Eur. Phys. J. C (2020) 80:1053
https://doi.org/10.1140/epjc/s10052-020-08620-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Deciphering the mechanism of near-threshold J/ψ photoproduction

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Received: 11 October 2020 / Accepted: 30 October 2020

Abstract The photoproduction of the J/ψ off the proton is believed to deepen our understanding of various physics issues. On the one hand, it is proposed to provide access to the origin of the proton mass, based on the QCD multipole expansion. On the other hand, it can be employed in a study of pentaquark states. The process is usually assumed to proceed through vector-meson dominance, that is the photon couples to a J/ψ which rescatters with the proton to give the $J/\psi p$ final state. In this paper, we provide a compelling hint for and propose measurements necessary to confirm a novel production mechanism via the $\Lambda_c\bar{D}^{(*)}$ intermediate states. In particular, there must be cusp structures at the $\Lambda_c\bar{D}^{(*)}$ thresholds in the energy dependence of the J/ψ photoproduction cross section. The same mechanism also implies the J/ψ-nucleon scattering lengths of order 1 mfm. Given this, one expects only a minor contribution of charm quarks to the nucleon mass.

1 Introduction

Understanding how strong interactions work in the nonperturbative regime of quantum chromodynamics (QCD) remains one of the most challenging tasks of the Standard Model. One fundamental problem tied to the nonperturbative nature of QCD is how the visible matter of the universe gets most of its mass that can be translated to how the proton and neutron—the fundamental ingredients of all kinds of nuclei in the universe—acquire their masses. It was suggested that the near-threshold production of heavy quarkonium is sensitive to the trace anomaly contribution to the nucleon mass [1–3] which may be measured at the Jefferson Laboratory and future electron-ion colliders [4] (for recent discussions see, for example, Refs. [5,6]). This suggestion is based on the vector-meson-dominance (VMD) model and the assumption that the nucleon interacts with a heavy quarkonium through multiple-gluon exchange, as illustrated in Fig. 1. If this is indeed the dominant mechanism, the near-threshold J/ψ photoproduction cross section would provide the link to the $J/\psi p$ elastic scattering amplitude at low energies which is fundamentally important because the $J/\psi p$ scattering length can be related to the nucleon matrix element of two-gluon operators and thereby to the trace anomaly contribution to the nucleon mass. Also, a possible existence of the quarkonium-nucleus bound states first proposed in Ref. [7] crucially depends on the strength of $J/\psi N$ interaction at low energies, characterised by the $J/\psi p$ scattering length. A loophole with this mechanism is, however, that it relies on the QCD multipole expansion, see below.

Another fundamental issue of nonperturbative QCD is that it is still unclear how the hadron spectrum is organized. In particular, exotic hadrons such as multiquark states are being sought experimentally and studied theoretically using

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Published online: 16 November 2020

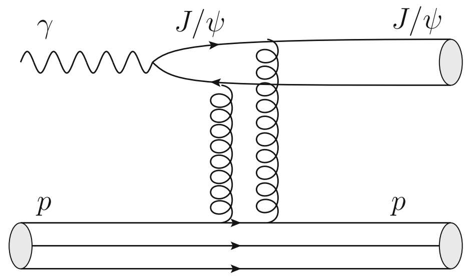

Fig. 1 Vector-meson dominance model mechanism for the near-threshold J/ψ photoproduction

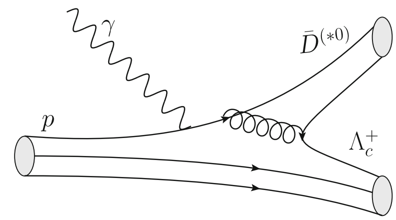

Fig. 2 Mechanism for the near-threshold J/ψ photoproduction through $\Lambda_c\bar{D}^{(*)}$ which then rescatter into $J/\psi p$

