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Near-threshold Photoproduction of ϕ Mesons from Deuterium

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We report the first, kinematically-complete measurement of the differential cross section of ϕ-meson photoproduction from deuterium near the production threshold for a proton using the CLAS detector and a tagged-photon beam in Hall B at Jefferson Lab. The measurement was carried out by a triple coincidence detection of a proton, K^+ and K^- near the theoretical production threshold of 1.57 GeV. The extracted differential cross sections $\frac{d\sigma}{dt}$ for the initial photon energy range of 1.65-1.75 GeV are consistent with predictions based on a quasifree mechanism. Our finding is different from recent LEPS results on ϕ-meson photoproduction from deuterium in a similar incident photon energy range, but in a different momentum transfer region.

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The subject of medium modification of properties of (light) vector mesons such as their masses and widths has been an important subject in nuclear physics, particularly in the context of partial restoration of chiral symmetry [1]. Among light vector mesons, the ϕ meson is considered an excellent candidate for the study of medium modification effects due to its narrow, vacuum width of 4.3 MeV/c^2. The first evidence for in-medium modification of the ϕ meson at normal nuclear density from hadronic reactions was reported by the KEK-PS E325 Collaboration [2], in which a mass shift of 3.4% and a width increase of a factor of 3.6 for ϕ momenta around 1 GeV/c from reaction $p+A \to \rho, \omega, \phi + X \to e^+e^- + X'$ were deduced.

Studies of ϕ-meson production from nuclei have generated new interest in the last a few years motivated largely by a number of new and interesting results reported by different experiments. A number of experiments reported larger values of ϕ-N total cross section extracted from photoproduction of ϕ-meson from nuclear targets than an upper limit of $\sigma_{\phi N} \simeq 11$ mb [3] obtained using the ϕ-meson photoproduction data on the proton and the vector meson dominance (VMD) model [4]. This upper limit is in agreement with the estimate from the additive quark model [5]. The LEPS collaboration [6] reported the A-dependence of ϕ-meson photoproduction from Li, C, Al, and Cu nuclear targets, and a larger value of $\sigma_{\phi N} \simeq 35^{+17}_{-11}$ mb was obtained, corresponding to a collisionally broadened width of 35 MeV, much larger than that reported by the KEK-PS E325 Collaboration [2]. The CLAS Collaboration also reported larger values of $\sigma_{\phi N}$ from a combined analysis [7] of the coherent [8] and incoherent ϕ-meson photoproduction from deuterium and a value larger than 20 mb is favored for $\sigma_{\phi N}$. Another recent CLAS experiment [9] reported a measured value in the range of 16-70 mb for $\sigma_{\phi N}$ from $\gamma A \to \phi X \to e^+e^- X$. More recently, the Anke Collaboration at COSY reported [10] a nuclear dependence of $A^{0.56\pm0.03}$ from $pA \to \phi X$ in the ϕ meson momentum region of 0.6 - 1.6 GeV/c. The comparison of the data with model calculations suggests an in-medium ϕ width about an order of magnitude larger than its vacuum value, which is consistent with a larger value of $\sigma_{\phi N}$ [6] taking into account the experimental uncertainties of both experiments.

In order to determine the medium modification of the properties of ϕ unambiguously, understanding reaction mechanisms of ϕ-meson production from nuclear targets is crucial because nuclear targets are necessary in experiments studying the medium effect. The deuteron, a loosely bound and the simplest nuclear system, provides an excellent testing ground to study the reaction mechanisms. Such a study has been reported [11] recently by the LEPS collaboration on the measurement of the incoherent $\gamma d \to \phi pn$ photoproduction near threshold at forward angles. The nuclear transparency ratio for ϕ has been extracted, which shows a large suppression consistent with the nuclear dependence reported [6] by the same collaboration previously using ϕ-meson photoproduction data from heavier nuclear targets. However, a recent theoretical study [12] of ϕ-meson photoproduction from a deuterium target shows that the contribution from rescattering at the kinematics of the LEPS experiment is small compared with the cross section of $\gamma p \to \phi p$ in free space.

