Eur. Phys. J. A (2019) **55**: 152
DOI 10.1140/epja/i2019-12846-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Production of $\phi(2170)$ and $\eta(2225)$ in a kaon induced reaction

Xiao-Yun Wang[1,a] and Jun He[2,b]

[1] Department of physics, Lanzhou University of Technology, Lanzhou 730050, China
[2] Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, Jiangsu 210097, China

Received: 30 April 2019 / Revised: 26 June 2019
Published online: 19 September 2019

Communicated by R. Rapp

Abstract. In this work, we study the production of strange quarkoniums, the $\phi(2170)$, also named $Y(2175)$, and the $\eta(2225)$, via a kaon induced reaction on a proton target in an effective Lagrangian approach. The total and differential cross sections of the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ are calculated by the Reggeized t-channel Born term under an assumption that the $\phi(2170)$ and $\eta(2225)$ are $\Lambda\bar{\Lambda}$ molecular states. At the center of mass energies of about 4.2 GeV, the total cross section for the $\phi(2170)$ production is predicted to be about 1 μb. The numerical results indicate that it is feasible to produce the $\phi(2170)$ via kaon beam scattering at the best energy window near 4.2 GeV. The total cross section for the $\eta(2225)$ production is smaller than that for the $\phi(2170)$ production and it may reach an order of the magnitude of 0.1 μb. The differential cross sections for both reactions at different center of mass energies are also presented. It is found that the Reggeized t channel gives a considerable contribution at forward angles. As the energy increases, the contribution from the t-channel almost concentrates at extreme forward angles. From these theoretical predictions, the relevant experimental research is suggested, which could provide important information to clarify the internal structure and production mechanism of these two strange quarkoniums.

1 Introduction

The K meson was first observed by the physicists Rochester and Butler [1], which opened the door to explore the strange particles. Naturally, the kaon beam becomes a powerful tool to explore strange hadron and hypernucleus. As of now, many strange quarkoniums have been observed and were listed in the *Review of Particle Physics* (PDG) [2]. However, the internal structure of the strange quarkoniums is still a confusing problem due to large nonperturbative effect in the light flavor sector. Some strange quarkoniums were also considered as exotic states which are beyond the conventional picture of meson composed of a quark pair. Among these strange quarkoniums, the $\phi(2170)$ and $\eta(2225)$ attract special attention in both experiment and theory.

In the PDG, the $\phi(2170)$, which is also named $Y(2175)$ in the literature, is listed as a vector state with quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$ with a suggested mass of 2188 ± 10 MeV and a suggested width of 83 ± 12 MeV [2]. The existence of the $\eta(2225)$ meson with quantum numbers $I^G(J^{PC}) = 0^+(1^{-+})$ was confirmed by the BESIII Collaboration [3] via a partial wave analysis of the decay process $J/\psi \to \gamma\phi\phi$, which has a mass of 2216^{+4+21}_{-5-11} MeV and a width of 185^{+12+43}_{-14-17} MeV. In conjunction with the experiment activities, the $\phi(2170)$ and $\eta(2225)$ arouse many concerns from the theoretical side. In the literature, these two states, $\phi(2170)$ and $\eta(2225)$, were interpreted as traditional $s\bar{s}$ meson [4–8], $\Lambda\bar{\Lambda}$ bound state [9–11], tetraquark state [12–14], hybrid state [4, 15], or ϕKK resonance state [16, 17].

Since the $\phi(2170)$ and $\eta(2225)$ were observed only in the J/ψ meson decay process or e^-e^+ collision, it is an interesting and important topic to study these two strange quarkoniums though different processes. In most theoretical interpretations, there exists a strange quark pair in these two states and they are prone to decay into K and K^* meson. For example, in ref. [11], the strong decays of $\phi(2170)$ and $\eta(2225)$ were calculated by taking the two states as bound states of $\Lambda\bar{\Lambda}$ in the molecular scenario. One notes that the partial decay widths of both $\phi(2170) \to KK$ and $\eta(2225) \to K^*K$ are very large. Thus we expect that the cross section of these two states produced by kaon beam on proton target will be large enough to be observed in the existent facilities. The kaon-induced reaction may be an effective way to study light strange meson, which is available at J-PARC [18], JLab [19], COMPASS@CERN [20], and OKA@U-70 [21]. The data from

