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Charmed hadron photoproduction at COMPASS

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Abstract: Photoproduction of the charmonium-like state $Z_c(4200)$ and the charmed baryon $\Lambda_c^*(2940)$ is investigated with an effective Lagrangian approach and the Regge trajectories applying to the COMPASS experiment. Combining the experimental data from COMPASS and our theoretical model we estimate the upper limit of $\Gamma_{Z_c(4200)\to J/\psi\pi}$ to be of about 37 MeV. Moreover, the possibility to produce $\Lambda_c^*(2940)$ at COMPASS is discussed. It seems one can try to search for this hadron in the missing mass spectrum since the t-channel is dominating for the $\Lambda_c^*(2940)$ photoproduction.

Keywords: charmed hadron; photoproduction; COMPASS

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1 Introduction

In past decades great progress has been achieved in hadron spectroscopy, largely due to the high quality photoproduction data obtained at electronmagnetic facilities. A series of exotic states recently found in such experiments promotes study of the inner structure of hadrons and the strong interaction [1, 2]. Photoproduction provides one of the most direct routes to information about the hadronic structure. The COMPASS experiment at CERN, running since 2002 and using a positive muon beam of 160 GeV/c (2002–2010) or 200 GeV/c momentum (2011), is the ideal platform for studying the photoproduction of particles at high energies since it covers the range of center-mass-energy W up to 19.4 GeV [3, 4]. The photoproduction processes at high energies can be described effectively with Regge-trajectory exchanges.

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In 2014 a new charged charmonium-like $Z_c^+(4200)$ was observed in the invariant mass spectrum of $J/\psi\pi^+$ with a significance of 6.2σ by the Belle Collaboration [5]. The relevant experimental results show that the spin-parity quantum number of $Z_c^+(4200)$ corresponds to 1^+. Furthermore, its mass and width are measured to be [5]

$$M = 4196^{+31+17}_{-29-13}\ \text{MeV},$$
$$\Gamma = 370^{+70+70}_{-70-132}\ \text{MeV}.$$

The charmonium-like $Z_c^+(4200)$ state is very broad and its inner structures were of particular interest to the researchers. Within the different theoretical frames the $Z_c^+(4200)$ was explained as the tetraquark or the molecule states etc. [6–9]. These experimental and theoretical results indicate that the $Z_c^+(4200)$ is the ideal candidate for investigation and understanding the nature of exotic charmonium-like states.

The charmed baryon $\Lambda_c^*(2940)$ was first discovered by the *BABAR* Collaboration [10] by analysis of the pD^0 invariant mass spectrum. Later, the Belle Collaboration [11] 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 [10, 11], which are consistent with each other:

$$\begin{aligned} BABAR: &\quad M = 2939.8 \pm 1.3 \pm 1.0\ \text{MeV}, \\ &\quad \Gamma = 17.5 \pm 5.2 \pm 5.9\ \text{MeV}, \\ \text{Belle}: &\quad M = 2938.0 \pm 1.3^{+2.0}_{-4.0}\ \text{MeV}, \\ &\quad \Gamma = 13^{+8+27}_{-5-7}\ \text{MeV}. \end{aligned}$$

However, the spin-parity of the $\Lambda_c^*(2940)$ state has not been determined yet in experiments. Since the nature of $\Lambda_c^*(2940)$ is still unclear, additional effort is needed to determine its real inner structure. As of now, all experimental observations of the $\Lambda_c^*(2940)$ have been performed in the e^+e^- collisions [10, 11]. Since there is no experimental information about the photoproduction of $\Lambda_c^*(2940)$, it is necessary to conduct a theoretical study of the photoproduction of this hadronic state.

In this paper, we give a brief overview of our theoretical results for the photoproduction of $Z_c(4200)$ and $\Lambda_c^*(2940)$. In the next section we discuss the photoproduction of $Z_c(4200)$ and the partial decay width $\Gamma_{Z(4200)\to J/\psi\pi}$. In Section III the results for $\Lambda_c^*(2940)$ production in the re-

