Photoproduction of the $f_2^* (1525)$ and $K_2^* (1430)$

Ju-Jun Xie,1,2,3 E. Oset,1,4 and Li-Sheng Geng5,3

1 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2 Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China
3 State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
4 Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC
Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain
5 School of Physics and Nuclear Energy Engineering and International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China

(Dated: October 3, 2015)

Assuming that the $f_2^* (1525)$ and $K_2^* (1430)$ resonances are dynamically generated states from the vector meson-vector meson interactions in S-wave with spin $S = 2$, we study the $\gamma p \rightarrow f_2^* (1525)p$ and $\gamma p \rightarrow K_2^* (1430)\Lambda(\Sigma)$ reactions. These reactions proceed in the following way: the incoming photon first mutates into a $\rho^0$, $\omega$, or $\phi$ meson via vector meson dominance, which then interacts with the $\rho^0$, $\omega$ or $K^*$ emitted by the incoming proton to form the tensor mesons $f_2^* (1525)$ and $K_2^* (1430)$. The picture is simple and has no free parameters, as all the parameters of the mechanism have been fixed in previous studies. We predict the differential and total cross sections of these reactions. The results can be tested in future experiments and therefore offer new clues about the nature of these tensor states.

PACS numbers: 13.60.Le, 13.75.Lb, 14.40.Cs

I. INTRODUCTION

Recent observations of the new baryonic $P_2^*$ states $^1$ and the mesonic $XYZ$ states $^2,^3$ by various collaborations have challenged the conventional wisdom that mesons are made of quark-antiquark pairs and baryons are composed of three (anti)quarks in the naive quark model. These findings have attracted a lot of attention from the theory side. Various explanations of these states have been proposed, such as molecules, multiquark compact objects, kinematic effects, or mixtures of components of different nature. Up to now none of them has been accepted unanimously. This is not surprising, given limited experimental constraints and the fact the various components of a hadron are not observables themselves. Furthermore, it is quite likely that a specific reaction or decay process can only review part of the nature of the hadrons under investigation. Clearly, the only way to understand the nature of a hadron is to examine it from all possible ways, both experimentally and theoretically.

Nevertheless, it seems clear that Nature is richer than it is preferred to be. In this respect, it is not surprising to find out that many low-lying states, even those long believed to be conventional $q\bar{q}$ (or $qqq$) states, may have large components of other nature. Indeed, it has been shown that many of the low-lying mesonic states can be understood not only as $q\bar{q}$ states but also as meson-meson molecules, dynamically generated in the so-called unitary approaches. One of such examples are the tensor states: $f_2 (1270)$, $f_2^* (1525)$, and $K_2^* (1430)$. They are found dynamically generated from the vector meson-vector meson interactions $^6,^8$, obtained in the coupled-channel Bethe-Salpeter equations by unitarizing the tree-level hidden gauge diagrams $^3,^4,^9$.

The molecular nature of these tensor states has been extensively tested in a large number of processes, for instance, the two-photon decay of the $f_2 (1270)$ $^{13}$: the two-photon and one photon-one vector decays of the $f_2 (1270)$, $f_2^* (1525)$ and $K_2^* (1430)$ $^{14}$: the $J/\psi \rightarrow \phi(\omega)f_2 (1270)$, $f_2^* (1525)$ and $J/\psi \rightarrow K^{*0}(892)K_2^* (1430)$ decays $^{15}$: the radiative decay of $J/\psi$ into $f_2 (1270)$ and $f_2^* (1525)$ $^{16}$: the $\psi(2S)$ decays into $\omega(\phi)f_2 (1270)$, $\omega(\phi)f_2^* (1525)$, $K^{*0}(892)K_2^* (1430)$ and the radiative decays of $\Upsilon(1S), \Upsilon(2S), \psi(2S)$ into $\gamma f_2 (1270)$, $\gamma f_2^* (1525)$, $\gamma f_0 (1370)$, and $\gamma f_0 (1710)$ $^{17,18}$: the ratio of the decay widths of $B^0 \rightarrow J/\psi f_2 (1270)$ to $B^0 \rightarrow J/\psi f_2^* (1525)$ $^{19}$.

