The $\psi^{(c)}p$ scattering length based on near-threshold charmoniums photoproduction

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(Dated: July 20, 2022)

Under the framework of Vector Meson Dominance model, the value of scattering length can be expressed as a function of the ratio between total cross section $\sigma(W)$ and $R(W)$, where $R(W)$ is the ratio between final momentum $|p_f|$ and initial momentum $|p_i|$ and positively correlated with the center-of-mass energy. Based on the theoretical study of charmoniums photoproduction within two gluon exchange model and effective pomeron model, we research the scattering lengths of vector mesons and proton interaction in this work. Results show that the scattering length $|a_{\psi J^p}|$ obtained from the two models are close and basically in agreement with the theoretical prediction of Strakovsky and co-workers. Additionally, we first calculate the scattering length of $\psi(2S)$-proton interaction in two gluon exchange model and effective pomeron model as $1.31\pm0.92$ am (1 am = $10^{-3}$ fm) and 3.24 $\pm$ 0.63 am, respectively. This is a little bit different from the two models and requires precise measurements from subsequent experiments. In short, our results will provide a theoretical reference for future studies on characterizing the vector meson-proton scattering length.

I. INTRODUCTION

The evaluation of the scattering lengths may serve as a unique input for QCD-motivated models of vector meson-nucleon interactions [1–4]. The behavior of the near-threshold cross section is related to vector meson-proton ($Vp$) scattering length [5]. Recently, scattering lengths for $\omega p, \phi p, J/\psi p$ and $Y p$ reactions have been reported using the recent photoproduction experiment data or quasi data [1–4]. However, there are also several $Vp$ scattering lengths that have not been studied for various reasons, such as one narrow vector meson: $D_0^+(2007)$, since no charm conservation, the reaction $\gamma p \rightarrow D_0^+(2007)p$ is impossible. Moreover, we find that there are no good threshold measurements for $\rho, K^*$ and $D^*$ meson photoproduction. As the excited states of $J/\psi$, it is of great interest to estimate the scattering length of vector meson $\psi(2S)$-proton interaction.

On the experimental side, the $J/\psi$ photoproduction off the proton was conducted with increasing precision over a large energy range [6–13], while the measurement of $\psi(2S)$ photoproduction data is very meager [14–16]. Considering $\psi(2S)$ and $J/\psi$ have close mass, both have $c\bar{c}$ structure, the same quantum numbers, spin and parity as photon which is $J^P(C) = 0^+(1^-)$, it is reasonable to study them with the same physical models and parameters. In our previous works [17], two gluon exchange model is applied to systematically analyze the $J/\psi$ and $\psi(2S)$ photoproduction data from threshold to medium energy (near 400 GeV) [6–13]. In the literatures [18, 19], the pomeron exchange process is considered to explain the photoproduction of charmoniums by JPAC collaboration. The numerical results from two gluon exchange model and effective pomeron model are both in agreement with $J/\psi$ experimental data, while the predicted photoproduction of $\psi(2S)$ in the two models at the threshold is basically consistent [17]. In this paper, we will use the predicted $\psi(2S)$ cross section data under the framework of the two models to extract the scattering lengths $|a_{\psi J^p}|$.

Many literatures give their scattering length results for proton interacts with vector meson by different methods. From a global fit to both differential and total cross section data, one work [20] extracted the scattering length $|a_{\psi J^p}|$ is 0.046 fm from $d\sigma/dt(s_{\text{thr}}, t=0)$. Ref. [21] discussed the charmoniums bound states in nuclei from the method of multipole expansion and low-energy QCD theorems. Provided in the Vector Meson Dominance (VMD) model [22, 23], the pomeron exchange process is considered to contribute to the photoproduction of charmoniums. Strakovsky and co-workers estimated the $J/\psi$-nucleon scattering length $|a_{J/\psi p}| = 3.08$ am (1 am = $10^{-3}$ fm) by fitting the recent GlueX total cross section data [4]. To avoid additional uncertainty when extrapolating the differential cross section to the nonphysical point $t=0$, the approach of ref. [20] is not adopted. Compared to other methods, the VMD model does not contain free parameters in the process from $\gamma p$ to $Vp$ reaction. It is superior for us to obtain qualitative estimates when extracting scattering lengths $|a_{Vp}|$. The scattering length $|a_{J/\psi p}|$ obtained by VMD model is smaller than other references. And this small value can be attributed to the size of the “Young” vector meson is smaller than that of the “old” one participating in the elastic $Vp \rightarrow Vp$ scattering, because $c\bar{c}$ pair lacks sufficient time to form the complete wave function of the vector meson [3].

