

JLab and J-PARC measurements for J/ψ production at threshold

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(Received 12 March 2026; accepted 19 May 2026; published 12 June 2026)

New threshold measurements for $\gamma p \rightarrow pJ/\psi \rightarrow p(\mu^+\mu^-)$ by 007 and $\gamma^* p \rightarrow pJ/\psi \rightarrow p(e^+e^-)$ by CLAS12 allow us to extend the previous phenomenological determination of the J/ψ -proton scattering length, $\alpha_{J/\psi p}$, using GlueX threshold data for $\gamma p \rightarrow pJ/\psi \rightarrow p(e^+e^-)$. The agreement between all three J/ψ datasets shows no indication of systematic differences between methodologies. Furthermore, perturbative QCD predictions support the phenomenological determination of heavy vector meson-nucleon scattering lengths. The role of the nucleon form factor, F_N , is discussed, and a possible correction to the phenomenological scattering length for heavy vector meson photoproduction is calculated using the pole form of F_N . Upcoming J-PARC threshold measurements of the reaction $\pi^- p \rightarrow nJ/\psi \rightarrow n(l^+l^-)$ will help to evaluate the possible role of heavy pentaquark, P_c , states in low-energy J/ψ production and the effects caused by the nucleon form factors.

DOI: [10.1103/3g18-qv5t](https://doi.org/10.1103/3g18-qv5t)

I. INTRODUCTION

There are no vector meson beams, so modern experiments using electromagnetic (EM) facilities attempt to access vector meson (V)-nucleon (N) interactions via EM production reactions, such as $ep \rightarrow e'Vp$ or $\gamma p \rightarrow Vp$. The J/ψ is a member of the vector meson family and has the same spin (J), parity (P), and charge conjugation (C) quantum numbers as the photon: $J^{PC} = 1^{--}$. One may therefore apply Sakurai’s vector meson dominance (VMD) model [1], assuming that a real photon can fluctuate into a

virtual V (J/ψ in our case), which subsequently scatters off a target nucleon.

The discovery of the J/ψ , the first heavy vector meson, 50 years ago at BNL [2] and SLAC [3] was termed the “November Revolution”. Beyond confirming the existence of the charm (c) quark and opening access to the study of the $c\bar{c}$ system, it has allowed the exploration of a variety of interesting aspects of physics. In particular, the heavy quark mass dependence of the properties of systems containing the heavy quark Q . Recall that the $Q\bar{Q}$ system is expected to have a small size $\propto 1/m_Q$ and that the predictions of perturbative QCD (pQCD) theory should be better justified here.

The Thomas Jefferson National Accelerator Facility (JLab), which currently operates with a 12 GeV beam of electrons, has the capacity to measure J/ψ photoproduction cross sections at threshold with high statistics. The threshold energy for a fixed proton target is $E = 8.2$ GeV. Table I lists several JLab measurements reported recently. The behavior of the cross section at threshold is sensitive to the scattering length, $\alpha_{J/\psi p}$, of the J/ψ -proton system.

The JLab measurements of J/ψ production are an important link in a chain of vector-meson photoproduction

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TABLE I. JLab measurements of the J/ψ photoproduction on the proton target at the threshold. The first column is the list of experiments, the second column is the luminosity for them, and the third column is the number of J/ψ events above the threshold.

Experiment	Luminosity (pb^{-1})	J/ψ (events)
GlueX [4]	68	469 ± 22
GlueX [5]	320	2270 ± 58
007 [6]	8.68×10^6	~ 2000
007 [7]	8.68×10^6	1041 ± 55
CLAS12 [8]	149	780 ± 40

measurements that enable a phenomenological analysis of trends in the vector-meson-proton scattering length (SL). Previous analyzes include $\gamma p \rightarrow \rho p$ (from CLAS12) [9,10], $\gamma p \rightarrow \omega p$ (from A2 at MAMI, ELPH, and CBELSA) [11–13], $\gamma p \rightarrow \phi p$ (from CLAS6 and LEPS) [13,14], and $\gamma p \rightarrow J/\psi p$ (from GlueX, 007, and CLAS12) [15,16]. While there has not yet been a measurement of threshold Υ -meson photoproduction, this will be possible at the future Electron Ion Collider (EIC), enabling an extension of the analysis to the Υ -proton system [17]. Results of these studies are shown in Table II.

Note that the SLs listed in Table II are much smaller than the size of either the proton (~ 1 fm) or the vector meson. This may be explained by the “young” meson hypothesis proposed first in [26] (see [17] for a discussion of the phenomenological treatment).

The point is that in photoproduction, the $Q\bar{Q}$ pair is produced at that point (locally) by the pointlike photon, and the heavy quarks do not have sufficient time to fly away at

the distances corresponding to the normal size of the vector meson wave function. That is, actually, we deal with the small size $Q\bar{Q}$ pair-proton interaction and not with the normal V -proton scattering. On the other hand, within pQCD, the corresponding cross section $\sigma((Q\bar{Q}) + p) \propto r^2$, where r is the antiquark-quark separation. Indeed, the small size (young) colorless object is almost sterile with respect to the QCD interaction. Therefore, the scattering length, i.e., the cross section measured in photo(electro)production, is smaller than that for the $Vp \rightarrow Vp$ interaction. This is an interesting effect (sometimes called the puzzle) that we can observe in photoproduction experiments.