The agreement with experimental data turns out to be quite good in general, providing support to the underlying assumption that these states contain large meson-meson components.

In a recent work $^{20}$, taking the molecular picture for the $f_2 (1270)$ resonance, the $\gamma p \rightarrow p f_2 (1270)$ reaction has been studied. It was found that the theoretical results of the differential cross sections are in agreement with the experimental data of Ref. $^{21}$, providing first support for the molecular picture of the $f_2 (1270)$ state in a baryonic reaction. In this work, we extend the formalism proposed in Ref. $^{20}$ to study the $\gamma p \rightarrow f_2^* (1525)p$ and $\gamma p \rightarrow K_2^* (1430)\Lambda(\Sigma)$ reactions. One should stress again that as the only way to unravel the nature of a hadron is via different reactions and decay processes, we deem such studies very timely and important.

The present article is organized as follows. In Sec. II, we...
we introduce the formalism and the main ingredients of the model. In Sec. [III] we present our main results, and a short summary and conclusions are given in Sec. [IV].

II. FORMALISM AND INGREDIENTS

A. Feynman amplitudes

From the perspective that the $f'_2(1525)$ and $K_2^*(1430)$ resonances are dynamically generated from the vector-vector ($VV$) interactions, the $f'_2(1525)$ and $K_2^*(1430)$ photoproductions proceed via the creation of two vector mesons by the $\gamma p$ initial state in a primary step and the following interaction (rescattering) of the two vector mesons, thus dynamically generating the resonance. This corresponding Feynman diagrams are shown in Fig. [1] for the $\gamma p \rightarrow f'_2(1525)p$ reaction and Fig. [2] for the $\gamma p \rightarrow K_2^*(1430)\Lambda(\Sigma)$ reaction.

\[
\begin{align*}
\gamma & \rightarrow p', \rho^0, \omega, \phi \\
& \rightarrow p, f'_2(1525) \\
p & \rightarrow p, q, p, p'
\end{align*}
\]

FIG. 1: Diagrammatic representation of the $f'_2(1525)$ photoproduction, where $k, p, p', q, p, p'$ are the four-momentum of the involved particles and $q = p' - p$.

\[
\begin{align*}
\gamma & \rightarrow k, \rho^0, \omega, \phi \\
& \rightarrow pK^*_2, f'_2(1525) \\
p & \rightarrow p, p', K^*_2, K^*(1430), K_2^{*0}(1430), K_2^{*-}(1430)
\end{align*}
\]

FIG. 2: Diagrammatic representation of the $\gamma p \rightarrow K_2^*(1430)\Lambda(\Sigma)$ reaction.

As can be seen from Figs. [1] and [2], the photon first gets converted into one vector meson, a characteristic of the local hidden gauge formalism, which then interacts with the other vector emitted by the proton. To evaluate the Feynman amplitudes, we need the coupling of the tensor meson to the respective vector mesons, $g_{TV}^V$, the $\gamma-V$ coupling, and the $VNN$ coupling. In the unitary approach, the amplitude close to a pole that represents a resonance can be written in the following way

\[
t_{\text{pole}} \simeq \frac{(g_{TV}^V)^2}{s - s_R} F_{\text{initial}}^2 P_{\text{final}}^2,
\]

where $s_R$ is the pole position and $g_{TV}^V$ the coupling of the resonance to the $VV$ component in isospin $I = 0(1/2)$ and spin $S = 2$. The Eq. (1) is the representation of a resonance amplitude, for instance the $f'_2(1525)$ and $K_2^*(1430)$ in the present case, as shown in Fig. [3](a). The $P_{\text{initial}}^2$ projects the initial and final $VV$ pair into spin two. Then the coupling of a tensor resonance to $VV$ is given by the diagram of Fig. [3](b), and is expressed in terms of the following vertex [13]

\[
t_{R \rightarrow VV} = g_{TV}^V P_{\text{initial}}^2,
\]

where the values for $g_{TV}^V$ are shown in Table [I] taken from Ref. [7].

