We published the result of a measurement of the differential cross section for the $\gamma n \rightarrow \pi^- p$ process from the CLAS detector at Jefferson Lab in Hall B for photon energies between 1.0 and 3.5 GeV and pion center-of-mass (c.m.) angles ($\theta_{\text{c.m.}}$) between 50° and 115°. In the paper, we confirm a previous indication of a broad enhancement around a c.m. energy ($\sqrt{s}$) of 2.1 GeV at $\theta_{\text{c.m.}} = 90°$ in the scaled differential cross section, $s^{7/4} \frac{d\sigma}{dt}$ and a rapid fall-off in a center-of-mass energy region of about 400 MeV following the enhancement. Our data show an angular dependence of this enhancement as the suggested scaling region is approached for $\theta_{\text{c.m.}}$ from 70° to 105°.

We published the result of a first measurement of the differential cross section of $\phi$-meson photoproduction for the $d(\gamma, pK^+K^-)n$ exclusive reaction channel from the CLAS detector at JLab in Hall B. A combined analysis using data from the $d(\gamma, pK^+K^-)n$ channel and those from a previous publication on coherent $\phi$ production on the deuteron has been carried out to extract the $\phi N$ total cross section. The extracted $\phi N$ total cross section favors a value above 20 mb. This value is larger than the value extracted using vector-meson dominance models for photoproduction on the proton.

Publications


Talks

1. “Cross-section measurement of the $\gamma n \rightarrow \pi^- p$ process from deuterium” DNP2008, Oct 23 - 26, 2008, Oakland, CA USA.

2. “A measurement of the differential cross section for the reaction $\gamma n \rightarrow \pi^- p$ from deuterium” GHP2009, Apr 29, 2009, Denver, CO USA.

3. “A measurement of the differential cross section for the reaction $\gamma n \rightarrow \pi^- p$ from deuterium” OCPA6, August 3 - 7, 2009, Lanzhou, China.
Measurement of the Differential Cross Section for the Reaction $\gamma n \rightarrow \pi^- p$ from Deuterium


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We report a measurement of the differential cross section for the $\gamma n \rightarrow \pi^- p$ process from the CLAS detector at Jefferson Laboratory in Hall B for photon energies between 1.0 and 3.5 GeV and pion center-of-mass (c.m.) angles ($\theta_{c.m.}$) between 50° and 115°. We confirm a previous indication of a broad enhancement around a c.m. energy ($\sqrt{s}$) of 2.1 GeV at $\theta_{c.m.} = 90°$ in the scaled differential cross section $s^{d\sigma/dt}$ and a rapid falloff in a center-of-mass energy region of about 400 MeV following the enhancement. Our data show an angular dependence of this enhancement as the suggested scaling region is approached for $\theta_{c.m.}$ from 70° to 105°.

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The $\gamma n \rightarrow \pi^- p$, $\gamma p \rightarrow \pi^+ n$, and $\gamma p \rightarrow \pi^0 n$ reactions are fundamental processes that are ideal candidates for the study of the strong interaction. At intermediate energies these processes have been used to study nucleon resonances and the transition from nucleon-meson to quark-gluon degrees of freedom. Recently at Jefferson Laboratory, the differential cross sections on the charged pion photoproduction on hydrogen (proton) and deuterium (deuteron) targets [1,2] have been measured at intermediate energies. These measurements have shown that the differential cross section for pion photoproduction at fixed c.m. angles of 70° and 90° seem to scale as $d\sigma/dt \propto s^{-(n-2)}$ as predicted by the constituent counting rule (CCR) [3,4]. Here $s$ is the invariant Mandelstam variable for the total energy squared, and $n$ is the total number of point particles and gauge fields involved. The CCR was proposed as a signature for the transition from the nucleon-meson to the quark-gluon picture. While such predicted scaling behavior has been seen in a number of exclusive reactions at a specific kinematic regime [5–11], questions remain such as why scaling seems to set in at a surprisingly low transverse momentum value above about 1.1 GeV/c [9,11]. If the observed scaling is the expected CCR, is there a clear signature for such a transition?

In addition to the onset of scaling, the recent charged pion photoproduction experiment [1,2] also observed an apparent enhancement in the scaled differential cross section at $\theta_{c.m.} = 90°$ and at $\sqrt{s} = 1.8–2.5$ GeV. Furthermore, just before the onset of scaling behavior, the scaled cross section drops by a factor of 4 in a very narrow c.m. energy range of few hundreds of MeV around $\sqrt{s} = 2.5$ GeV. Is this a signature for the transition from the nucleon-meson degrees of freedom to the quark-gluon degrees? The coarse energy binning of these data did not allow for a detailed investigation of either the true nature of the apparent scaling behavior or the observed enhancement, and it did not allow for an analysis of the drop in the differential cross section.

