

Rescattering effects in near-threshold J/ψ photoproduction

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We investigate near-threshold J/ψ photoproduction off the nucleon, focusing on hadronic rescattering effects induced by open-charm meson-baryon intermediate states. Beyond the conventional Pomeron-exchange mechanism, the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ channels are incorporated within an effective Lagrangian framework. The relevant production amplitudes are constructed at tree level from t -, s -, and u -channel diagrams in a gauge-invariant manner. The resulting total and t -dependent differential cross sections are compared with recent near-threshold data from the GlueX, J/ψ -007, and CLAS experiments at Jefferson Laboratory. We find that the open-charm rescattering contributions improve the description of the data, especially for the differential cross sections at large momentum transfer, and can generate cusplike enhancements near the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ thresholds within the present hadronic model. We further present model estimates for the associated open-charm production processes $\gamma p \rightarrow \bar{D}^{(*)0}\Lambda_c^+$, with total cross sections of the order of a few nanobarns.

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I. INTRODUCTION

Near-threshold photoproduction of the J/ψ meson off the nucleon has attracted considerable interest as a sensitive probe of the nucleon's gluonic structure and the QCD dynamics of the charmonium-nucleon interaction. Early measurements were performed at SLAC [1] and Fermilab [2,3] and later extended to much higher energies at HERA, where the H1 [4,5] and ZEUS [6] Collaborations measured exclusive $\gamma p \rightarrow J/\psi p$ cross sections up to $W \approx 300$ GeV. In this high-energy regime, the data are well described by soft- and hard-Pomeron exchanges within the Donnachie-Landshoff (DL) model [7–11], as well as by the soft-dipole Pomeron approach [12,13].

More recently, Jefferson Laboratory (JLab) has carried out high-precision measurements near threshold ($4.0 \leq W \leq 4.8$ GeV) through the GlueX [14,15], J/ψ -007 [16,17], and CLAS [18] experiments. These data provide new constraints on the reaction mechanisms underlying J/ψ photoproduction [19]. A variety of theoretical descriptions have been proposed, including the two-gluon exchange model [20], perturbative QCD approaches based on the nucleon's generalized parton distributions [21], and

scalar (0^{++}) and tensor (2^{++}) glueball exchanges within holographic QCD frameworks [22–25]. Complementary to these gluon-based approaches, Ref. [26] suggests that the $J/\psi N$ final-state interaction (FSI) may play an important role very close to threshold ($W \leq 4.2$ GeV), based on a phenomenological quark-nucleon potential combined with Pomeron exchange. In Refs. [27,28], the $\gamma \rightarrow c\bar{c} + \mathbb{P} \rightarrow J/\psi$ transition amplitude is formulated in terms of dressed-quark degrees of freedom, following the formalism of Ref. [29].

Beyond these partonic descriptions, Ref. [30] considered tree-level t -channel exchanges involving both light mesons and charmonium states. Although light mesons and charmonium exchanges are generally expected to be suppressed by the Okubo-Zweig-Iizuka rule [31–33] and by the heavy-quark mass, respectively, the light-meson contribution can nevertheless be non-negligible. In addition, the $J/\psi N$ FSI mediated by gluon exchange can further enhance the cross section very close to threshold.

Open-charm meson-baryon intermediate states have been studied extensively [34–37]. They are known to play an essential role in the formation of heavy-pentaquark candidates [38–45] and may also influence near-threshold J/ψ photoproduction. The closest open-charm channels, $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$, lie approximately 116 and 258 MeV above the J/ψ photoproduction threshold, respectively [46]. Whether cusp structures associated with these channels exist in this energy region remains under debate. For example, cusplike structures near these thresholds have been reported by the GlueX Collaboration [14,15] and

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supported by theoretical studies [47,48]. Meanwhile, very recent measurements of the differential cross sections through the dimuon decay channel ($J/\psi \rightarrow \mu^+\mu^-$) have been reported by the J/ψ -007 Collaboration [17]. However, the corresponding integrated cross sections show no clear evidence for open-charm contributions. Measurements of the total cross section by the CLAS Collaboration likewise suggest only a small contribution from open-charm channels, with a more gradual energy dependence [18].

In parallel, the LHCb Collaboration reported several hidden-charm pentaquark states in the $J/\psi p$ invariant-mass spectrum of $\Lambda_b \rightarrow J/\psi p K^-$ decays, including one narrow state below the $\bar{D}\Sigma_c$ threshold, $P_{c\bar{c}}(4312)$, and two narrow states below the $\bar{D}^*\Sigma_c$ threshold, $P_{c\bar{c}}(4440)$ and $P_{c\bar{c}}(4457)$ [49,50]. More recently, Ref. [51] reported a new state, $P_{c\bar{c}}(4337)$, in $B_s^0 \rightarrow J/\psi p \bar{p}$ decays, while the previously reported broad state $P_{c\bar{c}}(4380)$ below the $\bar{D}\Sigma_c^*$ threshold was not observed. These observations have motivated coupled-channel studies that explore the role of open-charm channels in the formation of heavy-pentaquark states [52–54].

We investigate the $\gamma p \rightarrow J/\psi p$ reaction by incorporating hadronic rescattering contributions [55,56] beyond the conventional Pomeron-exchange mechanism [7–11]. Specifically, we include the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ open-charm meson-baryon intermediate states and evaluate all relevant t -, s -, and u -channel diagrams at tree level within an effective Lagrangian framework, while constructing the resulting production amplitudes in a gauge-invariant manner. We show that, within the present hadronic model, the inclusion of these rescattering contributions can improve the description of recent near-threshold JLab data and generate cusplike enhancements near the corresponding open-charm thresholds. We also present model estimates for the associated open-charm production processes $\gamma p \rightarrow \bar{D}^{(*)0}\Lambda_c^+$.

The present work is organized as follows. In Sec. II, we outline the general formalism for the Pomeron-exchange and rescattering amplitudes in the $\gamma p \rightarrow J/\psi p$ reaction and describe in detail how the rescattering diagrams are constructed. In Sec. III, we present the results for the total and t -dependent differential cross sections and compare them with the JLab data. Predictions for open-charm production are also given. Finally, we summarize our findings and present our conclusions in the last section.

II. THEORETICAL FRAMEWORK

In this section, we present the theoretical framework for the process

$$\gamma(q) + p(p_i) \rightarrow J/\psi(k) + p(p_f). \quad (1)$$

We first consider Pomeron exchange as the background mechanism within the DL model [7–11] in Sec. II A.

We then incorporate rescattering contributions involving the intermediate $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ states in a gauge-invariant manner. The general formalism for the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ rescattering contributions is presented in Secs. II B 1 and II B 2, respectively.

A. Pomeron-exchange amplitude

The two-gluon exchange mechanism shown in Fig. 1 is effectively described by the DL model [7–11]. In this picture, the incoming photon first fluctuates into a $q\bar{q}$ pair, which subsequently interacts with the nucleon via Pomeron exchange before forming the final J/ψ meson. The quark-Pomeron vertex is constructed by analogy with the Pomeron-photon coupling, treating the Pomeron as a $C = +1$ isoscalar photon.

The Pomeron-exchange amplitude can be written as

$$T_{\mathbb{P}}(q, k) = i \frac{12e}{f_V} \beta_{q_V} F_V(t) \beta_{u/d} F_N(t) \times \bar{u}_N \epsilon_\nu^* [q^\mu g^{\mu\nu} - \gamma^\mu q^\nu] \epsilon_\mu u_N G_{\mathbb{P}}(s, t), \quad (2)$$

where ϵ_μ and ϵ_ν are the polarization vectors of the incoming photon and outgoing J/ψ meson, respectively. Here, u_N denotes the nucleon spinor, e is the elementary electric charge, and f_V is the vector-meson decay constant defined in the vector-meson dominance (VMD) convention; for the J/ψ , we use $f_{J/\psi} = 11.18$ [30]. All baryon Dirac spinors are normalized as $\bar{u}_B u_B = 1$. The Mandelstam variables are defined by $s = W^2 = (q + p_i)^2$, $t = (q - k)^2$, and $u = (q - p_f)^2$. The coupling constants $\beta_{u/d} = 2.07$ and $\beta_c = 0.323 \text{ GeV}^{-1}$ are chosen to reproduce the total cross section data for diffractive photoproduction of vector mesons at high photon energies.

The form factor for the Pomeron-vector-meson vertex and the isoscalar electromagnetic (EM) form factor of the nucleon are defined as [11,57]

$$F_V(t) = \frac{2\mu_0^2}{(1 - t/M_V^2)(2\mu_0^2 + M_V^2 - t)},$$

$$F_N(t) = \frac{4M_N^2 - 2.8t}{(4M_N^2 - t)(1 - t/0.71)^2}, \quad (3)$$

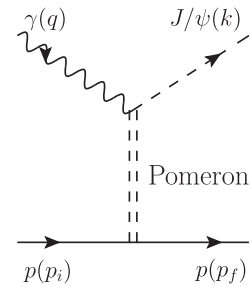


FIG. 1. Two-gluon exchange mechanism of $\gamma p \rightarrow J/\psi p$.

respectively, where $\mu_0^2 = 1.1 \text{ GeV}^2$, and M_V and M_N denote the vector-meson and nucleon masses, respectively.

The Regge propagator for the Pomeron is of the form [10]

$$G_{\mathbb{P}}(s, t) = \left(\frac{s}{s_0}\right)^{\alpha_{\mathbb{P}}(t)-1} \exp\left\{-\frac{i\pi}{2}[\alpha_{\mathbb{P}}(t) - 1]\right\}, \quad (4)$$

where the Pomeron trajectory is taken as $\alpha_{\mathbb{P}}(t) = 1.25 + \alpha'_{\mathbb{P}}t$, with $\alpha'_{\mathbb{P}} = 1/s_0 = 0.25 \text{ GeV}^{-2}$.