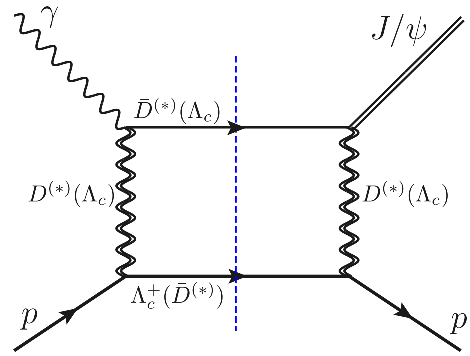

Fig. 3 Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state

phenomenological models, effective field theories and lattice QCD. In the last two decades, tens of states beyond the conventional quark model were found, many of them by different experiments in different reactions. However, their structure still needs to be resolved. For recent reviews on both theoretical and experimental aspects of exotics in the heavy quark sector see, for example, Refs. [8–16]. An intriguing recent discovery was a set of hidden-charm pentaquark candidates, observed in the Λ_b decays by the LHCb Collaboration [17,18] and called P_c states, which triggered a flood of theoretical investigations. However, a subsequent search of the P_c states in the GlueX experiment using the photoproduction process $\gamma p \to J/\psi p$ did not reveal any signal [19]. The analyses in Refs. [20,21] which conclude that the branching fraction of the $P_c \to J/\psi p$ should be at most a few per cent are also based on the VMD model: The photon is assumed to convert to a J/ψ which rescatters then with the proton target to form P_c states. In fact, VMD is generally assumed in estimating the cross sections for the photoproduction of hidden-charm and hidden-bottom pentaquark states [22–33].

The rich physical implications related to the photoproduction of the J/ψ off the proton provide a strong motivation to revise the assumptions underlying the VMD approach, and identify its possible caveats. Specifically, (i) the J/ψ attached to the photon is highly off-shell while the $J/\psi p$ scattering length is defined for the on-shell scattering amplitude; (ii) the $\Lambda_c^+\bar{D}^0$ threshold is only 116 MeV above the $J/\psi p$ threshold, rendering the contribution from the $\Lambda_c\bar{D}$ channel potentially sizeable and thus making the relation between the photoproduction cross section and the trace anomaly contribution to the nucleon mass even more obscure. In this paper, we investigate the implications of the latter observation.

We propose a new coupled-channel (CC) mechanism for the near-threshold J/ψ photoproduction which is not directly related to the nucleon matrix element of the gluonic operator since the $J/\psi p$ final state is produced through the nearby open-charm channels $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$, see Fig. 2. In particular, we demonstrate that the data recently measured at GlueX can be quantitatively understood using this mechanism with reasonable parameters. With this mechanism, the direct relation between the trace anomaly contribution to the nucleon mass and the J/ψ near-threshold photoproduction, that is present in the VMD model, is obscured. We discuss the implications of this mechanism, and suggest experimental observables which should allow one to test the picture outlined here.

2 Coupled-channel mechanism

The cross section for the inclusive production of a charm and anti-charm quark pair, $\gamma p \to c\bar{c}X$ with X denoting everything that is not detected, is about two orders of magnitude higher than that for the exclusive production of the J/ψ, $\gamma p \to J/\psi p$ (for a compilation of the data and a VMD model fit see Ref. [34]). This might indicate that the cross sections for the pairs of open-charm mesons and baryons are sizeable, which was also expected in Ref. [35]. Then, open-charm channels close to the $J/\psi p$ threshold could potentially contribute significantly to the $J/\psi p$ production. While there are no data for the photoproduction of open-charm channels in the pertinent energy region yet, it should be noted that the cross sections for the analogous reactions in the strangeness sector, $\gamma p \to K^+\Lambda/K^+\Sigma^0$ [36–40], are indeed much larger than that for the near-threshold ϕ meson production, $\gamma p \to \phi p$ [41–43].

For the $J/\psi p$ photoproduction off the proton, the closest open-charm channels are $\Lambda_c^+\bar{D}^0$ and $\Lambda_c^+\bar{D}^{*0}$ with the thresholds just 116 and 258 MeV above the $J/\psi p$ threshold, respectively. In this paper, we investigate the contribution of these channels to the $J/\psi p$ photoproduction. Not only is the cross section estimated by considering the exchange of $D^{(*)}$ and Λ_c^+, as shown in Fig. 3, but also are general features of the resulting rates identified and possible future experiments suggested to test the proposed mechanism.