Let us introduce several recent theoretical and lattice results to compare with the phenomenology.

Tang *et al.* (referred to hereafter as the Nanjing University group) have performed calculations of vector meson photoproduction from threshold to very high energies, assuming a production mechanism comprising a quark loop combined with Pomeron exchange [27]. They extract scattering lengths without requiring a fit to the data, arriving at $|\alpha_{\rho N}| = 184$ mfm, $|\alpha_{\phi N}| = 123$ mfm, $|\alpha_{J/\psi N}| = 6.34$ mfm, and $|\alpha_{\Upsilon N}| = 0.196$ mfm. These results are consistent within uncertainties (experimental and theoretical) with the phenomenological results (Table II).

A coupled-channel mechanism with VMD by Du *et al.* (hereafter referred to as the Bonn University group) gives $|\alpha^{J=1/2}| = 0.2 \dots 3.1$ mfm and $|\alpha^{J=3/2}| = 0.2 \dots 3.0$ mfm, where J corresponds to the total angular momentum of the $J/\psi p$ system [28]. This is consistent with the phenomenological results as well (Table II).

TABLE II. Vector meson photoproduction for reactions $\gamma p \rightarrow Vp$, where $V = \rho, \omega, \phi, J/\psi$, and Υ . The first column is the name of the Vs. The second column is their masses [18]. The third column is the photon threshold momentum in the center-of-mass (c.m.) for V photoproduction on the proton. The fourth column is the partial decay width $\Gamma(V \rightarrow e^+e^-)$ [18]. The fifth column shows the c.m. energy range for the total cross section measurements. The sixth column is the minimal momentum $q_{\min}$ in c.m. for the V accessible in the photoproduction experiments. The seventh column is the Vp SL using a phenomenological treatment by Eq. (8). The determination for the Υ is a theoretical projection made for the future EIC [17], and is not based on measured data.

Meson	Mass (MeV)	k_{thr} (MeV/c)	$\Gamma(V \rightarrow e^+e^-)$ (keV)	$W_{\min}-W_{\max}$ (MeV)	$q_{\min}$ (MeV/c)	$ \alpha_{Vp} $ (fm)
ρ	775.26	599.9	7.04	1737–1987 [19]	143	0.23 ± 0.03 [9]
				1873–2017 [20]		0.24 ± 0.02 [10]
ω	782.66	604.7	0.60	1724–1872 [11]	49	0.82 ± 0.03 [11]
				1710–1740 [12]		0.97 ± 0.26 [12]
				1770–1970 [21]		0.811 ± 0.019 [13]
ϕ	1019.460	754.0	1.27	2005–2245 [22]	216	0.063 ± 0.010 [14]
				1922–2320 [23]		0.109 ± 0.008 [13]
J/ψ	3096.900	1908.5	5.53	4054–4709 [4]	241	$(3.08 \pm 0.55) \times 10^{-3}$ [15]
				4075–4763 [24]	166	$(2.98 \pm 0.25) \times 10^{-3}$ [16]
				4254–4542 [6]	588	
				4254–4542 [7]	588	
				4085–4542 [8]	286	
Υ	9460.40	5157.0	1.340	10548–12348 [25]	521	$(0.51 \pm 0.03) \times 10^{-3}$ [17]

Wu *et al.* (hereafter referred to as the Tsinghua University group) report a calculation assuming J/ψ -nucleon scattering can occur through two distinct mechanisms; the coupled-channel mechanism via open-charm meson-baryon intermediate states ($\alpha_{J/\psi N} = -10 \dots -0.1$ mfm) and the soft-gluon exchange mechanism, which is dominant ($\alpha_{J/\psi N} \lesssim -160$ mfm) [29]. The model accounts only for pions and kaons in the t -channel, neglecting contributions from heavier mesons; thus, the final SL may be slightly larger.

The Lattice HAL Collaboration determined the J/ψ -nucleon SL using the elastic $(c\bar{c})p \rightarrow (c\bar{c})p$ reaction, resulting in $\alpha(^2S_{1/2}) = 380 \pm 40^{+0}_{-30}$ mfm [30]. The difference with respect to the phenomenology (Table II) may be explained by the fact that this reaction involves a vector meson in equilibrium (the “old” meson).

We need to have already summarized young versus old at this point... Furthermore, the Nanjing, Bonn, and Tsinghua groups calculated SLs in the photoproduction reaction $\gamma p \rightarrow Vp$, whereas in Lattice, the calculation considers the elastic $(c\bar{c})p$ reaction. It is puzzling that in the $(c\bar{c})p$ case, the SL is much larger. The young effect explains this puzzle.

Note that several previous theoretical results for the VN SL determination, including potential approaches and LQCD calculations, have yielded much larger SLs (see, for instance, Refs. [31–35]). Most likely, such a significant SL results from considerable distances in the tail of the Van der Waals potential, which in QCD should be mitigated by confinement [36].

