1 - 10 Pion-induced Production of the $Z_c(3900)$ off a Nuclear Target*

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The resonant structure $Z_c^{\pm}(3900)$ was reported recently by the BESIII and Belle Collaborations in the $J/\psi\pi^{\pm}$ invariant mass spectrum through the electron-positron collision process $e^+e^- \to J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4.26$ GeV[1, 2] and later in an analysis of the CLEO-c data[3]. Although such a resonant structure has been established in the experiment, its origin is still in debate. More experimental data will provide more opportunity to understand the structure of the so-called XYZ particles. Most of our experimental knowledge about XYZ particles is from the electron-positron collision or the B decays. In Ref.[4], the cross section of the $Z_c(3900)$ photoproduction off a proton was predicted to reach a maximum value of 50 to 100 nb at $\sqrt{s_{\gamma N}} \sim 10$ GeV. This prediction inspired an experiment at COMPASS, where photo-nucleon energies cover the range $\sqrt{s_{\gamma N}}$ from 7 to 19 GeV. Unexpectedly, no signal of the $Z_c(3900)$ was observed in the $J/\psi\pi^{\pm}$ mass spectrum[5]. It seems that the decay channel $Z_c(3900)^{\pm} \to J/\psi\pi^{\pm}$ cannot be the dominant one. Another possible explanation about the COMPASS result is that the theoretically predicted $Z_c(3900)$ photoproduction off a proton was overestimated. It is well known that the replacement of the proton target by the nuclear target will enhance the meson production[6, 7]. The nuclear target may be more appropriate for produce the XYZ particles. The high-energy pion beams are available in facilities such as J-PARC and COMPASS. It is interesting to make a theoretical prediction about the pion-induced production to evaluate the feasibility to observe the $Z_c(3900)$ in experiment with a nuclear target.

In this work, we focus on the charged pion (π^-)-induced production of the $Z_c^-(3900)$. Empirically, the s-channel and u-channel contributions are much smaller than t-channel contribution especially at high energies [8–10]. The known decay channel of the $Z_c(3900)$ with pions is $Z_c(3900) \to J/\psi\pi$, so we take the J/ψ as the exchanged meson in the t channel. Since the $J/\psi NN$ vertex is OZI suppressed, the Primakoff effect will be introduced here. As is well known in the photon-induced Primakoff effect, the high-energy pion beam will interact with the nucleon or nuclei through exchanging a virtual photon. Combined with the vector meson dominance (VMD) mechanism, the $Z_c(3900)$ can be produced. First, the cross sections for the $p(\pi^-, Z^-(3900))$ and $p(\pi^-, Z^-(3900) \to J/\psi\pi^-)$ reactions with variation of beam energies E_π are presented in Fig. 1 for reference.

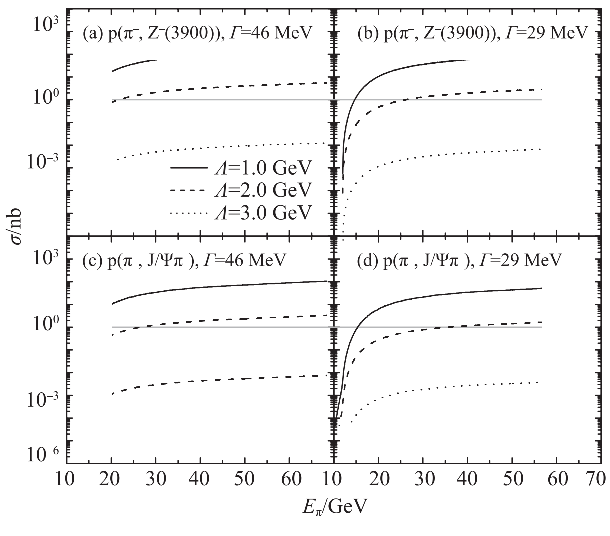

Fig. 1 Feynman diagrams for the $p(\pi^-, Z_c{}^-(3900))$and $p(\pi^-, Z_c^-(3900) \to J/\psi\pi^-)$ reactions.

The total cross section of the $p(\pi^-, Z_c^-(3900))$ reaction increases rapidly near the threshold and becomes relatively stable at about $E_\pi = 20$ GeV. With pion beam energy larger than 20 GeV, the production cross sections are in the order of magnitude of 1 nb with cutoff Λ in a range of $1 \sim 2$ GeV. The cross section for the $p(\pi^-, Z_c^-(3900) \to J/\psi\pi^-)$ reaction is also presented in Fig. 1 and a similar result is found as the $p(\pi^-, Z_c^-(3900))$ reaction because, in the calculation, we assume that the branch ratio of the $Z_c(3900) \to J/\psi\pi$ channel is 100%. The branch ratio has not been determined in the experiment. If we assume the branch ratio is 10%, a reasonable estimation about the order

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of magnitude of the cross section of the pion-induced $Z_c(3900)$ production off a proton is 0.1 nb. If we observe it in the $J/\psi\pi$ channel, the cross section will be suppressed further by an order of magnitude, but it is difficult to detect in the existing facilities.