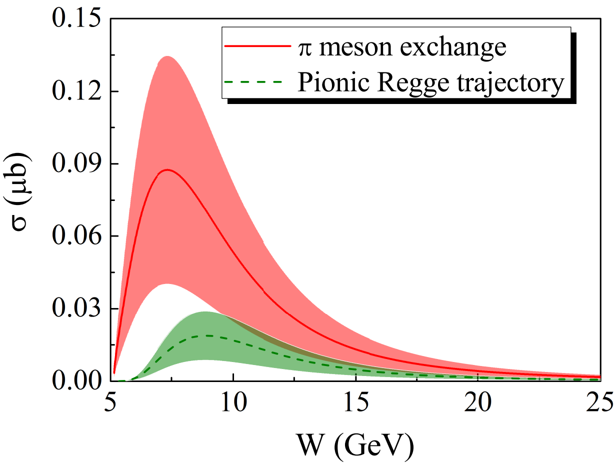

Figure 1: (Color online) The total cross section of the $\gamma p \to Z_c^+(4200)n$ reaction through π meson or pionic Regge trajectory exchange. Here, the numerical results are calculated with $\Gamma_{Z_c(4200)\to J/\psi\pi} = 87.3$ MeV, while the bands stand for the uncertainties with the variation of $\Gamma_{Z_c(4200)\to J/\psi\pi}$ from 40.2 to 131.4 MeV.

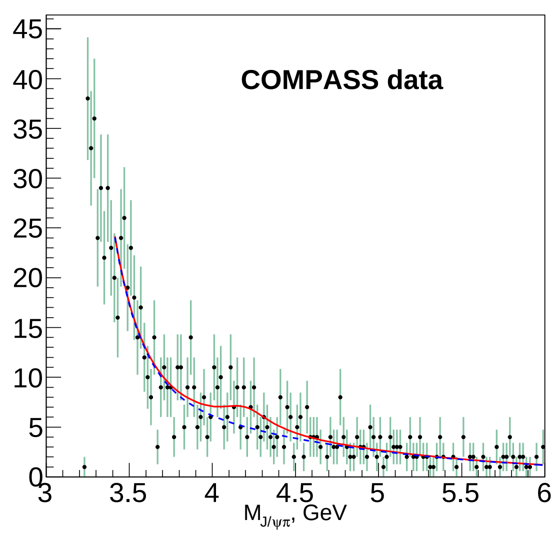

Figure 2: (Color online) Mass spectrum of the $J/\psi\pi^{\pm}$ state obtained by COMPASS [3]. The fitted function is shown as a red solid line. Dashed blue line corresponds to the continuum description.

action $\gamma n \to D^-\Lambda_c^*(2940)^+$ are presented. Finally this paper concludes with a short summary.

2 $Z_c(4200)$ photoproduction

In order to describe the production of $Z_c(4200)$ in the $\gamma p \to Z_c^+(4200)n$ reaction via the pion exchange, we introduce the pion Reggeized treatment by replacing the Feynman propagator by the Regge propagator (more details can be found in Ref. [12]). Fig. 1 presents the total cross section $\sigma(\gamma p \to Z_c^+ n)$ through the π meson or pionic Regge trajectory exchange by taking $\Lambda = 0.7$ GeV. It is found that the Reggeized treatment can lead to a lower cross section of the $Z_c^+(4200)$ photoproduction at high photon energies. Moreover, it is noted that the peak position of the total cross section moves to the higher energies when the Reggeized treatment is considered.

The $J/\psi\pi^{\pm}$ mass spectrum presented by the COMPASS collaboration in [3] does not exhibit any statistically significant structure at about 4.2 GeV (see Fig. 2). However, we can use this experimental result to estimate an upper limit for the value $BR(Z_c(4200) \to J/\psi\pi) \times \sigma_{\gamma N\to Z_c(4200)N}$.

With the normalization used in [3] this limit corresponds to the result

$$BR(Z_c(4200) \to J/\psi\pi) \times \sigma_{\gamma N\to Z_c(4200)N} < 340 \text{ pb}. \quad (1)$$

It can be used to estimate an upper limit for the partial width $\Gamma_{J/\psi\pi}$ of the decay $Z_c(4200) \to J/\psi\pi$ combined with our theoretical result. The production cross section, averaged over the W-range covered by COMPASS, is about $\Gamma_{J/\psi\pi} \times 91$ pb/MeV. Therefore

$$\frac{\Gamma_{J/\psi\pi}}{\Gamma_{tot}} \times \sigma_{\gamma N\to Z_c^{\pm}(4200)\,N} = \frac{\Gamma^2_{J/\psi\pi} \times 90 \text{ pb/MeV}}{\Gamma_{tot}} < 340 \text{ pb}. \quad (2)$$

Assuming $\Gamma_{\text{tot}} = 370$ MeV, we obtain an upper limit $\Gamma_{J/\psi\pi} < 37$ MeV.