In this Letter, we report on a measurement aimed at a mapping of the transition from one region to another and providing a detailed investigation of the observed enhancement and the drop in the differential cross section for the $\gamma n \rightarrow \pi^- p$ process. This measurement was carried out over the range $\sqrt{s}$ from 1.8 to 2.5 GeV with a very fine photon energy binning and a high statistical precision, using the Jefferson Laboratory CEBAF Large Acceptance Spectrometer (CLAS) [12] in Hall B.

The CLAS instrumentation was designed to provide large coverage of charged particles (8° ≤ $\theta$ ≤ 140°). It is divided into six sectors by six superconducting coils which generate a toroidal magnetic field. Each sector acts as an independent detection system that includes drift chambers (DCs), Cherenkov counters, scintillation counters (SCs), and electromagnetic calorimeters. The drift chambers determine the trajectories of charged particles. With the magnetic field generated by the superconducting coils, the momenta of the charged particle can be determined from the curvature of the trajectories. The scintillation counters measure the time-of-flight and provide charged particle identification when combined with the momentum information from the drift chambers. Details about the CLAS detector can be found in Ref. [12].

A 24-cm-long liquid-deuteron target was employed with the target cell positioned 25 cm upstream from the CLAS nominal center. A tagged-photon beam [13] generated by a 3.8-GeV electron beam incident on a gold radiator with a radiation length of $10^{-4}$ corresponded to a maximum $\sqrt{s}$ of 2.8 GeV for the process of interest. The event trigger required at least two charged particles in different sectors. Two magnetic field settings were used during the experiment, corresponding to a low-field setting (with toroidal magnet current $I = 2250$ A) for better forward angle coverage, and a high-field setting ($I = 3375$ A) for better momentum resolution. About $10^{10}$ triggers were collected during a running period of about two months.

The raw data collected from the experiment were first processed to calibrate and convert the information from the detector subsystems to physical variables for detected particles such as energy, momentum, position, and timing information. The events of interest for which the photon coupled to the neutron inside the deuteron were selected by ensuring a proton and a $\pi^-$ in the final state. The difference
of the reconstructed time of photon and charged particles at the reaction vertex was required to be within 1 ns to ensure that they came from the same accelerator electron bunch, which had a period of 2.004 ns. The momentum of the spectator proton in the deuteron is mostly below 200 MeV/c and is therefore not detected by CLAS. The 4 momentum of the undetected proton was reconstructed by energy-momentum conservation. Only events with missing mass around the proton mass were selected to make sure that the missing particle was the undetected proton. Shown in Fig. 1(a) is a typical reconstructed missing mass squared distribution. A 3σ cut was applied to identify the proton. Monte Carlo simulations for the γn → π− p process based on a phase space generator have been carried out to determine the acceptance. In the simulation, the neutron momentum distribution inside the deuteron is based on the deuteron wave function obtained from the Bonn potential [14]. Figure 1(b) shows the reconstructed proton momentum from the experimental data and the simulation. The excellent agreement between the data and the Monte Carlo for a missing momentum below 200 MeV/c justified the cut we used (shown by the dashed line) in our analysis to select the quasifree events of γn → π− p from deuterons.

To extract the cross section, the aforementioned phase space based simulation is used to correct for events lost due to geometrical constraints and detector inefficiencies. The response of the CLAS detector was simulated in GEANT. More than $10^8$ events were generated and passed through the simulation. The simulated data were then processed to incorporate the subsystem efficiencies and resolutions extracted from the experiment. The DC wire efficiency and SC efficiency were studied in detail. The “excluded-layer method” [15] was used to study the DC wire efficiency and identify the bad DC regions. The SC efficiency was extracted by studying the SC occupancies.

The correction due to the SC inefficiency is about 20% for the γn → π− p channel. All the simulated data were then processed by the same software used in the real data processing and analysis. The ratio between the events that passed the simulation and the generated events is a product of the detector efficiency and the acceptance.

The final state interaction (FSI) effects have been taken into account before one extracts cross sections on the neutron since a deuteron target is used. The FSI correction is calculated according to the Glauber formulation [16], and this correction is about 15%–30%, depending on energy and angle.