B. Rescattering amplitudes

The meson-baryon (MB) rescattering amplitude is given by [55,56]

$$T_{\text{Res}}(q, k) = \int d^3\mathbf{q}' B_{\gamma p \rightarrow MB}(q, q') \frac{1}{2E_M(\mathbf{q}') E_B(\mathbf{q}')} \frac{M_B}{E_B(\mathbf{q}')} \times G_{MB}(\mathbf{q}') V_{MB \rightarrow J/\psi p}(q', k). \quad (5)$$

Equation (5) represents the two-step process in which the initial γp state first produces an intermediate meson-baryon state MB , which then propagates and rescatters into the final $J/\psi p$ state. Here, $B_{\gamma p \rightarrow MB}$ denotes the production amplitude for the intermediate state, G_{MB} the meson-baryon propagator, and $V_{MB \rightarrow J/\psi p}$ the transition amplitude for the rescattering process $MB \rightarrow J/\psi p$. The corresponding Feynman diagram is shown in Fig. 2.

The meson-baryon propagator in Eq. (5) is given by

$$G_{MB}(\mathbf{q}') = \frac{1}{W - E_M(\mathbf{q}') - E_B(\mathbf{q}') + i\epsilon}, \quad (6)$$

where $E_M = \sqrt{M_M^2 + |\mathbf{q}'|^2}$ and $E_B = \sqrt{M_B^2 + |\mathbf{q}'|^2}$ are, respectively, the energies of the intermediate meson and baryon with three-momentum $\mathbf{q}'$, and W is the total center-of-mass (c.m.) energy. $B_{\gamma p \rightarrow MB}$ and $V_{MB \rightarrow J/\psi p}$ are constructed from t -, s -, and u -channel tree diagrams, as shown in Figs. 2(a)–2(c) and 2(d)–2(f), respectively.

For simplicity, we write $B(q, q') \equiv B_{\gamma p \rightarrow MB}(q, q')$ and $V(q', k) \equiv V_{MB \rightarrow J/\psi p}(q', k)$. Equation (5) can be rewritten as

$$T_{\text{Res}}(q, k) = \mathcal{P} \int \frac{d^3\mathbf{q}'}{2E_M(\mathbf{q}') E_B(\mathbf{q}') W - E_M(\mathbf{q}') - E_B(\mathbf{q}')} \frac{M_B}{E_B(\mathbf{q}')} B(q, q') V(q', k) - i \int \frac{d\Omega_{\mathbf{q}_0}}{2E_M(\mathbf{q}_0) E_B(\mathbf{q}_0)} \rho_{MB}(\mathbf{q}_0) B(q, q_0) V(q_0, k) \times \theta(W - M_M - M_B), \quad (7)$$

where $\theta(x)$ is the step function, $d\Omega_{\mathbf{q}_0}$ denotes the solid-angle element of the on-shell momentum $\mathbf{q}_0$, and ρ_{MB} is given by

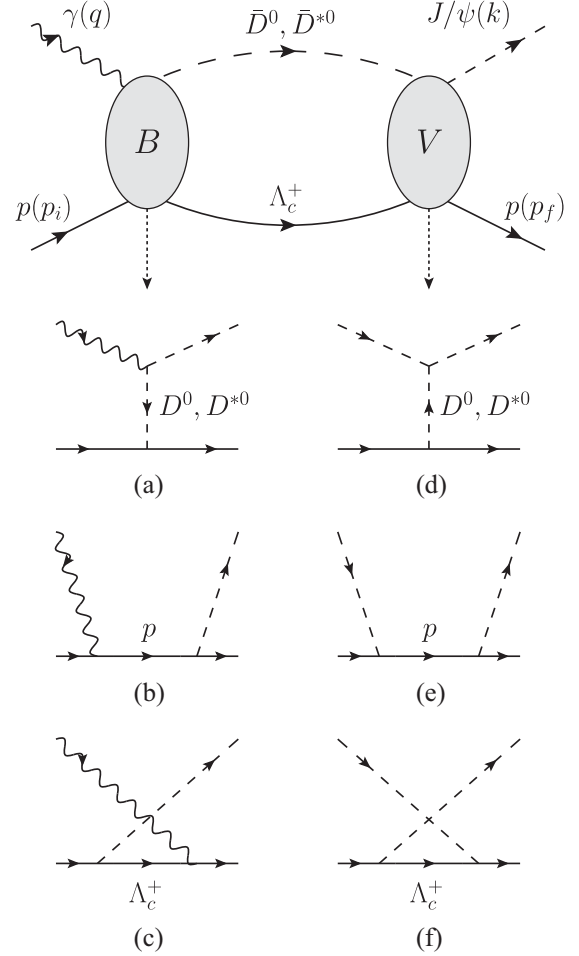


FIG. 2. Feynman diagrams for the $\gamma p \rightarrow \bar{D}^{(*)0} \Lambda_c^+ \rightarrow J/\psi p$ rescattering process. The t -, s -, and u -channel tree diagrams for the production amplitude $B_{\gamma p \rightarrow MB}$ and the transition amplitude $V_{MB \rightarrow J/\psi p}$ are shown in (a)–(c) and (d)–(f), respectively.

$$\rho_{MB}(\mathbf{q}_0) = \frac{\pi |\mathbf{q}_0| E_M(\mathbf{q}_0) E_B(\mathbf{q}_0)}{E_M(\mathbf{q}_0) + E_B(\mathbf{q}_0)}. \quad (8)$$

From the on-shell condition $W = E_M(\mathbf{q}_0) + E_B(\mathbf{q}_0)$, the magnitude of the on-shell momentum $|\mathbf{q}_0|$ is given by

$$|\mathbf{q}_0| = \frac{\sqrt{[W^2 - (M_M + M_B)^2][W^2 - (M_M - M_B)^2]}}{2W}. \quad (9)$$

The first term in Eq. (7) corresponds to the principal-value part, while the second term represents the on-shell singular part above the MB threshold. Summation over the polarization and spin indices of the intermediate states is implied.

For clarity, the full amplitude used in the calculation is written as

$$T_{\text{full}}(q, k) = T_{\mathbb{P}}(q, k) + T_{\text{Res}}(q, k), \quad (10)$$

where

$$T_{\text{Res}}(q, k) = \sum_{MB=\bar{D}^0\Lambda_c^+, \bar{D}^{*0}\Lambda_c^+} T_{\text{Res}}^{MB}(q, k). \quad (11)$$

Here, T_{Res}^{MB} represents the rescattering contribution through the intermediate channel MB . The two intermediate-channel amplitudes in Eq. (11) are summed coherently, as are the Pomeron and rescattering amplitudes in Eq. (10).

The unpolarized differential cross section is calculated as

$$\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt} = \frac{M_N^2}{16\pi W^2 |\mathbf{q}_{\text{c.m.}}|^2} \frac{1}{4} \sum_{\text{spin, pol}} |T_{\text{full}}|^2, \quad (12)$$

where $|\mathbf{q}_{\text{c.m.}}| = (W^2 - M_N^2)/(2W)$ is the magnitude of the initial-state c.m. momentum. The factor $1/4$ averages over the two photon polarizations and two initial-proton spin states, while the sum runs over all initial and final spin and polarization states. The total cross section is then given by

$$\sigma_{\gamma p \rightarrow J/\psi p}(W) = \int_{t_{\min}}^{t_{\max}} dt \frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt}, \quad (13)$$

where $t_{\min}$ and $t_{\max}$ are the kinematic limits determined by the masses of the initial and final states at a given W . For the associated open-charm production process $\gamma p \rightarrow MB$, we use

$$\frac{d\sigma_{\gamma p \rightarrow MB}}{dt} = \frac{M_N M_B}{16\pi W^2 |\mathbf{q}_{\text{c.m.}}|^2} \frac{1}{4} \sum_{\text{spin, pol}} |B_{\gamma p \rightarrow MB}|^2. \quad (14)$$

For the $MB = \bar{D}^{*0}\Lambda_c^+$ channel, the summation also includes the three physical polarization states of the vector meson. The corresponding total cross section is obtained by integrating Eq. (14) over the kinematic range appropriate to the MB final state.

The production $B_{\gamma p \rightarrow MB}$ and transition $V_{MB \rightarrow J/\psi p}$ amplitudes are constructed from the effective Lagrangians. The EM interaction can be written as

$$\begin{aligned} \mathcal{L}_{\gamma DD^*} &= g_{\gamma DD^*}^0 \epsilon^{\mu\nu\alpha\beta} \partial_\mu A_\nu (\partial_\alpha D_\beta^* \bar{D}^0 + \partial_\alpha \bar{D}_\beta^* D^0), \\ \mathcal{L}_{\gamma D^* D^*} &= -i g_{\gamma D^* D^*}^0 F^{\mu\nu} \bar{D}_\mu^* D_\nu^*, \\ \mathcal{L}_{\gamma NN} &= -e \bar{N} \left[\gamma_\mu - \frac{\kappa_N}{2M_N} \sigma_{\mu\nu} \partial^\nu \right] A^\mu N, \\ \mathcal{L}_{\gamma \Lambda_c \Lambda_c} &= -e \bar{\Lambda}_c \left[\gamma_\mu - \frac{\kappa_{\Lambda_c}}{2M_{\Lambda_c}} \sigma_{\mu\nu} \partial^\nu \right] A^\mu \Lambda_c, \end{aligned} \quad (15)$$

where A^μ , D , $D^{*\mu}$, Λ_c^+ , and N denote the photon, pseudo-scalar D , vector D^* , Λ_c , and nucleon fields, respectively. Here the D , D^* , and Λ_c correspond to the $D(1864)0^-$, $D^*(2007)1^-$, and $\Lambda_c(2286)1/2^+$ states, respectively. The EM field-strength tensor is defined by $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$. Because the exchanged $D^{(*)0}$ mesons are neutral [see

Fig. 2(a)], only the magnetic-type EM couplings contribute, through the γDD^* and $\gamma D^* D^*$ interaction terms.

The relevant coupling constants are given by

$$\begin{aligned} g_{\gamma DD^*}^0 &= 0.54 \text{ GeV}^{-1}, \\ g_{\gamma D^* D^*}^0 &= 0.64, \\ \kappa_p &= 1.79, \\ \kappa_{\Lambda_c} &= -0.025. \end{aligned} \quad (16)$$

The coupling $g_{\gamma DD^*}^0$ is extracted from the branching ratio $\text{Br}(D^{*0} \rightarrow D^0 \gamma) = 35.3\%$ [46], through the relation

$$\Gamma_{D^{*0} \rightarrow D^0 \gamma} = \frac{q_\gamma^3}{12\pi} (g_{\gamma DD^*}^0)^2, \quad (17)$$

with $q_\gamma = (M_{D^{*0}}^2 - M_{D^0}^2)/(2M_{D^{*0}})$. The total decay width of the D^{*0} meson, which has not yet been measured, is estimated using isospin symmetry [47]. The values in Eqs. (16) and (17) correspond to $\Gamma_{D^{*0}} \simeq 56 \text{ keV}$. The quantities κ_p [46] and κ_{Λ_c} [58] denote the anomalous magnetic moments of the proton and the Λ_c baryon, respectively.