[a] e-mail: xywang01@outlook.com
[b] e-mail: junhe@njnu.edu.cn (corresponding author)

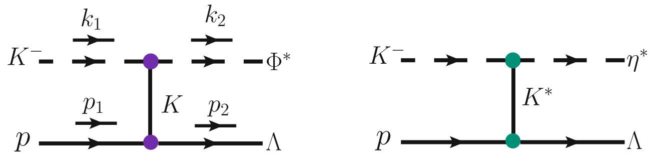

Fig. 1. (Color online) Feynman diagrams for the $K^-p \to \phi(2170)\Lambda$ reaction (left) and for the $K^-p \to \eta(2225)\Lambda$ reactions (right).

future experiments at those facilities will provide a good opportunity to deepen our understanding of internal structure of strange meson.

In this work, the strange quarkonium $\phi(2170)/\eta(2225)$ production via kaon induced reaction will be investigated. To this end we adopt here an effective Lagrangian approach in terms of only t channel with K/K^* exchange. In general, a phenomenological Regge treatment is successfully applied in meson production at high energies. The Regge model can reproduce the energy and t dependence of cross sections especially at forward angles. Since the experimental data of the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ are scare, in this paper, we pay special attention to the energy dependence of cross sections predicted with Regge model.

This paper is organized as follows. After introduction, we present formalism including Lagrangians and amplitudes of the $\phi(2170)/\eta(2225)$ production in sect. 2. Numerical results are discussed in sect. 3, followed by a brief summary in sect. 4.

2 Formalism

The strange quarkoniums $\phi(2170)$ and $\eta(2225)$ productions via kaon induced reactions on a proton target with t-channel K/K^* meson exchange are depicted in fig. 1. In ref. [11], the partial decay widths of the $\phi(2170)$ and $\eta(2225)$ were calculated by considering these two strange quarkoniums as $\Lambda\bar{\Lambda}$ bound states in the molecular scenario. The results shown that the partial decay widths $\Gamma_{\phi^* \to KK} \simeq 73.8$–$87.7\,\text{MeV}$ and $\Gamma_{\eta^* \to K^*K} \simeq 71.1$–$87.3\,\text{MeV}$, which are dominant in their total decay widths, respectively, [11]. Thus the production of these two strange quarkoniums will be calculated by taking the K or K^* exchange as the dominant contribution in the t channel.

In the present work, the contribution from s channel is omitted since it is usually negligibly small [22]. In the current work, the thresholds to produce the $\phi(2170)$ and the $\eta(2225)$ is higher than 3 GeV. In this energy region, the intermediate Λ^* in s channel can be well described by the Reggeized t channel adopted in this work due to the duality. For the Λ and Λ^* under the threshold, their contributions will be suppressed. If we assume the couplings between the Λ/Λ^* and the final state are not unusually strong, the s-channel contributions can be neglected. Usually, the contribution of the u channel with Λ exchange is also small and negligible at low energies if we assume the relevant couplings are not unusually strong [22]. Furthermore, at high energies, the contribution of the u channel to the total cross section will also become small and negligible when the Reggeized treatment was applied to the u channel. Hence, the contributions from the Λ in the u channel will not be included in the current calculation.

2.1 Lagrangians

For kaon induced production of the $\phi(2170)(\equiv \phi^*)$ and $\eta(2225)(\equiv \eta^*)$, the relevant Lagrangians for the t channel read as follows [23–25]:

$$\mathcal{L}_{\phi^*KK} = -ig_{\phi^*KK}[(\partial^\mu K)\bar{K} - (\partial^\mu \bar{K})K]\phi^*_\mu, \quad (1)$$

$$\mathcal{L}_{KN\Lambda} = ig_{KN\Lambda}\bar{N}\gamma_5\Lambda K + \text{H.c.} \quad (2)$$

$$\mathcal{L}_{\eta^*K^*K} = ig_{\eta^*K^*K}(K\partial_\mu\eta^* - \partial_\mu K\eta^*)K^{*\mu}, \quad (3)$$

$$\mathcal{L}_{K^*N\Lambda} = -g_{K^*N\Lambda}\bar{N}\left(\not{K}^* - \frac{\kappa_{K^*N\Lambda}}{2m_N}\sigma_{\mu\nu}\partial^\nu K^{*\mu}\right)\Lambda + \text{H.c.}, \quad (4)$$