The differential cross section in the c.m. frame of the γn system is then given by

$$\frac{d\sigma}{d\Omega_{c.m.}} = \frac{N}{t_\gamma \epsilon N_\gamma} A \frac{1}{\rho L N_A} \frac{1}{d\Omega_{c.m.}},$$

where $t_\gamma$ is the correction [16] for the FSI, $\epsilon$ is the product of the detector efficiency and acceptance, $N$ is the number of events, $N_\gamma$ is the total number of photons incident on the target, and $A$, $N_A$, $L$, $\rho$ are deuteron atomic mass, Avogadro’s number, target length, and target density, respectively. The scaled differential cross section is defined as

$$s^7 \frac{d\sigma}{dt} = s^7 \frac{d\sigma}{d\Omega_{c.m.}} \frac{d\Omega_{c.m.}}{dt} = s^7 \frac{d\sigma}{d\Omega_{c.m.}} \frac{\pi}{E_{c.m.}^\gamma p_{c.m.}^\pi},$$

where $E_{c.m.}^\gamma$ and $p_{c.m.}^\pi$ are the photon energy and π− momentum in the c.m. frame, respectively. The results from the high magnetic field setting are consistent with those from the low magnetic field setting within systematic uncertainties. The results from the two settings are combined.

There are three major sources of systematic uncertainties: the luminosity, the FSI correction, and the background. We studied the target thickness fluctuations as

![Graph](image1.png)

**FIG. 1** (color online). (a) Reconstructed missing mass squared of the spectator proton fitted with a Gaussian plus linear function. The arrow indicates the mass squared of the proton. (b) Reconstructed spectator proton momentum (missing momentum) from this experiment together with a Monte Carlo simulation.
seen by the beam, as well as the run-dependent and beam-current-dependent fluctuations of the normalized yield. All of them contribute to the uncertainty in the luminosity, and in total this uncertainty is less than 5%. The uncertainty of the Glauber calculation for the FSI correction was estimated to be 5% in Ref. [1]. To study the model uncertainty in calculating the FSI correction, we carried out another calculation using the approach of Ref. [17]. Both methods agree within 10%. A 10% systematic uncertainty to the differential cross section is assigned for the FSI correction. The background in the missing mass peak region is about 2%–7% depending on the photon energy, and an example is shown in Fig. 1(a). According to Monte Carlo simulations, the background could come from the poorly reconstructed real events due to the DC resolution. Therefore, no background was subtracted in this analysis; instead the fitted background was assigned as the systematic uncertainty. The total systematic uncertainty is the quadratic sum of all the systematic uncertainties, and is between 11% and 13% on the extracted differential cross sections.

Figure 2 shows the scaled differential cross section $s^2 d \sigma / d t$ as a function of $\sqrt{s}$ for $\theta_{c.m.} = 90^\circ$ for three different channels. The results from this experiment are shown in the middle panel as red solid circles with statistical uncertainties, and the systematic uncertainty is shown as a band. The error bars for E94-104 [1] include both the statistical and systematic uncertainties, while only statistical uncertainties are shown for the $\pi^0$ data [18] and the $\pi^+$ data [19]. All other world data are collected from Refs. [5,20]. Our data are consistent with the E94-104 results [1] within experimental uncertainties. With fine photon energy bins and high statistical precision, our data confirm a broad enhancement around $\sqrt{s}$ of 2.1 GeV in the scaled differential cross section. Our data also confirm a marked falloff of the differential cross section in a narrow energy window of about 400 MeV above this enhancement and the onset of the CCR scaling for $\sqrt{s}$ around 2.8 GeV as suggested by an earlier Jefferson Laboratory experiment [1] (shown as green solid squares). Similar behavior has been seen in the recent CLAS g1c $\pi^+$ photoproduction data [19] (magenta open squares in Fig. 2). While this falloff may be taken as a signature for the transition from nucleon-meson degrees of freedom to quark-gluon degrees of freedom, theoretical studies in this region are needed to confirm this speculation. Also shown are the results of the SAID SP09 partial wave analysis [19] (blue solid curve), the MAID07 model [21] (cyan dashed curve), and the prediction from a Regge approach [22] (black solid curve).

In the Regge calculation, no baryon resonances in this energy region were included. And the results did not predict the enhancement seen in our data. Thus the deviation is speculated to be due to baryon resonances [22].

While the SAID SP09 fit has been greatly improved by the CLAS $\pi^0$ [18], the $\pi^+$ data [19], and the Hall-A $\pi^-$ data [1,2], it does not give as good a description of our data near the peak of the enhancement. Further, it fails to constrain the $\pi^-$ channel and does not describe our data well above $\sqrt{s}$ of 2.3 GeV (not shown in Fig. 2). The precision data presented here will help to further constrain the SAID fit and will allow for a determination of the corresponding neutron electromagnetic parameters for resonances classified as 4 star by the PDG [23]. These studies will be reported in a future publication.

