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Physics Letters B 658 (2008) 209–215

PHYSICS LETTERS B

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Forward coherent ϕ-meson photoproduction from deuterons near threshold

LEPS Collaboration

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Received 9 July 2007; received in revised form 13 October 2007; accepted 9 November 2007

Available online 17 November 2007

Editor: V. Metag

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doi:10.1016/j.physletb.2007.11.009

Abstract

Differential cross sections and decay asymmetries for coherent ϕ-meson photoproduction from deuterons were measured for the first time at forward angles using linearly polarized photons at $E_\gamma = 1.5$–2.4 GeV. This reaction offers a unique way to directly access natural-parity pomeron dynamics and gluon exchange at low energies. The cross sections at zero degrees increase with increasing photon energy. The decay asymmetries demonstrate a complete dominance of natural-parity exchange processes, showing that isovector unnatural-parity π-meson exchange is small. Nevertheless the deduced cross sections of ϕ-mesons from nucleons contributed by isoscalar t-channel exchange processes are not well described by the conventional pomeron model.

PACS: 13.60.Le; 14.40.Cs; 25.20.Lj

Keywords: Photoproduction; ϕ-mesons; Deuterons; Coherent interaction

1. Introduction

The common asymptotic behavior of high-energy diffractive processes of hadron–hadron and photon–hadron interactions is traditionally interpreted as the exchange of a pomeron [1]. The slow rise of the total cross section, dominated by the soft nonperturbative strong interaction, could be described by a pomeron trajectory with the quantum numbers of the vacuum in Regge theory [2]. The physical particles responsible for pomeron exchange have not been conclusively identified, but such particles can exist in Quantum Chromodynamics (QCD) as glueballs, e.g. a $J^{PC} = 2^{++}$ glueball with a mass near 2 GeV/c^2 [3]. The behavior of pomeron exchange at low energies is not well understood because meson-exchange processes appear and become comparable near threshold and the applicability of pomeron theory might be doubtful [4]. Nonetheless, a particularly interesting and unique way of studying the possible pomeron exchange is $\phi(1020)$-meson photoproduction from hadrons. In this reaction pseudo-scalar π-meson exchange is, to first order, suppressed by the Okubo–Zweig–Iizuka (OZI) rule in the Vector Meson Dominance model (VMD) [5] because of the dominant $s\bar{s}$ quark content of ϕ-mesons. Furthermore, with the use of an isoscalar deuteron target, the coupling between isovector pions and deuterons is forbidden due to isospin conservation [6,7]. Accordingly, the coherent photoproduction of ϕ-mesons from deuterons becomes an excellent source of information for pomeron dynamics at low energies [8].

In addition, coherent ϕ-meson photoproduction provides the opportunity to observe additional exotic processes. Possible channels include Regge trajectories associated with particles containing gluonic degree of freedom (e.g., a daughter pomeron inspired by a scalar-type 0^{++} glueball [9], and scalar or tensor mesons [10–12]). The importance of this study is emphasized by the recent measurement of diffractive ϕ-meson photoproduction from protons near threshold [13]. The differential cross sections (extrapolated to zero degrees) have a local maximum around 2.0 GeV. It was conjectured that this structure was not solely due to the non-negligible pseudo-scalar-meson processes at low energies but is likely signaling new dynamics beyond the pomeron.

Besides the cross section information, the decay angular distribution of ϕ-mesons with respect to the photon polarization helps to differentiate the relative contributions from natural-parity (σ^N) and unnatural-parity exchange processes (σ^U) [14]. With the availability of linearly polarized photon beams, the smallness of unnatural-parity π and η-exchange and hence the dominance of natural-parity processes in the coherent production of ϕ-mesons from deuterons can be verified.

Recently CLAS experiment [15] also measured the coherent ϕ-meson production from deuterons at low energies but rather at backward angles and without the use of polarized photon beams. A total ϕ–N cross section at about 10 mb was determined in the framework of vector meson dominance. The comparison of the differential cross sections in the overlapped kinematic region between this study and the CLAS experiment will be made later.

2. Experimental procedure and setup

In this Letter, we present measurements of differential cross sections and decay asymmetries of coherent ϕ-meson photoproduction from liquid deuterium near threshold in the very forward direction with linearly polarized photons using the LEPS spectrometer [16]. Highly polarized photons were produced by backward Compton scattering with an ultra-violet Ar laser from 8 GeV electrons in the storage ring of SPring-8. The photon energy (E_γ) was determined by measuring the recoil electrons with a tagging spectrometer event by event. A liquid deuterium target with an effective length of 16 cm was employed. The integrated flux of the tagged photon beams was 4.47×10^{12} in this analysis. Charged particles produced at the targets were detected at forward angles with the LEPS spectrometer which consisted of a dipole magnet, a silicon-strip vertex detector, three multiwire drift chambers, a plastic scintillator (SC) behind the target, and a time-of-flight (TOF) hodoscope placed downstream of the tracking detectors. The charged particle identification was made by mass reconstruction using both time of flight and momentum information. The momentum resolution for 1 GeV/c particles was 6 MeV/c. The TOF resolution was 150 ps for a typical flight path length of 4 m. The mass resolution was 30 MeV/c^2 for a kaon of 1 GeV/c momentum. More details about experimental setup are given in Refs. [17,18].