\[
\begin{array}{|c|c|}
\hline
\text{Resonance Channel} & g_{TV}^V (\text{MeV}) \\
\hline
f'_2(1525) & \rho p \quad (-2443, 1509, 649) \\
\omega \omega & \quad (-2709, 18) \\
\phi \omega & \quad (5016, -i17) \\
K_2^*(1430) & \rho K^* \quad (10901, -i171) \\
\omega K^* & \quad (2267, -i13) \\
\phi K^* & \quad (2898, i17) \\
\hline
\end{array}
\]

The $\gamma-V$ conversion vertex can be obtained from the local hidden gauge Lagrangians [9–12] (see Ref. [22] for a practical set of rules) and one has [23]

\[
- \, i t_{\gamma V} = -i C_{\gamma V} \frac{e_M^2}{g} \epsilon_{\mu}(V) e^\mu(\gamma),
\]

where $C_{\gamma V}$ is the constant...
From this, one can easily obtain the weights \( W \) and normalization, which for polarons the coupling is multiplied by an extra factor to the resonances to the state in the good normalization and the couplings of the components of the \( K \) channel. In the case of two identical particles the coupling is multiplied by an extra factor of \( \sqrt{2} \) to restore the good normalization from the couplings calculated in Ref. [7] in the unitary approach as shown in Eqs. (14-20).

Gauge invariance imposes a stringent constraint on photoproduced processes, although sometimes not all of the terms needed to have gauge invariance are numerically relevant [21, 22]. Nevertheless, in the present case, a thorough study of gauge invariance was conducted in Ref. [22] for the radiative decay of axial vector mesons within the local hidden gauge approach, and in particular in Ref. [13] for the amplitude \( pp \to \rho \gamma \), which is similar to what we have here, with the two vector mesons interacting to produce the tensor states. There it is concluded that gauge invariance is encoded in the effective coupling of the tensor states to the two vector mesons.

Considering the weights given above, the \( T \) matrix for the diagram of Fig. 11 is given by

\[
-iT_{\gamma p \to f_2'(1525)p} = -ie(-
\begin{array}{c}
\frac{g_{pp}^\rho}{\sqrt{6}} + \frac{g_{pp}^\omega}{\sqrt{2}} + \frac{g_{pp}^{\phi \omega}}{2} \\
\frac{1}{2} \epsilon_1(\gamma_1) \epsilon_i(V) + \epsilon_1(\gamma_2) \epsilon_i(V) - \frac{1}{3} \epsilon_m(\gamma_1) \epsilon_m(V) \delta_{ij} \\
\frac{1}{q^2 - m_V^2} <p(M')|\gamma^\mu \epsilon_\mu(V)|p(M)>
\end{array}
\]

with \( M \) and \( M' \) the third spin component of the initial and final proton. The \( V \) stands for the exchanged \( \rho \) or \( \omega \). We take \( m_V = m_\rho = m_\omega = 780 \text{ MeV} \) in the present calculation. Next, we perform the sum over the polarizations of the vector meson exchanged in Fig. 1.
then we obtain

\[
T_{\gamma p \rightarrow f_2^0(1525)p} = e\left(-\frac{g_{f_2^0}^p}{\sqrt{6}} + \frac{g_{f_2^0\omega}^\phi}{\sqrt{2}} + \frac{g_{f_2^0\omega}^\omega}{\sqrt{2}} \right) \frac{1}{q^2 - m_{K^*}^2} \left[ \frac{1}{2} \epsilon_i(\gamma)(-g_{j\mu} + \frac{q_j q_{\mu}}{m_{K^*}^2}) + \frac{1}{2} \epsilon_j(\gamma)(-g_{i\mu} + \frac{q_i q_{\mu}}{m_{K^*}^2}) \right] - \frac{1}{3} \epsilon_m(\gamma) \delta_{ij}(-g_{m\mu} + \frac{q_m q_{\mu}}{m_{K^*}^2})] < p(M')|\gamma^\mu|p(M) >. \tag{22}
\]