In the near-threshold region, it is sufficient to consider effective Lagrangians that have the smallest number of derivatives, which are given as follows,

$$\mathcal{L}_{\Lambda_c DN} = -g_{D^*N\Lambda_c}\bar{\Lambda}_c\gamma_\mu N D^{*\mu} - ig_{DN\Lambda_c}\bar{\Lambda}_c\gamma_5 N D - g_{D^*N\Lambda_c}\bar{N}\gamma_\mu\Lambda_c D^{*\mu\dagger} - ig_{DN\Lambda_c}\bar{N}\gamma_5\Lambda_c D^\dagger, \quad (1)$$

$$\mathcal{L}_\psi = -g_{\psi DD^*}\psi_\mu\epsilon_{\mu\nu\alpha\beta}\left(\partial_\nu D_\alpha^*\partial_\beta D^\dagger - \partial_\nu D\partial_\beta D_\alpha^{*\dagger}\right), + ig_{\psi D^*D^*}\psi^\mu\left(D^{*\nu}\partial_\nu D_\mu^{*\dagger} - \partial_\nu D_\mu^* D^{*\nu\dagger} - D^{*\nu}\overleftrightarrow{\partial}_\mu D_\nu^{*\dagger}\right) - ig_{\psi DD}D^\dagger\overleftrightarrow{\partial}_\mu D\psi^\mu + g_{\psi\Lambda_c\Lambda_c}\bar{\Lambda}_c\gamma_\mu\psi^\mu\Lambda_c, \quad (2)$$

$$\mathcal{L}_\gamma = -g_{\gamma DD^*}F_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}(D_\alpha^*\overleftrightarrow{\partial}_\beta D^\dagger - D\overleftrightarrow{\partial}_\beta D_\alpha^{*\dagger}) - ig_{\gamma D^*D^*}F^{\mu\nu}D_\mu^{*\dagger}D_\nu^* - e\bar{\Lambda}_c\gamma_\mu A^\mu\Lambda, \quad (3)$$

where D and D^* refer to the fields for the neutral charmed mesons, e is the elementary (positive) electric charge ($\alpha = e^2/(4\pi) \simeq 1/137$) and the couplings $g_{\psi DD} = g_2 m_D\sqrt{m_\psi}$, $g_{\psi DD^*} = g_2\sqrt{m_\psi m_D/m_{D^*}}$, $g_{\psi D^*D^*} = g_2 m_{D^*}\sqrt{m_\psi}$ are related to the same coupling constant g_2 through heavy quark spin symmetry [44,45].

Since electric charge conservation law allows only for a contribution of the neutral $D^{(*)}$ mesons (see Fig. 3), the Lagrangian $\gamma D^{(*)}D^*$ in Eq. (3) contains only magnetic interactions. The corresponding couplings can be fixed directly from the data on the experimentally measured total width of the D^{*+} meson (the unknown total width of the D^{*0} meson is evaluated using isospin symmetry) and the branching fraction of the decay $D^{*0} \to D^0\gamma$ [46]. For the other couplings we employ predictions of phenomenological approaches, the corresponding values are collected in Table 1. We notice that using the couplings $g_{DN\Lambda_c} = -10.7$ and $g_{D^*N\Lambda_c} = -5.8$ obtained from the light-cone sum rules [49,50] give similar results which we therefore do not quote here.