The measurement of near-threshold $\psi(2S)$ photoproduction will give access to a variety of interesting physics aspects, e.g., trace anomaly, pentaquarks, cusp effects, vector-meson-nucleon scattering length and so on [22, 24]. Nowadays, the Electron Ion Colliders (EIC) are proposed to be built for probing the deepest structure inside the hadron [25]. Meanwhile, the opportunities for Chinese EIC are now under discussion and will be an important and interesting future machine to collect $\psi^{(c)}$ data [26]. Relevant measurements will advance our understanding of QCD which governs the properties of...
hadrons and the interactions involving hadrons.

The paper is organized as follows. The formulas of effective pomeron model, two gluon exchange model and an expression for scattering length \( r_0/p \) are provided in Sec.II. Next section, we show the numerical result on the explanations of the current experimental data of \( J/\psi \). Through the study of scattering length \( r_0(2S)/p \), the reliability of the two models and VMD method are determined. Then the results and discussion of \( r_0(2S)/p \) are obtained in Sec. III. A summary is given in Sec. IV.

II. FORMALISM

In quark-interchange mechanisms, some light quarks (such as \( \pi, \rho, \Delta \), etc.) are strongly suppressed in the heavy quarkonium photoproduction. So the channels are always dominated by two gluon exchange or pomeron exchange contributions. Actually, the two gluon exchange and pomeron contributions both reproduce well the existing data [27].

A. effective pomeron model

\[
\begin{array}{c}
\gamma VMD \rightarrow \psi^{(*)}
\end{array}
\]

FIG. 1. The schematic Feynman diagram of the effective pomeron model for \( J/\psi \) or \( \psi(2S) \) production.

The effective \( t \)-channel pomeron exchange contribution is shown in Fig. 1. Proposed by JPAC collaboration, an effective pomeron exchange model is used to have a systematical analysis for \( J/\psi \) and \( \psi(2S) \) photoproduction [18]. The differential cross section for \( \gamma p \rightarrow \psi^{(*)} p \) reaction takes the form [19]

\[
\frac{d\sigma}{dt} = \frac{4\pi\alpha}{64\pi W^2 p^2} \sum_{\lambda_f,\lambda_p,\lambda_{\psi^{(*)}},\lambda_p'} \left| \left\langle \lambda_{\psi^{(*)}},\lambda_p' | T | \lambda_f,\lambda_p \right\rangle \right|^2.
\]  

The amplitude in low energy regions is given by [19, 28]

\[
\left\langle \lambda_{\psi^{(*)}},\lambda_p' | T | \lambda_f,\lambda_p \right\rangle = F(W^2, t)\delta^t(p_f,\lambda_p)\gamma_{\mu\nu} (p_i,\lambda_p) \times e^\mu(p_f,\lambda_p) e^\nu(p_i,\lambda_p) \alpha^\nu - e^\mu(p_f,\lambda_p') e^\nu(p_i,\lambda_{\psi^{(*)}}) \alpha^\nu
\]

Here,

\[
F(W^2, t) = \frac{i\alpha_{\psi^{(*)}}}{W^2 - W^2_{th}} a(t - t_{min}) \frac{e_t(W^2 - t_{min})}{W^2}.
\]

\( \alpha(t) = \alpha_0 + \alpha' t \) is the pomeron trajectory [29]. \( W_0 = 1 \) GeV is the energy scale parameter. \( W_{th} = M_p + M_{\psi^{(*)}} \) is the energy threshold.