The evaluation of $\gamma p \rightarrow J/\psi p$ cross sections of the proton, which were reported by 007 [7] and CLAS12 [8], is challenging to extend beyond our previous phenomenological determination of $J/\psi p$ SL [15,16]. As we will show in Sec. V, the agreement in $\gamma p \rightarrow J/\psi p \rightarrow (e^+e^-)p$, $\gamma^* p \rightarrow J/\psi p \rightarrow (e^+e^-)p$, and $\gamma p \rightarrow J/\psi p \rightarrow (\mu^+\mu^-)p$ total cross sections between independent high-luminosity GlueX, 007, and CLAS12 measurements, and phenomenological analysis allows us to feel comfortable.

Recall that, strictly speaking, to measure the scattering length of J/ψ -proton interaction, we have to consider not the J/ψ photoproduction but J/ψ elastic scattering on the proton. In comparison with the elastic process in the case of photoproduction, we have three additional factors that may depend on the vector meson mass.

The point is that the zero mass of the incoming photon is much smaller than the vector meson mass M_V . In terms of VMD, the resulting amplitude is proportional to the $\gamma \rightarrow V$ transition coupling $f_V(M_V)$, the amplitude probability not to destroy the target proton $F_N(t)$, and the $c\bar{c} \rightarrow J/\psi$ transition form factor $F_\psi(t)$.

We have to emphasize that to produce a heavy (J/ψ) meson at the threshold, we need to have a rather large momentum transferred t . The value of t may be calculated using the relation

$$s + t + u = \sum_{i=1}^4 m_i^2 = 2m_N^2 + M_V^2, \quad (1)$$

where s , t , and u are Mandelstam variables. $m_{\text{photon}} = 0$.

Since at the threshold in the proton- J/ψ rest frame, both the vector meson and the proton are at rest, the values of s , t , and u can be expressed via the energy of the incoming proton, E , as $s = m_N^2 + M_V^2 + 2m_N M_V$, $t = 2m_N^2 - 2Em_N$, and $u = m_N^2 + M_V^2 - 2EM_V$. So we get from (1)

$$E = \frac{2m_N^2 + M_V^2 + 2m_N M_V}{2(M_V + m_N)} \quad \text{and} \quad (2)$$

$$t = 2m_N^2 - m_N \frac{2m_N^2 + M_V^2 + 2m_N M_V}{(M_V + m_N)}. \quad (3)$$

For the case of J/ψ at threshold $t = -2.2 \text{ GeV}^2$. Thus, the SL extracted via the VMD from the photoproduction of a heavy vector meson will be smaller than that in elastic meson-proton scattering by the factor $F_N(t)F_\psi(t)f_V(M_V^2)$. Note that the “elastic” proton form factor $F_N(t)$ is *not equal* to the electromagnetic form factor, $F_e(t)$. Its behavior depends on the particular dynamics of interaction. We do not know $F_N(t)$ experimentally, and for our numerical estimate, we will take the pole form,

$$F_N(t) = \frac{1}{1 - t/\Lambda^2}, \quad (4)$$

with $\Lambda^2 = 0.71 \text{ GeV}^2$ [this $F_N(t) = \sqrt{F_e(t)}$ looks reasonable, assuming that the two gluons describe the interaction exchange].

Since at the beginning the photon produces the $c\bar{c}$ pair at the point, and the size of the heavy vector boson is much smaller than the proton size, we expect that the factors f_V and F_ψ should be much flatter as a function of t . Therefore (keeping in mind the large uncertainty in F_N), we take $f_V F_\psi = 1$.

Note also that in the models [27,28], where the interaction is mediated by the heavy quark loop and the two gluon exchange, these factors are accounted for automatically.

Besides the form factor suppression, we expect a smaller SL due to the “young effect”, where the reaction, rather than proceeding through the V -proton interaction, proceeds through the interaction of the recently produced $Q\bar{Q}$ pair, whose size is smaller than that of the fully formed vector meson.

To study both the “form factor” and the “young effect” in more detail, it would be interesting to measure the electroproduction at Q^2 values comparable to $M_{J/\psi}^2$.

Another interesting piece of information may come from the J-PARC facility, which can measure the near-threshold

V production using neutral low- and high-energy pion beams [37].

II. J/ψ THRESHOLD MEASUREMENTS USING THE GLUEX SPECTROMETER

The GlueX spectrometer in JLab's Experimental Hall D has nearly full acceptance [38], which allows for a straightforward measurement of the total cross section, σ_t , for the reaction $\gamma p \rightarrow J/\psi p \rightarrow (e^+e^-)p$, and eliminates the need to extrapolate to low/high four-momentum transfer squared t . The GlueX Collaboration reported results from data collected in 2016–2017 (68 pb⁻¹) [4], and then updated this result from data collected over 2016–2018 (320 pb⁻¹) [5] (see Table I). J/ψ yields were extracted from fits of $M(e^+e^-)$ distributions, and the Bethe-Heitler (BH) reaction (1.2–2.5 GeV) was used for normalization. The GlueX Collaboration reported 18 total cross sections as a function of photon energy, E , and three differential cross sections as a function of t over the energy range $E = 8.2$ –11.4 GeV.