where ϕ^*, η^*, K, K^*, N, and Λ are the $\phi(2170)$, the $\eta(2225)$, the K, the tK^* meson, the nucleon, and the Λ fields, respectively. Here, by using the $SU(3)$ flavor symmetry relation [26, 27], the coupling constant $g_{KN\Lambda} = -13.24$ can be determined [23]. Moreover, we adopt coupling constants $g_{K^*N\Lambda} = -4.26$ and $\kappa_{K^*N\Lambda} = 2.66$ calculated by the Nijmegen potential [28]. The value of g_{ϕ^*KK} and $g_{\eta^*K^*K}$ can be determined from the decay width $\Gamma_{\phi^* \to KK}$ and $\Gamma_{\eta^* \to K^*K}$, respectively, [11]. Accordingly, one gets $g_{\phi^*KK} \simeq 2.81$ and $g_{\eta^*K^*K} \simeq 1.39$ by taking $\Gamma_{\phi^* \to KK} \simeq 81\,\text{MeV}$ and $\Gamma_{\eta^* \to K^*K} \simeq 79.2\,\text{MeV}$, respectively.

2.2 Amplitudes

According to above Lagrangians, the scattering amplitude of the $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ processes can be written as

$$i\mathcal{M}_{K^-p\to\phi(2170)\Lambda} = ig_{\phi^*KK}g_{KN\Lambda}F(q^2)\epsilon^\mu_{\phi^*}(k_2)\bar{u}_N(p_2) \times\gamma_5\frac{1}{t-m_K^2}(k_{1\mu}+q_\mu)u_\Lambda(p_1), \quad (5)$$

$$i\mathcal{M}_{K^-p\to\eta(2225)\Lambda} = g_{\eta^*K^*K}g_{K^*N\Lambda}F(q^2)\bar{u}_N(p_2) \times\left(\gamma_\nu - \frac{\kappa_{K^*N\Lambda}}{2m_N}\gamma_\nu\not{q}_{K^*}\right) \times\frac{\mathcal{P}^{\mu\nu}}{t-m_{K^*}^2}(k_{2\mu}+k_{1\mu})u_\Lambda(p_1), \quad (6)$$

with

$$\mathcal{P}^{\mu\nu} = i\left(g^{\mu\nu} + q^\mu_{K^*}q^\nu_{K^*}/m^2_{K^*}\right), \quad (7)$$

where $\epsilon^\mu_{\phi^*}$ is the polarization vector of the $\phi(2170)$ meson, and $\bar{u}_N$ or u_Λ is the Dirac spinor of nucleon or Λ baryon. For the t-channel exchange [25], the form factor $F(q^2) = (\Lambda_t^2 - m^2)/(\Lambda_t^2 - q^2)$ is adopted. Here, the $t = q^2 = (k_1 - k_2)^2$ is the Mandelstam variables. The cutoff Λ_t in form factor is the only free parameter and will be discussed in sect. 3.

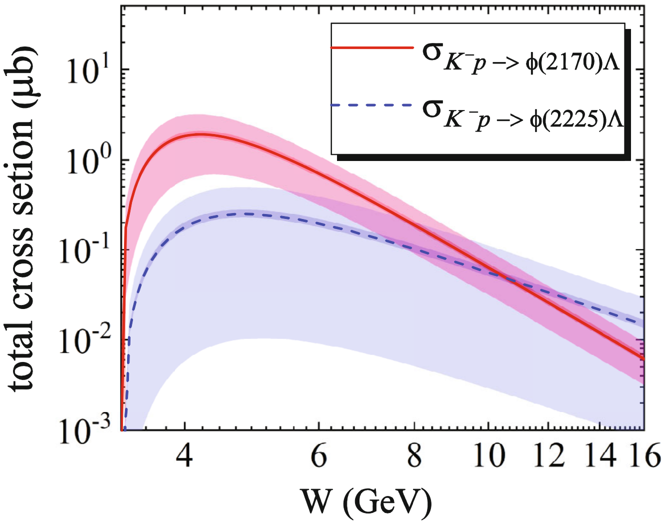

Fig. 2. (Color online) The energy dependence of the total cross section for the productions of the $\phi(2170)$ and the $\eta(2225)$ through t channel with cutoff $\Lambda_t = 1.6\pm0.5$ GeV. The Full (red) and dashed (blue) lines are for the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$, respectively. The bands stand for the error bar of cutoff Λ_t.