Figure 3 (top panel) shows the scaled differential cross section $s^2 d \sigma / d t$ as a function of $\sqrt{s}$ for $\theta_{c.m.} = 50^\circ$ to $115^\circ$ with an angular bin size of 5° for the $\gamma n \rightarrow \pi^+ p$ process. As in Fig. 2, the systematic uncertainties are shown as bands in Fig. 3. The arrows indicate the location of $\sqrt{s}$ corresponding to a pion transverse momentum ($p_T$) of 1.1 GeV/c. This $p_T$ value was suggested to govern the scaling onset by Refs. [9,11]. We note the large discrepancy between our results and those from Ref. [24] at $\theta_{c.m.} = 75^\circ$ and $95^\circ$. We also note that the SAID fits [18,19] did not include data from Ref. [24]. An angular-dependent feature in the scaled differential cross section is
clearly seen in our data. The aforementioned broad enhancement around a \( \sqrt{s} \) value of 2.1 GeV at \( \theta_{\text{c.m.}} = 90^\circ \) seems to shift as a function of \( \theta_{\text{c.m.}} \) from \( \sqrt{s} \) of 1.80 GeV at 50° to 2.45 GeV at 105° as shown by the red dotted lines. Our studies show that such behavior is not an artifact of the \( s^3 \) scaling factor. It is not clear whether this enhancement dies off for \( \theta_{\text{c.m.}} > 105^\circ \) or it shifts to further higher energies. The blue dashed lines indicate the locations of the nucleon resonances around 1.2 GeV and 1.5 GeV which, as expected, do not change with \( \theta_{\text{c.m.}} \). However, such an angular-dependent enhancement is not seen in the \( \pi^+ \) (see the bottom panel of Fig. 3) and \( \pi^0 \) channels from the proton. The SAID FA09 prediction is also shown in Fig. 3 (blue solid curve), and it does show an enhancement around \( \sqrt{s} \) of 2.2 GeV which is not angular dependent. Our studies show that such a behavior is not due to the FSI correction. The observed angular-dependent enhancement structure in the \( \pi^- \) channel could be due to some unknown resonances which couple differently to the neutron channel than to the proton channel. Polarization data from all three channels and partial wave analysis are necessary in order to understand the nature of this enhancement and its angular dependence in the \( \pi^- \) channel.

The data presented in this Letter are the first high statistical precision measurement of the differential cross section of the \( \gamma n \rightarrow \pi^- p \) process in the region \( \sqrt{s} \approx 1.8-2.5 \) GeV with fine photon energy bins, and a pion center-of-mass angle between 50° and 115°. Our data suggest a possible signature for the transition to the CCR scaling region, in the form of a falloff of the scaled cross section over a narrow energy range. An angular-dependent enhancement in the scaled differential cross section has been seen for the first time in our data, which is different from that of the \( \gamma p \rightarrow \pi^+ n \) process, and it is also different from the lastest SAID prediction.

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The extraction of $\phi$–$N$ total cross section from $d(\gamma, pK^+K^-)n$

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Multi-gluon exchange between hadrons, known as pomeron exchange, is a fundamental process and plays an important role in high-energy interactions. At lower energies, this exchange manifests itself in a QCD van der Waals interaction [1]. Studying multi-gluon exchange at lower energies is challenging because at low energies hadron–hadron interactions are dominated by quark exchange. However, multi-gluon exchange is expected to be dominant in the interaction between two hadrons when they have no common quarks. The \( \phi \) meson is unique in that it is nearly an \( s \bar{s} \) state and hence gluon exchange is expected to dominate the \( \phi-N \) scattering process.

Direct measurement of the \( \phi-N \) cross section is not possible due to lack of \( \phi \) meson beams. An upper limit of \( \sigma_{\phi N} \lesssim 11 \text{ mb} \) [2] is obtained using the \( \phi \) photoproduction data on the proton and the vector meson dominance (VMD) model [3], which is in agreement with the estimate from the additive quark model [4]. In a geometric interpretation of hadron–proton total cross sections [5], the radius of the \( \phi \) meson \( r_{\phi} \) can be estimated from the comparison of the total cross sections of \( \pi-N \) (\( \sigma_{\pi N} \)) and \( \phi-N \) (\( \sigma_{\phi N} \)) scattering. The value of \( \sigma_{\phi N} \) is \( \sim 24 \text{ mb} \) [5] and the \( \pi \) radius \( r_{\pi} \) is \( \sim 0.65 \text{ fm} \) [5]. An upper limit of \( \sigma_{\phi N} \sim 11 \text{ mb} \) [2] leads to an upper limit value of \( \sim 0.43 \text{ fm} \) for \( r_{\phi} \).