Following the same procedure, we obtain the transition amplitudes for \(\gamma p \rightarrow K_2^+(1430)\Lambda(\Sigma)\):

\[
T_{\gamma p \rightarrow K_2^+(1430)\Lambda} = e\left(-\frac{g_{K_2^+}^p}{2} + \frac{g_{K_2^+\omega}^\phi}{\sqrt{6}} + \frac{g_{K_2^+\omega}^\omega}{3\sqrt{2}} \right) \frac{1}{q^2 - m_{K^*}^2} \left[ \frac{1}{2} \epsilon_i(\gamma)(-g_{j\mu} + \frac{q_j q_{\mu}}{m_{K^*}^2}) + \frac{1}{2} \epsilon_j(\gamma)(-g_{i\mu} + \frac{q_i q_{\mu}}{m_{K^*}^2}) \right] - \frac{1}{3} \epsilon_m(\gamma) \delta_{ij}(-g_{m\mu} + \frac{q_m q_{\mu}}{m_{K^*}^2})] \times < \Lambda(M')|\gamma^\mu|p(M) >. \tag{23}
\]

\[
T_{\gamma p \rightarrow K_2^+(1430)\Sigma^0} = e\left(-\frac{g_{K_2^+}^p}{2} + \frac{g_{K_2^+\omega}^\phi}{6} + \frac{g_{K_2^+\omega}^\omega}{3\sqrt{2}} \right) \frac{1}{q^2 - m_{K^*}^2} \left[ \frac{1}{2} \epsilon_i(\gamma)(-g_{j\mu} + \frac{q_j q_{\mu}}{m_{K^*}^2}) + \frac{1}{2} \epsilon_j(\gamma)(-g_{i\mu} + \frac{q_i q_{\mu}}{m_{K^*}^2}) \right] - \frac{1}{3} \epsilon_m(\gamma) \delta_{ij}(-g_{m\mu} + \frac{q_m q_{\mu}}{m_{K^*}^2})] \times < \Sigma(M')|\gamma^\mu|p(M) >. \tag{24}
\]

\[
T_{\gamma p \rightarrow K_2^+\Sigma^+(1430)} = e\left(-\frac{g_{K_2^+}^p}{\sqrt{6}} + \frac{g_{K_2^+\omega}^\phi}{3\sqrt{2}} + \frac{g_{K_2^+\omega}^\omega}{3} \right) \frac{1}{q^2 - m_{K^*}^2} \left[ \frac{1}{2} \epsilon_i(\gamma)(-g_{j\mu} + \frac{q_j q_{\mu}}{m_{K^*}^2}) + \frac{1}{2} \epsilon_j(\gamma)(-g_{i\mu} + \frac{q_i q_{\mu}}{m_{K^*}^2}) \right] - \frac{1}{3} \epsilon_m(\gamma) \delta_{ij}(-g_{m\mu} + \frac{q_m q_{\mu}}{m_{K^*}^2})] \times < \Sigma(M')|\gamma^\mu|p(M) >. \tag{25}
\]

where we take \(m_{K^*} = m_{K^{*+}} = m_{K^{*0}} = 893.1\) MeV.

In Eqs. 22-24, the latin indices run over 1, 2, 3 and the \(\mu\) index from 0, 1, 2, 3.

Then one can easily calculate \(\sum \sum |T|^2\). Here we give explicitly the case of the \(\gamma p \rightarrow f_2^0(1525)p\) reaction, as an example,

\[
\sum \sum |T|^2 = \frac{e^2}{96\pi m_p^2(q^2 - m_{f_2^0}^2)^2} - \frac{g_{f_2^0\omega}^\phi}{\sqrt{6}} - \frac{g_{f_2^0\omega}^\omega}{\sqrt{2}}
\]

\[
\sum \sum \sum \sum [\frac{1}{2} \epsilon_i(\gamma)(-g_{j\mu} + \frac{q_j q_{\mu}}{m_{K^*}^2}) + \frac{1}{2} \epsilon_j(\gamma)(-g_{i\mu} + \frac{q_i q_{\mu}}{m_{K^*}^2}) ] - \frac{1}{3} \epsilon_m(\gamma) \delta_{ij}(-g_{m\mu} + \frac{q_m q_{\mu}}{m_{K^*}^2})] \times < p(M')|\gamma^\mu|p(M) >. \tag{26}
\]

where all the indices and the two photon polarizations should be summed over, with the following expressions of the latter,

\[
e^{(1)}(\gamma) = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}; \quad e^{(2)}(\gamma) = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \tag{27}
\]

where we have assumed that the photon travels in the Z direction.