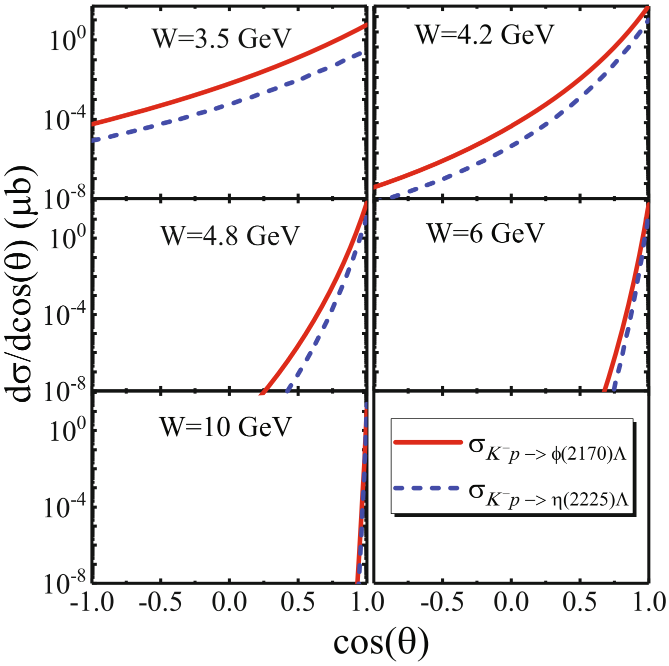

Fig. 3. (Color online) The differential cross section $d\sigma/d\cos\theta$ of the $\phi(2170)$ and $\eta(2225)$ production at different center-of-mass energies $W = 3.5, 4.2, 4.8, 6$ and 10 GeV. The Full (red) and dashed (blue) lines are for the $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ process, respectively. Here, one take the cutoff $\Lambda_t = 1.6$.

2.3 Reggeized t-channel

Usually, the Regge trajectory model is successful in analyzing hadron production at high energies [22, 23, 29–33]. The Reggeization can be done by replacing the t-channel propagator in the Feynman amplitudes (eqs. (5) and (6)) with the Regge propagator as follows:

$$\frac{1}{t-m_K^2} \to \left(\frac{s}{s_{scale}}\right)^{\alpha_K(t)} \frac{\pi\alpha'_K}{\Gamma[1+\alpha_K(t)]\sin[\pi\alpha_K(t)]}, \quad (8)$$

$$\frac{1}{t-m_{K^*}^2} \to \left(\frac{s}{s_{scale}}\right)^{\alpha_{K^*}(t)-1} \frac{\pi\alpha'_{K^*}}{\Gamma[\alpha_{K^*}(t)]\sin[\pi\alpha_{K^*}(t)]}. \quad (9)$$

The scale factor s_{scale} is fixed at 1 GeV. In addition, the Regge trajectories $\alpha_K(t)$ and $\alpha_{K^*}(t)$ read as [32]

$$\alpha_K(t) = 0.70(t-m_K^2), \qquad \alpha_{K^*}(t) = 1 + 0.85(t-m_{K^*}^2). \quad (10)$$

It is noted that no additional parameter is introduced after the Reggeized treatment applying.

3 Numerical results

With the preparation in the previous section, the cross section of the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ can be calculated. The differential cross section in the center of mass (c.m.) frame is written as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{k}_2^{\text{c.m.}}|}{|\vec{k}_1^{\text{c.m.}}|}\left(\frac{1}{2}\sum_\lambda |\mathcal{M}|^2\right), \quad (11)$$

where $s = (k_1 + p_1)^2$, and θ denotes the angle of the outgoing ϕ^*/η^* meson relative to K beam direction in the c.m. frame. $\vec{k}_1^{\text{c.m.}}$ and $\vec{k}_2^{\text{c.m.}}$ are the three-momenta of initial K beam and final ϕ^*/η^*, respectively. One notes that both the $\phi(2170)$ and the $\eta(2225)$ have large widths. If we consider the width in the calculation, the thresholds will not be fixed but varied in an energy region. As seen later, the best energy window to observe these two states is not close to the threshold. Hence, for simplification, we do not consider the effect of the width on the thresholds.