Since the D^{*0} is unstable, treating the $\bar{D}^{*0}\Lambda_c^+$ intermediate state as an effective stable two-body channel is an approximation. To estimate the effect of the finite D^{*0} width, we make the replacement

$$\begin{aligned} &\frac{1}{W - E_{D^*}(\mathbf{q}') - E_{\Lambda_c}(\mathbf{q}') + i\epsilon} \\ &\rightarrow \frac{1}{W - E_{D^*}(\mathbf{q}') - E_{\Lambda_c}(\mathbf{q}') + i\Gamma_{D^{*0}}/2}, \end{aligned} \quad (18)$$

with $\Gamma_{D^{*0}} = 56 \text{ keV}$. Because the D^{*0} is exceptionally narrow, the resulting smearing is expected to be small on the energy scale relevant to the present analysis. Indeed, the replacement in Eq. (18) introduces a characteristic smearing scale $\Delta W \simeq \Gamma_{D^{*0}}/2 \simeq 28 \text{ keV}$ in the total c.m. energy. Since $W^2 = M_N^2 + 2M_N E_\gamma$, this corresponds, at the $\bar{D}^{*0}\Lambda_c^+$ threshold, $W \simeq 4.29 \text{ GeV}$, to a laboratory photon-energy scale $\Delta E_\gamma \simeq (dE_\gamma/dW)\Delta W = (W/M_N)\Delta W \simeq 0.13 \text{ MeV}$. This smearing scale is negligible compared with both the characteristic $\mathcal{O}(100 \text{ MeV})$ variation scale of the calculated cusplike structures in E_γ and the photon-energy bin widths used in the JLab measurements [14,15,18]. We have also explicitly verified that the constant-width prescription in Eq. (18) yields changes that are indistinguishable on the scale of the figures. Accordingly, the $\bar{D}^{*0}\Lambda_c^+$ propagator used in all numerical results shown below is evaluated in the zero-width limit using the $i\epsilon$ prescription in Eq. (6), with its decomposition into principal-value and on-shell singular parts given in Eq. (7).

The effective Lagrangians involving the J/ψ meson are given by

$$\begin{aligned}\mathcal{L}_{\psi DD} &= -ig_{\psi DD}\psi^\mu(\bar{D}\partial_\mu D - \partial_\mu \bar{D}D), \\ \mathcal{L}_{\psi DD^*} &= -g_{\psi DD^*}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\partial_\alpha D^*\bar{D} + \partial_\alpha \bar{D}^*D), \\ \mathcal{L}_{\psi D^*D^*} &= ig_{\psi D^*D^*}\psi^\mu(D^{*\nu}\partial_\nu\bar{D}_\mu^* - \partial_\nu D_\mu^*\bar{D}^{*\nu} - D^{*\nu}\overleftrightarrow{\partial}_\mu\bar{D}_\nu^*), \\ \mathcal{L}_{\psi\Lambda_c\Lambda_c} &= g_{\psi\Lambda_c\Lambda_c}\bar{\Lambda}_c\gamma_\mu\psi^\mu\Lambda_c, \\ \mathcal{L}_{\psi NN} &= -g_{\psi NN}\bar{N}\gamma_\mu\psi^\mu N,\end{aligned}\quad (19)$$

where ψ^μ denotes the $J/\psi(3096)1^-$ field. The coupling constants are obtained from VMD [59], yielding

$$\begin{aligned}g_{\psi DD} &= g_{\psi D^*D^*} = 7.44, \\ g_{\psi DD^*} &= 3.84 \text{ GeV}^{-1},\end{aligned}\quad (20)$$

while $g_{\psi\Lambda_c\Lambda_c}$ is determined using SU(4) flavor symmetry [60],

$$g_{\psi\Lambda_c\Lambda_c} = -1.4. \quad (21)$$

The ψpp coupling constant is extracted from the branching ratio $\text{Br}(J/\psi \rightarrow p\bar{p}) = 0.2120\%$ and the total decay width $\Gamma_{J/\psi} = 92.6 \text{ keV}$ [46]. Using these values, we obtain

$$|g_{\psi NN}| = |g_{\psi pp}| = 2.18 \times 10^{-3}, \quad (22)$$

through the relation

$$\Gamma_{J/\psi \rightarrow p\bar{p}} = \frac{2}{3\pi} \frac{q_N^3}{M_{J/\psi}^2} g_{\psi pp}^2, \quad (23)$$

with $q_N = \sqrt{M_{J/\psi}^2 - 4M_N^2}/2$.

The effective Lagrangians for the meson-baryon interactions are given by

$$\begin{aligned}\mathcal{L}_{DN\Lambda_c} &= -ig_{DN\Lambda_c}D\bar{\Lambda}_c\gamma_5 N + \text{H.c.}, \\ \mathcal{L}_{D^*N\Lambda_c} &= -g_{D^*N\Lambda_c}D^{*\mu}\bar{\Lambda}_c\gamma_\mu N + \text{H.c.}\end{aligned}\quad (24)$$

The coupling constants are determined using SU(4) flavor symmetry [60],

$$g_{DN\Lambda_c} = -13.5, \quad g_{D^*N\Lambda_c} = -5.6. \quad (25)$$

These values are close to those obtained from the light-cone sum rule approach [61,62]: $g_{DN\Lambda_c} = -10.7$, $g_{D^*N\Lambda_c} = -5.8$.

We now describe how the $B_{\gamma p \rightarrow MB}$ and $V_{MB \rightarrow J/\psi p}$ amplitudes in Eq. (5) are constructed by considering the intermediate $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ states. We also describe how gauge invariance is preserved when hadronic form

factors are introduced. The relevant four-momenta are defined as

$$\begin{aligned}\gamma(q) + p(p_i) &\rightarrow \bar{D}^{(*)0}(q') + \Lambda_c^+(p') \\ &\rightarrow J/\psi(k) + p(p_f).\end{aligned}\quad (26)$$

1. $\bar{D}^0\Lambda_c^+$ intermediate state

We first consider the production amplitude $B_{\gamma p \rightarrow \bar{D}^0\Lambda_c^+}$. For the t -channel diagram shown in Fig. 2(a), D^0 exchange does not contribute because the $\gamma\bar{D}^0D^0$ coupling vanishes for the electrically neutral D^0 , whereas the D^* -exchange amplitude is gauge invariant by construction. The s - and u -channel contributions in Figs. 2(b) and 2(c) are not individually gauge invariant, but their sum is. Accordingly, the $\gamma p \rightarrow \bar{D}^0\Lambda_c^+$ production amplitude is constructed in a gauge-invariant form as follows:

$$B_{\gamma p \rightarrow \bar{D}^0\Lambda_c^+} = \mathcal{M}_{B,t}^{D^*} F_t^{D^*} + (\mathcal{M}_{B,s}^p + \mathcal{M}_{B,u}^{\Lambda_c}) F_{s,u}^C. \quad (27)$$

Here, $\mathcal{M}$ denotes an individual Born subamplitude. Equation (27) shows that the production amplitude is written as the sum of two separately gauge-invariant parts: the D^* -exchange t -channel contribution and the combined s - and u -channel contributions. Since the latter become gauge invariant only through their sum, a common form factor $F_{s,u}^C$ is introduced for the combined $(s+u)$ contribution in order to preserve gauge invariance after including hadronic form factors.

The t -, s -, and u -channel amplitudes are given by

$$\begin{aligned}\mathcal{M}_{B,t}^{D^*} &= -\frac{g_{\gamma DD^*} g_{D^*N\Lambda_c}}{q_t^2 - M_{D^*}^2} \epsilon^{\mu\nu\alpha\beta} \bar{u}_{\Lambda_c} \gamma_\mu q_\nu q_\alpha \epsilon_\beta u_N, \\ \mathcal{M}_{B,s}^p &= i \frac{e g_{DN\Lambda_c}}{q_s^2 - M_N^2} \bar{u}_{\Lambda_c} \gamma_5 (\not{q}_s + M_N) \\ &\quad \times \left[\not{\epsilon} - \frac{\kappa_p}{4M_N} (\not{\epsilon} \not{q} - \not{q} \not{\epsilon}) \right] u_N, \\ \mathcal{M}_{B,u}^{\Lambda_c} &= i \frac{e g_{DN\Lambda_c}}{q_u^2 - M_{\Lambda_c}^2} \bar{u}_{\Lambda_c} \left[\not{\epsilon} - \frac{\kappa_{\Lambda_c}}{4M_{\Lambda_c}} (\not{\epsilon} \not{q} - \not{q} \not{\epsilon}) \right] \\ &\quad \times (\not{q}_u + M_{\Lambda_c}) \gamma_5 u_N,\end{aligned}\quad (28)$$

where ϵ_μ is the polarization vector of the incoming photon, and the exchanged four-momenta are defined by

$$q_t = q - q', \quad q_s = q + p_i, \quad q_u = p_i - q'. \quad (29)$$

Because of the finite size of hadrons, we introduce the hadronic form factors in Eq. (27),

$$F_t^{D^{(*)}} = \left(\frac{\Lambda_1^4}{\Lambda_1^4 + (q_t^2 - M_{D^{(*)}}^2)^2} \right)^2, \\ F_{s,u}^C = \left(\frac{\Lambda_2^4}{\Lambda_2^4 + (q_s^2 - M_N^2)^2} \right) \left(\frac{\Lambda_2^4}{\Lambda_2^4 + (q_u^2 - M_{\Lambda_c}^2)^2} \right). \quad (30)$$

Next, the transition amplitude $V_{\bar{D}^0 \Lambda_c^+ \rightarrow J/\psi p}$ can be written as

$$V_{\bar{D}^0 \Lambda_c^+ \rightarrow J/\psi p} = \mathcal{M}_{V,t'}^D F_{t'}^D + \mathcal{M}_{V,t'}^{D^*} F_{t'}^{D^*} \\ + (\mathcal{M}_{V,s'}^P + \mathcal{M}_{V,u'}^{\Lambda_c}) F_{s',u'}^C. \quad (31)$$

This expression is analogous to Eq. (27).