III. J/ψ THRESHOLD MEASUREMENTS USING HMS AND SHMS SPECTROMETERS

The 007 Collaboration experimented in 2019 in JLab's Experimental Hall C using an untagged photon beam scattering off a proton target, with the High Momentum Spectrometer (HMS) and the Super High Momentum Spectrometer (SHMS) used to detect lepton pairs from J/ψ decay [6,39]. The experiment covered an energy range of $E = 9.2$ –10.5 GeV. The collaboration first reported 10 differential cross sections as a function of t for the reaction $\gamma p \rightarrow J/\psi p \rightarrow (e^+e^-)p$ [6]. Subsequently, 007 reported 10 samples of total and differential cross sections as a function of t for $\gamma p \rightarrow J/\psi p \rightarrow (\mu^+\mu^-)p$ [7]. The two datasets were collected simultaneously (Table I), but they are statistically independent. The latter is the first measurement at the threshold using the $J/\psi \rightarrow \mu^+\mu^-$ decay mode. The normalization methods for the two results differ slightly. In the case of the first publication [6], the BH reaction provided the absolute normalization (similar to GlueX [4]). In the second publication, the total cross sections were determined directly from the differential cross sections [7].

IV. J/ψ THRESHOLD MEASUREMENTS USING THE CLAS12 SPECTROMETER

The CLAS12 Spectrometer [40] in JLab's Experimental Hall B has measured differential cross sections for the reaction $\gamma^* p \rightarrow J/\psi p \rightarrow (e^+e^-)p$ (Table I), where γ^* is used to denote quasi-real photoproduction. The experiment was conducted with a primary electron beam. Results were published for events with a squared invariant mass of the virtual photon, Q^2 , less than 0.1 GeV². Data were collected in the fall of 2018 and the spring of 2019, covering the

photon energy range $E = 8.4$ –10.5 GeV. CLAS12 reported 12 differential cross sections as a function of t , from which 10 total cross sections were determined as a function of E [8]. CLAS12 likewise used the BH reaction for absolute normalization.

V. J/ψ N SCATTERING LENGTH: PHENOMENOLOGICAL ANALYSIS

For the evaluation of the *absolute value* of J/ψ p SL, we apply the VMD approach that links the near-threshold photoproduction total cross section of $\gamma p \rightarrow Vp$ and elastic scattering $Vp \rightarrow Vp$ [11,17], where $V = J/\psi$ is applicable in our case. VMD accounts for the (virtually admixed) hadronic part of the photon, through which the photon couples to hadronic matter. The applicability of the VMD model was recently explored in Ref. [41] and in a previous theoretical study [42,43].

To avoid adding additional theoretical uncertainties, we do not; (i) determine the sign of SL, (ii) separate the Re and Im parts of SL, nor (iii) extract total angular momentum 1/2 and 3/2 contributions for the J/ψ p system.

Traditionally, the total cross section, σ_t , for near-threshold binary inelastic reactions

$$ab \rightarrow cd \quad (5)$$

with

$$m_a + M_b < m_c + M_d \quad (6)$$

is expressed as a series in *odd* powers of the c.m. momentum q of the V :

$$\sigma_t = aq + bq^3 + cq^5, \quad (7)$$

where the linear term reflects the contributions of two independent S -wave amplitudes with a total spin of 1/2 and/or 3/2. Contributions to the cubic term originate from both P -wave amplitudes and the c.m. energy (W) dependence of S -wave amplitudes, while the fifth-order term arises from D -wave amplitudes as well as from the W dependencies of the S - and P -wave amplitudes. We assume that there are no VN resonance states below the experimental $q_{\min}$, which are provided in Table II.

The absolute value of the VN SL ($|\alpha_{VN}|$) is determined by the interplay of strong or hadronic [$h^2 = a$ from Eq. (7)] and EM dynamics [$B^2 = \frac{\alpha}{12\pi} \frac{m_V k_{\text{thr}}}{\Gamma(V \rightarrow e^+e^-)}$] [11]:

$$|\alpha_{VN}|^2 = (hB)^2 = a \left[\frac{\alpha}{12\pi} \frac{M_V k_{\text{thr}}}{\Gamma(V \rightarrow e^+e^-)} \right], \quad (8)$$

where α is the fine structure constant (1/137.036) [18], M_V is the mass of the V [18], k_{thr} is the photon threshold momentum in the c.m. for V photoproduction on the

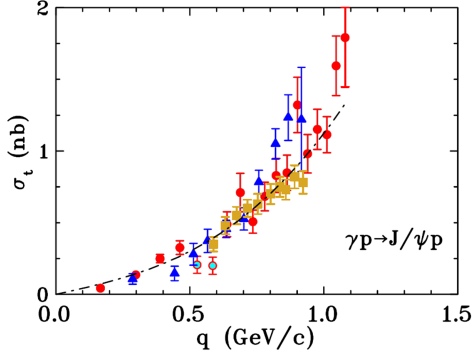


FIG. 1. The total $\gamma p \rightarrow J/\psi p$ cross sections, σ_t , as a function of the J/ψ c.m. momentum reported by the GlueX Collaboration (red filled circles) [5] (two points are filled in cyan at the dip around $q = 0.5$ – 0.6 GeV/c are discussed in the main text), the 007 Collaboration (shown in yellow-filled squares [7]), and the CLAS12 Collaboration (shown in blue-filled triangles) [8]. The black dash-dotted curves represent polynomial fits to σ_t using Eq. (7).