B. Differential cross section

The differential cross section for \(\gamma p \rightarrow f_2(1525)p\) and \(\gamma p \rightarrow K_2^+(1430)\Lambda(\Sigma)\) reactions are given by

\[
\frac{d\sigma}{dt} = \frac{m^2}{16\pi s|k|^2} \sum \sum |T|^2, \tag{28}
\]

with \(s\) the invariant mass squared of the \(\gamma p\) system, and \(m^2 = m_p^2\) for \(\gamma p \rightarrow f_2(1525)p\) reaction, \(m^2 = m_p m_\Lambda\) for \(\gamma p \rightarrow K_2^{*+}(1430)\Lambda\) reaction, and \(m^2 = m_p m_{\Sigma}\) for \(\gamma p \rightarrow K_2^+(1430)\Sigma\) reaction. The \(k\) is the three momenta of the initial photon in the center of mass frame (c.m.), and \(t = q^2 = (p - p')^2\).

The Eq. 28 can be generalized for the case when the \(f_2(1525)\) \((K_2^+(1430))\) is explicitly allowed to decay into \(KK\) \((K\pi)\) by working out the three body phase space and we find

\[
\frac{d^2\sigma}{dM_{inv}dt} = \frac{m^2}{8\pi^2 s|k|^2} \left| M_{inv}^2 - M_R^2 + i M_{inv} M_R \right|^2 \times \sum \sum |T|^2, \tag{29}
\]

where \(M_{inv}\) is the invariant mass distribution of the \(KK\) or \(K\pi\), \(\Gamma_R\) is the total decay width of the \(f_2^0(1525)\)

\[1\] We take \(m_{\Sigma^0} = m_{\Sigma^+} = 1191\) MeV and \(m_{K^{*+}} = m_{K^{*0}} = 1429\) MeV in this work.
or $K_2^*(1430)$ and $\Gamma_1$ is the partial decay width of the $f_2^0(1525) \to KK$ or $K_2^*(1430) \to K\pi$. In the present study, we choose the following decay modes: $f_2^0(1525) \to K^+K^-$, $K_2^{*+}(1430) \to K^0\pi^+$, and $K_2^{*0}(1430) \to K^+\pi^-$. The $f_2^0(1525) \to K^+K^-$ decay accounts for 1/2 of the $KK$ decay of the $f_2^0(1525)$ which is 89% of the $\Gamma_{f_2^0(1525)}$, while the $K_2^{*+}(1430) \to K^0\pi^+$ or $K_2^{*0}(1430) \to K^+\pi^-$ decay accounts for 2/3 of the $K\pi$ decay of the $K_2^*(1430)$ which is 50% of $\Gamma_{K_2^*(1430)}$. Since the $f_2^0(1525) \to KK$ and $K_2^*(1430) \to K\pi$ decays are in $D$-wave, in order to have $\Gamma_1$ and $\Gamma_\pi$ in the range of invariant masses that we consider, we take

$$\Gamma_{f_2^0 \to KK}(M_{inv}) = \Gamma_{f_2^0 \to KK}(\tilde{q}_{KK}) \frac{M_{f_2^0}^2}{M_{inv}^2}, \quad \text{(30)}$$

$$\Gamma_{f_2^0}(M_{inv}) = 0.89\Gamma_{f_2^0}(\tilde{q}_{KK}) \frac{M_{f_2^0}^2}{M_{inv}^2} + 0.11\Gamma_{f_2^0}(\tilde{q}_{KK})^5, \quad \text{(31)}$$

with $\Gamma_{f_2^0} = 73$ MeV, $\Gamma_{f_2^0} = 32.5$ MeV, $M_{f_2^0} = 1525$ MeV [26], and

$$\tilde{q}_{KK} = \lambda^{1/2}(M_{inv}^2, m_K^2, m_K^2), \quad \text{(32)}$$

$$\tilde{q}_{KK} = \lambda^{1/2}(M_{f_2^0}^2, m_K^2, m_K^2), \quad \text{(33)}$$

where $\lambda$ is the Kållen function with $\lambda(x, y, z) = (x - y - z)^2 - 4xyz$.