Another important aspect of ϕ-meson production from nuclear targets near threshold is related to experimental investigations of the existence of a $\phi - N$ bound state. The QCD van der Waals interaction, mediated by multi-gluon exchanges, is dominant when two interacting color-singlet hadrons have no common valence quarks. Bound states of η_c with ^{3}He and heavier nuclei were predicted [13, 14]. Similarly, one expects that the attractive QCD van der Waals force also dominates the ϕ-N interaction. A bound state of ϕ-N was found to be possible by Gao, Lee, and Marinov [15]. Such a bound state was also predicted by Huang, Zhang, and Yu using a chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the Resonant Group Method (RGM) equation [16]. Subthreshold production kinematics have been proposed [15] as advantageous for the search of $\phi - N$ bound states from nuclear targets.

In this paper, we report on the first kinematically-complete measurement of differential cross sections from near-threshold production of ϕ mesons from a deuterium target by a triple coincidence detection of K^+, K^-, and proton. The measurement was carried out using the CLAS detector [17] at Jefferson Lab. The incident photon energy range used in this analysis is 1.65 - 1.75 GeV, which is above the ϕ-meson photoproduction threshold ($E_\gamma^{thres.} = 1.57$ GeV) from a free proton target. However, due to the requirement of a triple-coincidence detection and the imperfect acceptance of the detector at forward angles, the reconstructed ϕ event in this analysis originated mostly from photoproduction on a high-momentum proton inside the deuteron, and is below the CLAS production threshold for $\gamma p \to \phi p \to K^+K^-p$. Such production therefore images subthreshold production of ϕ-meson from nuclear targets and as such is important for future experimental search for a ϕ-N bound state.

High statistics data were collected during the CLAS g10 running period [18] from a 24-cm-long liquid-deuterium target. A tagged-photon beam was used, which was generated by a 3.8-GeV electron beam incident on a gold radiator with a thickness of 10^{-4} radiation lengths. The photon flux was measured by the Hall B photon-tagging system [19]. Two settings of the CLAS magnetic field were used during the experiment, corresponding to a low-field setting (with a toroidal magnet current I=2250 A) for better forward-angle coverage, and a high-field setting (I=3375 A) for better momentum resolution. The reaction $d(\gamma, \phi p)n$ was measured by detecting kaons from the ϕ-meson decay ($\phi \to K^+K^-$, branching ratio about 0.5), using the same data set as in Refs. [7, 8, 20].

The K^+, K^-, and the proton were selected based on the particle charge, momentum, and time-of-flight information. The reaction $d(\gamma, \phi p)n$ was identified in the missing mass squared distribution by applying a $\pm 3\sigma$ cut on the missing neutron peak. The energy threshold for the $\gamma N \to \phi N$ reaction is 1.57 GeV. However, due to the minimum detection threshold for charged particles, the CLAS acceptance determined threshold is around 1.75 GeV. This is demonstrated in our analysis as no ϕ events at incident photon energies below 1.75 GeV can be identified from the g10 hydrogen data set, which was taken during the g10 running period for calibration purposes. This finding is consistent with the hydrogen results from the CLAS g11 [21] high statistics data set. Table I summarizes the differences between the g10 and g11 experimental settings. Fig. 1 (left panel) shows the invariant mass distribution of the K^+K^- before the acceptance correction from the g10 deuterium data set, where the ϕ peak is clearly visible. Also shown in Fig. 1 (right panel) is the corresponding spectrum from the g11 hydrogen data set normalized to the g10 integrated luminosity for nucleons. The yield of the g11 hydrogen is ~ 1.5 events per 2.5 MeV around the reconstructed ϕ meson mass, which is strongly suppressed compared to that of the g10 deuteron (~ 23 events per 2.5 MeV) due to the energy threshold of producing a ϕ meson on a nucleon at the kinematic settings of g10 and g11. Therefore, the photon energy range used to extract the near-threshold cross section for ϕ-meson photoproduction from deuterium is between 1.65 GeV and 1.75 GeV in this work. The chosen photon energy range was further confirmed by simulating the $\gamma + p \to p + \phi$ process for the g10 configuration.