proton, a is the linear coefficient obtained from fits to the V photoproduction cross sections [Eq. (7)], and $\Gamma(V \rightarrow e^+e^-) = 5.53 \pm 0.10$ keV is the partial decay width [18]. Following PDG2024, one can assume that $\Gamma(J/\psi \rightarrow e^+e^-) = \Gamma(J/\psi \rightarrow \mu^+\mu^-)$ [18].

The fit of high-luminosity GlueX, recent 007, and CLAS12 data is shown in Fig. 1 by a black dot-dashed curve. The best-fit results are summarized in Table III.

The stability of the leading linear term a from Eq. (7) is demonstrated by comparing fits to the low (high) luminosity GlueX data and the combined fit of high luminosity GlueX, 007, and CLAS12 results (Table III).

One concern is the apparent dip in the GlueX data at approximately $q = 0.5$ – 0.6 GeV/c. This could hypothetically be caused by destructive interference between a resonant s -channel pentaquark state, plausibly the $P_c(4312)^+$ observed at LHCb [44], and nonresonant J/ψ production [45]. If this were the case, it could bias the results of a fit based on Eq. (7). Therefore, we have examined the results of fits to the GlueX data with ($\chi^2/\text{d.o.f.} = 1.56$) and without ($\chi^2/\text{d.o.f.} = 0.97$) two data points at the location of the dip (indicated by cyan-filled points in Fig. 1). Of course, the pure polynomial expansion is not sufficient to describe the presence of the resonance, and accounting for these points, we get a larger χ^2 ; however, as seen from Table III, thanks to the narrow width of the pentaquark resonance, the resulting values of SL are practically the same (within the error bars). That is, we see that the presence or the absence of the resonance does not affect our SL result. While the 007 data lacks coverage in q to make a firm statement about the existence of a dip, the more recent CLAS12 electroproduction data do not show evidence of a dip. Still, uncertainties are very large (low statistics).

TABLE III. The J/ψ - p scattering lengths extracted from the GlueX measurements on a free proton. The first column lists the minimal c.m. momentum $q_{\min}$ for J/ψ accessible in the photoproduction experiments. The second column gives the linear coefficient a obtained from fits to the J/ψ production cross sections using Eq. (7). The third column gives $\chi^2/\text{d.o.f.}$. The fourth column presents the corresponding SL, derived from the parameter a via the phenomenological approach using Eq. (8).

$q_{\min}$ (MeV/c)	a ($\times 10^{-6}$ $\mu\text{b}/(\text{MeV}/c)$)	$\chi^2/\text{d.o.f.}$	$ \alpha_{J/\psi p} $ (mfm)
244 [4]	0.46 ± 0.16 [15] ^a	0.64	3.08 ± 0.55 [15]
166 [5]	0.43 ± 0.10 [16] ^b	1.56	2.89 ± 0.34 [16]
166 [5]	0.44 ± 0.10 ^c	0.97	2.95 ± 0.34
166 [5]	0.41 ± 0.08 ^d	0.93	2.74 ± 0.27

^aFit to only the GlueX low-luminosity data.

^bFit to only the GlueX high-luminosity data.

^cFit to the GlueX high-luminosity data excluding two data points ($q = 0.5$ – 0.6 GeV/c) associated with a dip possibly attributable to the LHCb $P_c(4312)^+$ state [44].

^dCombined fit of GlueX high-luminosity, 007, and CLAS12 data.

In addition to examining the total cross sections, this dip may also be considered from the perspective of differential cross sections. The high-luminosity GlueX paper [5] reported $d\sigma/dt$ for three photon energy ranges; (i) $E = 8.20$ – 9.28 GeV, (ii) $E = 9.28$ – 10.36 GeV, and (iii) $E = 10.36$ – 11.44 GeV. Figure 13 of Ref. [5] demonstrated that distributions (ii) and (iii) look similar, and the data were fitted with two exponents. At the same time, distribution (i) showed that the slope of one exponent changed sign. This bin is associated with the dip at $q = 0.5$ – 0.6 GeV/c. This effect may indicate a singularity associated with the results reported in Ref. [45].

VI. VECTOR MESON NUCLEON SCATTERING LENGTH PUZZLE

In this section, we aim to summarize our current state in the VN SL puzzle.

Fits to data from A2, CLAS6, CLAS12, GlueX, and 007 (as well as to theoretical predictions in the case of Υ [17]) for the total threshold $\gamma p \rightarrow Vp$ cross sections are shown in Fig. 2 as black dot-dashed curves.