B. two gluon exchange model

\[
\begin{array}{c}
\gamma VMD \rightarrow \psi^{(*)}
\end{array}
\]

\[
\begin{array}{c}
\gamma VMD \rightarrow \psi^{(*)}
\end{array}
\]

FIG. 2. The schematic Feynman diagrams of the two gluon exchange model for \( J/\psi \) or \( \psi(2S) \) production.

The picture of the double gluon exchange between the nucleon state and the quark-antiquark pair is illustrated in Fig. 2. The differential cross section of \( \psi^{(*)} \) photoproduction is given as [30, 31]

\[
\frac{d\sigma}{dt} = \frac{\pi^2 \Gamma_{\psi^{(*)} \rightarrow \gamma^* M}}{6\alpha m_q^5} \left[ xg(x, m_{\psi^{(*)}}^2) \right]^2 \exp(b^\psi \cdot t),
\]

where \( x = m_{\psi^{(*)}}^2/W^2; \alpha_s = 0.5 \) is the strong coupling constant [32]; \( \alpha \) is the fine-structure constant; \( m_q \) is the mass of charm quark; \( \Gamma_{\psi^{(*)} \rightarrow \gamma^* M} \) is the radiative decay [33]. \( xg(x, m_{\psi^{(*)}}^2) \) defines the gluon distribution function at \( Q^2 = m_{\psi^{(*)}}^2 \), which is parameterized using a simple function form \( xg(x, m_{\psi^{(*)}}^2) = A_0 x^{c_1}(1 - x)^{c_2} \) [34]. The exponential slope parameter \( b^\psi \) can use the standard form based on the Regge phenomenology [16, 35] for \( \psi(2S) \) and similar form [30] for \( J/\psi \).

The total cross section is obtained by integrating the differential cross section (Eq. (1) or (4)) over the allowed kinematical range from \( t_{min} \) to \( t_{max} \), the total cross section can be written as,

\[
\sigma = \int_{t_{max}}^{t_{min}} dt \frac{d\sigma}{dt}.
\]

Here, the limiting values \( t_{min} \) and \( t_{max} \) are

\[
t_{max}(t_{min}) = m_1^2 + m_2^2 - 2E_1 E_3 \pm 2|p_1||p_3|.
\]

The energies and momenta of the photon and meson in the center-of-mass (c.m.) frame are

\[
|p_1| = \frac{1}{2W} \sqrt{W^4 - 2(m_1^2 + m_2^2)W^2 + (m_1^2 - m_2^2)^2};
\]

\[
|p_3| = \frac{1}{2W} \sqrt{W^4 - 2(m_1^2 + m_2^2)W^2 + (m_2^2 - m_3^2)^2};
\]

\[
E_1 = \sqrt{|p_1|^2 + m_1^2}, \quad E_3 = \sqrt{|p_3|^2 + m_3^2}.
\]
C. VMD model and scattering length $|\alpha_{Vp}|$

The ratio between the initial c.m. momentum and the final momentum $R(W)$ is used as

$$R(W) = \frac{||p||}{|p|}.$$  \hspace{1cm} (10)

Note that, $R(W)$ has a range of $R(W) \in [0, 1)$ and is positively correlated with the c.m. energy. $R(W) \rightarrow 0$ respects $W \rightarrow W_{\text{thr}}$ while $R(W) \rightarrow 1$ respects $W \rightarrow \infty$. The ratio of total cross section $\sigma(R)$ and $R$ is given by

$$\sigma(R)/R = a_1(R),$$  \hspace{1cm} (11)

where the function $a_1(R)$ can be described by Eq. (1), (4) and (5).

The $Vp$ scattering length is related to the near-threshold photoproduction of vector mesons. In this paper, the VMD model is used to connect the reaction $\gamma p \rightarrow Vp$ and $Vp \rightarrow Vp$. Applying the effective VMD approach, the near-threshold cross section during the elastic scattering processes becomes [22]

$$\sigma|_{th} = \frac{\pi a^2}{g_V^2} \left( \frac{d\sigma(Vp \rightarrow Vp)}{d\Omega} \right)|_{th},$$  \hspace{1cm} (12)

where the VMD coupling constant $g_V$ is deduced from the leptonic decay width $\Gamma_{\epsilon' \epsilon}$ as [4]

$$g_V = \sqrt{\frac{\pi a^2 M_V}{3f_V^2 \epsilon' \epsilon}}.$$  \hspace{1cm} (13)