Since there does not exist the experimental data for the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$, here we give the prediction of the cross section of these two reactions as presented in figs. 2, 3. In these calculations, the cutoff parameter in the form factor is the only free parameter. In ref. [32], for the Reggeized t channel with K or K^* exchange, the experimental data can be reproduced well by taking cutoff $\Lambda_t = 1.55$ GeV. Moreover, in our previous work [34], the fitted value of free parameter $\Lambda_t = 1.60 \pm 0.03$ GeV was obtained for the reaction $\pi^-p \to f_1(1420)n$ via t channel in a Regge model, which is also a reasonable value for the reaction $K^-p \to f_1(1420)\Lambda$ through K^* exchange. Thus the cutoff $\Lambda_t \simeq 1.6$ GeV will be taken in the current work.

In fig. 2 we present the total cross section of the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ within the Regge model by taking $\Lambda_t = 1.6 \pm 0.5$ GeV, respectively. It is found that the line shape of the total cross section of the interaction $K^-p \to \phi(2170)\Lambda$ goes up very rapidly and has a peak around $W = 4.2$ GeV. The total cross section of the $\phi(2170)$ production in K induced reaction can reach up about $1.9\,\mu$b at $W = 4.2$ GeV, which indicates that the

$W \simeq 4.2\,\text{GeV}$ is the best energy window for searching for the $\phi(2170)$ via kaon induced reaction.

From fig. 2 we also found that the total cross section of the $K^-p \to \eta(2225)\Lambda$ process goes up slowly and has a bump at $4\,\text{GeV} \lesssim W \lesssim 6\,\text{GeV}$ because the K^* exchange is dominant in the $\eta(2225)$ production while the K exchange is dominant in the $\phi(2170)$ production [32,34]. At larger cutoff, the total cross section of $K^-p \to \eta(2225)\Lambda$ process is about one order of magnitude lower than that for the $\phi(2170)$ production. At smaller cutoff, the total cross section for the $\eta(2225)$ production decreases rapidly with the decrease of the cutoff due to the larger mass of the exchanged K^* meson.

In fig. 3, we present the prediction of differential cross section of the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ within the Regge model by taking a cutoff $\Lambda_t = 1.6\,\text{GeV}$. It can be seen that the differential cross sections of these two reactions are very sensitive to the θ angle and show strong forward-scattering enhancements especially at higher energies. Based on the results, the measurement at forward angles is suggested, which can be used to check the validity of the Reggeized treatment.

4 Summary and discussion

In this work, we study the reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ with an effective Lagrangian approach and the Regge trajectories model. The numerical results indicate that the total cross section of the $\phi(2170)$ production can reach an order of magnitude of $1\,\mu\text{b}$ at reasonable cutoffs, which means that it is feasible to search for the $\phi(2170)$ by kaon beam. Moreover, as we expected, the differential cross sections of both reactions $K^-p \to \phi(2170)\Lambda$ and $K^-p \to \eta(2225)\Lambda$ are sensitive to the θ angle and gives a considerable contribution at forward angles.

The $\eta(2225)$ production is more dependent on the cutoff, and has a smaller cross section than the $\phi(2170)$. The line shape of total cross section shows the monotonically decreasing behavior, which is different from the result with the Feynman model [32,34]. Usually, in the Regge model the K^* trajectory will be naturally decreasing. Besides, there is a clear bump structure in the total cross section at $4\,\text{GeV} \lesssim W \lesssim 6\,\text{GeV}$, which indicates that energies at 4–6 GeV is the best window for searching for the $\eta(2225)$ via reaction $K^-p \to \eta(2225)\Lambda$.

The high-precision data are expected at the facilities, such as the J-PARC, JLab, and COMPASS, which can provide good kaon beams. Our theoretical results provide valuable information for these possible experiments of searching for the $\phi(2170)$ at these facilities. The high precision data expected from the kaon induced interaction and other production mechnisms, such as photoproduction at GlueX@CEBAF 12 GeV upgraded [35], will provide a clearer picture of the interaction mechanism of strange quarkoniums production.

