




**$J/\psi$   $p$  scattering length from GlueX threshold measurements**Igor I. Strakovsky <sup>1,\*</sup>, Denis Epifanov <sup>2,3</sup> and Lubomir Pentchev <sup>4</sup><sup>1</sup>*Department of Physics, Institute for Nuclear Studies, The George Washington University, Washington, D.C. 20052, USA*<sup>2</sup>*Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia*<sup>3</sup>*Novosibirsk State University, Novosibirsk 630090, Russia*<sup>4</sup>*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

(Received 3 December 2019; accepted 20 March 2020; published 10 April 2020)

The quality of the recent GlueX  $J/\psi$  photoproduction data from Hall D at Jefferson Laboratory and the proximity of the data to the energy threshold, gives access to a variety of interesting physics aspects. As an example, an estimation of the  $J/\psi$ -nucleon scattering length  $\alpha_{J/\psi p}$  is provided within the vector meson dominance model. It results in  $|\alpha_{J/\psi p}| = (3.08 \pm 0.55(\text{stat.}) \pm 0.42(\text{syst.}))$  mfm which is much smaller than a typical size of a hadron.

DOI: [10.1103/PhysRevC.101.042201](https://doi.org/10.1103/PhysRevC.101.042201)

Since the discovery of the  $J/\psi(1S)$  resonance [1,2], it became an attractive probe to study interactions with hadronic matter. The  $J/\psi$  is a vector meson and our understanding of the coupling of the other vector mesons, such as  $\omega$ ,  $\rho$ , and  $\phi$  to hadrons, has been strongly influenced by the photoproduction cross sections of these particles. In particular, the cross sections at small momentum transfer are characterized by an energy-independent exponential function of the square of the momentum transfer. Explicit models, such as vector meson dominance (VMD), enable one to calculate the meson-hadron couplings from these cross sections. As a consequence, it is natural to study the photoproduction of the  $J/\psi(1S)$  in order to compare it to the other vector mesons. The exclusive near-threshold photoproduction of charmonium allows for the study of the  $J/\psi N$  interaction dominated by hard gluon exchange (due to the heavy charm quarks), thus providing a unique probe of the gluonic field in the nucleon at high  $x$ . The behavior of the cross section near threshold is related to the  $J/\psi N$  scattering length, which can be used to study the binding of charmonium with the nucleon and nuclei.

The aim of the present contribution is the evaluation of the  $J/\psi$ - $p$  scattering length from the  $J/\psi$  photoproduction data. Our analysis is based on the vector dominance model [3,4] relying on the transparent current-field identities of Kroll, Lee, and Zumino [5]. VMD does not contain free parameters and can be used for a variety of qualitative estimates of observables in the vector meson photoproductions [6,7] at least as the first step towards their more extended theoretical

studies. The use of the vector dominance model in case of the  $J/\psi$  requires special attention due to the high mass of the meson. For critical review of the vector dominance model, we refer to papers of Boreskov and co-workers [8,9] and references there.

Recently, the GlueX Collaboration reported the first total cross section  $\sigma_t$  measurements for the exclusive reaction  $\gamma p \rightarrow J/\psi p$  at threshold [10]. This is a unique experiment that measured  $\sigma_t(E)$  from threshold at a photon energy of  $E_\gamma = 8.2$  GeV to 11.85 GeV. Previous old measurements at Cornell [11] at 11 GeV and SLAC [12] above 13 GeV were inclusive and also on nuclear targets. Thanks to the full acceptance of the GlueX detector for this reaction, this measurement avoids uncertainties in the determination of  $\sigma_t$  from the forward differential cross sections that affected the SLAC experiment. The GlueX experiment uses tagged real photons produced from 12 GeV electrons by coherent Bremsstrahlung on a thin diamond radiator. The coherent peak was set at  $E_\gamma$  right above the threshold, 8.2–9 GeV, allowing to do measurements very close to the threshold where the cross section vanishes. The full acceptance of the GlueX detector is achieved by means of a solenoidal magnet with central and forward tracking systems and a barrel electromagnetic calorimeter, all inside the magnet, and additional calorimeter and time-of-flight systems covering the detector in the forward direction.