The production of ϕ-mesons was identified via the charged kaon decay mode with the detection of K^+ and K^- in the fi-

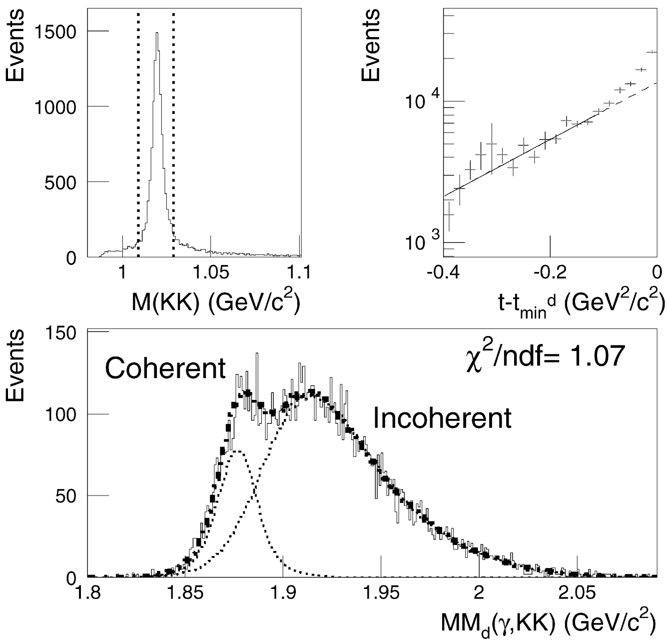

Fig. 1. The distributions of invariant mass (top, left), squared four-momentum transfer (top, right) and missing mass for a deuteron target as $\mathrm{MM_d}(\gamma, \mathrm{KK})$ for the events of a $\mathrm{K^+K^-}$ pair (bottom). The two dashed lines on the distribution of invariant mass $\mathrm{M(K^+K^-)}$ show the final cut to select the ϕ events. The $\mathrm{MM_d}(\gamma, \mathrm{KK})$ spectrum is shown with fit of MC-simulated coherent and incoherent components and the χ^2 value of the fit. See the details about the lines in the plot of momentum transfer distribution in text.

nal state. The vertex positions of $\mathrm{K^+K^-}$ pairs were required to be within the target boundaries. A clear signal of ϕ-mesons was seen in the invariant mass of $\mathrm{K^+K^-}$ pairs, $\mathrm{M(K^+K^-)}$, for $E_\gamma = 1.5$–2.4 GeV as shown in Fig. 1. A cut on the invariant mass of $|\mathrm{M(K^+K^-)} - \mathrm{M}_\phi| < 0.01\ \mathrm{GeV}/c^2$, was applied to select the ϕ-meson events, either through coherent or incoherent production. The background in the selected signal region is estimated to be about 5–10% by Monte Carlo simulations of coherent and incoherent reactions and two background processes: quasi-free production of the $\Lambda(1520)$ and non-resonant $\mathrm{K^+K^-}$. We define $\tilde{t}^{\mathrm{d}}$ as $t - t^{\mathrm{d}}_{\mathrm{min}}$ where t is the squared four-momentum transfer and $t^{\mathrm{d}}_{\mathrm{min}}$, the minimum of t corresponding to the production of ϕ-mesons off a deuteron target at a polar angle (θ) of zero degrees. For selected ϕ events in $|\tilde{t}^{\mathrm{d}}| < 0.4\ \mathrm{GeV}^2/c^2$, the yields as a function of squared four-momentum transfer, $t - t^{\mathrm{d}}_{\mathrm{min}}$ (acceptance corrected), and distribution of missing mass using a deuteron as the rest target ($\mathrm{MM_d}(\gamma, \mathrm{KK})$) are also depicted in Fig. 1. Due to the deuteron form factor and the range of acceptance, the coherent events were observed mostly in the region of very small $|\tilde{t}^{\mathrm{d}}|$ as illustrated by an excess of yields at $|\tilde{t}^{\mathrm{d}}| < 0.1\ \mathrm{GeV}^2/c^2$ above an exponential extrapolation from the outer region of $0.1 < |\tilde{t}^{\mathrm{d}}| < 0.4\ \mathrm{GeV}^2/c^2$.