However, from the observed \( A \)-dependence of nuclear \( \phi \) photoproduction, a larger value of \( \langle \text{inelastic} \rangle \sigma_{\phi N}^{\text{inel}} \sim 35 \text{ mb} \) [6], which is part of the total \( \sigma_{\phi N} \) is obtained, which suggests a larger \( r_{\phi} \) value than 0.43 fm. Medium modification of the vector meson properties [7] (such as radius) or channel coupling effects [2] have been proposed to explain the aforementioned difference in the cross section for the \( \phi \) meson. A similar phenomenon has been observed for the \( J/\Psi \) meson [8] and the color transparency effect is proposed [9] to explain the observation.

In this Letter, we present a determination of \( \sigma_{\phi N} \) using the differential cross section of the incoherent \( \phi \)-meson photoproduction from deuterium. This process takes advantage of the rescattering of a \( \phi \) meson from the spectator nucleon. In the reaction \( \gamma + d \to \phi + p + n \), the rescattering process will dominate for the kinematics where both nucleons are energetic. The deuteron is a system of loosely bound nucleons and, hence, nuclear medium effects should not play a significant role in the \( \phi-N \) scattering process. In the analysis of incoherent \( \phi \)-meson photoproduction from deuteron, the \( \phi-N \) interaction is parametrized as \( \frac{d\sigma}{d^2t} \propto \sigma_{\phi N}^2 \cdot e^{-b_{\phi N} t} \) [10–12], where \( b_{\phi N} \) characterizes the \( t \)-dependence of the differential cross section, and \( t \) is defined as the four-momentum transfer squared between the photon and the \( \phi \) meson. A \( \chi^2 \) analysis is performed for both processes \( (\gamma + d \to \phi + d) \) as in [13] and \( (\gamma + d \to \phi + p + n) \) in this Letter to constrain the values of \( \sigma_{\phi N} \) and \( b_{\phi N} \).

The rescattering of a \( \phi \) meson off a nucleon in the deuteron was used to study the \( \phi-N \) interaction in a recent analysis of CLAS g10 data using coherent \( \phi \) photoproduction, \( \gamma + d \to \phi + d \) [13]. In the coherent \( \phi \) production process, rescattering dominates in the high \( t \) region. Results of Ref. [13] agree with the VMD prediction (where \( b_{\phi N} \) is assumed to be the one in the \( \phi \)-meson photoproduction from a nucleon), however, larger \( \sigma_{\phi N} \) values showed better agreement with the estimate from the additive quark model [4] and the vector meson dominance (VMD) model [3], which is in agreement with the estimate from the additive quark model [4].
agreement with the data if one allowed the slope ($\beta_{0N}$) of the $t$-dependence of the $\phi$–$N$ scattering process to be different.

The reaction $\gamma(d,\phi)p\pi^0$ was measured by detecting kaons from the $\phi$-meson decay ($\phi \rightarrow K^+K^-$, branching ratio about 0.5) using the same data set as in Ref. [13]. A tagged-photon beam was generated by a 3.8-GeV electron beam incident on a gold radiator ($10^{-4}$ radiation length). The photon flux was measured by the CLAS photon-tagger system [14]. The data were collected from a 24-cm-long liquid-deuteron target in the CLAS detector [15] at JLab.

Events having the final state $\gamma + d \rightarrow K^+K^-p + X$ were selected using a triple coincidence detection of a proton, a $K^+$ and, a $K^-$. Each particle was selected based on particle charge, momentum, and Time-of-Flight (TOF) information. The reaction $d(\gamma, pK^-\pi^0)n$ was identified in the missing mass squared distribution by the missing neutron shown in Fig. 1a. In the figure, the position of the neutron mass squared is shown by the dotted line. A $\pm 3\sigma$ cut was employed to select the $pK^-\pi^0(n)$ final state events.

Once the reaction $d(\gamma, pK^-\pi^0)n$ was identified, the number of $\phi$ mesons was obtained by subtracting the background under the $\phi$ peak (invariant mass spectrum of the $K^+$ and $K^-$) in the $\pm 3\sigma$ region (see Fig. 1b). The $K^+K^-$ invariant mass distribution was fitted using a Breit–Wigner function convoluted with the exponential resolution, plus a function to model the background in each photon energy and $|t t_0|$ bin, where $t_0$ is the minimum $t$ value for a given photon energy. The background shape was assumed to be [13]:

$$f(x) = a\sqrt{x^2 - (2M_K)^2} + b(x^2 - (2M_K)^2) \quad (x > 2M_K),$$

$$f(x) = 0 \quad (x < 2M_K).$$

(1)

where $x$ is the invariant mass of the $K^+K^-$, $M_K$ is the kaon mass, and $a$ and $b$ are fitting parameters. The background was also fitted with a linear shape. The results from fitting these two shapes were compared to estimate the systematic uncertainties due to the subtraction of the background.