Run Period	Magnet Current	Target Material	Target Length	Target Position	Accumulated Flux
g10	2250 (A)	LD$_2$	24 cm	-25 cm	1.266×10^{12}
g10	2250 (A)	LH$_2$	24 cm	-25 cm	7.508×10^{10}
g11	1930 (A)	LH$_2$	40 cm	-10 cm	4.316×10^{12}

TABLE I: A comparison of the g10 and g11 experimental settings. The accumulated photon flux is for the E_γ range of 1.65-1.75 GeV. The "-10 cm" means that the target center of the g11 hydrogen target is 10 cm upstream from the nominal center of CLAS.

Once the reaction $d(\gamma, pK^+K^-)n$ was identified, the number of ϕ mesons was obtained by subtracting the background under the ϕ peak (invariant mass spectrum of the K^+ and K^-) in the $\pm 3\sigma$ region (see Fig. 1). The K^+K^- invariant mass distribution was fitted using a Breit-Wigner function convoluted with the experimental resolution, plus a function to model the background in each kinematic bin. The experimental resolution on the missing mass ranged from 1.2 to 1.7 MeV for different t bins. They were obtained by fitting the invariant mass distribution of the Monte-Carlo simulation. The background shape was assumed to be [8]:

$$\begin{aligned} f(x) &= a\sqrt{x^2 - (2M_K)^2} + b\left(x^2 - (2M_K)^2\right) \text{ for } x > 2M_K \\ f(x) &= 0 \text{ for } x < 2M_K, \end{aligned} \tag{1}$$

where x is the invariant mass of the K^+K^-, M_K is the kaon mass, and a and b are fitting parameters. Such a fit was performed separately for each t bin, and the t dependence of the background was effectively included in the fitting parameters a and b. In addition, the background was also fitted to a straight line. The results from fitting these two shapes were compared in order to estimate the systematic uncertainties due to the subtraction of the background.

GEANT3 Monte-Carlo (MC) simulations were carried out to model detector efficiencies and resolutions for this

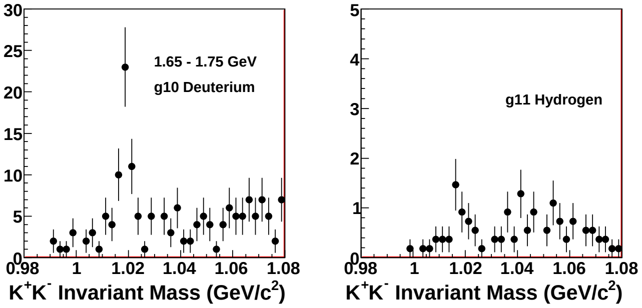

FIG. 1: The K^+K^- invariant mass distribution from the CLAS g10 deuterium data for E_γ = 1.65-1.75 GeV (left panel). The x-bin size is 2.5 MeV. The corresponding distribution from the CLAS g11 hydrogen data set in the same photon energy range is shown in the right panel.

reaction channel. A quasifree event generator was used for the near-threshold kinematics. It generated pK^+K^- three-body events with a random photon energy based on the photon energy distribution of the data in the energy range of interest. The initial momentum of the nucleon inside the deuteron was chosen using the Bonn potential wavefunction [22]. The spectator nucleon was assumed to be on-shell, whereas the struck nucleon was assumed to be off-shell before absorbing a photon. Isospin symmetry was assumed for the ϕ-meson photoproduction from the nucleon. The events were then checked to ensure energy conservation. The MC events were generated based on a Breit-Wigner shape of the resonance centered at the ϕ mass of 1.019 GeV^2 with a full width at half maximum (FWHM) of Γ=4.26 MeV. The ϕ meson decay angular distribution and cross section are based on the g11 hydrogen data [23].