Near-threshold cross sections of good accuracy allow the extraction of various useful parameters, in particular, resonance masses and scattering lengths, see, for instance, Ref. [13]. In general, the total cross section for an inelastic reaction  $ab \rightarrow cd$  with particle masses  $m_a + m_b < m_c + m_d$  can be written as  $\sigma_t = \frac{q}{W} F(W^2)$ , where  $W$  is the center-of-mass (c.m.) total energy and  $q$  is the c.m. momentum of the final-state particles. The factor  $F(W^2)$ , which does not vanish at threshold, comes from the sum of production amplitudes squared, and  $\frac{q}{W}$  from the integration over the final-state phase space. Because  $W^2$  is linearly related to the photon energy

\*Corresponding author: [igor@gwu.edu](mailto:igor@gwu.edu)

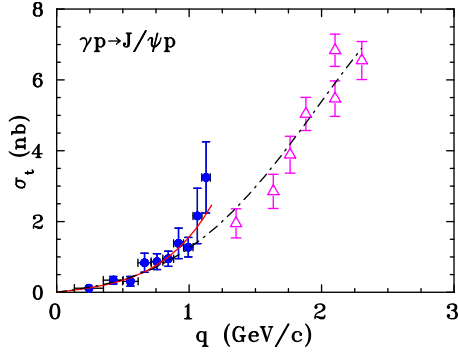


FIG. 1. Results of the GlueX work (blue solid circles) for the  $\gamma p \rightarrow J/\psi p$  total cross sections  $\sigma_t$  [10] are shown as a function of the c.m. momentum  $q$  of the final-state particles. The previous SLAC data [12] (where the determination of  $\sigma_t$  from the differential cross sections was performed in Ref. [10]) are shown by the magenta open triangles. The vertical error bars represent the total uncertainties of the results (summing statistical and systematic uncertainties in quadrature). The horizontal error bars for the GlueX data reflect the energy binning. The red solid curve shows the fit of the GlueX data with Eq. (1), while the black dot-dashed curve shows a combined fit of the GlueX and SLAC data with Eq. (1).

$E_\gamma$  for the charmonium photoproduction, the value of  $\sigma_t$  as a function of the photon energy in the laboratory frame  $E_\gamma$  reaches zero at the threshold energy  $E_\gamma = E_\gamma^{th}$  without any singularity (i.e., if the final-state  $S$  wave does not vanish at threshold).

Traditionally, the  $\sigma_t$  behavior of a binary inelastic reaction near threshold can be described as a series of odd powers of  $q$ . In the energy range under study,

$$\sigma_t(q) = a_1 q + a_3 q^3 + a_5 q^5, \quad (1)$$

is enough to describe the near threshold cross section  $\sigma_t(q)$  quite well. The fit of the GlueX data with Eq. (1) is shown in Fig. 1 by a solid red curve. The fit of both GlueX and SLAC data is shown in Fig. 1, as well, by a black dot-dashed curve. The best-fit results are summarized in Table I. Note that the SLAC experiment measured the differential cross section  $d\sigma/dt$  at  $t = t_{\min}$  as a function of  $E_\gamma$ . To calculate the total cross sections from the SLAC data, we have used a dipole  $t$ -dependence as was done in Ref. [10].

The parameter  $a_1$  as obtained from the fit of the GlueX data alone and both the GlueX and SLAC data agree within the uncertainties (Table I), the near threshold behavior is

TABLE I. The fit of the GlueX [10] (second column) and GlueX with SLAC [12] (third column) data with Eq. (1). Error bars of the GlueX data represent the total uncertainties (summing statistical and systematic uncertainties in quadrature).

$a_i$	GlueX Data	GlueX and SLAC Data
$a_1$ [nb/(GeV/c)]	$0.46 \pm 0.16$	$0.53 \pm 0.12$
$a_3$ [nb/(GeV/c) <sup>3</sup> ]	$0.83 \pm 0.91$	$0.78 \pm 0.16$
$a_5$ [nb/(GeV/c) <sup>5</sup> ]	$0.28 \pm 0.87$	$-0.06 \pm 0.03$
$\chi^2/\text{dof}$	0.67	0.98

very similar for both curves. The linear term in Eq. (1) is determined here by the  $S$  waves only (with total spin 1/2 and/or 3/2). The contributions to the cubic term come from both the  $P$ -wave amplitudes and the  $W$  dependence of the  $S$ -wave amplitudes, and the fifth-order term arises from the  $D$  waves and the  $W$  dependencies of the  $S$  and the  $P$  waves.

The  $\sigma_t(\gamma p \rightarrow J/\psi p)$  data is related to the  $J/\psi N$  scattering length,  $\alpha_{J/\psi p}$ , by the threshold relation

$$\frac{d\sigma(J/\psi p \rightarrow J/\psi p)}{d\Omega}\Big|_{th} = |\alpha_{J/\psi p}|^2. \quad (2)$$

In fact, the cross section includes contributions from two independent  $S$ -wave scattering lengths with total spins 1/2 and 3/2.