The total cross sections for the $A(\pi^-, Z^-(3900))$ and $A(\pi^-, Z_c^-(3900) \to J/\psi\pi^-)$ reactions with variation of the beam energies E_π are calculated and presented in Fig. 2.

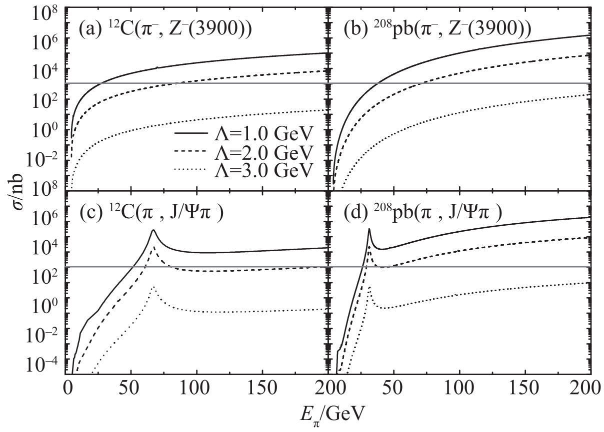

Fig. 2 The total cross sections for the $A(\pi^-, Z_c{}^-(3900))$ reaction (panels a and b) and $A(\pi^-, Z^-(3900) \to J/\psi\pi^-)$ reaction (panels c and d) versus the π^--beam energy E_π with $\Gamma = 29$ MeV and $A = {}^{12}$C (panels a and c) and ^{208}Pb (panels b and d).

Obvious enhancement of the $Z_c(3900)$ production can be observed after replacing the proton target with the nuclear target. At energies higher than about 30 GeV, the cross sections with two nuclei are in the order of magnitude of 1 000 nb or more with cutoff Λ in a range of $1 \sim 2$ GeV, with which the cross section with the proton target is in the order of magnitude of 1 nb. A conservative estimation about the order of magnitude of the total cross section of the $A(\pi^-, Z_c^-(3900))$ reaction is 1 000 nb if the beam energy is large enough. It is also found that the cross section for the heavier nuclei ^{208}Pb is larger than that of the light nuclei ^{12}C. It is reasonable to estimate that the $Z_c(3900)$ production off a nuclear target is in the order of magnitude of 100 nb, based on the calculation in this work with an assumption of branch ratio of the $Z_c(3900)$ decay in the $J/\psi\pi$ channel as 10%. If observed in the $J/\psi\pi$ channel, the cross section is in the order of magnitude of 10 nb.

Based on the results, we suggest the experimental study of the Z(3900) by using high-energy pion beams with nuclear targets at facilities such as COMPASS and J-PARC. The enhancement of the meson production with a nuclear target compared with a proton target is not limited to the $Z_c(3900)$ considered in the current work, which should exist in the production of other XYZ particles. In the literature, predictions of photon- or pion-induced productions of XYZ particles with a proton target have been suggested by many authors[4, 8, 9]. Based on the predictions in this work, we suggest studying the XYZ particle production with a nuclear target rather than a proton target.

References

[1] M. Ablikim, M. N. Achasov, X. C. Ai, et al., [BESIII Collaboration], Phys. Rev. Lett., 110(2013)252001.

[2] Z. Q. Liu, C. P. Shen, C .Z. Yuan, et al., [Belle Collaboration], Phys. Rev. Lett., 110(2013)252002.

[3] T. Xiao, S. Dobbs, A. Tomaradze, et al., Phys. Lett. B, 727(2013)366.

[4] Q. Y. Lin, X. Liu, H. S. Xu, Phys. Rev. D, 88(2013)114009.

[5] C. Adolph, R. Akhunzyanov, M. G. Alexeev, et al., Phys. Lett. B, 742(2015)330.

[6] J. Badier, J. Boucrot, J. Bourotte, et al., [NA3 Collaboration], Z. Phys. C, 20(1983)101.

[7] M. M. Kaskulov, U. Mosel, Phys. Rev. C, 84 065206 (2011)

[8] X. H. Liu, Q. Zhao, F. E. Close, Phys. Rev. D, 77(2008)094005.

[9] J. He, X. Liu, Phys. Rev. D, 80(2009) 114007.

[10] Y. Huang, J. He, H. F. Zhang, et al., J. Phys. G, 41(2014)115004.