This project is supported by the National Natural Science Foundation of China under Grants No. 11705076 and No. 11675228. We acknowledge the Natural Science Foundation of Gansu province under Grant No. 17JR5RA113. This work is partly supported by the HongLiu Support Funds for Excellent Youth Talents of Lanzhou University of Technology.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: All data generated during this study are contained in this published article.]

References

1. G.D. Rochester, C.C. Butler, Nature **160**, 855 (1947).
2. Particle Data Group (M. Tanabashi *et al.*), Phys. Rev. D **98**, 030001 (2018).
3. BESIII Collaboration (M. Ablikim *et al.*), Phys. Rev. D **93**, 112011 (2016).
4. G.J. Ding, M.L. Yan, Phys. Lett. B **657**, 49 (2007).
5. X. Wang, Z.F. Sun, D.Y. Chen, X. Liu, T. Matsuki, Phys. Rev. D **85**, 074024 (2012).
6. S.S. Afonin, I.V. Pusenkov, Phys. Rev. D **90**, 094020 (2014).
7. D.M. Li, B. Ma, Phys. Rev. D **77**, 094021 (2008).
8. D.M. Li, S. Zhou, Phys. Rev. D **78**, 054013 (2008).
9. C. Deng, J. Ping, Y. Yang, F. Wang, Phys. Rev. D **88**, 074007 (2013).
10. L. Zhao, N. Li, S.L. Zhu, B.S. Zou, Phys. Rev. D **87**, 054034 (2013).
11. Y. Dong, A. Faessler, T. Gutsche, Q. Lü, V.E. Lyubovitskij, Phys. Rev. D **96**, 074027 (2017).
12. Z.G. Wang, Nucl. Phys. A **791**, 106 (2007).
13. H.X. Chen, X. Liu, A. Hosaka, S.L. Zhu, Phys. Rev. D **78**, 034012 (2008).
14. N.V. Drenska, R. Faccini, A.D. Polosa, Phys. Lett. B **669**, 160 (2008).
15. G.J. Ding, M.L. Yan, Phys. Lett. B **650**, 390 (2007).
16. A. Martinez Torres, K.P. Khemchandani, L.S. Geng, M. Napsuciale, E. Oset, Phys. Rev. D **78**, 074031 (2008).
17. S. Gomez-Avila, M. Napsuciale, E. Oset, Phys. Rev. D **79**, 034018 (2009).
18. T. Nagae, Nucl. Phys. A **805**, 486 (2008).
19. GlueX Collaboration (S. Adhikari *et al.*), arXiv:1707.05284 [hep-ex].
20. NA62-RK and NA48/2 Collaborations (B. Velghe), Nucl. Part. Phys. Proc. **273-275**, 2720 (2016).
21. OKA Collaboration (V. Obraztsov), Nucl. Part. Phys. Proc. **273-275**, 1330 (2016).
22. X.Y. Wang, J. He, Phys. Rev. D **96**, 034017 (2017).
23. X.Y. Wang, J. He, Phys. Rev. C **93**, 035202 (2016).
24. H.Y. Ryu, A.I. Titov, A. Hosaka, H.C. Kim, Prog. Theor. Exp. Phys. **2014**, 023D03 (2014).
25. X.H. Liu, Q. Zhao, F.E. Close, Phys. Rev. D **77**, 094005 (2008).
26. Y. Oh, H. Kim, Phys. Rev. C **73**, 065202 (2006).
27. Y. Oh, H. Kim, Phys. Rev. C **74**, 015208 (2006).
28. V.G.J. Stoks, T.A. Rijken, Phys. Rev. C **59**, 3009 (1999).

29. X.Y. Wang, X.R. Chen, Eur. Phys. J. A **51**, 85 (2015).
30. H. Haberzettl, X.Y. Wang, J. He, Phys. Rev. C **92**, 055503 (2015).
31. X.Y. Wang, J. He, H. Haberzettl, Phys. Rev. C **93**, 045204 (2016).
32. S. Ozaki, H. Nagahiro, A. Hosaka, Phys. Rev. C **81**, 035206 (2010).
33. X.Y. Wang, J. He, Phys. Rev. D **95**, 094005 (2017).
34. X.Y. Wang, J. He, Q. Wang, H. Xu, Phys. Rev. D **99**, 014020 (2019).
35. GlueX Collaboration (A. Austregesilo), Int. J. Mod. Phys. Conf. Ser. **46**, 1860029 (2018).