Similarly, for the $K_2^*$ decay modes, we take

$$\Gamma_{K_2^* \to K\pi}(M_{inv}) = \Gamma_{K_2^* \to K\pi}(\tilde{q}_{K\pi}) \frac{M_{K_2^*}^2}{M_{inv}^2}, \quad \text{(34)}$$

$$\Gamma_{K_2^*}(M_{inv}) = 0.5\Gamma_{K_2^*}(\tilde{q}_{KK}) \frac{M_{K_2^*}^2}{M_{inv}^2} + 0.5\Gamma_{K_2^*}, \quad \text{(35)}$$

with $\Gamma_{K_2^*} = 104$ MeV, $\Gamma_{K_2^*} = 34.7$ MeV [26], and

$$\tilde{q}_{K\pi} = \lambda^{1/2}(M_{inv}^2, m_{K\pi}^2, m_{K\pi}^2), \quad \text{(36)}$$

$$\tilde{q}_{K\pi} = \lambda^{1/2}(M_{K_2^*}^2, m_{K\pi}^2, m_{K\pi}^2). \quad \text{(37)}$$

### III. NUMERICAL RESULTS

In Ref. [26] three models were considered, one is the one we exposed here, and the other two contained an additional tensor $\rho\nu\nu$ coupling and Regge propagators. The results obtained there were very similar and in this exploratory work we perform calculations only with one of the models as specified above.

In Fig. 4 we show $d^2\sigma/dM_{inv}dt$ for the $\gamma p \to pK^+K^-$ reaction at $E_\gamma = 3.4$ GeV and $t = -1.2$ GeV$^2$.

![Fig. 4](image)

In Fig. 5 we show $d^2\sigma/dM_{inv}dt$ for the $\gamma p \to \Lambda(1430)K\pi$ reaction at $E_\gamma = 3.4$ GeV and $t = -1.2$ GeV$^2$.

![Fig. 5](image)

Fig. 6 shows $d\sigma/dt$ at $E_\gamma = 3.4$ GeV for the four reaction modes studied. We see that the slopes for the four reactions are quite similar.
In recent years, it has been found that the $f_2^*(1525)$ and $K_2^*(1430)$ resonances, though long been accepted as ordinary $q\bar{q}$ states, can be dynamically generated from the vector meson-vector meson interaction, and therefore qualify as vector-vector molecules. Many studies adopting such a scenario have been performed in mesonic reactions and all yield positive results. In the present work, we have proposed to test the molecular picture in the photonuclear reaction. The elements needed for the test are very simple, which makes particularly transparent the interpretation of the results. On one side the $f_2^*(1525)$ and $K_2^*(1430)$ couple to $VV$ in $I = 0$ and $I = 1/2$, respectively, and the couplings have been fixed before in the unitary approach that generates the $f_2^*(1525)$ and $K_2^*(1430)$ as a $VV$ molecule based on the local hidden gauge formalism for the interaction of vector mesons. On the other side, with these couplings and the vector meson dominance hypothesis, incorporated in the local hidden gauge approach, the photon gets converted into one of the vector mesons, which interact with the vector meson emitted by the incoming proton to generate the $f_2^*(1525)$ and $K_2^*(1430)$ resonances. With this simple picture we predict both the differential and total cross sections, which could be tested by future experiments, such as those at CLAS.

IV. CONCLUSIONS

We stress again that the reaction formalism advocated here involves no free parameters, which allow us to make predictions for total cross sections. The differential and total cross sections can be checked in future experiments, such as those at CLAS. In this sense, the reaction mechanism can be easily tested.