The D^0 - and D^{*0} -exchange amplitudes in the t channel [Fig. 2(d)], together with the proton- and Λ_c^+ -exchange amplitudes in the s and u channels [Figs. 2(e) and 2(f)], are given by

$$\mathcal{M}_{V,t'}^D = i \frac{g_{\psi DD} g_{D N \Lambda_c}}{q_t'^2 - M_D^2} \varepsilon^{\mu} (q' - q_t')_{\mu} \bar{u}_N \gamma_5 u_{\Lambda_c}, \\ \mathcal{M}_{V,t'}^{D^*} = \frac{g_{\psi DD^*} g_{D^* N \Lambda_c}}{q_t'^2 - M_{D^*}^2} \varepsilon^{\mu\nu\alpha\beta} \bar{u}_N \gamma_{\mu} q'_{\nu} k_{\alpha} \varepsilon_{\beta}^* u_{\Lambda_c}, \\ \mathcal{M}_{V,s'}^P = i \frac{g_{\psi NN} g_{D N \Lambda_c}}{q_s'^2 - M_N^2} \bar{u}_N \varepsilon^* (\not{q}'_s + M_N) \gamma_5 u_{\Lambda_c}, \\ \mathcal{M}_{V,u'}^{\Lambda_c} = -i \frac{g_{\psi \Lambda_c \Lambda_c} g_{D N \Lambda_c}}{q_u'^2 - M_{\Lambda_c}^2} \bar{u}_N \gamma_5 (\not{q}'_u + M_{\Lambda_c}) \varepsilon^* u_{\Lambda_c}, \quad (32)$$

where ε_{μ} is the polarization vector of the outgoing J/ψ meson. The exchanged four-momenta are defined by

$$q_t' = k - q', \quad q_s' = k + p_f, \quad q_u' = p_f - q'. \quad (33)$$

For consistency, we adopt the same form for the form factors in Eq. (31) as in Eq. (30),

$$F_{t'}^{D^{(*)}} = \left(\frac{\Lambda_1^4}{\Lambda_1^4 + (q_t'^2 - M_{D^{(*)}}^2)^2} \right)^2, \\ F_{s',u'}^C = \left(\frac{\Lambda_2^4}{\Lambda_2^4 + (q_s'^2 - M_N^2)^2} \right) \left(\frac{\Lambda_2^4}{\Lambda_2^4 + (q_u'^2 - M_{\Lambda_c}^2)^2} \right). \quad (34)$$

2. $\bar{D}^{*0} \Lambda_c^+$ intermediate state

We next consider the production amplitude $B_{\gamma p \rightarrow \bar{D}^{*0} \Lambda_c^+}$. For the t -channel diagram shown in Fig. 2(a), the amplitudes corresponding to both D^0 - and D^{*0} -exchanges are individually gauge invariant and are included in this work. By contrast, the s - and u -channel contributions in Figs. 2(b) and 2(c), as in the $\bar{D}^0 \Lambda_c^+$ case, are not individually gauge invariant, although their sum is. Accordingly, the $\gamma p \rightarrow \bar{D}^{*0} \Lambda_c^+$ production amplitude is constructed in a gauge-invariant form as

$$B_{\gamma p \rightarrow \bar{D}^{*0} \Lambda_c^+} = \tilde{\mathcal{M}}_{B,t}^D F_t^D + \tilde{\mathcal{M}}_{B,t}^{D^*} F_t^{D^*} \\ + (\tilde{\mathcal{M}}_{B,s}^P + \tilde{\mathcal{M}}_{B,u}^{\Lambda_c}) F_{s,u}^C. \quad (35)$$

Here, $\tilde{\mathcal{M}}$ denotes an individual Born subamplitude for the $\bar{D}^{*0} \Lambda_c^+$ channel, with the tilde distinguishing it from the corresponding subamplitudes for the $\bar{D}^0 \Lambda_c^+$ channel. We use the same form factors as in Eq. (30), but with different cutoff masses, $\Lambda_1 \rightarrow \Lambda_3, \Lambda_2 \rightarrow \Lambda_4$. The relevant amplitudes are given by

$$\tilde{\mathcal{M}}_{B,t}^{D^0} = i \frac{g_{\gamma DD^*} g_{D N \Lambda_c}}{q_t'^2 - M_D^2} \varepsilon^{\mu\nu\alpha\beta} q_{\mu} q'_{\nu} \varepsilon_{\alpha} \varepsilon_{\beta}^* \bar{u}_{\Lambda_c} \gamma_5 u_N, \\ \tilde{\mathcal{M}}_{B,t}^{D^{*0}} = -\frac{g_{\gamma D^* D^*} g_{D^* N \Lambda_c}}{q_t'^2 - M_{D^*}^2} \bar{u}_{\Lambda_c} \left[\gamma_{\mu} - \frac{1}{M_{D^*}^2} \not{q}_t' q_{t\mu} \right] u_N \\ \times (q^{\nu} \varepsilon^{\mu} - q^{\mu} \varepsilon^{\nu}) \varepsilon_{\nu}^*, \\ \tilde{\mathcal{M}}_{B,s}^P = \frac{e g_{D^* N \Lambda_c}}{q_s'^2 - M_N^2} \bar{u}_{\Lambda_c} \varepsilon^* (\not{q}'_s + M_N) \\ \times \left[\not{\varepsilon} - \frac{\kappa_p}{4M_N} (\not{\varepsilon} \not{q}' - \not{q}' \not{\varepsilon}) \right] u_N, \\ \tilde{\mathcal{M}}_{B,u}^{\Lambda_c} = \frac{e g_{D^* N \Lambda_c}}{q_u'^2 - M_{\Lambda_c}^2} \bar{u}_{\Lambda_c} \left[\not{\varepsilon} - \frac{\kappa_{\Lambda_c}}{4M_{\Lambda_c}} (\not{\varepsilon} \not{q}' - \not{q}' \not{\varepsilon}) \right] \\ \times (\not{q}'_u + M_{\Lambda_c}) \varepsilon^* u_N, \quad (36)$$

where the exchanged four-momenta are defined in Eq. (29). ε_{μ} and ε_{ν}^* denote the polarization vectors of the incoming photon and outgoing D^* meson, respectively.

Similarly, the transition amplitude $V_{\bar{D}^{*0} \Lambda_c^+ \rightarrow J/\psi p}$ is constructed as

$$V_{\bar{D}^{*0} \Lambda_c^+ \rightarrow J/\psi p} = \tilde{\mathcal{M}}_{V,t'}^D F_{t'}^D + \tilde{\mathcal{M}}_{V,t'}^{D^*} F_{t'}^{D^*} \\ + (\tilde{\mathcal{M}}_{V,s'}^P + \tilde{\mathcal{M}}_{V,u'}^{\Lambda_c}) F_{s',u'}^C. \quad (37)$$

We use the same form factors as in Eq. (34), with the replacements $\Lambda_1 \rightarrow \Lambda_3, \Lambda_2 \rightarrow \Lambda_4$. The amplitudes corresponding to Figs. 2(d)–2(f) are given by

$$\tilde{\mathcal{M}}_{V,t'}^{D^0} = -i \frac{g_{\psi DD^*} g_{D N \Lambda_c}}{q_t'^2 - M_D^2} \varepsilon^{\mu\nu\alpha\beta} q'_{\mu} k_{\nu} \varepsilon_{\alpha} \varepsilon_{\beta}^* \bar{u}_N \gamma_5 u_{\Lambda_c}, \\ \tilde{\mathcal{M}}_{V,t'}^{D^{*0}} = \frac{g_{\psi D^* D^*} g_{D^* N \Lambda_c}}{q_t'^2 - M_{D^*}^2} \bar{u}_N \left[\gamma_{\mu} - \frac{1}{M_{D^*}^2} \not{q}_t' q'_{t\mu} \right] u_{\Lambda_c} \\ \times [(\varepsilon^* \cdot \varepsilon') q'^{\mu} - (q_t' \cdot \varepsilon') \varepsilon'^{\mu} - \varepsilon^* \cdot (q' - q_t') \varepsilon'^{\mu}], \\ \tilde{\mathcal{M}}_{V,s'}^P = \frac{g_{\psi NN} g_{D^* N \Lambda_c}}{q_s'^2 - M_N^2} \bar{u}_N \varepsilon^* (\not{q}'_s + M_N) \varepsilon' u_{\Lambda_c}, \\ \tilde{\mathcal{M}}_{V,u'}^{\Lambda_c} = -\frac{g_{\psi \Lambda_c \Lambda_c} g_{D^* N \Lambda_c}}{q_u'^2 - M_{\Lambda_c}^2} \bar{u}_N \varepsilon' (\not{q}'_u + M_{\Lambda_c}) \varepsilon^* u_{\Lambda_c}, \quad (38)$$

where the exchanged four-momenta are defined in Eq. (33), and ε'_{μ} and ε_{ν} denote the polarization vectors of the incoming D^* meson and outgoing J/ψ meson, respectively.

III. NUMERICAL RESULTS

We now present and discuss our numerical results. The cutoff masses in Eqs. (30) and (34) are determined by fitting to the near-threshold $\gamma p \rightarrow J/\psi p$ data [14–18] and are fixed as

$$\begin{aligned} \Lambda_1 &= 1.58, & \Lambda_2 &= 2.35, \\ \Lambda_3 &= 1.18, & \Lambda_4 &= 2.25, \end{aligned} \quad (39)$$

in units of GeV.