Since only the ϕ-meson was identified in the final state, the separation of coherent and incoherent interactions could not be performed on a event-by-event basis. Instead, the individual yields were disentangled by fitting the distributions of missing mass $\mathrm{MM_d}(\gamma, \mathrm{KK})$ where the reaction of coherent ϕ production from deuterons, $\gamma \mathrm{d} \to \phi \mathrm{d}$, has a structure peaking at the mass of deuterons $1.875\ \mathrm{GeV}/c^2$, as shown in Fig. 1. This distribution is nicely reproduced by the sum of individual ones generated by Monte Carlo (MC) simulations. The MC simulations were done using the GEANT3 software package [19]. Geometrical acceptance, energy and momentum resolutions and the efficiency of detectors were included. A photon energy resolution of 10 MeV was determined from the width of the missing mass spectra of the ϕ events in data from a hydrogen target.

The $\mathrm{MM_d}(\gamma, \mathrm{KK})$ distribution of incoherent events is affected by the Fermi motion and the offshell effects of the target nucleons inside deuterium. The treatment of offshell effects was found to be the dominant source of systematic errors in this work. Two kinds of approaches were studied for the estimate of systematic bias. In the first approach [20], the spectator nucleon was assumed to be on-shell and the total energy of the target nucleon was determined under the condition of Fermi momenta generated by a parameterization with the PARIS potential [21].

Assuming isospin symmetry in the photoproduction of ϕ-mesons from a free nucleon, the event weighting was characterized by the measured differential cross section from protons $d^2\sigma/dE^{\mathrm{eff}}_\gamma\, dt$ [13] where E^{eff}_γ is the effective photon energy giving the same center-of-mass energy $\sqrt{s}$ of an on-shell target nucleon at rest. The interference between isoscalar η and isovector π exchange could lead to isospin asymmetry. However the OZI effect and the smallness of the η–N coupling strongly suppress this interference effect and thus the isospin asymmetry of the differential cross sections in the forward direction are expected to be small [10].

The second approach differs from the previous one in that the degree by which the target nucleon is offshell was randomly selected between zero and the full scale in each event whereas the mass of target remained unchanged after the interaction. The kinematics of the produced ϕ-meson were determined by the final two-body phase space distribution. The mean values and statistic errors of the measurements using these two approaches were averaged for the final ones, and the difference of mean values were used for the estimation of the systematic uncertainty.

3. Results

First we constructed the differential cross sections in the region $1.57 < E_\gamma < 2.37$ GeV and $|\tilde{t}^{\mathrm{d}}| < 0.4\ \mathrm{GeV}^2/c^2$. Sets of missing mass spectra of selected ϕ events, in the bin sizes of 0.1 GeV for E_γ and $0.02\ \mathrm{GeV}^2/c^2$ for $\tilde{t}^{\mathrm{d}}$, were fitted with those of MC simulated coherent and incoherent events and background processes. The distribution of background processes overlapped with those of incoherent events. With a proper normalization of photon beam flux, number of target atoms, tagger efficiency, transporting efficiency and branching ratio of charged decay of ϕ-mesons, the differential cross sections of the coherent events $d\sigma/d\tilde{t}^{\mathrm{d}}$ are displayed in Fig. 2. The errors (and same below) are shown by error bars where the smaller range is statistical errors and the whole range is the square root sum of statistical and systematic uncertainties. The systematic uncertainties come from the disentangle-

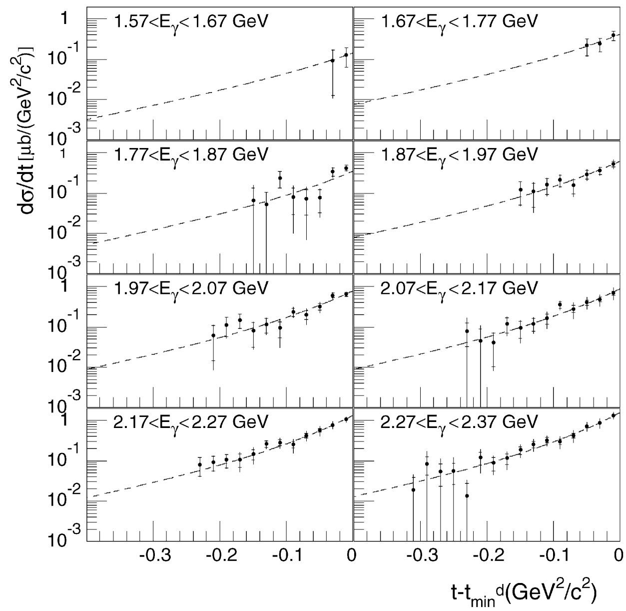

Fig. 2. The differential cross sections of the coherent events $d\sigma/d\tilde{t}^{\mathrm{d}}$ ($\tilde{t}^{\mathrm{d}} \equiv t - t^{\mathrm{d}}_{\mathrm{min}}$) in various E_γ bins. The smaller error bars represent the range of statistical errors. The dashed lines are the result of a fit using an exponential function multiplied by the deuteron form factor.

