^{*+}$ reaction at the center-of-mass (c.m.) frame is given by

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{k}_3^{\rm c.m.}|}{|\vec{k}_1^{\rm c.m.}|}\left(\frac{1}{4}\sum_{\lambda}|\mathcal{M}|^2\right), \tag{21}$$

where θ denotes the angle of the outgoing D^- meson relative to beam direction in the c.m. frame, while $\vec{k}_1^{\rm c.m.}$. and $\vec{k}_3^{\rm c.m.}$. are the three-momenta of the initial γ and final D^- meson, respectively.

C. Differential cross section $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0}d\Omega$

Since the $\Lambda_c^*(2940)$ has a coupling with pD^0, it is interesting to discuss the pD^0 invariant mass or angle distributions for the Dalitz process $\gamma n \to D^- D^0 p$. However, it is difficult to distinguish the two spin-parity assignments of the $\Lambda_c^*(2940)$ state from that first order differential cross section [21]. Thus we shall concentrate only on the second order differential cross section of $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0}d\Omega$, which may provide useful information for clarifying the spin-parity of the $\Lambda_c^*(2940)$ state.

The second order differential cross section for the $\gamma n \to D^- D^0 p$ reaction[2] is written as

$$\begin{aligned} \frac{d\sigma^2_{\gamma n \to D^- D^0 p}}{dM_{pD^0}d\Omega} &= \frac{m_N^2}{2^{10}\pi^5\sqrt{s}(p_1 \cdot p_2)} \\ &\quad \times \int \sum_{\rm spin}|\mathcal{M}|^2|\vec{p}_3||\vec{p}_5^*|d\Omega_5^*, \end{aligned} \tag{22}$$

where M_{pD^0} is the invariant mass of the final pD^0 system. $|\vec{p}_3|$ and Ω are the three-momentum and solid angle of the final D^- meson in the center-of-mass frame of the initial γn

---

[2] In some theoretical works, it is indicated that the ground state $\Lambda_c(2286)$ also has a coupling with pD^0. However, it should be noted that the coupling constant of $\Lambda_c(2286)ND$ is determined from $SU(4)$ invariant Lagrangians with a great uncertainty. Also, the mass of $\Lambda_c(2286)$ is about 650 MeV smaller than that of $\Lambda_c^*(2940)$, which means that the effects from the $\Lambda_c(2286)$ state around the $M_{pD^0} = m_{\Lambda_c^*}$ should be small because of the narrow total decay width of the $\Lambda_c^*(2940)$ state. Thus the $\Lambda_c(2286)$ is not included in these present calculations.

system, while $|\vec{p}_5^*|$ and Ω_5^* are the three-momentum and solid angle of the outing proton in the final pD^0 system.

III. RESULTS

As shown in the previous section, for the $\gamma n \to D^- \Lambda_c^{*+}$ process, the s-channel with nucleon pole exchange, the t-channel with D and D^* exchange, and the u-channel with Λ_c^* exchange and contact term are considered.

Since the cutoff parameter Λ related to the form factor is the only free parameter, according to usual practice [5,21,37], we take the cutoff parameter as $\Lambda = \Lambda_N = \Lambda_D = \Lambda_{D^*} = \Lambda_{\Lambda_c^*} = 3.0$ GeV in the sprit of minimizing the free parameters. For comparison, the numerical results of the full model with $\Lambda = 1.5$ GeV are also presented in Fig. 3, which indicate that the cross section with $\Lambda = 1.5$ GeV is smaller than that of $\Lambda = 3.0$ GeV. Moreover, from Fig. 3 one notices that the contribution from the t-channel with D^* exchange plays a dominant role[3] in the $\gamma n \to D^- \Lambda_c^{*+}$ reaction, while the contribution from the D exchange is very small. The s-channel with nucleon pole exchange gives a considerable contribution near the threshold. Besides, the contributions from the u-channel with Λ_c^* exchange and contact term are so small that they can be negligible. With the comparison, it is found that the s-channel nucleon pole exchange has more influence on $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^-$ than that of $J^P = \frac{1}{2}^+$.

Figure 4 presents the differential cross section for the $\gamma n \to D^- \Lambda_c^{*+}$ process for the cases of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^\pm$. It is noticed that all the curves show strong forward-scattering enhancements, due to the D^* exchange in the t-channel dominantly.

Figure 5 presents the differential cross section $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0} d\Omega$ at the mass $M_{pD^0} = 2.94$ GeV for the cases of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^\pm$. It is found that the absolute value of the differential cross section $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0} d\Omega$ for two spin-parity assignments is very different, which can be checked by further experiment.

IV. $\Lambda_c^*(2940)$ PRODUCTION AT COMPASS

The COMPASS experiment at CERN has run since 2002 using a positive muon beam of 160 GeV/c (2002–2010) or 200 GeV/c momentum (2011), scattered off solid ^{6}LiD (2002–2004) or NH$_3$ targets (2006–2011). It covers the range of W up to 19.4 GeV. The integrated luminosity of γN interaction multiplied by the general efficiency of the setup, corresponding to the period of data taking between 2002 and 2011, can be estimated based on the number of exclusively produced J/ψ mesons [38]. We calculate it to be of about 10 pb^{-1}.