Combining Eq. (11), (12) and (13), scattering length $|\alpha_{Vp}|$ is given as

$$|\alpha_{Vp}| = \frac{g_V}{2\pi} \sqrt{\frac{a_1(R)}{\alpha}}.$$  \hspace{1cm} (14)

The scattering length $|\alpha_{Vp}|$ can also be expressed by differential photoproduction cross section. When the c.m. energy $W$ approaches the threshold, the total cross section is related to the differential cross section as [36]

$$\sigma|_{th} = \left|\frac{d\sigma}{dt}\right|_{th} = 4|p||p| \left|\frac{d\sigma}{dt}\right|_{th}.$$  \hspace{1cm} (15)

Combining Eq. (12) and (15), we can obtain the relation between the differential cross section of $\gamma p \rightarrow Vp$ reaction and scattering length as

$$\left|\frac{d\sigma}{dt}\right|_{th} = \frac{\pi a^2}{g_V^2 |p|^2} \cdot |\alpha_{Vp}|^2.$$  \hspace{1cm} (16)

If setting $\left|\frac{d\sigma}{dt}\right|_{th} = b_1$, the scattering length $|\alpha_{Vp}|$ is given as

$$|\alpha_{Vp}| = \frac{g_V |p|}{\pi} \sqrt{\frac{b_1}{\alpha}}.$$  \hspace{1cm} (17)

Note that, $b_1$ and $|p|$ must satisfy the conditions that obtained from the threshold.

### III. RESULTS AND DISCUSSIONS

In our previous work, the free parameters $A_0, A_1$ and $A_2$ in two gluon exchange model were obtained by a global analysis of both the total cross section data below medium energy [6–13] and the near-threshold ($W = 4.58$ GeV) differential cross section data of $J/\psi$ [6]. JPAC collaboration determined the free parameters $A_{J/\psi}$, $a_0$, $a'$ and $\alpha_0$ by fitting the total cross section of $J/\psi$ experimental data [6, 9]. The fitted parameters from the two models are listed in Tab. 1 and II. The numerical results of $\gamma p \rightarrow J/\psi p$ from two gluon exchange model and effective pomeran model are shown in Fig. 3 and 4, compared with GlueX, SLAC and HERMES experiments [6, 9, 37]. We perceive that the two models are reliable to explain $J/\psi p$ photoproduction.

According to the obtained total cross section from models, Eq. (11) and (14), the $J/\psi p$ scattering length as a function of $R$ is shown in Fig. 5 (blue-solid curve). Listed in Table III, the...
average value of scattering length $|\alpha_{J/\psi}|$ is $3.85 \pm 0.96$ am from two gluon exchange model and $3.75 \pm 0.84$ am from effective pomeron model. Here the range of $R$ is selected as $[0, 0.5]$. Note that $R = 0.5$ corresponds to c.m. energy $W = 4.79$ GeV, which represents a near-threshold energy. We also compared our results with the phenomenological result [36] and odd-polynomial fitted result [4]. Our results are in agreement with the above phenomenological results.

We also extract the scattering lengths from the total cross section GlueX data, as shown in the black circles in Fig. 5. Ref. [36] obtained $|\alpha_{J/\psi}| = 3.83 \pm 0.98$ am (the green circle in Fig. 5) derived from the differential cross section GlueX data. Although this energy ($W = 4.59$ GeV) is a little far from the threshold, the value of scattering length is close to our estimation from two models and other works [4, 36]. Therefore, the scattering lengths extracted from the differential cross section experimental data may be more advantageous, compared with the instability extracted from total cross section data.