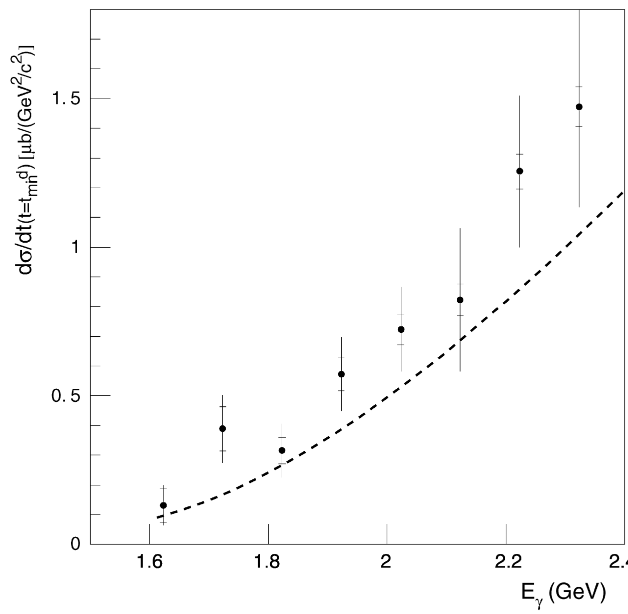

Fig. 3. The fitted $d\sigma/dt$ at $t = t^{\mathrm{d}}_{\mathrm{min}}$ as a function of photon energy. The smaller error bars represent the range of statistical errors. The dashed line is the predictions of $d\sigma^{\gamma\mathrm{d}}/dt$ at zero degree by a model including pomeron and η-exchange processes [6,7].

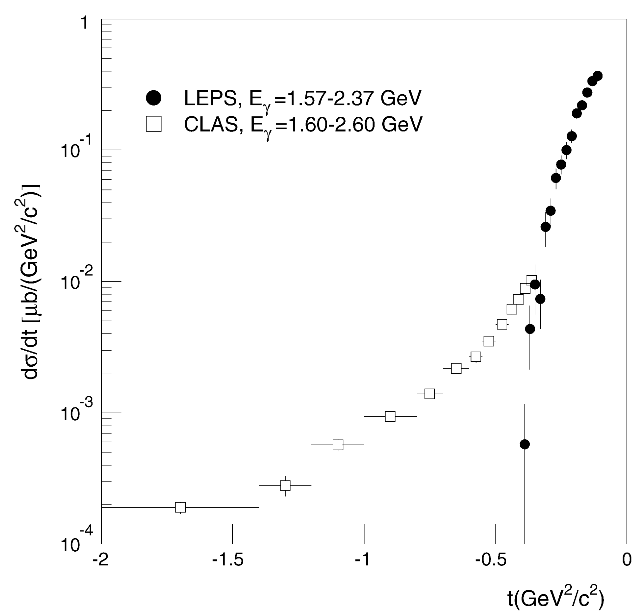

Fig. 4. Comparison of differential cross sections of the coherent ϕ-photoproduction from deuterons from LEPS (this study) and CLAS [15]. Only statistical errors are displayed. The energy ranges for two measurements are also shown.

ment fit (25–30%), background (3%), luminosity (5%) and track reconstruction efficiency (5–10%). The fit was done with an expression inspired by a single-scattering diagram [22]: $d\sigma/d\tilde{t}^{\mathrm{d}} = ae^{-b\tilde{t}^{\mathrm{d}}}[F^{\mathrm{d}}(\frac{1}{4}t)]^2/[F^{\mathrm{d}}(\frac{1}{4}t^{\mathrm{d}}_{\mathrm{min}})]^2$ where $F^{\mathrm{d}}(t)$ is the deuteron form factor and two fit parameters are a, the $\gamma\mathrm{d} \to \phi\mathrm{d}$ cross section at $t = t^{\mathrm{d}}_{\mathrm{min}}$, and b the exponential slope. Since no strong E_γ dependence is seen for b across our energy range, a fit with a single slope parameter b was used to determine the intercept, a, at each E_γ bin. The slope parameter b was found to be $5.5 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{sys})\ c^2/\mathrm{GeV}^2$, larger than that measured in the $\gamma p \to \phi p$ reaction $3.38 \pm 0.23\ c^2/\mathrm{GeV}^2$ at the same energy region [13]. It is noted that the systematic error of the slope parameter is about 10%, which is less than the cross section uncertainties. The reason is two-fold: for one, the main systematic errors in the cross sections $d\sigma/d\tilde{t}^{\mathrm{d}}$ (from the uncertainties in disentangling coherent and incoherent) vary in a more or less coherent way across all t bins; second, the slope parameter in the fitting function has a non-linear t-dependence.