3 $\Lambda_c^*(2940)$ photoproduction

We also studied the production of the $\Lambda_c^*(2940)$ state in the $\gamma n \to D^-\Lambda_c^{*+}$ process (more details can be found in Ref. [13]). Fig. 3 shows the total cross section for the $\gamma n \to D^-\Lambda_c^{*+}$ process for two sets of J^P: $\frac{1}{2}^+$ and $\frac{1}{2}^-$. One can notice that the contribution from the t-channel with D^* exchange is dominant, while the contributions from t-channel with the D meson, s-channel with the nucleon pole, u-channel with the Λ_c^* exchange and the contact term are small.

Based on the integrated luminosity and the calculated $\Lambda_c^*(2940)$ production cross section value of 0.02 μb ($J^P = \frac{1}{2}^+$, Λ=3.0 GeV, $\Gamma_{\Lambda_c^*\to pD^0} = 0.21$ MeV) one can expect to find in the COMPASS muon sample data 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 number can be compared with the COMPASS open charm leptoproduction results based on the data collected between 2002 and 2007 [14], where the number of reconstructed $D^0 \to K^+\pi^-$ decays (BR=3.88%) exceeded 5×10^4.

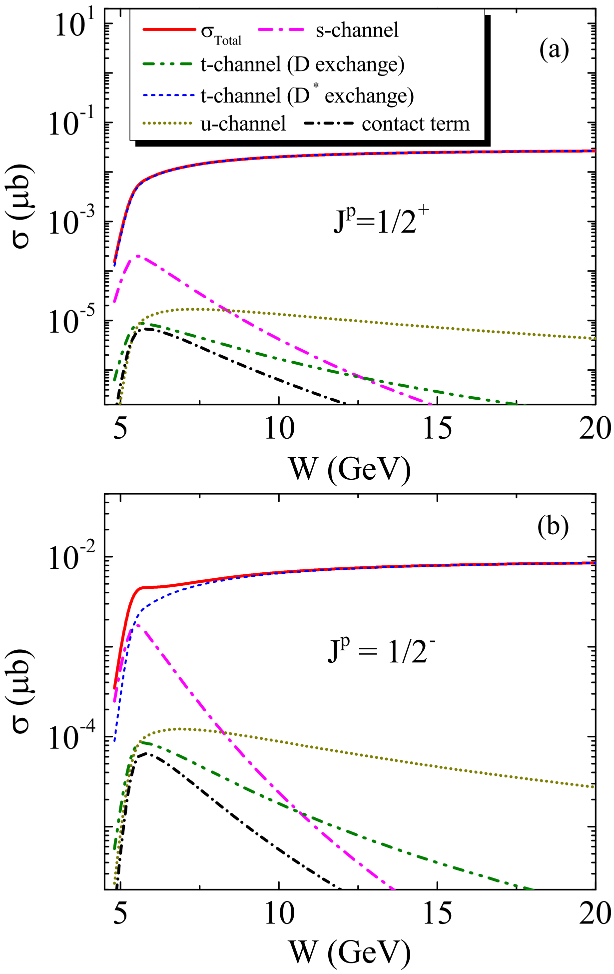

Figure 3: (Color online) (a): The total cross section of the $\gamma n \rightarrow D^- \Lambda_c^{*+}$ process for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^+$. (b) is same as the (a), but for the case of $\Lambda_c^*(2940)$ with $J^P = \frac{1}{2}^-$. Here, the cross section are calculated with $\Lambda = 3.0$ GeV.

Since the t-channel is dominant, the energy transferred to the $\Lambda_c^*(2940)$ produced is small, and it decays almost at rest with the momentum of the proton and the D^0-meson in the centre-of-mass system of 0.42 GeV/c. Such low-momenta particles are almost invisible for the COMPASS tracking system while energetic D^--meson can be easily detected. So in spite of the impossibility of observing the $\Lambda_c^*(2940)$ decay directly, its production should manifest itself in the missing mass spectrum.

4 Summary

We investigated the photoproduction of the charmonium-like $Z_c(4200)$ state and the charmed $\Lambda_c^*(2940)$ baryon. The upper limit for the partial decay width of $Z_c(4200) \rightarrow J/\psi\pi$ is established using the COMPASS results, which may provide valuable information for a better understanding of the nature of this particle. The possibility to observe the production of the charmed $\Lambda_c^*(2940)$ baryon at the COMPASS conditions is also studied. It should be noted that we only considered the case of $\Lambda_c^*(2940)$ with $J = 1/2$. This work constitutes a first step in that direction.

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