Basing on the integrated luminosity mentioned above and the calculated $\Lambda_c^*(2940)$ production cross section value of 0.02 μb ($J^P = \frac{1}{2}^+$, $\Lambda = 3.0$ GeV, $\Gamma_{\Lambda_c^* \to pD^0} = 0.21$ MeV) we can expect to find in the COMPASS muon data sample collected between 2002 and 2011 up to 0.9×10^5 $\Lambda_c^*(2940)$ baryons produced via the reaction $\gamma n \to D^- \Lambda_c^{*+}$. This estimation is done by neglecting the nuclear collective effects and assuming an effective amount of neutrons in the target of about 45%. This number can be compared with the COMPASS open charm leptoproduction results based on the data collected between 2002 and 2007 [39], where the number of reconstructed $D^0 \to K^+ \pi^-$ decays (BR = 3.88%) exceeded 5×10^4.

Since the t-channel is dominating, the energy transferred to the produced $\Lambda_c^*(2940)$ is small and it decays almost at rest with the momentum of the proton and D^0-meson in the center-of-mass system of 0.42 GeV/c. Such low-momenta particles are almost invisible for the COMPASS tracking system while energetic D^--mesons can be easily detected. So in spite of the impossibility to observe the $\Lambda_c^*(2940)$

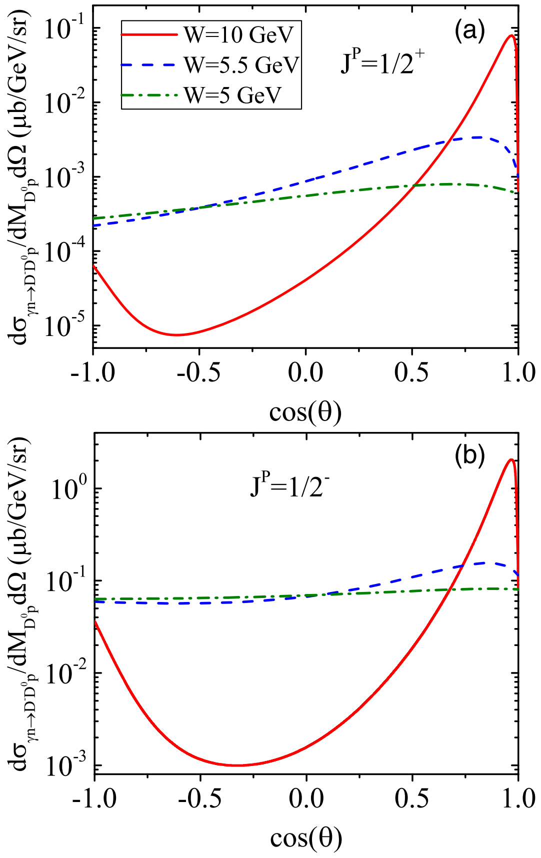

FIG. 5 (color online). (a): Differential cross section $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0} d\Omega$ for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^+$ at $W = 5$, 5.5, 10 GeV. (b): The same as (a), but for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^-$.

---

[3] In this work, as mentioned above, the relevant coupling constants are taken from Refs. [6,7] by assuming the charmed $\Lambda_c^*(2940)$ as a molecular state of $D^{*0}p$. Thus the dominant t-channel with D^* exchange contribution can be understood easily since the $\Lambda_c^*(2940)$ has a strong coupling with the $D^{*0}p$.

decay directly, its production should manifest itself in the missing mass spectrum.

V. SUMMARY

Within the frame of the effective Lagrangian approach, the photoproduction of charmed $\Lambda_c^*(2940)$ baryons in the $\gamma n \to D^- \Lambda_c^{*+}$ process via *s*-, *t*-, *u*-channel and contact term is investigated based on the conditions of the COMPASS experiment.

The numerical results indicate:

(I) The *t*-channel with D^* exchange plays a dominant role in the $\gamma n \to D^- \Lambda_c^{*+}$ reaction, while the contributions from the *t*-channel *D* exchange as well the *u*-channel Λ_c^* exchange and contact term are very small. The *s*-channel with nucleon pole exchange gives a considerable contribution at the threshold.

(II) According to our estimations, a sizable number of events related to the $\Lambda_c^*(2940)$ has already been produced at the COMPASS facility, which means that it is feasible to search for the charmed $\Lambda_c^*(2940)$ baryon produced via γn interaction. In the case of success, it would be the first observation of direct production of $\Lambda_c^*(2940)$.

(III) The absolute value of the differential cross section $d\sigma^2_{\gamma n \to D^- D^0 p}/dM_{pD^0} d\Omega$ for the two assignments $J^P = \frac{1}{2}^{\pm}$ for the $\Lambda_c^*(2940)$ state are much different. Thus we suggest that this observable can be measured in the further COMPASS experiment to clarify the nature of the $\Lambda_c^*(2940)$ state.