The corresponding results for the SLs are shown in Fig. 3 as a function of the inverse vector-meson mass, $1/M_V$. Starting from the ϕ -meson and for higher masses, the SLs are significantly smaller than the typical hadron size of about 1 fm, indicating an increasing transparency of the proton for these mesons.

Note that the results in Fig. 3 do not account for the t dependence of $f_V F_\psi F_N$ form factors, while for the low energies at the threshold, the value of $t = t_{\min}$ can be quite large ($t = -2.2$ GeV² for J/ψ photoproduction).

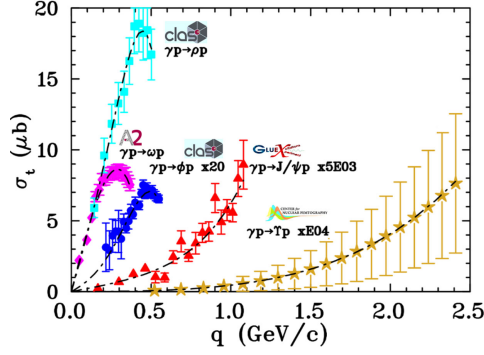


FIG. 2. The total threshold $\gamma p \rightarrow Vp$ cross section, σ_t , derived from the A2 (magenta filled diamonds) [11], CLAS12 (cyan filled squares) [9], CLAS6 (blue filled circles) [14], and high-luminosity GlueX (red filled triangles) [15] data, and simulated EIC quasidata [17] based on the theoretical predictions of Ref. [25] (based at the Center for Nuclear Fentography) are shown as a function of the c.m. momentum q of the final-state Vs. The vertical error bars represent the total uncertainties of the data, which sum statistical and systematic uncertainties in quadrature. Black dash-dotted curves show the fits of the data and quasi-data to a series of odd powers of q using Eq. (7).

To account for the form factor, we have to divide the obtained SL by $F_N(t)$.¹

This enlarges the values for the SLs, but the results (shown in Table IV) are still much less than 1 fm.²

A. Theoretical uncertainties

Aside from the experimental error bars, the uncertainties in our results arise from the accuracy of the VMD model.

First, this is the possible contribution of the quark-antiquark states (produced by the photon), other than the vector meson of interest. In terms of the dispersion relation over the mass of the intermediate state, besides the resonance peak, there may exist another contribution. The hope is that this contribution is negligibly small.

Next, the role of the form factors. On one hand, the momentum transfer needed to produce a heavy vector meson at threshold is quite large (see Table IV). On the other hand, the meaning/physics of the form factor is the probability of keeping the particle intact, and not producing some complicated excited state. However, working very

¹As discussed earlier, thanks to the small size of the heavy vector meson, we take $f_V F_\psi = 1$.

²At the moment, we have used the pole form factor (4). Using the exponential form, $F_N = F_{\text{exp}}(t) = \exp(bt)$ produces a strange, nonphysical result. Indeed, let us fix the slope b from the proton electromagnetic radius, $r_e = 0.84$ fm. Since in the electromagnetic case the photon transfers its momentum to *one* quark, while in our case, via the two gluon exchange, this momentum is transferred to two quarks, we take the four times smaller value, $b = \langle r_e^2 \rangle / (6 \times 4)$. This leads to the results shown in the fifth column of Table IV. Note that now we get the Υ -p SL *larger* than that for J/ψ , which is nonphysical.

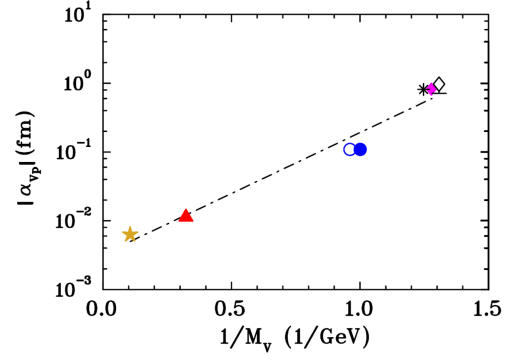


FIG. 3. Comparison of $|\alpha_{Vp}|$ estimated from threshold V photoproduction on the proton target assuming VMD versus the inverse mass of the Vs, i.e., $1/M_V$. Input data for phenomenological analyses came from A2 at MAMI (magenta filled diamond) [11], ELPH (black open diamond) [12], and CBELSA/TAPS (black asterisk) [13] Collaborations for the ω -meson case; CLAS6 (blue filled circle) [14] and LEPS (black open circle) [13] Collaborations for the ϕ -meson case; GlueX, 007, and CLAS12 (red filled triangle) Collaborations for the J/ψ -meson case; and theoretical predictions from the Center for Nuclear Fentography (yellow filled star) [17, 25] for the Υ -meson case. The black dash-dotted line is a hypothetical fit to the data from Refs. [11, 14, 17] with high-luminosity GlueX, 007, and CLAS12 for $J/\psi p$ results using Eq. (9) and corrected by the nucleon pole form factor.

close to the threshold, we have no phase space sufficient to produce the new system with the same quantum numbers (say, the baryon charge $B = 1$), except for the proton and our vector meson. That is, it seems reasonable to set $F_N = 1$ (and $f_V F_\psi = 1$) and say that the dynamics of interaction account for the large momentum transferred; therefore, we must consider the obtained SL (third column in Table IV) as the real scattering length of the photoproduction on the proton.