A Monte Carlo (MC) [16] simulation of the CLAS detector was carried out to determine the efficiency for the detection of the $\gamma + d \rightarrow p + K^+K^-$ reaction. Two event generators were used in two different missing neutron momentum regions. A quasi-free event generator for the $\gamma + p \rightarrow \phi + p$ process in the deuteron was employed for the missing neutron momentum distribution below 0.18 GeV/c, where the agreement between the MC simulation and the data is very good. The deuteron wave function was based on the Bonn potential [17]. The differential cross sections from CLAS [18] for $\phi$ photoproduction from the proton were used. For the missing neutron momentum greater than 0.18 GeV/c, the generated events were weighted by $\frac{d\sigma}{dt} |_{\phi(N)}$ from Ref. [10] to include both the resonance centered at the $\phi$ mass of 1.019 GeV/$c^2$ and with a FWHM of 0.0044 GeV/$c^2$. The $\phi$-meson angular distribution was taken as [19]:

$$W(\cos(\theta_H)) = \frac{3}{2} \left( 1 - \rho_{00}^\phi \right) \sin^2 \theta_H + \rho_{00}^\phi \cos^2 \theta_H + \alpha \cos \theta_H,$$

(2)

where $\rho_{00}^\phi$ is the spin density matrix element, $\theta_H$ denotes the polar angle of the $K^+$ in the $\phi$-meson rest frame, and $\alpha$ accounts for an interference between the $\phi$ and the non-resonant $S$-wave $K^+K^-$ pair production [20]. Helicity conserving amplitudes give $\rho_{00}^\phi = 0$, while single-helicity flip amplitudes require $\rho_{00}^\phi \neq 0$. A value of 0.1 (0.05) was used for $\rho_{00}^\phi$ ($\alpha$) in the MC simulation. The MC generated events were used as input to the GEANT3-based CLAS simulation [16]. They were then reconstructed using the same event reconstruction algorithm as was used for the data. The acceptance was obtained by the ratio of the number of events that passed the analysis cuts to the number of generated $\phi$ events. The average differential cross section for each photon energy and $|t t_0|$ bin was extracted by dividing the normalized yield (number of selected events divided by the integrated photon flux including the DAQ dead time, the target thickness, the $\phi$ decay branching ratio and $|t t_0|$ bin size) by the acceptance which includes the detection efficiency. The differential cross sections were then bin-centered at fixed $t$ values and a finite binning correction was applied.

Several sources contribute to the overall systematic uncertainty in extracting the differential cross section. The systematic uncertainties associated with particle identification and the missing mass cut were determined to be 0.5–7.0% and 0.5–5.0%, which are the values found across the different bins of photon energy and $t$, respectively. These were determined by varying the corresponding cuts by $\pm 10\%$. The uncertainties in the parameters of the $\phi$ decay angular distribution, $\rho_{00}^\phi$ and $\alpha$, were 10% and 5% [18,20], respectively, leading to 1.5–6.5% systematic uncertainties. The background obtained from the non-linear background shape was on average 5% smaller than that from the linear background. The systematic uncertainties from the acceptance dependence on the cross section model varied from 0.5% to 9%. The uncertainty in the photon flux was 5% [21,22]. The uncertainty of the bin-centering corrections were typically between 0.5% and 6.0%, based on our current knowledge of the CLAS detector and the uncertainty in the input cross section. Combining all systematic uncertainties in quadrature, the overall systematic uncertainties vary from 7%–18% depending on the kinematics.

In Figs. 2, differential cross sections, $\frac{d\sigma}{dt}$ from this work (red solid circles) for the reaction $\gamma + d \rightarrow \phi + p + n$ are presented. In Figs. 2a and 2b, we present $\frac{d\sigma}{dt}$ as a function of $|t t_0|$ for a photon energy range of 1.65–2.62 GeV and 2.62–3.59 GeV, respectively (same as those in Ref. [13]). The detected proton and the missing neutron momentum span a range of 0.18 to 2.0 GeV/c (Figs. 2a and 2b). For the low missing momentum region (the momenta of the reconstructed neutron smaller than 0.18 GeV/c), cross sections over the same photon energy ranges are shown in Figs. 2c and 2d. The error bars shown are the statistical uncertainties, and the overall systematic uncertainties are shown by the black band. Also plotted are the predictions [10] for quasi-free $\phi$ production and rescattering based on the model assumptions of pomeron exchange or the two-gluon exchange interaction in the $\phi$–$N$ rescattering process.