The $d\sigma/dt$ at $\theta = 0$ determined in the coherent ϕ-meson events with a deuterium target as a function of photon energy are displayed in Fig. 3. The energy dependence of $d\sigma^{\gamma\mathrm{d}}/dt$ shows a steady increase with the photon energy. The solid line displays the calculation of $d\sigma^{\gamma\mathrm{d}}/dt$ by a model taking account of pomeron and η-exchange processes [6,7] and clearly the data is under-predicted.

In Fig. 4 we overlay two complementary measurements of differential cross sections of coherent ϕ-photoproduction from deuterons at low energies: one at the forward direction for $1.57 < E_\gamma < 2.37$ GeV in the current study and the other at the large $|t|$ region within $1.6 < E_\gamma < 2.6$ GeV by CLAS [15]. The energy ranges for these two measurements are mostly overlapping but it is slightly wider for CLAS. The agreement is fairly reasonable at the overlapped $|t|$ region of these two measurements.

The normalized decay angular distributions of $\mathrm{W}(\cos\Theta)$ and $\mathrm{W}(\Phi - \Psi)$ in the Gottfried–Jackson frame for the ϕ-produced events were obtained in the region of $|\tilde{t}^{\mathrm{d}}| < 0.1\ \mathrm{GeV}^2/c^2$ for $1.87 < E_\gamma < 2.37$ GeV. Here, Θ and Φ denote the decay polar and azimuthal angles, respectively, of the K^+ in the ϕ-meson rest frame. The y-axis of the ϕ-meson rest frame is perpendicular to the production plane of the ϕ-meson in the center-of-mass frame and the choice of z-axis is along the momentum of the incident photon. The azimuthal angle between the photon polarization and production plane is denoted by Ψ. Events of $E_\gamma < 1.9$ GeV were excluded due to insufficient statistics in the angular bins. The polar angle distribution $W(\cos\Theta)$ is consistent with $(3/4)\sin^2\Theta$, the same as the results from protons [13]. This indicates the dominance of helicity-conserving processes in t-channel exchange for the photoproduction of ϕ-mesons from deuterons.

The distribution of $W(\Phi - \Psi)$ is parameterized as $1 + 2P_\gamma \bar{\rho}^1_{1-1} \cos[2(\Phi - \Psi)]$ [23], where P_γ is the degree of polarization of the photon beams. In the case of pure helicity-conserving amplitudes, the decay asymmetry $\bar{\rho}^1_{1-1}$ becomes equivalent to half of either the parity asymmetry $P_\sigma(\equiv (\sigma^N - \sigma^U)/(\sigma^N + \sigma^U))$ [10] or the decay asymmetry $\Sigma_\phi(\equiv (\rho^1_{1-1} + \rho^1_{11})/(\rho^0_{1-1} + \rho^0_{11}))$ [6] and is 0.5(−0.5) for pure natural (unnatural)-parity processes. We disentangled the decay asymmetry of coherent ($\bar{\rho}^1_{1-1}{}^{\text{co}}$) and incoherent ($\bar{\rho}^1_{1-1}{}^{\text{inco}}$) interactions in the following way. The events were divided into two, by a missing-mass ($\text{MM}_\text{d}(\gamma, \text{KK})$) cut, MM_div, of 1.89 GeV/c^2. Two sets of decay angular distributions $W_{a,b}(\Phi - \Psi)$ were constructed and are shown at top of Fig. 5. The subscript a (b) denotes the events whose missing mass are smaller (greater) than 1.89 GeV/c^2. Afterwards the average decay asymmetry ($\langle\bar{\rho}^1_{1-1}\rangle_{a,b}$) was obtained by fitting $W_{a,b}(\Phi - \Psi)$ with $1 + 2P_\gamma \bar{\rho}^1_{1-1} \cos[2(\Phi - \Psi)]$ azimuthal distributions individually. A larger angular asymmetry was seen for the events with smaller missing mass [24]. This is interpreted as the difference of the mixing percentage ($R_{a,b}$) of coherent and incoherent events distributed in the two separate regions of $\text{MM}_\text{d}(\gamma, \text{KK})$ and their individual decay asymmetries. The $R_{a,b}$ were determined by fits of simulated missing mass distributions and hence the individual decay asymmetry was extracted under the assumption of linear weighting from each component, $\langle\bar{\rho}^1_{1-1}\rangle_{a,b} = R_{a,b}\bar{\rho}^1_{1-1}{}^{\text{co}} + (1 - R_{a,b})\bar{\rho}^1_{1-1}{}^{\text{inco}}$.