Finally, recall that we are actually dealing with the $Q\bar{Q}$ -proton interaction and not with the elastic $Vp \rightarrow Vp$ scattering. The size of this pair, produced by the pointlike photon, is smaller than the normal vector meson size.³ Thus, it is natural to expect a smaller cross-section. This “young effect” explains the relatively small values of SL measured in photoproduction.

B. Some speculations

As seen in Fig. 3, our analysis shows an almost linear increase (on an exponential scale) in

$$|\alpha_{Vp}| \propto \exp(1/M_V), \quad (9)$$

³We calculate the amplitude of $Q\bar{Q} \rightarrow V$ transition within the nonrelativistic QCD using the vector meson wave function $\Psi(r=0)$ at zero (r is the quark-quark separation).

TABLE IV. The values of obtained scattering length for vector meson photoproduction neglecting, SL, and accounting, $SL/F_N(t)$, for the nucleon form factor effects. The first column is the name of V . The second column is the phenomenological SL using the conventional VMD. The third column is the $t = t_{\min}$. The fourth column is the corrected SL using the nucleon pole form factor, $F_N(t)$, using Eq. (4). No theoretical uncertainties added. The fifth column is the corrected SL using the nucleon exponential form factor, $b = 0.76 \text{ GeV}^{-2}$. The sixth column is the predictions using naive pQCD (current paper). The seventh column is the predictions using the QCD model from Ref. [27]. Uncertainties in the second column came from our phenomenological fit of total threshold cross sections of heavy vector meson photoproduction using Eq. (7). While uncertainties in the fourth column do not include the theoretical uncertainties.

Meson	Photoproduction SL (fm)	$-t_{\min} \text{ (GeV}^2\text{)}$	$SL/F_N(t) \text{ (fm)}$	$SL/\exp(bt) \text{ (fm)}$	pQCD (fm)	dynSL [27] (fm)
ϕ	0.063 ± 0.010 [14]	0.50	0.109 ± 0.017	0.092	0.065	0.123
J/ψ	0.00274 ± 0.00027^a	2.22	0.0113 ± 0.0011	0.016	0.0029	0.00634
Υ	0.00051 ± 0.00003 [17]	8.07	0.0063 ± 0.0004	0.23	0.00047	0.00196

^aJoint fit result of the threshold total cross sections of the high-luminosity GlueX, 007, and CLAS12 J/ψ data from the fourth row of Table III.

with increasing $1/M_V$. This is an interesting observation; however, the behavior (9) does not satisfy the expected asymptotics $\alpha_{Vp} \rightarrow 0$ as $M_V \rightarrow \infty$.

In fact, in pQCD, the $p \rightarrow V$ scattering amplitude is driven by the strong coupling α_s and the separation of the corresponding quarks. This separation (in zero approximation) is proportional to $1/M_V$ or $1/m_Q$, where m_Q is the *current* quark mass.

Taking the *current* quark masses as $m_s = 0.1 \text{ GeV}$, $m_c = 1.3 \text{ GeV}$, and $m_b = 4.2 \text{ GeV}$, along with the constant $\Lambda = 350 \text{ MeV}$ [18], and inserting

$$\alpha_{Vp} = \frac{1}{30} 0.197 [\text{fm} \cdot \text{GeV}] \frac{\alpha_s(m_Q)}{m_Q}, \quad (10)$$

with one-loop

$$\alpha_s = (4\pi/b_0)/\ln(m_Q^2/\Lambda^2), \quad (11)$$

but if $\alpha_s > 1$, then $\alpha_s = 1$ (i.e., α_s is frozen at 1; and b_0 is the one-loop β -function coefficient $b_0 = 8.33$ for 4 light quarks: u , d , s , and c). One can obtain rather good results; $|\alpha_{\phi N}| = 65 \text{ mfm}$, $|\alpha_{J/\psi N}| = 2.9 \text{ mfm}$, and $|\alpha_{\Upsilon N}| = 0.47 \text{ mfm}$.

Of course, the expression (10) is not the real pQCD calculation. This is just a naive estimate. However, it demonstrates that the observed SLs are consistent with pQCD and account for the suppression due to the young effect.

Recall that the aim of our paper is not to build a model that describes the data, but rather to conduct a phenomenological analysis. [The model(s) and the corresponding theoretical uncertainties can be found, e.g., in [27,28]].