To sum up, we suggest that this experiment be carried out at COMPASS, which not only helps in testing the above theoretical predictions for the photoproduction of the $\Lambda_c^*(2940)$ state but also provides important information for clarifying the nature of the charmed $\Lambda_c^*(2940)$ baryon. It is worthwhile to point out that it is not possible to give a very precise theoretical result for the production of $\Lambda_c^*(2940)$ because the partial decay width of $\Lambda_c^*(2940)$ is only a theoretical value and not a real width measured by experiment. However, from the experimental point of view, the partial decay width of $\Lambda_c^*(2940)$ is a key factor to determine the spin-parity of $\Lambda_c^*(2940)$. Thus the experiment on measuring the partial decay width of $\Lambda_c^*(2940)$ is also encouraged.

ACKNOWLEDGMENTS

The authors would like to acknowledge Valery Lyubovitskij and Amand Faessler for useful discussions. Meanwhile, X. Y. W. is grateful Dr. Ju-Jun Xie for the 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 the Chinese Academy of Science (Grant No. Y101020BR0).

---

[1] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[2] E. Klempt and J. M. Richard, Rev. Mod. Phys. **82**, 1095 (2010).

[3] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 012001 (2007).

[4] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 082001 (2007).

[5] Y. Dong, A Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **90**, 094001 (2014).

[6] Y. Dong, A Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **81**, 014006 (2010).

[7] Y. Dong, A Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **82**, 034035 (2010).

[8] X. G. He, X.-Q. Li, X. Liu, and X.-Q. Zeng, Eur. Phys. J. C **51**, 883 (2007).

[9] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986); L. A. Copley, N. Isgur, and G. Karl, Phys. Rev. D **20**, 768 (1979); **23**, 817(E) (1981).

[10] C. Chen, X. L. Chen, X. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **75**, 094017 (2007).

[11] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Lett. B **659**, 612 (2008).

[12] X. H. Zhong and Q. Zhao, Phys. Rev. D **77**, 074008 (2008).

[13] H. Y. Cheng and C. K. Chua, Phys. Rev. D **75**, 014006 (2007).

[14] S. M. Gerasyuta and E. E. Matskevich, Int. J. Mod. Phys. E **17**, 585 (2008).

[15] W. Roberts and M. Pervin, Int. J. Mod. Phys. A **23**, 2817 (2008).

[16] C. Garcia-Recio, V. K. Magas, T. Mizutani, J. Nieves, A. Ramos, L. L. Salcedo, and L. Tolos, Phys. Rev. D **79**, 054004 (2009).

[17] D. Gamermann, C. E. Jimenez-Tejero, and A. Ramos, Phys. Rev. D **83**, 074018 (2011).

[18] J. He and X. Liu, Phys. Rev. D **82**, 114029 (2010).

[19] P. G. Ortega, D. R. Entem, and F. Fernandez, Phys. Lett. B **718**, 1381 (2013).

[20] J. He, Z. Ouyang, X. Liu, and X.-Q. Li, Phys. Rev. D **84**, 114010 (2011).

[21] J. J. Xie, Y.-B. Dong, and X. Cao, Phys. Rev. D **92**, 034029 (2015).

[22] P. Abbon *et al.* (COMPASS Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **577**, 455 (2007).

[23] Ph. Abbon *et al.* (COMPASS Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **779**, 69 (2015).

[24] B. S. Zou and F. Hussain, Phys. Rev. C **67**, 015204 (2003).

[25] X. Y. Wang, J. J. Xie, and X. R. Chen, Phys. Rev. D **91**, 014032 (2015).

[26] X. Y. Wang, X. R. Chen, and A. Guskov, Phys. Rev. D **92**, 094017 (2015).

[27] X. Y. Wang and X. R. Chen, Europhys. Lett. **109**, 41001 (2015).

[28] X. Y. Wang, X. Cao, J. J. Xie, and X. R. Chen, Phys. Rev. C **92**, 015202 (2015).

[29] X. Y. Wang and X. R. Chen, Eur. Phys. J. A **51**, 85 (2015).

[30] A. Faessler, Th. Gutsche, M. A. Ivanov, J. G. Komer, V. E. Lyubovitskij, D Nicmorus, and K. Pumsa-ard, Phys. Rev. D **73**, 094013 (2006).

[31] R. A. Williams, C. R. Ji, and S. R. Cotanch, Phys. Rev. C **43**, 452 (1991).

[32] Y. H. Chen and B. S. Zou, Phys. Rev. C **88**, 024304 (2013).

[33] T. Feuster and U. Mosel, Phys. Rev. C **58**, 457 (1998).

[34] T. Feuster and U. Mosel, Phys. Rev. C **59**, 460 (1999).

[35] P. Gao, J. J. Wu, and B. S. Zou, Phys. Rev. C **81**, 055203 (2010).

[36] H. Haberzettl, K. Nakayama, and S. Krewald, Phys. Rev. C **74**, 045202 (2006).

[37] J. Haidenbauer and G. Krein, Phys. Lett. B **687**, 314 (2010).

[38] C. Adolph *et al.* (COMPASS Collaboration), Phys. Lett. B **742**, 330 (2015).

[39] C. Adolph *et al.* (COMPASS Collaboration), Phys. Rev. D **87**, 052018 (2013).