In the VMD framework,  $\alpha_{J/\psi p}$  appears also in the  $\gamma p \rightarrow J/\psi p$  cross section near threshold [7]:

$$\sigma_t(\gamma p \rightarrow J/\psi p)\Big|_{th} = \frac{q}{k} \frac{4\alpha\pi^2}{g_{J/\psi\gamma}^2} |\alpha_{J/\psi p}|^2, \quad (3)$$

where  $k$  is the c.m. momentum of the incident photon at the  $\gamma p \rightarrow J/\psi p$  threshold,  $\alpha$  is the fine-structure constant,  $M$  is the  $J/\psi$  mass, and  $g_{J/\psi\gamma} = 5.58 \pm 0.07$  is the  $\gamma \rightarrow J/\psi$  coupling, as determined from the  $J/\psi \rightarrow e^+e^-$  decay width [14]. This result came recently from the KEDR Collaboration that determined  $\Gamma(J/\psi \rightarrow e^+e^-)$  using the KEDR detector at the VEPP-4M  $e^+e^-$  collider. Summing the statistical and systematic uncertainties in quadrature, one gets  $\Gamma(J/\psi \rightarrow e^+e^-) = (5.55 \pm 0.11)$  keV. As known in VMD, the coupling  $g_{J/\psi\gamma}$  is related to the electron width of the vector meson  $\Gamma(J/\psi \rightarrow e^+e^-)$  as

$$g_{J/\psi\gamma} = \sqrt{\frac{\pi\alpha^2 M}{3\Gamma(J/\psi \rightarrow e^+e^-)}}. \quad (4)$$

Combining Eq. (3) with the  $a_1$  value from fitting Eq. (1) to the GlueX  $\sigma_t(\gamma p \rightarrow J/\psi p)$  data given in Table I results in

$$|\alpha_{J/\psi p}| = \frac{g_{J/\psi\gamma}}{2\pi} \sqrt{\frac{ka_1}{\alpha}} = (3.08 \pm 0.55) \text{ mfm}, \quad (5)$$

which should be considered just as an estimate assuming only the sequence  $\gamma \rightarrow J/\psi$ ,  $J/\psi p \rightarrow J/\psi p$ . Taking into account the overall systematics of the GlueX data of 27%, we obtain finally  $|\alpha_{J/\psi p}| = (3.08 \pm 0.55(\text{stat.}) \pm 0.42(\text{syst.}))$  mfm.

To estimate the theoretical uncertainty related to the VMD model, we refer back to 1977, when Boreskov and Ioffe [8] estimated the cross section of  $J/\psi$  photoproduction in a peripheral model and found a strong energy dependence close to threshold because the nondiagonal  $\gamma p \rightarrow J/\psi p$  must have larger transfer momenta versus elastic scattering. This results in a violation of VMD by a factor of 5 or so. In 1993, Boreskov and co-workers showed that a fluctuation of a photon into open charm is preferable than into a  $J/\psi$  [9]. In addition, in Eq. (3) we have not included a factor introduced in the VMD model in Ref. [15], which takes into account the difference between polarization degrees of freedom in the  $\gamma p \rightarrow J/\psi p$  and  $pJ/\psi \rightarrow pJ/\psi$  reactions. Such a factor that equals 2/3 at threshold for the  $S$  wave has not been used in the previous analysis of the scattering length and we consider it as a systematic uncertainty related to the VMD model.

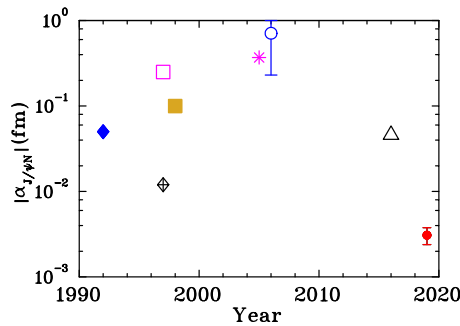


FIG. 2. Comparison of different determinations of  $|\alpha_{J/\psi p}|$  scattering length. The red filled circle shows our result, the black open triangle is from Ref. [16], the blue open circle is from Ref. [20], the magenta star is from Ref. [17], the yellow filled square is from Ref. [21], the magenta open square is from Ref. [18], the black open diamond with cross is from Ref. [22], and the blue filled diamond is from Ref. [19]. Note that the values from Refs. [18,21] (yellow filled and magenta open square, respectively) are negative.