In [10], the neutron–proton rescattering amplitude has been taken into account and treated in the same way as in the analysis of the $d(e,e'p)n$ channel [23,24]. The models for the $\phi$ photoproduction on the proton [25,26] used in Ref. [10] describe the published experimental cross sections [20,27] reasonably well for photon energies in the vicinity of 3.4 GeV and above. However, at low photon energies the model underestimates the experimental cross sections of $\gamma + p \rightarrow \phi + p$ [18] above $|t t_0| = 1 \ (\text{GeV}/c)^2$ by a factor that can reach 10 at $2.5 \ (\text{GeV}/c)^2$. The extracted cross sections [28] of the $\gamma + p \rightarrow \phi + p$ from the $d(\gamma, \phi)p\pi^0n$ channel at low neutron missing momentum from this work are in good agreement with the extracted cross sections of $\gamma + p \rightarrow \phi + p$ [18]. The flattening behavior of the experimental cross sections with increasing $|t t_0|$ values is well accounted for by the coupling between the $\phi$ and $\omega$ production channels [29], which is discussed later. This channel coupling effect has not yet been implemented in Laget’s code that we use, and its effect will be investigated in a future study.

We simply note that in the high missing momentum region where contributions of rescattering processes ($\phi$–$N$ or $N$–$N$)
are significant, the dominant contribution to the matrix element comes from the photoproduction of $\phi$ on a nucleon at rest, which gets its measured momentum in the rescattering process (we refer to Ref. [10] for a detailed discussion). The consequence is that in the scattering loop the elementary photoproduction amplitude $\gamma + N \rightarrow \phi + N$ is almost the same as in the quasifree case, when the spectator is at rest. The amplitude for the $\gamma + d \rightarrow \phi + p + n$ process can be written as:

$$A = A_{\phi p}^{QS} \otimes (1 + A_{pn}^{fsi} + A_{\phi n}^{fsi}) + A_{\phi n}^{QS} \otimes (1 + A_{pn}^{fsi} + A_{\phi n}^{fsi})$$

$$= (A_{\phi p}^{QS} + A_{\phi n}^{QS}) \otimes (1 + A_{pn}^{fsi} + A_{\phi n}^{fsi}),$$

(3)

where $A_{\phi n}^{QS}, A_{pn}^{fsi}$ and $A_{\phi n}^{fsi}$ are the amplitude for the $\phi$-meson photoproduction from nucleon, the amplitude for the proton–neutron final state interaction, and the amplitude for the $\phi$–$N$ final state interaction, respectively. The second step assumes isospin symmetry for the $\phi$–$N$ interaction. The $\otimes$ represents a convoluted integral over final momentum. Thus, deviations from data in the model cross section of $\phi$ photoproduction from nucleons will lead to deviations of the calculated cross sections in the high spectator nucleon momentum region from the data, even without final state interaction effects. In order to minimize this effect, we form the following ratio between the results with a high spectator momentum cut and the results with a low spectator momentum cut for each value of $|t - t_0|:

$$R = \frac{\sigma_H}{\sigma_L} = \frac{\int_0^{2.8\text{ GeV}} \frac{d\sigma}{dP_{\text{miss}}}}{\int_0^{1.8\text{ GeV}} \frac{d\sigma}{dP_{\text{miss}}}}.$$

(4)

The comparison of the experimental ratios to the model calculations from Ref. [10] are presented in Fig. 3. The experimental data are shown with statistical uncertainties. The systematic uncertainties are shown by the black band. In the low energy range, $E_\gamma = 1.65$–2.62 GeV (Fig. 3a), the data are best described by the parameters of $\sigma_{\phi N} = 10$ mb and $\beta_{\phi N} = 6$ (GeV/c)$^{-2}$. In the range $E_\gamma = 2.62$–3.59 GeV, the data can be described well by all four calculations shown in Fig. 3 including the rescattering effect.

In order to constrain the value of $\sigma_{\phi N}$ using our data, a $\chi^2$ analysis was performed for results from both the $\gamma + d \rightarrow \phi + p + n$ process ($R = T^2$) and the published $\gamma + d \rightarrow \phi + d$ coherent channel [13] by mapping the phase space of $\sigma_{\phi N}$ and $\beta_{\phi N}$. The $\chi^2$ is defined as:

$$\chi^2 = \sum_{i=1}^{N} \frac{(R_{\text{data}} - R_{\text{cal}})^2}{\delta R_{\text{data}}^2},$$

(7)

where $N$ is the number of data points, $R_{\text{data}}$ ($R_{\text{cal}}$) is the cross section ratio defined in Eq. (3) for data (calculation). The $\delta R_{\text{data}}$ is quadrature sum of the point-to-point systematic uncertainty and the statistical uncertainty. For the coherent process, $R_{\text{data}}$ ($R_{\text{cal}}$) is the differential cross section data (calculation). The calculations of Laget [10], which include pomeron exchange for the elementary $\phi$ meson photoproduction cross section on the nucleon, are used for the $\gamma + d \rightarrow \phi + p + n$ channel. The pomeron and the two-gluon exchange versions of the model lead to very similar results at $|t - t_0|$ values smaller than 1.5 (GeV/c)$^{-2}$, as can be seen in Figs. 2 and 3. For the coherent production channel, calculations from Sargsian et al. [11,12] are used.