Figure 3 shows the total cross section for $\gamma p \rightarrow J/\psi p$ as a function of the laboratory photon energy E_γ , calculated in a model including Pomeron exchange and hadronic

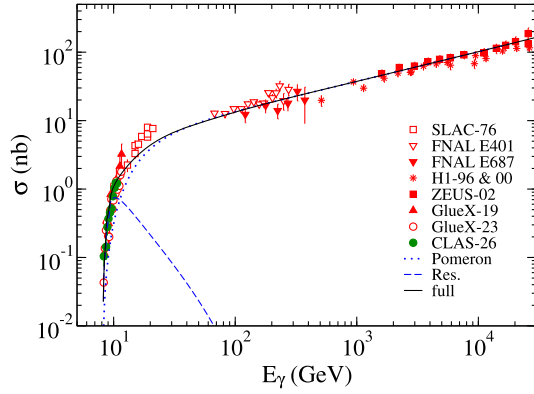


FIG. 3. The total cross section for $\gamma p \rightarrow J/\psi p$ as a function of the laboratory photon energy E_γ . The dotted, dashed, and solid curves denote the Pomeron contribution, the rescattering contribution, and the full result, respectively. The results are compared with the SLAC [1], Fermilab [2,3], H1 [4,5], ZEUS [6], GlueX [14,15], and CLAS [18] data from threshold up to $E_\gamma \simeq 10^4$ GeV.

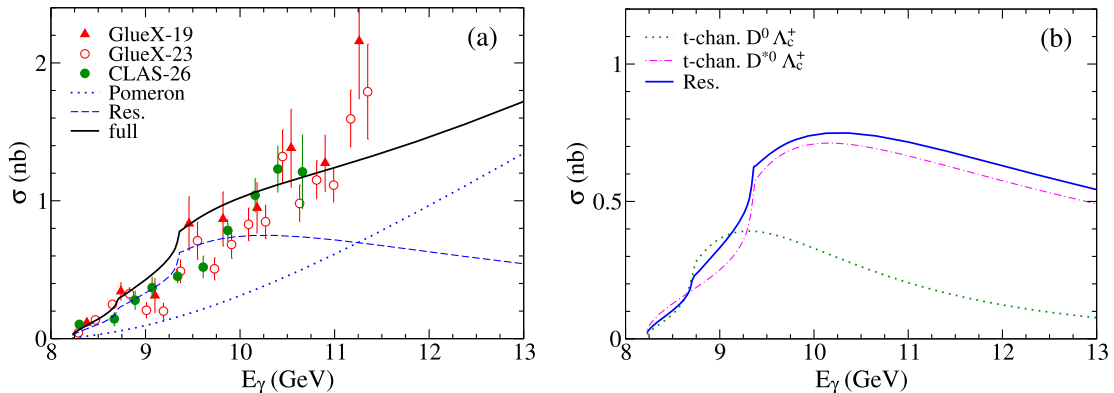


FIG. 4. (a) The total cross section for $\gamma p \rightarrow J/\psi p$ as a function of the laboratory photon energy E_γ , compared with the GlueX [14,15] and CLAS [18] data in the near-threshold region. The blue dotted and dashed curves and the black solid curve represent the Pomeron contribution, the rescattering contribution, and the full result, respectively. (b) Decomposition of the rescattering contribution. The green dotted and magenta dot-dashed curves represent the t -channel-only contributions from the $\bar{D}^0 \Lambda_c^+$ and $\bar{D}^{*0} \Lambda_c^+$ intermediate states, respectively. The blue solid curve denotes the full rescattering result, obtained by coherently summing the two intermediate-state amplitudes and including all t -, s -, and u -channel diagrams in both the production and transition amplitudes.

rescattering through the intermediate $\bar{D}^0 \Lambda_c^+$ and $\bar{D}^{*0} \Lambda_c^+$ states, from threshold up to $E_\gamma \simeq 10^4$ GeV. The dotted, dashed, and solid curves represent the Pomeron contribution, the rescattering contribution, and the full result, respectively. At high energies, the cross section is dominated by Pomeron exchange within the DL model [7–11] and is consistent with the available data [2–6]. Although the rescattering contribution becomes negligible at high energies, it can be significant near threshold and modify the energy dependence of the cross section. The convergence of the integration for the rescattering amplitude [see Eq. (5)] has been verified.

To illustrate the near-threshold effects of the rescattering mechanism, Fig. 4 presents the total cross section in the range $8 \leq E_\gamma \leq 13$ GeV. As shown in Fig. 4(a), Pomeron exchange (blue dotted) alone underestimates the JLab data [14,15,18], suggesting that additional near-threshold mechanisms may be relevant. The meson-baryon rescattering contribution (blue dashed) can generate cusplike enhancements near the $\bar{D}^0 \Lambda_c^+$ and $\bar{D}^{*0} \Lambda_c^+$ thresholds, thereby improving the description of the GlueX data [14,15] within the present model. At the same time, the recent CLAS data [18] do not favor such pronounced cusp structures and instead exhibit a smoother energy dependence, a trend that is also compatible with the recent J/ψ -007 data [17]. These comparisons indicate that rescattering effects can provide an important near-threshold contribution, although the magnitude and detailed line shape of the threshold enhancements remain model dependent.

It is also worth noting that some of the JLab data [14,15,18] suggest a possible structure around $E_\gamma \simeq 10.5$ GeV, close to the nominal $\bar{D}^{*0} \Sigma_c^{*+}$ threshold, where Σ_c^{*+} denotes the $\Sigma_c(2520)^+$. In contrast to the exceptionally narrow D^{*0} , the $\Sigma_c(2520)^+$ has a width of

$\Gamma \simeq 17$ MeV [46], so this channel does not produce a sharp two-body branch point on the real axis. A realistic treatment would require incorporating the Σ_c^* spectral function together with the corresponding stable multiparticle channels. Such an analysis is beyond the scope of the present work.

The individual rescattering contributions are displayed in Fig. 4(b). The blue solid curve represents the full rescattering result obtained from all t -, s -, and u -channel diagrams in the production B and transition V amplitudes of Fig. 2 and is consistent with the blue dashed curve in Fig. 4(a). The green dotted and magenta dot-dashed curves show the contributions obtained by retaining only the t -channel diagrams in Figs. 2(a) and 2(d) for the intermediate $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ states, respectively. These t -channel terms provide the dominant part of the rescattering contribution, whereas the s - and u -channel terms are suppressed by 3–7 orders of magnitude in the cross section relative to the corresponding t -channel terms, depending on the energy and the intermediate channel. They also decrease more rapidly with energy and are therefore not shown separately.

The decomposition in Eq. (7) shows that the present calculation includes the leading one-loop rescattering contribution, $B_{\gamma p \rightarrow MB} G_{MB} V_{MB \rightarrow J/\psi p}$, with both its principal-value and on-shell singular parts. Since the production and transition kernels are evaluated at the Born level and repeated MB interactions are not resummed, this is not a fully unitarized coupled-channel calculation. Accordingly, while the nominal threshold positions are fixed kinematically within the zero-width approximation, the magnitudes and detailed line shapes remain model dependent.

For clarity, the principal-value and on-shell singular parts of the dominant t -channel rescattering contributions from the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ intermediate states are presented separately in Fig. 5. The on-shell singular parts vanish below their thresholds and turn on at $E_\gamma \simeq 8.72$ and 9.36 GeV, respectively, whereas the principal-value parts exhibit a nonanalytic change in slope at the same energies. Within the zero-width approximation, this reflects the square-root branch points associated with the opening of the corresponding two-body channels, whose nominal threshold positions are fixed by the hadron masses. Since the tree-level t -channel kernels contain no absorptive phases, the explicit factor of $-i$ multiplying the on-shell singular term in Eq. (7) places the two parts in quadrature, so that their interference vanishes in the unpolarized cross section. Their incoherent sum gives the solid curves in Fig. 5 and produces the corresponding cusplike structure. This incoherence, however, applies only to the principal-value and on-shell singular parts of a given intermediate-state t -channel amplitude. The two intermediate-channel amplitudes themselves are summed coherently according to Eq. (11), so their energy-dependent interference is retained. The blue solid curve in Fig. 4(b), which also

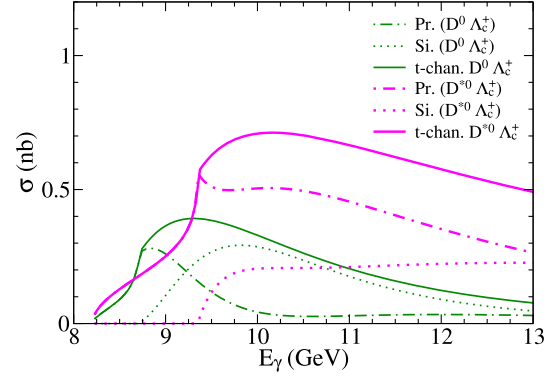


FIG. 5. Cross section contributions from the principal-value (dot-dashed curves) and on-shell singular (dotted curves) parts of the dominant t -channel rescattering amplitudes for the $\bar{D}^0\Lambda_c^+$ (thin curves) and $\bar{D}^{*0}\Lambda_c^+$ (thick curves) intermediate states. The solid curves show the incoherent sums of these two contributions for the respective intermediate states and coincide with the corresponding individual t -channel curves in Fig. 4(b).

includes the s - and u -channel diagrams in both the production and transition amplitudes, is therefore not obtained by simply adding the two individual t -channel cross sections shown in that panel.

Figure 6 presents the differential cross sections $d\sigma/dt$ at 12 different photon energies, compared with the J/ψ -007 [16] (squares), GlueX-23 [15] (open circles), CLAS [18] (filled circles), and GlueX-19 [14] (triangles) data. While the Pomeron contribution decreases rapidly with increasing $|t|$, the rescattering contribution becomes increasingly important in the large- $|t|$ region. As a result, the full calculation provides a much improved description of the JLab data over the Pomeron contribution alone, especially at relatively large momentum transfer. Although the full results still tend to slightly overestimate some data points in the backward region, they remain in reasonable agreement with the overall trend of the data, particularly in the forward and intermediate regions.