The ϕ-meson differential photoproduction cross section on a hydrogen target ($\frac{d\sigma}{dt}$ vs. $t - t_0$) was obtained using a fit to the g11 data in $E_\gamma = 1.625 - 3.775$ GeV range. Here t is the four-momentum transfer squared, $(P_\phi - P_\gamma)^2$, and t_0 is the maximum t value for a given photon energy because t is negative. In addition, the event generator included the $N - N$ and $\phi - N$ final-state interactions (FSIs). The Jost function approach [24] was used for the $N - N$ FSI. The $\phi - N$ FSI, which was assumed to be incoherent from the original ϕ-meson photoproduction process, was modeled based on the vector meson dominance (VMD) model, in which the t-dependence of the $\phi - N$ elastic scattering cross section is the same as that of ϕ-meson photoproduction. A fitting procedure, in which the strength of $N - N$ and $\phi - N$ FSIs were obtained, was then used to optimize the ϕ-meson photoproduction model so that the resulting Monte-Carlo distributions match those of the data. Fig. 2 shows the comparison in the missing momentum distribution for the data (solid triangles) and the MC (solid circles).

MC-generated events were used as input to the GEANT3-based CLAS simulation [25]. They were then reconstructed using the same 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 ϕ events. The average differential cross sections were extracted by dividing the normalized yield by the acceptance. The differential cross sections were then bin-centered at fixed t values with a finite binning correction.

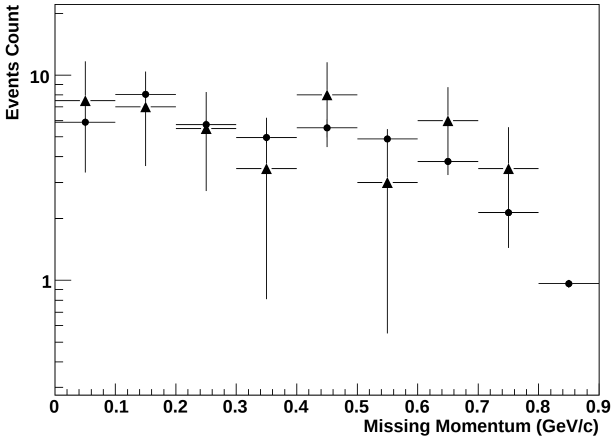

FIG. 2: Missing momentum distributions are shown for data (solid triangles) and MC (solid circles), where the MC results are normalized to the luminosity of the data. Both $\phi - N$ and $N - N$ FSI are included in the Monte Carlo.

Several sources contribute to the overall systematic uncertainty in the differential cross section. The systematic uncertainties associated with particle identification and the missing mass cut were 4.2 - 12.9% and 1.4 - 10.9%, respectively. These values were determined by varying the corresponding cuts by ±10% in each t bin. The angular distributions of the ϕ-meson's decay products in its rest frame and the $\cos(\theta_{\mathrm{c.m.}})$ distribution of the ϕ meson were uncertain to within 10% and 5% [23, 26], respectively, leading to 5.2-13.2% systematic uncertainties. The background obtained from the non-linear background shape was on average 8% smaller than that from the linear background. A conservative 8% systematic uncertainty is assigned for the background subtraction procedure. The systematic uncertainties due to the effect of FSIs were obtained by varying the fitted strengths of the $N - N$ FSI and the $\phi - N$ FSI by 30% and 50%, respectively. The systematic errors vary from 4% to 17% for different t bins. The uncertainty in the photon flux was 5% [20, 27]. The uncertainty of the bin-centering correction was assumed to be 30% of the size of the correction based on knowledge of the CLAS acceptance and the input cross section model, which is obtained from the g11 data [23]. The absolute size of bin-centering corrections