In the above study, we found that the scattering lengths $|\alpha_{J/\psi}|$ given by the two models are approximate and consistent with other literatures [4, 36]. The reliability of the two models and VMD method was determined. Next, we will extend the study to $\psi(2S) p$ scattering length based on the above study. The photoproduction of $\psi(2S)$ is obtained by using the same parameters listed in Tab. I and II. Note that, the parameter $A_{\psi(2S)}$ in Eq. (3) can be written as $A_{\psi(2S)} = R_{\psi(2S)} A_{J/\psi}$, and the relative strength $R_{\psi(2S)} = 0.55$ is obtained from the extraction by CLEO [18, 38]. Then the $\psi(2S) p$ scattering length as a function of $R$ is shown in Fig. 6 (Red-dashed curve). We obtained calculation results from two gluon exchange model and effective pomeron model to be $1.31 \pm 0.92$ am and $3.24 \pm 0.63$ am, respectively (table IV). Note that, the value of $|\alpha_{J/\psi}|$ is bigger than $|\alpha_{\psi(2S)}|$ in both models. Because of the difference in the size of the total cross section predicted by the two models, the $|\alpha_{\psi(2S)}|$ scattering length is a little bit different. Precise results require more measurement from sub-

**TABLE III.** Comparison of different determinations of $|\alpha_{J/\psi}|$ from different method.

| method                        | $|\alpha_{J/\psi}|$ (am) |
|-------------------------------|-------------------------|
| odd-polynomial fit [4]        | 3.08 ± 0.55             |
| phenomenological result [36] | 3.64 ± 0.26             |
| two gluon exchange model      | 3.85 ± 0.96             |
| (this work)                   |                         |
| effective pomeron model       | 3.75 ± 0.84             |

FIG. 4. The differential cross section of $\gamma p \rightarrow J/\psi p$ as a function of $-t$. The curves have the same meaning as in Fig. 3. Data are from Ref. [6].

FIG. 5. The obtained scattering length $|\alpha_{J/\psi}|$ as a function of $R$. The black circles show the results derived from the GlueX total cross section data. The green circle shows the results derived from the GlueX differential cross section data [36]. The curves have the same meaning as in Fig. 3.

FIG. 6. The obtained scattering length $|\alpha_{\psi(2S)}|$ as a function of $R$. The curves have the same meaning as in Fig. 3.
and Fig. as a function of the length is studied using quasi data generated from the QCD hypothetical \[9.4603 (0 \pm 0.03) (\text{GeV})\]. What is more, the absolute value of the \(\alpha\) scattering length (MAMI) \[9.4603 \pm 0.03\]. Based on the recent threshold measurements of the photoproduction of \(\omega\) and \(\phi\) mesons off the proton by the A2 (MAMI) [1] and CLAS (JLab) [39], one can determine vector meson proton scattering lengths \(|\alpha_{Vp}|\) using the VMD model [1, 2]. What is more, the absolute value of the \(\Upsilon\) scattering length is studied using quasi data generated from the QCD model [3, 40]. The corresponding results for the scattering lengths are shown in Table V and Fig. 7 as a function of the inverse vector meson mass. Concretely, the relationship including \(\omega, \phi, J/\psi, \psi(2S)\), and \(\Upsilon\) can be determined as \[|\alpha_{\Upsilon p}| < |\alpha_{\phi(2S)p}| < |\alpha_{J/\psi p}| < |\alpha_{\phi p}| < |\alpha_{\omega p}|\]. Actually, the binding energy \(E_b\) in nuclear matter can be determined by scattering length \(|\alpha_{Vp}|\). In a linear density approximation, the binding energy \(E_b\) can be written as \[E_b = \frac{2\pi (M_N + M_{\phi(2S)}) \alpha_{\phi(2S)p}}{M_N M_{\phi(2S)}} \rho_{\text{nm}},\]

in which the nuclear matter density \(\rho_{\text{nm}} = 0.17 \text{ fm}^{-3}\). Usually, we define the initial stage of meson formation as “young” stage of meson, and there is also a binding energy between meson and nucleon. The \(\psi(2S)\) binding energy in nuclear matter is calculated as \(0.073 \text{ MeV}\). Therefore, the smallness of the binding energy may be related to the “Young” age of the vector mesons participating in the interaction with the proton. As a primitive meson, its properties show some differences. The weak combination between \(\psi(2S)\) and proton can promote the reaction of \(\psi(2S) p \rightarrow \psi(2S) p\). Moreover, if it is assumed that the interaction between vector meson and nucleon needs more time to reach equilibrium specifically for slow heavy quarkoniums \(J/\psi, \psi(2S)\), and \(\Upsilon\), this means that the “Young” vector meson effect is more pronounced for heavy quarkoniums. For light vector mesons (such as \(\omega, \phi\), etc.), this “Young” vector meson effect may be relatively weak.