Figs. 4a and 4b show the confidence level for both processes in the two photon energy regions. While the energy dependence in $\sigma_{\phi N}$ and $\beta_{\phi N}$ might be a possible explanation for the difference between Figs. 4a and 4b, the combined analysis favors a value of $\sigma_{\phi N}$ larger than 20 mb. Our results are consistent with that extracted from the SPring-8 data [6] in which Li, C, Al and Cu nuclear targets were used. Further more, our combined analysis gives a lower bound of 6 (GeV/c)$^{-2}$ for the $\rho_{\phi N}$ parameter.

Medium modifications that have been suggested by the SPring-8 data [6] can hardly explain a large $\sigma_{\phi N}$ cross section (large $r_0$) in deuterium. More likely it may reflect the fact that other mechanisms, beyond np and $\phi N$ rescattering, are at play and are more important than the medium modifications, for example the QCD van der Waals force. On the one hand, the coupling of the $\phi$ (via two-gluon exchange) to hidden color components [30] inside the deuteron may contribute to large missing momenta and leave less room for $\phi$–$N$ rescattering. On the other hand, the coupling to a cryptoexotic baryon (baryon with hidden strangeness), $B_\phi = uuds\bar{s}$,
Fig. 2. Differential cross section $\frac{d\sigma}{dt}$ from $\gamma(d,K^+K^-p)n$ process for photon energies of 1.65–2.62 GeV (a), (c) and 2.62–3.59 GeV (b), (d). The missing momentum is higher than 0.18 GeV/c in (a) and (b), and lower than 0.18 GeV/c in (c) and (d). The results of this work are shown in red solid circles. The black bands represent the systematic uncertainties. The label “30 + 10” indicates the calculation from Laget [10] with $\sigma_N^{\gamma} = 30 \text{ mb}$ and $\beta_N = 10 \text{ (GeV/c)}^{-2}$. The legend for the calculations is presented for better visibility and it applies to all four panels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

Fig. 3. Cross section ratio between the high and the low missing momentum regions for photon energies of 1.65–2.62 GeV (a) and 2.62–3.59 GeV (b). The results of this work are shown in red solid circles. The black bands represent the systematic uncertainties. We use same notations as those in Fig. 2 for calculations from Laget [10]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

may also contribute [2]. However, the most likely explanation lies in the $\omega$-$\phi$ mixing. The photon produces an $\omega$ meson on one nucleon, which elastically scatters on the second nucleon before transforming into a $\phi$ meson. The corresponding matrix element has the same structure as the elastic $\phi$ rescattering matrix element that we considered in our analysis. An effective $\sigma_{\phi N}$ cross section value can be written as:

$$
\sigma_{\phi N}^{\text{eff}} \sim \sigma_{\phi N} + \sigma_{\omega N} \sqrt{\frac{\sigma_{\gamma N \rightarrow \omega N} \sigma_{\gamma N \rightarrow \phi N}}{\sigma_{\gamma N \rightarrow \omega N}}} g_{\omega \rightarrow \phi}.
$$

With the experimental value of $\frac{\sigma_{\phi N}}{\sigma_{\gamma N \rightarrow \omega N}} \sim 50$ [27,31] in a $-t$ region of 1 to 3 (GeV/c)^2, and the $\omega$-$\phi$ mixing coefficient $g_{\omega \rightarrow \phi} \sim 0.09$ [32], one can reconcile the effective $\phi N$ cross section of $\sim 30 \text{ mb}$ with the VMD values of the $\sigma_{\omega N} (\sim 25 \text{ mb})$ and $\sigma_{\phi N} (\sim 10 \text{ mb})$ [29]. One way to put the $\phi$-$N$ cross section on more solid ground would be to select the part of the phase space where the $\phi$-$N$ rescattering dominates, using the method proposed in Ref. [10]. Future high statistics data from a luminosity upgraded CLAS12 [33] detector will help disentangle these possibilities. Furthermore, fu-
ture improved and new theoretical calculations will allow us to study the model uncertainty in the extraction of the $\phi$--$N$ total cross section.

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