The decay asymmetries $\bar{\rho}^1_{1-1}{}^{\text{co}}$ as a function of photon energy at $E_\gamma = 1.87$–2.37 GeV are shown at the bottom of Fig. 5. The results are consistent in four choices of missing mass cut for division MM_div: 1.875, 1.88, 1.89 and 1.90 GeV/c^2. Results using the cut of 1.89 GeV/c^2 are presented because of the smallest statistical errors. Calculation of systematic uncertainties include those in $R_{a,b}$, from disentanglement procedures (5–15%), and the missing-mass cut for event division MM_div (10–20%). As mentioned above for the slope parameter, the systematic error of $\bar{\rho}^1_{1-1}{}^{\text{co}}$ is less affected by the disentanglement uncertainties than those of cross sections.

A very large decay asymmetry of 0.48 ± 0.07(stat) ± 0.10(sys) was observed, contrasting with a value of 0.2 from the proton [13]. Within errors, our measurement reaches the maximum boundary corresponding to a pure natural-parity exchange process, showing that coherent ϕ-meson production from deuterons is predominantly from natural-parity processes. This suggests the absence of π-exchange, together with a negligible contribution of η-exchange in the sector of unnatural-parity exchanges [6,7].

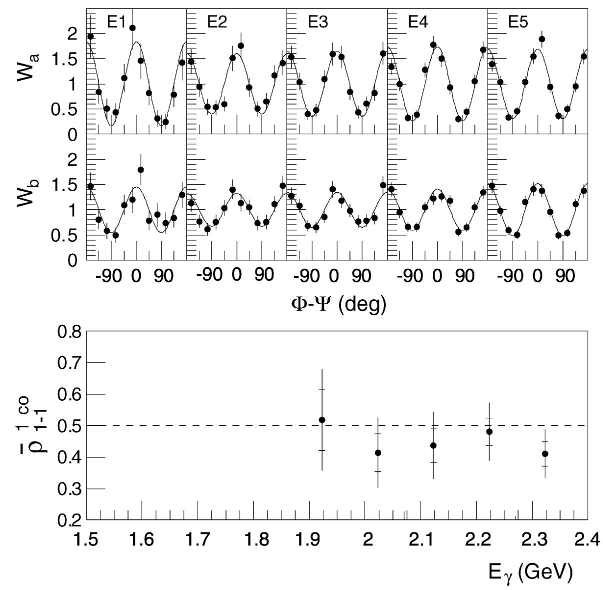

Fig. 5. The decay angular distributions $W_{a,b}(\Phi - \Psi)$ of K^+K^--pair events overlaid with the fit in five E_γ bins of equal width and the decay asymmetry $\bar{\rho}^1_{1-1}{}^{\text{co}}$ of $\gamma\text{d} \to \phi\text{d}$ as a function of photon energy. The subscript a (b) denotes the events of missing mass smaller (larger) than 1.89 GeV/c^2. The E_γ binning starts from $E_1 = (1.87, 1.97)$ GeV and ends at $E_5 = (2.27, 2.37)$ GeV.

4. Discussion

Supported by a strong dominance of natural-parity helicity-conserving exchange processes, the $d\sigma/dt$ at $\theta = 0$ for $\gamma\text{d} \to \phi\text{d}$ are expected to reflect pomeron exchange and the other natural-parity exchange processes at low energies. Under the conditions of small momentum transfer and negligible unnatural-parity and helicity-nonconserving processes, the differential cross section of coherent production from deuterons $d\sigma^{\gamma\text{d}}/dt$ may be approximated as $4S^N(t)d\sigma^{\gamma N;\text{T}=0}/dt$ where $S^N(t)$ is the natural-parity deuteron form factor and $d\sigma^{\gamma N;\text{T}=0}/dt$ is the cross section of ϕ-meson photoproduction from nucleons by isoscalar (T = 0) t-channel exchange processes [22]. Depending on the choice of the total ϕ–N cross section between 10 and 30 mb, there is about 2–7% uncertainty resulting from the omission of Glauber shadowing in the factorization approximation.