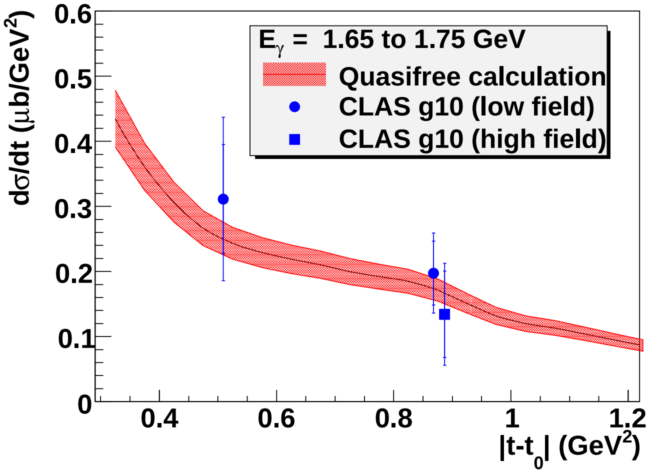

FIG. 3: (Color online) ϕ photoproduction differential cross sections from deuterium are plotted as a function of $|t - t_0|$. The inner error bars are the statistical uncertainties, and the outer error bars are the quadrature sum of systematic and statistical uncertainties.

E_γ (GeV)	$\lvert t - t_0\rvert$ (GeV^2)	$\frac{d\sigma}{dt}$ (μb/GeV^2)	stat. uncer.	sys. uncer.
1.65-1.75	0.509	0.31	0.084	0.094
1.65-1.75	0.887	0.20	0.049	0.037
1.65-1.75	0.924	0.13	0.066	0.041

TABLE II: Tabulated results on the ϕ-meson photoproduction from deuterium for an E_γ range of 1.65 to 1.75 GeV.

was between 1% and 10%. Combined in quadrature, the overall systematic errors vary from 18% − 32% depending on the kinematics.

The ϕ-meson photoproduction cross sections for the deuteron are tabulated in Table II and are plotted as a function of $|t - t_0|$ in Fig. 3 for a photon energy range of 1.65-1.75 GeV. The solid circles are results obtained from the CLAS g10 low-field setting, whereas the solid square is the result from the high-field setting. The quasifree calculation is also plotted for comparison together with its uncertainty (shown as a band in Fig. 3). This simple calculation is based on a quasifree picture with the ϕ-meson differential photoproduction cross section from the proton which is based on the g11 data [23]. The principle of this calculation is the same as that for the event generator used in the MC. The systematic uncertainty for this calculation is about 10% due to the uncertainty in the input cross section. The extracted differential cross section for ϕ-meson photoproduction is consistent with the quasifree calculation within uncertainties. Our finding is consistent with theoretical calculations presented in Ref. [12]. However, they are not consistent with the recent LEPS results [11] from deuterim in a similar photon energy range, but in a smaller momentum transfer region. The corresponding $|t - t_0|$ range for the LEPS data in a photon energy range of 1.65 to 1.75 GeV is less than 0.2 GeV^2. Future studies both in experiment and in theory are important to clarify the situation.

In summary, we have extracted for the first time the differential cross section on ϕ-meson photoproduction from deuterium from a kinematically-complete measurement below the production threshold for the proton accessible on CLAS. The chosen incident photon energy range is 1.65-1.75 GeV, which is near the 1.57 GeV production threshold for protons. Our extracted differential cross sections are in agreement with predictions from a simple quasifree picture. This finding is consistent with the recent theoretical study of this reaction [12], though inconsistent with the recent LEPS results in a somewhat different kinematic region. Further, our data provide information on ϕ-meson subthreshold photoproduction cross section from a deuterium target. Although heavier nuclear targets will be ideal for future dedicated searches for a ϕ-N bound state, the extracted cross sections from deuterium reported in this paper will help provide information on the expected production rate of the ϕ-N bound state from heavier nuclear targets.

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