3 Comparison with the data

The amplitude for the box diagram from Fig. 3 is evaluated using a dispersion relation as

$$\frac{1}{\pi}\int_{\rm th}^{s_{\rm cut}}\frac{\mathcal{A}_{\gamma p\to\Lambda_c^+\bar{D}^{(*)0}}(s')\rho(s')\mathcal{A}_{J/\psi p\to\Lambda_c^+\bar{D}^{(*)0}}(s')}{s'-s}ds', \quad (4)$$

with th $= (m_{\Lambda_c} + m_{\bar{D}^{(*)}})^2$, where both amplitudes $\mathcal{A}$ involved are worked out using the Lagrangians (1)–(3), and $\rho = q_{\rm cm}/(8\pi\sqrt{s})$ is the two-body phase space with $\sqrt{s}$ and $q_{\rm cm}$ the energy and the magnitude of the three-momentum in the center-of-mass frame, respectively. The dispersive integral in Eq. (4) is cut off at

$$\sqrt{s_{\rm cut}} = \sqrt{q_{\rm max}^2 + m_{\Lambda_c}^2} + \sqrt{q_{\rm max}^2 + m_D^2}, \quad (5)$$

with a natural value for $q_{\rm max}$ being about 1 GeV. Only the contribution of the S wave is retained for the open-charm system $\bar{D}^{(*)}\Lambda_c$ near threshold while both S and D waves are considered for the $J/\psi p$ and γp systems.

To take into account that the exchanged particles (doubly-wavy lines in Fig. 3) are off-shell with a potentially large virtuality, we augment them with a single-pole form factor [44,51,52],

$$F(t) = \frac{\Lambda^2 - m_{\rm ex}^2}{\Lambda^2 - t}, \quad (6)$$

with $m_{\rm ex}$ the mass of the exchanged particle, which is consistent with the QCD counting rules [44,51]. A natural value for the cutoff Λ is the mass of the lowest neglected exchange particle, so that we set [52]

$$\Lambda = m_{\rm ex} + \eta\Lambda_{\rm QCD}, \quad (7)$$

where $\Lambda_{\rm QCD} \simeq 250$ MeV and the parameter η which depends on both exchanged and external particles [52] is expected to be of order unity. For simplicity, if not stated otherwise, we set $\eta = 1$ and $\Lambda_{\rm QCD} = 250$ MeV for all exchanged particles.

The cross section as a function of the photon energy calculated using the amplitude (4) with the parameters from Table 1 is shown in Fig. 4 in comparison with the data. No parameter is fitted or fine-tuned. Although the approach used suffers from several uncertainties (badly determined couplings and form factors and only a limited set of diagrams considered to be mentioned in the first place), we notice that not only does the cross section we obtain appear to have the right order of magnitude but it also demonstrates a shape compatible with the data. We therefore dare to conclude that the open-charm loop mechanism advocated here does indeed have the opportunity to make an important, possibly dominating, contribution to the J/ψ photoproduction off the nucleon.

4 Predictions and possible tests

We collect several immediate predictions of the mechanism discussed in this paper, and enumerate further experimental tests which should allow either to consolidate or falsify the picture outlined here.

Table 1 Values of the couplings in the Lagrangians in Eqs. (1)–(3) used in the calculation

Coupling	$g_{\gamma DD^*}$	$g_{\gamma D^* D^*}$	$g_{DN\Lambda_c}$	$g_{D^*N\Lambda_c}$	$g_{\psi\Lambda_c\Lambda_c}$	$g_{\psi DD}$
Value	0.134 GeV^{-1}	0.641	−4.3	−13.2	−1.4	7.44
Source	Experimental data [46]		SU(4) [47,48]			VMD [47,48]