IV. SUMMARY

In this paper, the value of the scattering length is expressed as a function of the ratio between \(\sigma(W)\) and \(R(W)\) within the VMD model. This description can avoid delivering unnecessary inaccuracy in numerical calculation. It is not only suitable for extracting the scattering length from the experimental data directly, but also convenient for observing the near-threshold overall situation for theoretical model. In this paper, we research the \(J/\psi\) and \(\phi(2S)\) scattering lengths according to the theoretical study of charmoniums photoproduction within two gluon exchange model and effective pomeran model. The scattering lengths \(|\alpha_{J/\psi p}|\) and \(|\alpha_{\phi(2S)p}|\) are basically consistent with several other theoretical predictions. Moreover, the scattering length of \(\psi(2S)\) – proton interaction extracted from two gluon exchange model is \(1.31 \pm 0.92 \text{ am}\). Additionally, \(|\alpha_{\phi(2S)p}| = 3.24 \pm 0.63 \text{ am}\) extracted from effective pomeran model. The value of \(|\alpha_{J/\psi p}|\) is bigger than \(|\alpha_{\phi(2S)p}|\) in both models. And these results satisfy the nonlinear exponential increase \(|\alpha_{Vp}| \propto \exp(1/m_v)\) basically. According to the present results, it can be roughly concluded that one of the main factors affecting the scattering length \(|\alpha_{Vp}|\) is the size of the corresponding cross section of vector meson photoproduction. For example, the cross section of the \(\phi\) meson photoproduction is more than two orders of magnitude higher than the cross section of \(J/\psi\) photoproduction, and correspondingly, the scattering length \(|\alpha_{\phi p}|\) is nearly twenty times higher than the \(|\alpha_{J/\psi p}|\). In addition, the cross section at the threshold is generally more complicated, and the results given

### Table V. The values of scattering length \(|\alpha_{Vp}|\) from \(\omega, \phi\), and \(\Upsilon\) meson.

| vector meson | \(m_V\) (GeV) | \(|\alpha_{Vp}|\) (fm) |
|--------------|-------------|------------------|
| \(\omega\)   | 0.87265     | 0.82 \pm 0.03 [1]|
| \(\phi\)     | 1.01946     | 0.063 \pm 0.010 [2]|
| \(\Upsilon\) | 9.4603      | (0.51 \pm 0.03) \times 10^{-3} [3]|

![Fig. 7. Comparison of the scattering lengths \(|\alpha_{Vp}|\) as a function of the inverse mass of vector mesons, including \(\omega, \phi, J/\psi, \phi(2S)\), and \(\Upsilon\). The magenta-circles show the analysis from two gluon exchange model, black-squares from effective pomeran model. The red-solid line is hypothetical [3].](image)
by the two models also show differences. However, due to the lack of experimental data, especially the experimental data of $\psi(2S)$ photoproduction, the scattering length of $\psi(2S)$-proton cannot be determined very accurately. Therefore, to better determine the scattering lengths of vector mesons and proton interaction, more high-precision experimental measurements for the photo/electro-production of charmoniums are highly needed, which can not only be realized in the JLab experiment [6], but also within the capabilities of EicC and US-EIC facility [25, 26].

V. ACKNOWLEDGMENTS

X.-Y. Wang would like to acknowledge Dr. Daniel Winney for useful discussion about the effective pomeron model. This project is supported by the National Natural Science Foundation of China (Grant Nos. 12065014 and 12047501), and by the West Light Foundation of The Chinese Academy of Sciences, Grant No. 21JR7RA201. IIS was supported in part by the US Department of Energy, Office of Science, Office of Nuclear Physics, under Award No. DE-SC0016583.

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