Nevertheless, the present estimate for the absolute value  $|\alpha_{J/\psi p}|$  using the near-threshold photoproduction of charmonium data from the GlueX Collaboration is within the broad range defined by other  $\alpha_{J/\psi p}$  values available in the literature:  $0.046 \pm 0.005$  fm from a global fit to both previous differential and total cross section data [16], 0.37 fm from the multipole expansion and low-energy theorems in QCD [17],  $-0.25$  fm from the gluonic van der Waals interaction [18], 0.05 fm from a multipole expansion for heavy-quarkonia interactions with gluon fields and low-energy QCD theorems for gluon interactions with nucleons [19],  $0.71 \pm 0.48$  fm from lattice QCD calculations [20],  $-0.1$  fm from QCD sum rules [21], and 0.012 fm from the gauge-invariant quark-antiquark Greens function for the expression of the nonrelativistic meson scattering amplitude on the external gluon field [22] (see Fig. 2).

Our result disagrees with the recent work of Ref. [16] based on the fit of the previous data from SLAC and other

data far away from the threshold [12]. Note that our value of  $|\alpha_{J/\psi p}|$  is much less than the recent  $\omega$  photoproduction at the threshold result from the A2 Collaboration at MAMI for the  $\omega p$  scattering length  $|\alpha_{\omega p}| = (0.82 \pm 0.03)$  fm [13] and much less than a typical size of a hadron.

In summary, an experimental study of charmonium photoproduction off the proton was conducted by the GlueX Collaboration at JLab [10]. The proximity of the new GlueX data to the threshold allows to estimate the  $J/\psi p$  scattering length within the VMD model. Note that the first data bin (Fig. 1) has a weighted average of  $q = 230$  MeV/c, or  $1/q = 0.86$  fm is of the order of the proton size. Our result for the  $|\alpha_{J/\psi N}|$  scattering length disagrees with previous theoretical results individually, though it is within the wide range of these predictions. Our small value of the scattering length (regardless of its sign) vs a typical size of a hadron, 1 fm, indicates that the proton is transparent for  $J/\psi$ . Within VMD the  $J/\psi$  photo production is suppressed as  $m_\omega^2/m_{J/\psi}^2$  as compared with the  $\omega$  photoproduction. Present and future experiments at Jefferson Lab that are aimed to measure the charmonium production off proton and nuclei [23–26] will allow further studies of the  $J/\psi N$  interaction and will give also access to a variety of other interesting physics aspects that are present in the near-threshold region.

We thank Konstantin Boreskov, Alexander Titov, and Arkady Vainstein for useful remarks and continuous interest in the paper and Daniel Carman, Eugene Chudakov, and Michael Eides for valuable comments. This work was supported in part by the US Department of Energy, Office of Science, Office of Nuclear Physics under Award No. DE-SC0016583 and Contract No. DE-AC05-06OR23177. One of the authors (I.I.S.) highly appreciates the hospitality extended to him by the Munich Institute for Astro- and Particle Physics (MIAPP) of the DFG cluster of excellence ‘‘Origin and Structure of the Universe’’ which is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy - EXC-2094-390783311.

