J/ψp Scattering Length from GlueX Threshold Measurements

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The quality of the recent GlueX J/ψ 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/ψ-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.

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Since the discovery of the $J/\psi(1S)$ resonance [1, 2], it became an attractive probe to study interactions with hadronic matter. The J/ψ is a vector meson and our understanding of the coupling of the other vector mesons, such as ω, ρ, and ϕ 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 to probe 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. A large scattering length corresponds to a high binding energy. A small positive or negative scattering length $\alpha_{J/\psi N}$ may indicate a weakly repulsive or attractive or $J/\psi N$ interaction if there is no $J/\psi N$ bound state.

Recently, the GlueX Collaboration reported the first total cross section σ_t measurements for the exclusive reaction $\gamma p \to J/\psi p$ at threshold [3]. 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 [4] at 11 GeV and SLAC [5] 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 σ_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_γ 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. [6]. In general, the total cross section for an inelastic reaction $ab \to cd$ with particle masses $m_a + m_b < m_c + m_d$ can be written as $\sigma_t = \frac{q}{W} \cdot F(W^2)$, 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 E_γ for the charmonium photoproduction, the value of σ_t as a function of the photon energy in the laboratory frame E_γ 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 σ_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,

$$\sigma_t(q) = a_1 q + a_3 q^3 + a_5 q^5 \tag{1}$$

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_γ. To calculate the total cross sections from the SLAC data, we have used a dipole t-dependence as was done in Ref. [3].

TABLE I. The fit of the GlueX [3] (2nd colomn) and GlueX with SLAC [5] (3rd colomn) 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±0.16	0.53±0.12
a_3 [nb/(GeV/c)^3]	0.83±0.91	0.78±0.16
a_5 [nb/(GeV/c)^5]	0.28±0.87	-0.06±0.03
χ^2/dof	0.67	0.98

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 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.

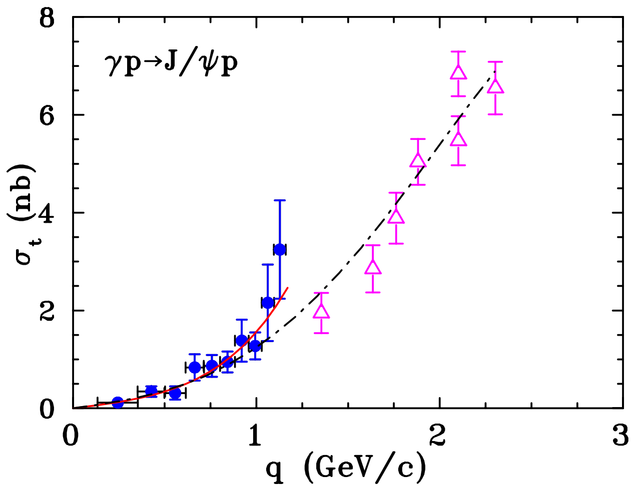

FIG. 1. Results of the GlueX work (blue solid circles) for the $\gamma p \to J/\psi p$ total cross sections σ_t [3] are shown as a function of the c.m. momentum q of the final-state particles. The previous SLAC data [5] (where the determination of σ_t from the differential cross sections was performed in Ref. [3]) 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).

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

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

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 $\gamma p \to J/\psi p$ cross-section near threshold [7]:

$$\sigma_t(\gamma p \to J/\psi p)|_{th} = \frac{q}{k} \cdot \frac{4\alpha\pi^2}{g^2_{J/\psi\gamma}} \cdot |\alpha_{J/\psi p}|^2, \tag{3}$$

where k is the c.m. momentum of the incident photon at the $\gamma p \to J/\psi p$ threshold, α is the fine-structure constant, M is the J/ψ mass, and $g_{J/\psi\gamma} = 5.58 \pm 0.07$ is the $\gamma \to J/\psi$ coupling, as determined from the $J/\psi \to e^+e^-$ decay width [8]. This result came recently from the KEDR Collaboration that determined $\Gamma(J/\psi \to e^+e^-)$ using the KEDR detector at the VEPP-4M e^+e^- collider. Summing the statistical and systematic uncertainties in quadrature, one gets $\Gamma(J/\psi \to e^+e^-) = (5.55 \pm 0.11)$ keV. As known in VMD, the coupling $g_{J/\psi\gamma}$ is related to the electron width of the vector meson $\Gamma(J/\psi \to e^+e^-)$ as:

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

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

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

which should be considered just as an estimate assuming only the sequence $\gamma \to J/\psi$, $J/\psi p \to J/\psi p$. 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 [9] estimated the cross section of J/ψ photoproduction in a peripheral model and found a strong energy dependence close to threshold because the non-diagonal $\gamma p \to J/\psi p$ 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/ψ [10]. In addition, in Eq. (3) we have not included a factor introduced in the VMD model in Ref. [11], which takes into account the difference between polarization degrees of freedom in the $\gamma p \to J/\psi p$ and $pJ/\psi \to pJ/\psi$ 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.

Nevertheless, the present estimate for $|\alpha_{J/\psi p}|$ 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±0.005 fm from a global fit to both previous differential and total cross section data [12], 0.37 fm from the multipole expansion and low-energy theorems in QCD [13], -0.25 fm from the gluonic van der Waals interaction [14], 0.05 fm from a multipole expansion for heavy-quarkonia interactions with gluon fields and low-energy QCD theorems for gluon interactions with nucleons [15], 0.71±0.48 fm from Lattice QCD calculations [16], -0.1 fm from QCD sum rules [17], and 0.012 fm from the gauge-invariant quark-antiquark Greens function for the expression of the non-relativistic meson scattering amplitude on the external gluon field [18] (see Fig. 2).

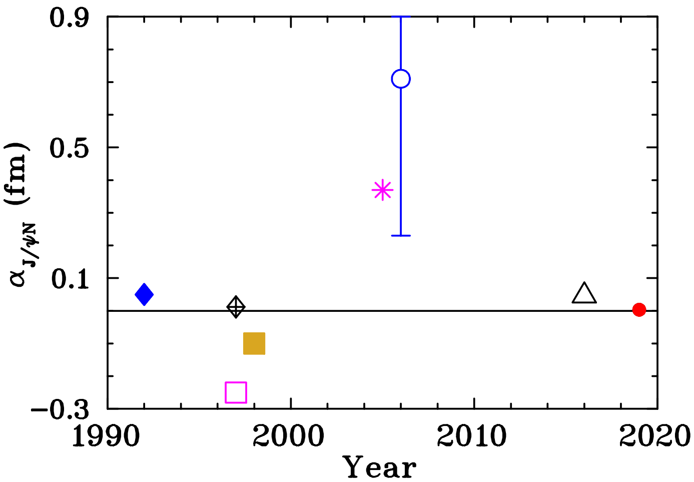

FIG. 2. Comparison of different determinations of $\alpha_{J/\psi p}$ scattering length. The red filled circle shows our result, the black open triangle is from Ref. [12], the blue open circle is from Ref. [16], the magenta star is from Ref. [13], the yellow filled square is from Ref. [17], the magenta open square is from Ref. [14], the black open diamond with cross is from Ref. [18], and the blue filled diamond is from Ref. [15].

Our result disagrees with the recent work of Ref. [12] based on the fit of the previous data from SLAC and other data far away from the threshold [5]. Note that our value of $|\alpha_{J/\psi p}|$ is much less than the recent ω photoproduction at the threshold result from the A2 Collaboration at MAMI for the ωp scattering length $|\alpha_{\omega p}| = (0.82 \pm 0.03)$ fm [6] 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 [3]. 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 scattering length vs a typical size of a hadron, 1 fm, indicates that the proton is transparent for J/ψ. Within VDM the J/ψ photo production is suppressed as $m_\omega^2/m_{J/\psi}^2$ as compared with the ω photoproduction. Present and future experiments at Jefferson Lab that are aimed to measure the charmonium production off proton and nuclei [19–22] 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.

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