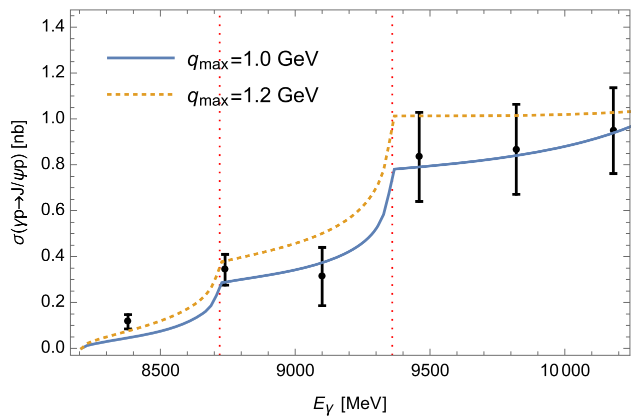

Fig. 4 Comparison of the J/ψ photoproduction through the open-charm loops as shown in Figs. 2 and 3 with the GlueX data [19]. E_γ is the photon energy in the rest frame of the initial proton. Since we consider only the $\Lambda_c\bar{D}^{(*)}$ channels, the comparison with the data is only shown up to $E_\gamma = 10.2$ GeV though a qualitative agreement up to the highest GlueX data point 11.6 GeV is also achieved. The vertical dotted lines indicate the $\Lambda_c\bar{D}^{(*)}$ thresholds

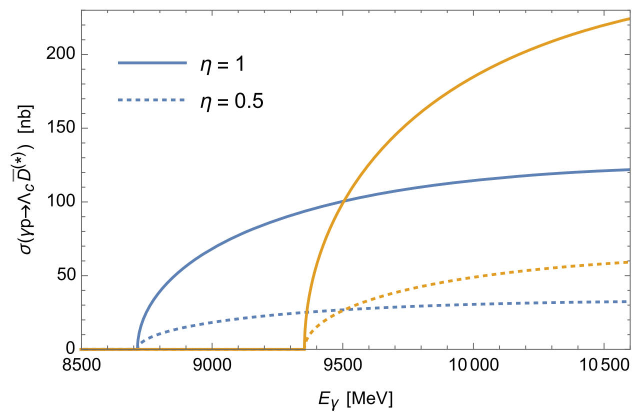

Fig. 5 Estimates of the cross sections for the $\gamma p \to \Lambda_c\bar{D}$ (blue curves) and $\gamma p \to \Lambda_c\bar{D}^*$ (orange curves) reactions

4.1 Threshold cusps

The hypothesis that the suggested production mechanism through charmed intermediate states indeed dominates the J/ψ production leads to a unique prediction that can be verified in near-future experiments: There must be sizeable cusps at the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ thresholds. This is a universal phenomenon for S-wave thresholds, and the cusp shape is a measure of the strength of the transition leading to the cusp (for a recent review of cusps in hadronic reactions, see Ref. [15]). Consequently, in the present data shown in Fig. 4, one is tempted to interpret a relatively low cross section at $E_\gamma = 9.1$ GeV as an indication of a nontrivial energy dependence of the cross section near an open-charm meson-baryon threshold. The presence of such cusps as a clear indication of the importance of the charm loops is a central finding of this paper.

4.2 Production of open-charm final states

Within the model advocated in this work we are in a position to provide an order-of-magnitude estimate (neglecting the fine cusp structure that should also be present at the $\Lambda_c\bar{D}^*$ threshold) for the not yet measured reactions $\gamma p \to \Lambda_c\bar{D}^{(*)}$, see Fig. 5. As an illustration of the sensitivity to the form factor, we show the results for $\eta = 0.5$ and 1.

The cross sections of the $\gamma p \to \Lambda_c\bar{D}^{(*)}$ reactions were calculated in Ref. [30] considering exchanges of s-channel hidden-charm pentaquarks and t-channel D^* mesons using the VMD model. The corresponding predictions appear an order of magnitude smaller than those presented in Fig. 5, which provides an additional support for the importance of the open-charm mechanism suggested in this work.

4.3 J/ψ-nucleon scattering lengths

The suggested approach can be employed to evaluate the J/ψ-nucleon scattering lengths, replacing the photon by a J/ψ in Fig. 3. The results then appear to have the order of several units of mfm. In particular, varying the parameter η, which affects this observable most strongly, between $\eta = 0.5$ and $\eta = 2$, we find

$$\left|a^{J=1/2}\right| = 0.2\ldots3.1 \text{ mfm}, \quad \left|a^{J=3/2}\right| = 0.2\ldots3.0 \text{ mfm}, \tag{8}$$