[1] J. J. Aubert *et al.* (E598 Collaboration), *Phys. Rev. Lett.* **33**, 1404 (1974).  
 [2] J. E. Augustin *et al.* (SLAC-SP-017 Collaboration), *Phys. Rev. Lett.* **33**, 1406 (1974); *Adv. Exp. Phys.* **5**, 141 (1976).  
 [3] M. Gell-Mann and F. Zachariasen, *Phys. Rev.* **124**, 953 (1961).  
 [4] J. J. Sakurai, *Currents and Mesons* (The University of Chicago Press, Chicago, 1969).  
 [5] N. M. Kroll, T. D. Lee, and B. Zumino, *Phys. Rev.* **157**, 1376 (1967).  
 [6] M. F. M. Lutz, G. Wolf, and B. Friman, *Nucl. Phys. A* **706**, 431 (2002); *Erratum -* **765**, 495 (2006).  
 [7] A. I. Titov, T. Nakano, S. Date, and Y. Ohashi, *Phys. Rev. C* **76**, 048202 (2007).  
 [8] K. G. Boreskov and B. L. Ioffe, *Yad. Fiz.* **25**, 806 (1977) [*Sov. J. Nucl. Phys.* **25**, 331 (1977)].  
 [9] K. Boreskov, A. Capella, A. Kaidalov, and J. Tran Thanh Van, *Phys. Rev. D* **47**, 919 (1993).  
 [10] A. Ali *et al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019).  
 [11] B. Gittelman, K. M. Hanson, D. Larson, E. Loh, A. Silverman, and G. Theodosiou, *Phys. Rev. Lett.* **35**, 1616 (1975).  
 [12] U. Camerini *et al.*, *Phys. Rev. Lett.* **35**, 483 (1975).  
 [13] I. I. Strakovsky *et al.* (A2 Collaboration at MAMI) *Phys. Rev. C* **91**, 045207 (2015).  
 [14] V. V. Anashin *et al.* (KEDR Collaboration), *J. High Energy Phys.* **05** (2018) 119.  
 [15] V. Kubarovsky and M. B. Voloshin, *Phys. Rev. D* **92**, 031502(R) (2015).  
 [16] O. Gryniuk and M. Vanderhaeghen, *Phys. Rev. D* **94**, 074001 (2016).  
 [17] A. Sibirtsev and M. B. Voloshin, *Phys. Rev. D* **71**, 076005 (2005).  
 [18] S. J. Brodsky and G. A. Miller, *Phys. Lett. B* **412**, 125 (1997).  
 [19] A. B. Kaidalov and P. E. Volkovitsky, *Phys. Rev. Lett.* **69**, 3155 (1992).  
 [20] A. Ali *et al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019).  
 [21] B. Gittelman, K. M. Hanson, D. Larson, E. Loh, A. Silverman, and G. Theodosiou, *Phys. Rev. Lett.* **35**, 1616 (1975).  
 [22] U. Camerini *et al.*, *Phys. Rev. Lett.* **35**, 483 (1975).  
 [23] I. I. Strakovsky *et al.* (A2 Collaboration at MAMI) *Phys. Rev. C* **91**, 045207 (2015).  
 [24] V. V. Anashin *et al.* (KEDR Collaboration), *J. High Energy Phys.* **05** (2018) 119.  
 [25] V. Kubarovsky and M. B. Voloshin, *Phys. Rev. D* **92**, 031502(R) (2015).  
 [26] O. Gryniuk and M. Vanderhaeghen, *Phys. Rev. D* **94**, 074001 (2016).  
 [27] A. Sibirtsev and M. B. Voloshin, *Phys. Rev. D* **71**, 076005 (2005).  
 [28] S. J. Brodsky and G. A. Miller, *Phys. Lett. B* **412**, 125 (1997).  
 [29] A. B. Kaidalov and P. E. Volkovitsky, *Phys. Rev. Lett.* **69**, 3155 (1992).

- [20] K. Yokokawa, S. Sasaki, T. Hatsuda, and A. Hayashigaki, *Phys. Rev. D* **74**, 034504 (2006).
- [21] A. Hayashigaki, *Prog. Theor. Phys.* **101**, 923 (1999).
- [22] V. I. Shevchenko, *Phys. Lett. B* **392**, 457 (1997).
- [23] Mapping the spectrum of light quark mesons and gluonic excitations with linearly polarized photons, Spokesperson: C. A. Meyer, JLab E12-06-102, Newport News, VA, USA, 2006, [https://www.jlab.org/exp\\_prog/proposals/06/PR12-06-102.pdf](https://www.jlab.org/exp_prog/proposals/06/PR12-06-102.pdf); An initial study of mesons and baryons containing strange quarks with GlueX, JLab E12-13-003, Newport News, VA, USA, 2013, [https://www.jlab.org/exp\\_prog/proposals/13/PR12-13-003.pdf](https://www.jlab.org/exp_prog/proposals/13/PR12-13-003.pdf).
- [24] Near threshold  $J/\psi$  photoproduction and study of LHCb pentaquarks with CLAS12, Spokespersons: S. Stepanyan, M. Battaglieri, A. Celentano, R. De Vita, and V. Kubarovsky, JLab E12-12-001A, Newport News, VA, USA, 2012, [https://www.jlab.org/exp\\_prog/proposals/17/E12-12-001A.pdf](https://www.jlab.org/exp_prog/proposals/17/E12-12-001A.pdf).
- [25] Study of  $J/\psi$  photoproduction off deuteron, spokespersons: Y. Ilieva, B. McKinnon, P. Nadel-Turonski, V. Kubarovsky, S. Stepanyan, and Z. W. Zhao, JLab E12-11-003B, Newport News, VA, USA, 2011, [https://www.jlab.org/exp\\_prog/proposals/18/E12-11-003B.pdf](https://www.jlab.org/exp_prog/proposals/18/E12-11-003B.pdf).
- [26] A search for the LHCb charmed “pentaquark” using photoproduction of  $J/\psi$  at threshold in Hall C at Jefferson lab, Spokespersons: Z.-E. Meziani, S. Joosten, M. Paolone, E. Chudakov, and M. Jones, JLab E12-16-007, Newport News, VA, USA, 2016, [https://www.jlab.org/exp\\_prog/proposals/16/PR12-16-007.pdf](https://www.jlab.org/exp_prog/proposals/16/PR12-16-007.pdf).