Fig. 6 shows the deduced $d\sigma^{\gamma N;\text{T}=0}/dt$ in this study and the existing data of $d\sigma^{\gamma p}/dt$ from threshold up to $E_\gamma = 6$ GeV, all extrapolated to $\theta = 0$ [13,25], in comparison with the corresponding theoretical predictions [6,7,23]. The solid line displays the calculation of $d\sigma^{\gamma N;\text{T}=0}/dt$ by a model taking into account of pomeron and η exchange processes whereas the dashed line is for $d\sigma^{\gamma p}/dt$ with the inclusion of isovector π-meson exchange. It is interesting that both $d\sigma^{\gamma N;\text{T}=0}/dt$ and $d\sigma^{\gamma p}/dt$ at low energies are not consistent with the model calculation even though the data at higher energies are rather well described. The points of $d\sigma^{\gamma N;\text{T}=0}/dt$ which represent the contribution by the pomeron trajectory are mostly underpredicted by the model. At this moment our measurement, with its limited accuracy, cannot determine the precise energy dependence of any specific mechanism. Nevertheless the data

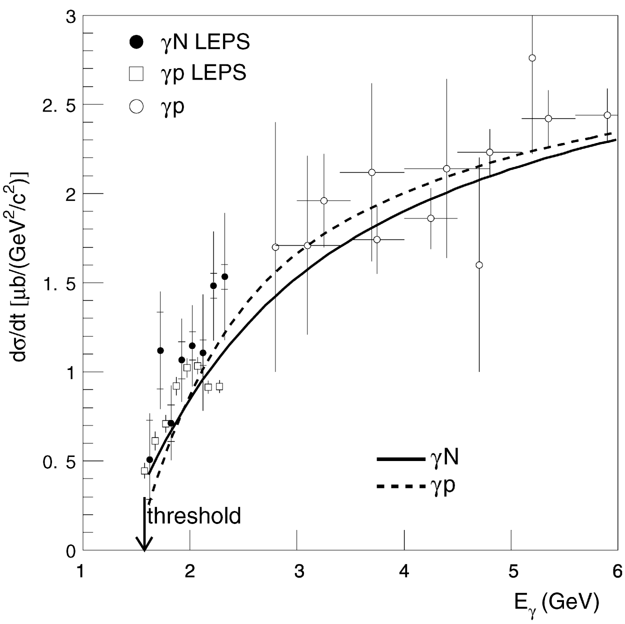

Fig. 6. Data of the cross section of ϕ-meson photoproduction from nucleons by isoscalar t-channel exchange processes $d\sigma^{\gamma N;\mathrm{T}=0}/dt$, deduced from coherent production from deuterons in this study and the existing data of $d\sigma^{\gamma p}/dt$ up to $E_\gamma = 6$ GeV [13,25]. All are extrapolated to $\theta = 0$. The solid and dashed lines represent the predictions of $d\sigma^{\gamma N;\mathrm{T}=0}/dt$ and $d\sigma^{\gamma p}/dt$ respectively by a model including pomeron exchange and π and η processes [6,7,23]. There is no contribution of isovector π-exchange in $d\sigma^{\gamma N;\mathrm{T}=0}/dt$ due to isospin conservation. The threshold of the $\gamma p \to \phi p$ reaction is labeled and the data below 2.5 GeV are shifted by -50 MeV for the clarity of display.

does hint at either a different energy dependence for standard pomeron exchange or the appearance of new dynamics like a daughter pomeron, in the near-threshold region. For future measurements of coherent production, it will be essential to identify the deuterons or one of the break-up nucleons in the final state in order to reduce the systematic errors caused by the disentanglement procedure in this work.

Information of the ϕ–N scattering length, which is crucial for modern QCD inspired models, could be obtained from the cross section at zero degrees near the threshold. In Fig. 6, both $d\sigma^{\gamma N;\mathrm{T}=0}/dt$ and $d\sigma^{\gamma p}/dt$ appear to be finite at the threshold of the $\gamma p \to \phi p$ reaction. It is noted that the production cross section $d\sigma$ is zero near the threshold (because of the phase space factor), but it is not the case for $d\sigma/dt$, which has a finite limit at the threshold as pointed out in Ref. [26]. A value of around 0.15 fm for the ϕ–N scattering length is found to be consistent with these data close to the threshold [26]. Finally, the observation of finite differential cross sections at threshold does not support the use of a kinematical factor q_ϕ^2/q_γ^2 in the model description of $d\sigma/dt$ [27], where q_ϕ and q_γ are the ϕ-meson and photon momenta in the center-of-mass system. With the factor q_ϕ^2/q_γ^2, the cross section $d\sigma/dt$ is destined to be zero at threshold because q_ϕ becomes zero and q_γ remains finite.