Figure 7 compares our results for the total cross section with those of Refs. [26,30], both of which employ the same DL model for the Pomeron-exchange process. In Ref. [26], a dynamical model based on a phenomenological charm-quark–nucleon (c - N) potential, v_{cN} , is additionally considered, as illustrated in Fig. 8. The potential is parametrized as

$$v_{cN}(r) = \alpha \left(\frac{e^{-\mu_1 r}}{r} - \frac{e^{-\mu_2 r}}{r} \right), \quad (40)$$

where $\alpha = -0.145$, $\mu_1 = 0.3$ GeV and $\mu_2 = 1.5$ GeV [26]. The form of $v_{cN}(r)$ is chosen such that the resulting $V_{J/\psi N}(r)$ potential reproduces the Yukawa-type behavior at large distances, consistent with lattice QCD calculations [63]. It also provides a description of the JLab data including the $J/\psi N$ FSI. The VN potential is

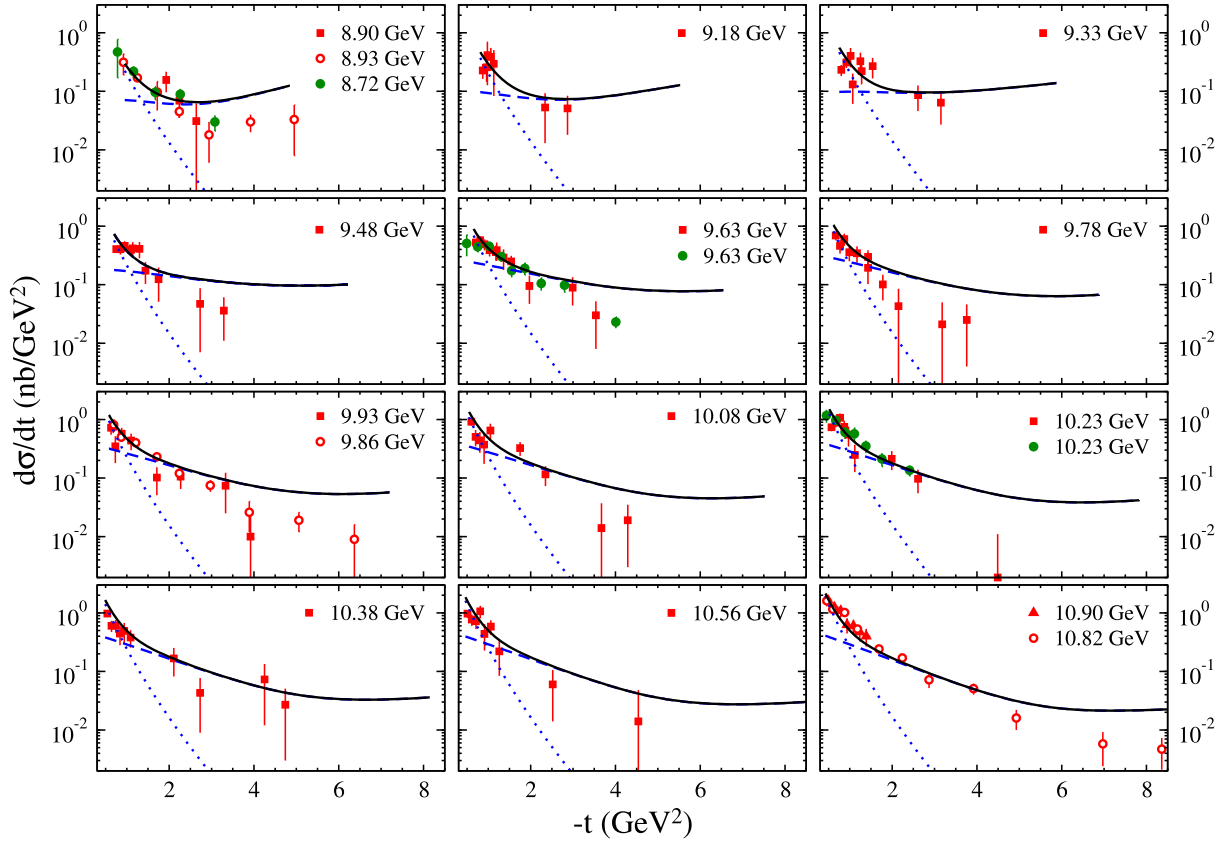


FIG. 6. Differential cross sections $d\sigma/dt$ as functions of $-t$ at various photon energies, compared with the J/ψ -007 [16] (squares), GlueX-23 [15] (open circles), CLAS [18] (filled circles), and GlueX-19 [14] (triangles) data. The curve notations are the same as those in Fig. 4(a).

constructed by folding the charm-quark–nucleon interaction v_{cN} with the vector-meson wave function ϕ_V obtained from a constituent quark model [64],

$$V_{VN,VN} = \langle \phi_V, N | \sum_c v_{cN} | \phi_V, N \rangle. \quad (41)$$

In this approach, the commonly used VMD assumption is not employed. By contrast, Ref. [30] incorporates a

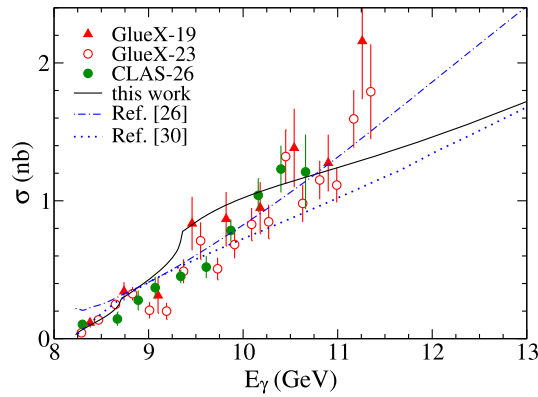


FIG. 7. The total cross section obtained in this work is compared with those of Refs. [26,30]. Experimental data are taken from the GlueX [14,15] and CLAS [18] Collaborations.

t -channel meson-exchange mechanism, in which light-meson exchanges play an important role. As shown in Fig. 7, the smooth energy dependence observed by the CLAS Collaboration [18] is also supported by the results of Refs. [26,30]. The existence and interpretation of cusplike structures in near-threshold J/ψ photoproduction therefore remain open issues, which need to be clarified by future experimental and theoretical studies.

We note that the dynamical model of Ref. [26] includes the $J/\psi N$ FSI but does not include explicit $\gamma p \rightarrow \bar{D}^{(*)0} \Lambda_c^+$ production vertices or a coupled-channel treatment of the corresponding open-charm meson-baryon states. The model therefore does not provide predictions for the

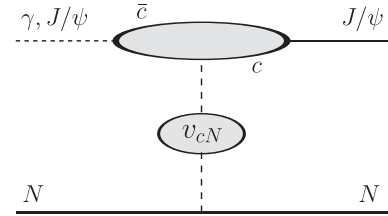


FIG. 8. Quark-antiquark loop mechanism for $\gamma, J/\psi + N \rightarrow J/\psi + N$ induced by a phenomenological charm-quark–nucleon potential v_{cN} .

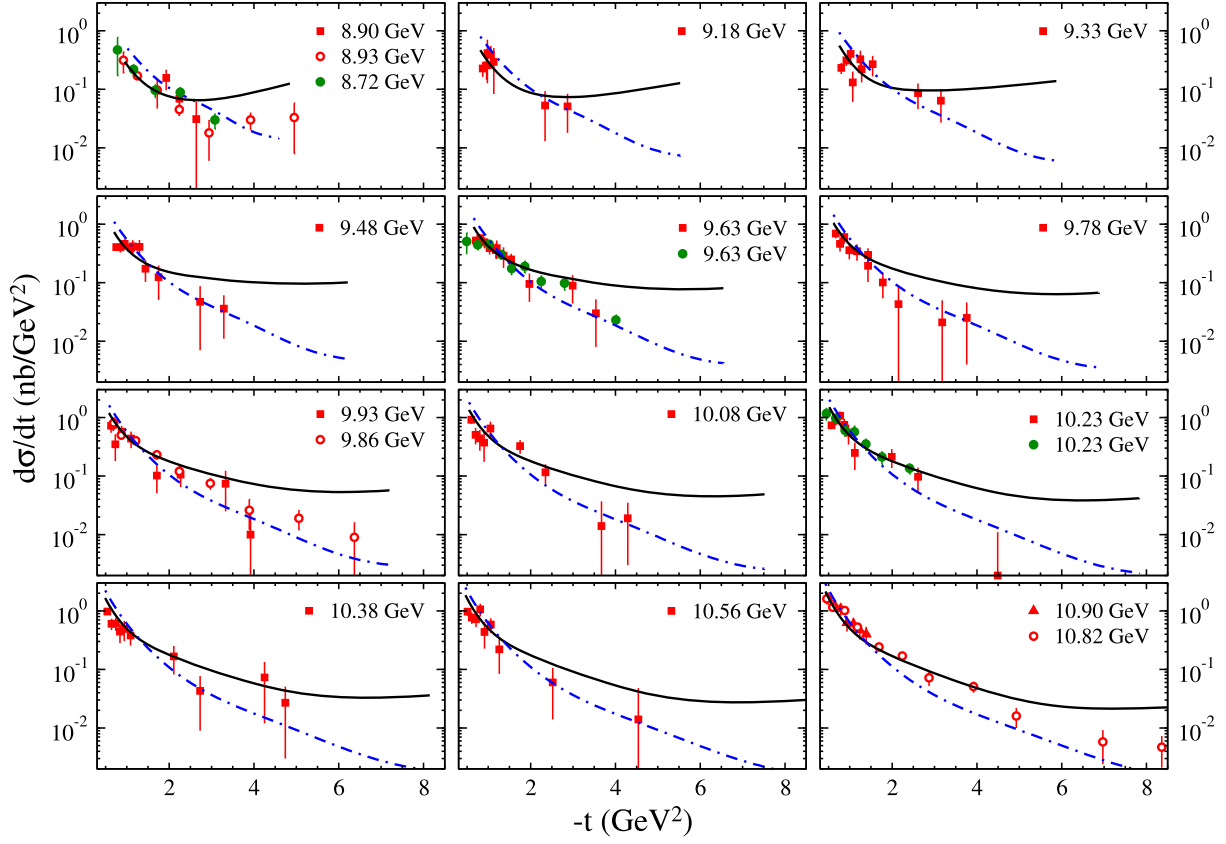


FIG. 9. Differential cross sections obtained in this work (black solid) are compared with those of Ref. [26] (blue dot-dashed). Experimental data are taken from the J/ψ -007 [16] (squares), GlueX-23 [15] (open circles), CLAS [18] (filled circles), and GlueX-19 [14] (triangles) Collaborations.

corresponding open-charm production cross sections; obtaining such predictions would require a substantial extension. Consequently, the corresponding open-charm threshold discontinuities and associated cusp structures are absent in that model.

