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.
Since the discovery of the $J/\psi(1S)$ resonance \cite{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. 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 $J/\psi N$ interaction if there is no $J/\psi N$ bound state.

Recently, the GlueX Collaboration reported the first total cross section $\sigma$ measurements for the exclusive reaction $\gamma p \rightarrow J/\psi p$ at threshold \cite{3}. This is a unique experiment that measured $\sigma_t(E)$ from threshold at a photon energy of $E_\gamma = 8.2 \text{ GeV}$ to $11.85 \text{ GeV}$. Previous old measurements at Cornell \cite{4} at $11 \text{ GeV}$ and SLAC \cite{5} above $13 \text{ GeV}$ 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, $8.2 - 9 \text{ GeV}$, 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. \cite{6}. 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 $\sigma_t = F(W^2) \cdot F(W^2)$, 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 $F(W^2)$ from the integration over the final-state phase space. Because $W^2$ is linearly related to the photon energy $E_\gamma$ 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 $E_\gamma = E_{\gamma}^\text{th}$ 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,

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

(1)

is enough to describe the near threshold cross section $\sigma_t(q)$ quite well. The fit of the GlueX data with Eq. \cite{3} is shown in Fig. \ref{fig} by a solid red curve. The fit of both GlueX and SLAC data is shown in Fig. \ref{fig} as well, by a black dot-dashed curve. The best-fit results are summarized in Table \ref{table} Note that the SLAC experiment measured the differential cross-section $d\sigma/dt$ at $t = t_{\text{min}}$ 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. \cite{3}.

**TABLE I.** The fit of the GlueX \cite{3} (2nd column) and GlueX with SLAC \cite{5} (3rd column) data with Eq. \cite{3}. 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 |
| $\chi^2$/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 \ref{table}), the near threshold behavior is very similar for both curves. The linear term in Eq. \cite{3} 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 $\sigma_t(\gamma p \to J/\psi p)$ data is related to the $J/\psi N$ scattering length, $\alpha_{J/\psi p}$, by the threshold relation:

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

(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]:

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

(3)

where $k$ is the c.m. momentum of the incident photon at the $\gamma p \to J/\psi p$ 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 $\gamma \to J/\psi$ 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:

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

(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

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

(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 $|\alpha_{J/\psi p}| = (3.08 \pm 0.55\text{(stat.)} \pm 0.42\text{(syst.)})$ fm.

To estimate the theoretical uncertainty related to the VMD model, we refer back to 1977, when Boreskov and Ioffe \cite{9} estimated the cross section of $J/\psi$ photoproduction in a peripheral model and found a strong energy dependence close to threshold because the non-diagonal $\gamma p \rightarrow J/\psi p$ 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 $J/\psi$ \cite{10}. In addition, in Eq. (3) we have not included a factor introduced in the VMD model in Ref. \cite{11}, 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.

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 \cite{12}, 0.37 fm from the multipole expansion and low-energy theorems in QCD \cite{13}, -0.25 fm from the gluonic van der Waals interaction \cite{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 \cite{15}, 0.71±0.48 fm from Lattice QCD calculations \cite{16}, -0.1 fm from QCD sum rules \cite{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 \cite{18} (see Fig. 2).

Our result disagrees with the recent work of Ref. \cite{12} based on the fit of the previous data from SLAC and other data far away from the threshold \cite{4}. 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 $|\alpha_{\omega p}| = (0.82\pm0.03)$ fm \cite{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 \cite{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 $J/\psi$. Within VDM 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 \cite{19,22} will allow further

![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. \cite{12}, the blue open circle is from Ref. \cite{16}, the magenta star is from Ref. \cite{13}, the yellow filled square is from Ref. \cite{17}, the magenta open square is from Ref. \cite{14}, the black open diamond with cross is from Ref. \cite{18}, and the blue filled diamond is from Ref. \cite{15}.](image-url)
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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