C. Other comments

Actually, Eq. (8) from the paper by Titov *et al.* [46] gives the relationship between the scattering lengths of ϕN and ωN using $SU(3)_{\text{flavor}}$ symmetry:

$$|\alpha_{\phi N}| = \epsilon |\alpha_{\omega N}|, \quad (12)$$

where $\epsilon \equiv -tg(\Delta\theta_V)$ and $\Delta\theta_V \simeq 3.7^\circ$ represents the deviation of the ϕ — ω mixing angle from the ideal mixing angle. (The vector mixing angle $\theta_V = 36.5^\circ$ is very close to the ideal mixing angle [18].) The relation (12) assumes that SL originates from the light (u , d) quarks only, most likely from the nucleon resonances. The ratio of our phenomenological SL determination ($|\alpha_{\omega N}| = 0.82 \text{ fm}$ [11] and $|\alpha_{\phi N}| = 0.063 \text{ fm}$ [14]), taken from Table II, is $\epsilon = \frac{|\alpha_{\phi N}|}{|\alpha_{\omega N}|} = \frac{0.063}{0.82} = 0.077$. It corresponds to $\Delta\theta_V \simeq 4.4^\circ$. That is in perfect agreement with the result from [46].

In $SU(3)_{\text{flavor}}$, there should be a similar relation for $|\alpha_{\phi N}|$ with $|\alpha_{\omega N}|$ and $|\alpha_{\phi N}|$ with $|\alpha_{\rho N}|$. However, for the ρ , it may be partly spoiled by the large ρ width. Besides this, in the ρp case, the result may be affected by the *isobars* ($I = 3/2$). That is likely why $|\alpha_{\omega N}| \simeq 4|\alpha_{\rho N}|$, as was reported recently [9].

VII. J/ψ MEASUREMENTS USING MARQ AND DILEPTON DETECTORS AT J-PARC

The new high-energy $\pi 20$ beamline, utilized by the P111 experiment [37], allows precise threshold measurements of the $\pi^- p \rightarrow J/\psi n$ reaction using a method independent of the VMD model. The J/ψ production will be reconstructed in both e^+e^- and $\mu^+\mu^-$ dilepton decay channels. The near-threshold cross section for the $\pi^- p \rightarrow J/\psi n$ reaction remains unmeasured; previous studies have only established upper limits. Theoretical predictions for the J/ψ production cross section span a wide range, from 0.1 pb to 50 nb [47–50], depending on interpretations of these limits. If the cross section reaches approximately 4 nb at $p = 9.5 \text{ GeV}/c$, the anticipated J/ψ yield in the momentum range $p = 8.2\text{--}11.0 \text{ GeV}/c$ is estimated to be 1.0×10^4 events. These results are essential for advancing the phenomenological understanding of the SL puzzle (in particular, the role of form factors near the threshold) and for investigating potential effects related to the LHCb heavy pentaquarks (P_c) [44].

Furthermore, the J-PARC experiment aims to search for isospin partners of the P_c states via the $\pi^- p \rightarrow J/\psi n$

reaction near the threshold. The P111 setup, which integrates both the MARQ and dilepton detectors, enables precise measurements of both hidden-charm and open-charm channels—including $\Lambda_c^{(*)}\bar{D}^{(*)}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}$ —thus allowing a comprehensive coupled-channel analysis near the P_c states [44]. If the P_c states strongly couple to $\Sigma_c^{(*)}\bar{D}^{(*)}$, the pion-induced reaction would be expected to dominate over the photon-induced reaction, provided $g_{\Lambda_c N \bar{D}} \gg g_{\Sigma_c N \bar{D}}$.

VIII. SUMMARY

The J/ψ -proton SL, phenomenologically determined using recent 007 and CLAS12 measurements of J/ψ photo(electro)production at threshold using both $J/\psi \rightarrow l^+l^-$ decay channels, together with previous GlueX measurements with the $J/\psi \rightarrow e^+e^-$ decay, is in perfect agreement.

We used the concept of the young vector meson hypothesis, which may explain the fact that the obtained SL value for ϕ -meson nucleon, compared to the typical hadron size of 1 fm, indicates that the proton is more transparent for ϕ -meson than for ω -meson and is much more transparent for J/ψ -meson:

$$|\alpha_{Tp}| \ll |\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| \ll |\alpha_{\omega p}|. \quad (13)$$

We have shown that the pQCD estimate is consistent with our phenomenological treatment of the heavy-vector-meson photoproduction data at threshold.

The puzzle of the dynamics of $q\bar{q}$, $s\bar{s}$, and $c\bar{c}$ interactions with the qqq system at the threshold remains an open question that the upcoming J-PARC measurements will resolve.

Polarized measurements are essential for model-independent partial-wave analysis. J/ψ is somewhat polarized, but it is much less polarized than Drell-Yan dileptons, as FNAL measurements of the polarization of J/ψ in pA inclusive production at 800 GeV have shown [51,52]. The J/ψ polarization matrix is measured via the angular distribution of electrons in $J/\psi \rightarrow e^+e^-$ decay. The JLab data and J-PARC experiment P111 may help resolve the polarization effects in quarkonium production.

ACKNOWLEDGMENTS

We thank our Referee for discussing the nucleon form factor contribution. We thank Yuri Dokshitzer, Atsushi Hosaka, Sasha Titov, Jen Chieh Peng, Pierre Chatagnon, Sylvester Joosten, Valery Kubarovsky, and Sun Young Ryu for their valuable comments and discussions. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award No. DE-SC0016583, and by the National Research Foundation of Korea (NRF), the Korean government (MSIT), under Grant No. RS-2024-00436392.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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