A complementary description was recently presented in Ref. [28]. In contrast to Ref. [26], where the $J/\psi N$ FSI is argued to play a dominant role very close to threshold, Ref. [28] describes the reaction through a dynamical $\gamma \rightarrow c\bar{c} + \mathbb{P} \rightarrow J/\psi$ transition involving dressed-quark degrees of freedom. In this framework, the photon-to- J/ψ transition is treated using dressed-quark propagators, a dressed-photon-quark vertex, and the J/ψ Bethe-Salpeter amplitude. The resulting momentum-dependent quark-loop dynamics plays an important role near threshold and provides a reasonable description of the available near-threshold data without invoking an explicit $J/\psi N$ FSI.

Figure 9 compares our results for the t -dependent differential cross sections with those of Ref. [26]. The two theoretical results are, in general, consistent with the JLab data in the forward region, corresponding to small momentum transfer ($-t \leq 2 \text{ GeV}^2$). The results of Ref. [26] exhibit a steeper falloff with increasing $-t$ and remain in good agreement with the JLab data at relatively large momentum transfer.

The size of the cusp structures is connected to the relevant open-charm reactions $\gamma p \rightarrow \bar{D}^0 \Lambda_c^+$ and $\gamma p \rightarrow \bar{D}^{*0} \Lambda_c^+$. Our model estimates for their total cross sections are presented in Fig. 10. The total cross sections increase with photon energy up to $E_\gamma \simeq 15 \text{ GeV}$, reaching values of the order of a few nanobarns, and then gradually decrease at higher energies. Their normalization is sensitive to the phenomenological form factors and cutoff parameters. Our results are smaller

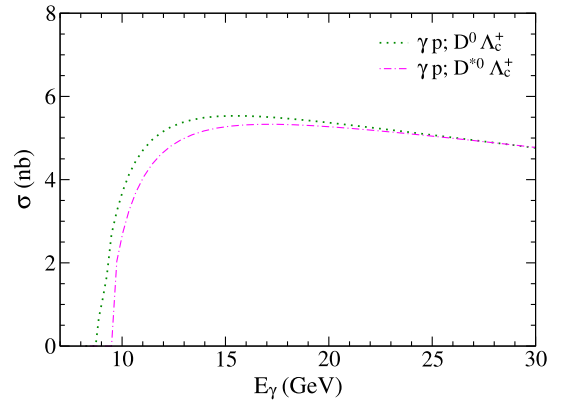


FIG. 10. Model estimates for the total cross sections of the $\gamma p \rightarrow \bar{D}^0 \Lambda_c^+$ and $\gamma p \rightarrow \bar{D}^{*0} \Lambda_c^+$ reactions.

than those of Ref. [48], where total cross sections of $\sigma \gtrsim 10$ nb are obtained, and are much smaller than those of Ref. [37], which predicts values on the order of 100–200 nb.

IV. SUMMARY AND CONCLUSIONS

In this work, we investigated near-threshold J/ψ photoproduction based on the DL Pomeron-exchange mechanism supplemented by hadronic rescattering contributions from the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ intermediate states. The production and transition amplitudes were constructed by combining tree-level subamplitudes in a gauge-invariant manner. Within the present hadronic model, the rescattering amplitudes can generate noticeable enhancements near the $\bar{D}^0\Lambda_c^+$ and $\bar{D}^{*0}\Lambda_c^+$ thresholds and improve the description of the GlueX total cross section data [14,15]. In addition, while the Pomeron contribution decreases rapidly with increasing $|t|$, the open-charm rescattering contributions provide sizable effects at larger momentum transfer, leading to a better description of the differential cross sections [14–16,18]. The dominant effect arises from the t -channel parts of the production and transition subamplitudes, while the corresponding s - and u -channel contributions are strongly suppressed.

Comparison with more recent JLab data suggests that the reaction mechanism for near-threshold J/ψ photoproduction is not yet fully understood. In particular, a smoother energy dependence has been observed by the J/ψ -007 [17] and CLAS [18] Collaborations. Moreover, the structure around $E_\gamma \simeq 10.5$ GeV [14,15,18] may reflect the influence of additional nearby open-charm channels, such as $\bar{D}^{*0}\Sigma_c^{*+}$, which are not included in the present analysis. A more complete treatment of these additional channels within a fully unitarized coupled-channel framework, including the finite widths of unstable particles, will therefore be important for achieving a deeper understanding of the threshold region. If confirmed, such cusplike structures could indicate significant coupled-channel dynamics and hadronic rescattering effects in near-threshold J/ψ photoproduction. This would also make the extraction of gluonic properties of the nucleon, including possible information related to the trace anomaly, more model dependent.

Similar cusplike structures have also been discussed in the strange sector. In ϕN photoproduction [65], for example, a pronounced cusp appears near $W \simeq 2.2$ GeV

only at very forward angles ($\cos\theta \gtrsim 0.9$) [66], suggesting an important role for intermediate strange-meson-baryon loops, such as the $K^*\Sigma(1385)$, $K\Lambda(1670)$, and $K\Sigma(1660)$ channels. A similar forward-angle enhancement has been reported in $K^+\Sigma^0$ photoproduction near $W \simeq 1.9$ GeV [67]. These observations may indicate rescattering effects near the open- and hidden-strangeness thresholds, in connection with hadronic bound states such as $K\Lambda(1405)$, $K\Sigma(1385)$, and ϕN . In $K^0\Sigma^+$ photoproduction, on the other hand, the cross section drops sharply near the $K^*\Lambda$ and $K^*\Sigma$ thresholds [68], although it remains unclear whether this behavior should be interpreted as a cusp. An alternative explanation has been proposed in terms of a $K^*\Sigma$ molecular bound state in a coupled-channel approach [69,70], possibly related to the light-pentaquark candidate $P_s^+(2071)3/2^-$. Such a state may be viewed as a light-flavor partner of the heavy pentaquark $P_{cc}(4457)$, although its spin parity has not yet been determined.

These observations suggest that future measurements of open-charm photoproduction reactions, such as $\gamma N \rightarrow \bar{D}^{(*)}\Lambda_c$ and related channels involving Σ_c baryons, could provide useful information on the possible role of heavy-pentaquark states. In particular, our model estimates that the total cross sections for $\gamma p \rightarrow \bar{D}^0\Lambda_c^+$ and $\gamma p \rightarrow \bar{D}^{*0}\Lambda_c^+$ are of the order of a few nanobarns. Measurements of these channels would provide a direct test of the rescattering scenario explored in this work. Extending the present model to the strangeness sector discussed above is also of considerable interest, and work in this direction is currently underway.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

[1] U. Camerini, J. G. Learned, R. Prepost, C. M. Spencer, D. E. Wiser, W. Ash, R. L. Anderson, D. Ritson, D. Sherden, and C. K. Sinclair, Photoproduction of the ψ particles, *Phys. Rev. Lett.* **35**, 483 (1975).

[2] M. E. Binkley *et al.*, J/ψ photoproduction from 60 to 300 GeV/c, *Phys. Rev. Lett.* **48**, 73 (1982).

[3] P. L. Frabetti *et al.*, A measurement of elastic J/ψ photoproduction cross section at Fermilab E687, *Phys. Lett. B* **316**, 197 (1993).