Acknowledgments

One of us, E. O., wishes to acknowledge support from the Chinese Academy of Science (CAS) in the Program of Visiting Professorship for Senior International Scientists (Grant No. 2013T2J0012). L.S.G. thanks the Institute for Nuclear Theory at University of Washington for its hospitality and the Department of Energy for partial support during the completion of this work. This work is partly supported by the Spanish Ministerio de Economia y Competitividad and European FEDER funds under the contract number FIS2011-28853-C02-01 and FIS2011-28853-C02-02, and the Generalitat Valenciana in the program Prometeo II-2014/068. We acknowledge the support of the European Community-Research Infrastructure Integrating Activity Study of Strongly Interacting Matter (acronym HadronPhysics3, Grant Agreement n. 283286) under the Seventh Framework Programme of EU. This work is also partly supported by the National Natural Science Foundation of China under Grant Nos. 11475227, 1375024, and 11522539. This work is also supported by the Open Project Program of State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, China (No.Y5KF151CJ1).
[1] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001 (2015).
[2] S. L. Olsen, Front. Phys. China. 10, 121 (2015).
[3] X. Liu, Chin. Sci. Bull. 59, 3815 (2014).
[4] G. T. Bodwin, E. Braaten, E. Eichten, S. L. Olsen, T. K. Pedlar and J. Russ, arXiv:1307.7425.
[5] N. Brambilla et al., Eur. Phys. J. C 71, 1534 (2011).
[6] R. Molina, D. Nicmorus and E. Oset, Phys. Rev. D 78, 114018 (2008).
[7] L. S. Geng and E. Oset, Phys. Rev. D 79, 074009 (2009).
[8] L. S. Geng, E. Oset, R. Molina and D. Nicmorus, PoS EFT 09, 040 (2009).
[9] M. Bando, T. Kugo, S. Uehara, K. Yamawaki and T. Yanagida, Phys. Rev. Lett. 54, 1215 (1985).
[10] M. Bando, T. Kugo and K. Yamawaki, Phys. Rept. 164, 217 (1988).
[11] M. Harada and K. Yamawaki, Phys. Rept. 381, 1 (2003).
[12] U. G. Meissner, Phys. Rept. 161, 213 (1988).
[13] H. Nagahiro, J. Yamagata-Sekihara, E. Oset, S. Hirenzaki and R. Molina, Phys. Rev. D 79, 114023 (2009).
[14] T. Branz, L. S. Geng and E. Oset, Phys. Rev. D 81, 054037 (2010).
[15] A. Martinez Torres, L. S. Geng, L. R. Dai, B. X. Sun, E. Oset and B. S. Zou, Phys. Lett. B 680, 310 (2009).
[16] L. S. Geng, F. K. Guo, C. Hanhart, R. Molina, E. Oset and B. S. Zou, Eur. Phys. J. A 44, 305 (2010).
[17] L. Dai and E. Oset, Eur. Phys. J. A 49, 130 (2013).
[18] L. R. Dai, J. J. Xie and E. Oset, Phys. Rev. D 91, no. 9, 094013 (2015).
[19] J. J. Xie and E. Oset, Phys. Rev. D 90, 094006 (2014).
[20] J. J. Xie and E. Oset, Eur. Phys. J. A 51, no. 9, 111 (2015).
[21] M. Battaglieri et al. [CLAS Collaboration], Phys. Rev. D 80, 072005 (2009).
[22] H. Nagahiro, L. Roca, A. Hosaka and E. Oset, Phys. Rev. D 79, 014015 (2009).
[23] A. Ramos and E. Oset, Phys. Lett. B 727, 287 (2013).
[24] B. Borasoy, P. C. Bruns, U.-G. Meissner and R. Nissler, Phys. Rev. C 72, 065201 (2005).
[25] M. Doring, E. Oset and D. Strottman, Phys. Rev. C 73, 045209 (2006).
[26] K. A. Olive et al. [Particle Data Group Collaboration], Chin. Phys. C 38, 090001 (2014).