5. Summary

In summary we present measurements of coherent photoproduction of ϕ-mesons from deuterons using linearly polarized photons at forward angles in the low energy region of $E_\gamma = 1.5$–2.4 GeV. The cross section at $\theta = 0$ shows a strong increase with photon energy and a complete dominance of helicity-conserving natural-parity exchange processes. The absence of unnatural-parity isovector π-exchange, together with negligible contribution of η-exchange is inferred. It is found that $\gamma\langle N\rangle \to \phi\langle N\rangle$ cross sections for isoscalar t-channel exchange at $\theta = 0$ as a function of beam energy were not consistent with the prediction of the conventional pomeron model. Either a modified energy dependence for the pomeron trajectory or additional natural-parity processes beyond pomeron exchange in the near-threshold region would be compatible with our measurement. This measurement will serve as an important constraint on the theoretical modeling of pomeron trajectory and additional exotic channels in the low-energy regime and help to understand the strong coupling region of QCD. Solving the experimental challenge of directly identifying the deuteron in the final state of forward coherent interactions will be essential for future measurements to provide enough accuracy to pin down the energy dependence of any specific mechanism.

Acknowledgements

The authors thank the SPring-8 staff for supporting the BL33LEP beam line and the LEPS experiment. We thank A.I. Titov for many fruitful discussions. This research was supported in part by the Ministry of Education, Science, Sports and Culture of Japan, by the National Science Council of Republic of China (Taiwan), Korea Research Foundation (KRF) and National Science Foundation (USA).

References

[1] J.R. Forshaw, D.A. Ross, Quantum Chromodynamics and the Pomeron, Cambridge Univ. Press, 1997;
S. Donnachie, G. Dosch, P. Landshoff, O. Nachtmann, Pomeron Physics and QCD, Cambridge Univ. Press, 2002, and references therein.
[2] P.D.B. Collins, An Introduction to Regge Theory and High-Energy Physics, Cambridge Univ. Press, 1977.
[3] F.J. Llanes-Estrada, S.R. Cotanch, P.J. de A. Bicudo, J.E.F.T. Ribeiro, A. Szczepaniak, Nucl. Phys. A 710 (2002) 45.
[4] A. Donnachie, P.V. Landshoff, Phys. Lett. B 296 (1992) 227.
[5] L. Stodolsky, Phys. Rev. Lett. 18 (1967) 135.
[6] A.I. Titov, M. Fujiwara, T.-S.H. Lee, Phys. Rev. C 66 (2002) 022202(R).
[7] A.I. Titov, B. Kämpfer, Phys. Rev. C 76 (2007) 035202.
[8] T.H. Bauer, R.D. Spital, D.R. Yennie, F.M. Pipkin, Rev. Mod. Phys. 50 (1978) 261.
[9] T. Nakano, H. Toki, Proceedings of the International Workshop on Exciting Physics and New Accelerators Facilities, World Scientific, 1997;
L.S. Kisslinger, W.-H. Ma, Phys. Lett. B 485 (2000) 367.
[10] A.I. Titov, T.-S.H. Lee, H. Toki, O. Streltsova, Phys. Rev. C 60 (1999) 035205.
[11] R.A. Williams, Phys. Rev. C 57 (1998) 223.
[12] J.M. Laget, Phys. Lett. B 489 (2000) 3133.
[13] T. Mibe, et al., Phys. Rev. Lett. 95 (2005) 182001.
[14] K. Schilling, P. Seyboth, G. Wolf, Nucl. Phys. B 15 (1970) 397.
[15] T. Mibe, et al., CLAS Collaboration, nucl-ex/0703013.
[16] T. Nakano, et al., Nucl. Phys. A 684 (2001) 71.
[17] M. Sumihama, et al., Phys. Rev. C 73 (2006) 035214.
[18] H. Kohri, et al., Phys. Rev. Lett. 97 (2006) 082003.
[19] R. Brun, et al., CERN Applications Software Group, CERN Program Library Long Writeup W5013, 1993.

[20] P. Benz, et al., Nucl. Phys. B 65 (1973) 158.
[21] M. Lacombe, et al., Phys. Lett. B 101 (1981) 139.
[22] V. Franco, R. Glauber, Phys. Rev. 142 (1966) 1195;
Y. Eisenberg, et al., Nucl. Phys. B 42 (1972) 349.
[23] A.I. Titov, T.-S.H. Lee, Phys. Rev. C 67 (2003) 065205.
[24] K. Horie, et al., in: Seventeenth International Conference on Particles and Nuclei, in: AIP Conference Proceedings, vol. 842, 2006, pp. 510–512.
[25] The Durham HEP Database, http://durpdg.dur.ac.uk.
[26] A.I. Titov, et al., Phys. Rev. C 76 (2007) 048202.
[27] D.P. Barber, et al., Z. Phys. C 12 (1982) 1;
A. Sibirtsev, et al., Eur. Phys. J. A 29 (2006) 209.