- [4] S. Aid *et al.* (H1 Collaboration), Elastic and inelastic photoproduction of J/ψ mesons at HERA, *Nucl. Phys.* **B472**, 3 (1996).
- [5] C. Adloff *et al.* (H1 Collaboration), Elastic photoproduction of J/ψ and Υ mesons at HERA, *Phys. Lett. B* **483**, 23 (2000).
- [6] S. Chekanov *et al.* (ZEUS Collaboration), Exclusive photoproduction of J/ψ mesons at HERA, *Eur. Phys. J. C* **24**, 345 (2002).
- [7] A. Donnachie and P. V. Landshoff, Elastic scattering and diffraction dissociation, *Nucl. Phys.* **B244**, 322 (1984).
- [8] A. Donnachie and P. V. Landshoff, Dynamics of elastic scattering, *Nucl. Phys.* **B267**, 690 (1986).
- [9] A. Donnachie and P. V. Landshoff, Exclusive rho production in deep inelastic scattering, *Phys. Lett. B* **185**, 403 (1987).
- [10] A. Donnachie and P. V. Landshoff, Small x: Two pomerons!, *Phys. Lett. B* **437**, 408 (1998).
- [11] A. Donnachie and P. V. Landshoff, Charm production at HERA, *Phys. Lett. B* **470**, 243 (1999).
- [12] R. Fiore, L. L. Jenkovsky, and F. Paccanoni, Photoproduction of heavy vector mesons at HERA: A test field for diffraction, *Eur. Phys. J. C* **10**, 461 (1999).
- [13] E. Martynov, E. Predazzi, and A. Prokudin, Photoproduction of vector mesons in the soft dipole pomeron model, *Phys. Rev. D* **67**, 074023 (2003).
- [14] A. Ali *et al.* (GlueX Collaboration), First measurement of near-threshold J/ψ exclusive photoproduction off the proton, *Phys. Rev. Lett.* **123**, 072001 (2019).
- [15] S. Adhikari *et al.* (GlueX Collaboration), Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region, *Phys. Rev. C* **108**, 025201 (2023).
- [16] B. Duran *et al.*, Determining the gluonic gravitational form factors of the proton, *Nature (London)* **615**, 813 (2023).
- [17] S. Joosten *et al.* (J/ψ -007 Collaboration), Near-threshold $J/\psi \rightarrow \mu^+\mu^-$ photoproduction and the gluonic gravitational form factors of the proton, [arXiv:2602.14416](https://arxiv.org/abs/2602.14416).
- [18] P. Chatagnon *et al.* (CLAS Collaboration), Measurement of the near-threshold J/ψ photoproduction cross section with the CLAS12 experiment, *Phys. Rev. C* **113**, 065203 (2026).
- [19] T.-S. H. Lee, S. Sakinah, and Y. Oh, Models of J/ψ photoproduction reactions on the nucleon, *Eur. Phys. J. A* **58**, 252 (2022).
- [20] F. Zeng, X. Y. Wang, L. Zhang, Y. P. Xie, R. Wang, and X. Chen, Near-threshold photoproduction of J/ψ in two-gluon exchange model, *Eur. Phys. J. C* **80**, 1027 (2020).
- [21] Y. Guo, X. Ji, and Y. Liu, QCD Analysis of near-threshold photon-proton production of heavy quarkonium, *Phys. Rev. D* **103**, 096010 (2021).
- [22] Y. Hatta and D. L. Yang, Holographic J/ψ production near threshold and the proton mass problem, *Phys. Rev. D* **98**, 074003 (2018).
- [23] Y. Hatta, A. Rajan, and D. L. Yang, Near threshold J/ψ and Υ photoproduction at JLab and RHIC, *Phys. Rev. D* **100**, 014032 (2019).
- [24] K. A. Mamo and I. Zahed, Diffractive photoproduction of J/ψ and Υ using holographic QCD: Gravitational form factors and GPD of gluons in the proton, *Phys. Rev. D* **101**, 086003 (2020).
- [25] K. A. Mamo and I. Zahed, Electroproduction of heavy vector mesons using holographic QCD: From near threshold to high energy regimes, *Phys. Rev. D* **104**, 066023 (2021).
- [26] S. Sakinah, T. S. H. Lee, and H. M. Choi, Dynamical model of J/ψ photoproduction on the nucleon, *Phys. Rev. C* **109**, 065204 (2024).
- [27] L. Tang, Y. X. Yang, Z. F. Cui, and C. D. Roberts, J/ψ photoproduction: Threshold to very high energy, *Phys. Lett. B* **856**, 138904 (2024).
- [28] L. Tang, H. Y. Xing, M. Ding, and C. D. Roberts, Exclusive photoproduction of light and heavy vector mesons: Thresholds to very high energies, *Eur. Phys. J. C* **86**, 284 (2026).
- [29] M. A. Pichowsky and T. S. H. Lee, Exclusive diffractive processes and the quark substructure of mesons, *Phys. Rev. D* **56**, 1644 (1997).
- [30] S. H. Kim, J/ψ -meson photoproduction off the nucleon in a dynamical model, *Phys. Lett. B* **868**, 139725 (2025).
- [31] S. Okubo, ϕ -meson and unitary symmetry model, *Phys. Lett.* **5**, 165 (1963).
- [32] G. Zweig, CERN Reports No. CERN-TH-401 and No. CERN-TH-412, 1964, [10.17181/CERN-TH-412](https://arxiv.org/abs/10.17181/CERN-TH-412).
- [33] J. Iizuka, Systematics and phenomenology of meson family, *Prog. Theor. Phys. Suppl.* **37**, 21 (1966).
- [34] J. J. Wu, R. Molina, E. Oset, and B. S. Zou, Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV, *Phys. Rev. Lett.* **105**, 232001 (2010).
- [35] M. Z. Liu, Y. W. Pan, F. Z. Peng, M. Sánchez Sánchez, L. S. Geng, A. Hosaka, and M. Pavon Valderrama, Emergence of a complete heavy-quark spin symmetry multiplet: Seven molecular pentaquarks in light of the latest LHCb analysis, *Phys. Rev. Lett.* **122**, 242001 (2019).
- [36] C. Fernández-Ramírez, A. Pilloni, M. Albaladejo, A. Jackura, V. Mathieu, M. Mikhasenko, J. A. Silva-Castro, and A. P. Szczepaniak (JPAC Collaboration), Interpretation of the LHCb $P_c(4312)^+$ signal, *Phys. Rev. Lett.* **123**, 092001 (2019).
- [37] M. L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meißner, J. A. Oller, and Q. Wang, Interpretation of the LHCb P_c states as hadronic molecules and hints of a narrow $P_c(4380)$, *Phys. Rev. Lett.* **124**, 072001 (2020).
- [38] Q. Wang, X. H. Liu, and Q. Zhao, Photoproduction of hidden charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$, *Phys. Rev. D* **92**, 034022 (2015).
- [39] V. Kubarovsky and M. B. Voloshin, Formation of hidden-charm pentaquarks in photon-nucleon collisions, *Phys. Rev. D* **92**, 031502 (2015).
- [40] M. Karliner and J. L. Rosner, Photoproduction of exotic baryon resonances, *Phys. Lett. B* **752**, 329 (2016).
- [41] A. N. Hiller Blin, C. Fernández-Ramírez, A. Jackura, V. Mathieu, V. I. Mokeev, A. Pilloni, and A. P. Szczepaniak, Studying the $P_c(4450)$ resonance in J/ψ photoproduction off protons, *Phys. Rev. D* **94**, 034002 (2016).
- [42] X. Y. Wang, X. R. Chen, and J. He, Possibility to study pentaquark states $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ in $\gamma p \rightarrow J/\psi p$ reaction, *Phys. Rev. D* **99**, 114007 (2019).
- [43] J. J. Wu, T. S. H. Lee, and B. S. Zou, Nucleon resonances with hidden charm in γp reactions, *Phys. Rev. C* **100**, 035206 (2019).
- [44] D. Winney, C. Fanelli, A. Pilloni, A. N. Hiller Blin, C. Fernández-Ramírez, M. Albaladejo, V. Mathieu,

- V. I. Mokeev, and A. P. Szczepaniak (JPAC Collaboration), Double polarization observables in pentaquark photoproduction, *Phys. Rev. D* **100**, 034019 (2019).
- [45] I. Strakovsky, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, and R.L. Workman, Plausibility of the LHCb $P_c(4312)^+$ in the GlueX $\gamma p \rightarrow J/\psi p$ total cross sections, *Phys. Rev. C* **108**, 015202 (2023).
- [46] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [47] M.L. Du, V. Baru, F.K. Guo, C. Hanhart, U. G. Meißner, A. Nefediev, and I. Strakovsky, Deciphering the mechanism of near-threshold J/ψ photoproduction, *Eur. Phys. J. C* **80**, 1053 (2020).
- [48] D. Winney *et al.* (JPAC Collaboration), Dynamics in near-threshold J/ψ photoproduction, *Phys. Rev. D* **108**, 054018 (2023).
- [49] R. Aaij *et al.* (LHCb Collaboration), Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays, *Phys. Rev. Lett.* **115**, 072001 (2015).
- [50] R. Aaij *et al.* (LHCb Collaboration), Observation of a narrow pentaquark state, $P_c(4312)^+$, and of the two-peak structure of the $P_c(4450)^+$, *Phys. Rev. Lett.* **122**, 222001 (2019).
- [51] R. Aaij *et al.* (LHCb Collaboration), Evidence for a new structure in the $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s^0 \rightarrow J/\psi p \bar{p}$ decays, *Phys. Rev. Lett.* **128**, 062001 (2022).
- [52] S. Clymton, H.-Ch. Kim, and T. Mart, Production mechanism of the hidden charm pentaquark states $P_{c\bar{c}}$, *Phys. Rev. D* **110**, 094014 (2024).
- [53] X. Zhang, Pentaquarks P_c in a dynamical coupled-channel approach of $\gamma p \rightarrow J/\psi p$ reaction, *Eur. Phys. J. C* **85**, 1120 (2025).
- [54] B. Wu, X.K. Dong, M.L. Du, F.K. Guo, and B.S. Zou, Deciphering the mechanism of J/ψ -nucleon scattering, *Fund. Res.* **5**, 2530 (2025).
- [55] T. Sato and T.S.H. Lee, Meson exchange model for πN scattering and $\gamma N \rightarrow \pi N$ reaction, *Phys. Rev. C* **54**, 2660 (1996).
- [56] Y. Oh and T.S.H. Lee, ρ meson photoproduction at low energies, *Phys. Rev. C* **69**, 025201 (2004).
- [57] A.I. Titov and T.S.H. Lee, Spin effects and baryon resonance dynamics in ϕ meson photoproduction at few GeV, *Phys. Rev. C* **67**, 065205 (2003).
- [58] A. S. Fomin, S. Barsuk, A. Y. Korchin, V. A. Kovalchuk, E. Kou, M. Liul, A. Natchii, E. Niel, P. Robbe, and A. Stocchi, The prospect of charm quark magnetic moment determination, *Eur. Phys. J. C* **80**, 358 (2020).
- [59] Y. Oh, W. Liu, and C. M. Ko, J/ψ absorption by nucleons in the meson-exchange model, *Phys. Rev. C* **75**, 064903 (2007).
- [60] W. Liu, C.M. Ko, and Z.W. Lin, Cross-section for charmonium absorption by nucleons, *Phys. Rev. C* **65**, 015203 (2002).
- [61] A. Khodjamirian, C. Klein, T. Mannel, and Y.M. Wang, Form factors and strong couplings of heavy baryons from QCD light-cone sum rules, *J. High Energy Phys.* **09** (2011) 106.
- [62] A. Khodjamirian, C. Klein, T. Mannel, and Y.M. Wang, How much charm can PANDA produce?, *Eur. Phys. J. A* **48**, 31 (2012).
- [63] T. Kawanai and S. Sasaki, Charmonium-nucleon potential from lattice QCD, *Phys. Rev. D* **82**, 091501 (2010).
- [64] J. Segovia, D.R. Entem, F. Fernandez, and E. Hernandez, Constituent quark model description of charmonium phenomenology, *Int. J. Mod. Phys. E* **22**, 1330026 (2013).
- [65] S.H. Kim, T.S.H. Lee, S.i. Nam, and Y. Oh, Dynamical model of ϕ meson photoproduction on the nucleon and ^4He , *Phys. Rev. C* **104**, 045202 (2021).
- [66] B. Dey *et al.* (CLAS Collaboration), Data analysis techniques, differential cross sections, and spin density matrix elements for the reaction $\gamma p \rightarrow \phi p$, *Phys. Rev. C* **89**, 055208 (2014); **90**, 019901(E) (2014).
- [67] T. C. Jude *et al.*, Observation of a cusp-like structure in the $\gamma p \rightarrow K^+\Sigma^0$ cross section at forward angles and low momentum transfer, *Phys. Lett. B* **820**, 136559 (2021).
- [68] R. Ewald *et al.* (CBELSA/TAPS Collaboration), Anomaly in the $K_S^0\Sigma^+$ photoproduction cross section off the proton at the K^* threshold, *Phys. Lett. B* **713**, 180 (2012).
- [69] S.i. Nam, Studies on the $K^*\Sigma$ bound-state via $K^+p \rightarrow K^+\phi p$, *Phys. Rev. D* **103**, 054040 (2021).
- [70] K.P. Khemchandani, H. Kaneko, H. Nagahiro, and A. Hosaka, Vector meson-baryon dynamics and generation of resonances, *Phys. Rev. D* **83**, 114041 (2011).