where J corresponds to the total angular momentum of the J/ψ-nucleon system. These numbers are comparable with the recent estimation of the $J/\psi p$ scattering length from the GlueX data using the VMD model [53,54] but much smaller than the results of the two-gluon exchange calculation using the multipole expansion [55,56], for a summary of the results from other calculations we refer to Ref. [54]. The interactions between a nucleon and a quarkonium have also been studied on lattice, e.g., in Refs. [57–60]. In the most recent lattice QCD calculation of $J/\psi N$ scattering of Ref. [57], the lattice spectra in the one-channel approximation were found to be consistent with an almost non-interacting $J/\psi N$ system. As stressed in Ref. [57], the lattice results suggest that the existence of the P_c resonances within a one-channel $J/\psi N$ scattering is not favored in QCD and that the strong coupling between the NJ/ψ with other two-hadron channels might be responsible for the existence of the P_c resonances. This conclusion is in line with the current analysis.

5 Summary

In this paper, we provided evidence that the near-threshold J/ψ photoproduction could well be dominated by loops with open charm hadrons. We found that the existing experimental data on $\gamma p \to J/\psi p$ can be described within the suggested mechanism through the $\Lambda_c \bar{D}^{(*)}$ intermediate states if all the parameters of the model take their natural values. We identified a clear experimental signature for this picture: The process is necessarily accompanied by the appearance of two pronounced cusps located at the $\Lambda_c \bar{D}$ and the $\Lambda_c \bar{D}^*$ thresholds, and found the existing data consistent with this feature within their accuracy. Since the strength of the cusps is connected to the rate for $\gamma p \to \Lambda_c \bar{D}^{(*)}$, we also provided an estimate for the expected rate into the open-charm channels and extracted the J/ψ-nucleon scattering length. Although all predictions reported in this paper should be regarded as order-of-magnitude estimates, their agreement with the existing data on the J/ψ photoproduction off the proton is remarkable. Therefore, further experimental tests of these predictions are crucial to get a deeper understanding of the J/ψ photoproduction reaction. The ongoing measurements of the J/ψ photoproduction in Hall C at Jefferson Laboratory [26], which has higher statistics than GlueX, and measurements of the $\Lambda_c \bar{D}^{(*)}$ production will provide crucial information. The prediction of the tiny J/ψ-nucleon scattering lengths can be tested using lattice QCD.

It should be stressed that if the open-charm loops discussed above indeed dominate the J/ψ-nucleon scattering, as suggested in this paper, the connection between the trace anomaly and the J/ψ-nucleon scattering length is lost. This is similar to the observation that the ratio of the decays $\psi(2S) \to J/\psi(\pi^0/\eta)$ cannot be used for an extraction of the light quark mass ratio m_u/m_d if charmed meson loops contribute to the transitions significantly [61]. This observation is intimately related to the QCD multipole expansion, that does not seem work well in certain processes related to charmonium systems. A further test of this physics discussed here would be a lattice calculation of the J/ψ-nucleon scattering lengths, which could only be estimated in the approach used here.

Acknowledgements This work is supported in part by the Chinese Academy of Sciences (CAS) under Grants no. XDB34030303 and no. QYZDB-SSW-SYS013, by the National Natural Science Foundation of China (NSFC) under Grants no. 11835015, no. 11947302 and no. 11961141012, by the NSFC and the Deutsche Forschungsgemeinschaft (DFG) through the funds provided to the Sino-German Collaborative Research Center "Symmetries and the Emergence of Structure in QCD" (NSFC Grant no. 11621131001, DFG Grant no. CRC110), and by the CAS Center for Excellence in Particle Physics (CCEPP). U.-G.M. is also supported by CAS through the President's International Fellowship Initiative (PIFI) (Grant no. 2018DM0034) and by the VolkswagenStiftung (Grant no. 93562). Work of V.B. and A.N. was supported by the Russian Science Foundation (Grant no. 18-12-00226). Work of I.S. was supported in part by the US Department of Energy, Office of Science, Office of Nuclear Physics under Award no. DE-SC0016583.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: This is a theoretical study and no experimental data were generated.]

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