Measurement of the incoherent $\gamma d \to \phi pn$ photoproduction near threshold

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Abstract

We report measurements of differential cross sections and decay asymmetries of incoherent $\phi$-meson photoproduction from the deuteron at forward angles using linearly polarized photons at $E_\gamma =1.5$-2.4 GeV. The nuclear transparency ratio for the deuteron shows a large suppression, and is consistent with the $A$-dependence of the ratio observed in a previous measurement with nuclear targets. The reduction for the deuteron cannot be adequately explained in term of isospin asymmetry. The present results suggest the need of refining our understanding of the $\phi$-$N$ interaction within a nucleus.

Key words: photoproduction, $\phi$ mesons, deuterons, incoherent interaction

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1. Introduction

The origin of hadron mass is one of the most fundamental questions in understanding the strong interaction. It is generally believed that the dynamical breaking of chiral symmetry is responsible for formation of composite hadrons and the origin of their masses. A partial restoration of chiral symmetry \cite{1} may occur in hot or dense nuclear matter. The corresponding change of the chiral condensate would lead to a modification of hadron properties in the nuclear medium. There have been many experiments to search for such modifications in the collisions of hadron, heavy-ion and photon beams with nuclear targets.

In particular the $\phi$ vector meson is a good probe because of its narrow width in free space (4.26 MeV/$c^2$) and the small $\phi$-$N$ interaction cross section. In the case of the $\rho$ and $\omega$ mesons, the overlap of two peaks with different widths along with strong final-state interactions with the nuclear medium, makes it difficult to single out the intrinsic in-medium modification of either one of the two mesons. In contrast, any modification to the lineshape of $\phi$ meson in the nuclear medium remains mostly unaffected by hadronic interactions, and can be identified more easily and with less ambiguity. The first evidence for the in-medium mass shift of $\phi$ mesons was reported in the pA reaction at the normal nuclear density \cite{2,3}.

An alternative way is to determine the in-medium width of $\phi$ mesons by measuring the nuclear transparency ratio (or sur-
vival probability) \( T_A = \sigma_A / (A \sigma_N) \), where \( \sigma_A \) is the incoherent \( \phi \)-meson production cross section from the nuclear target with an atomic mass \( A \), and \( \sigma_N \) is the cross section from a free proton \([4, 5]\). A broadened width in the nuclear medium would produce an increase of the \( \phi \)-N inelastic cross section, thus leading to a drop of \( T_A \) below unity. Experimentally, strong attenuation was observed in the \( \phi \) photoproduction from Li, C, Al and Cu nuclei \([6]\). In a simple Glauber approximation, the inelastic \( \phi \)-N cross section \( \sigma^{\text{inel}}_{\phi N} \) was determined to be about 35 mb from the measured A-dependence, which is significantly larger than the total \( \phi \)-N cross section of about 13 mb estimated by using the vector-meson dominance model in \( \phi \) photoproduction off the proton at \( E_\gamma = 3-6 \) GeV \([7]\). A recent measurement of coherent \( \phi \)-meson photoproduction off the deuteron at CLAS is compatible with a \( \sigma_{\phi N} \) of 30 mb together with a large transverse slope for the \( \phi N \rightarrow \phi N \) process \([8]\).

Subsequent theoretical studies \([9, 10]\) have confirmed that it is necessary to introduce a large \( \sigma^{\text{inel}}_{\phi N} \) in the range of 30-60 mb or invoke a coupled-channel effect of \( \omega-\phi \) mixing \([10]\) for describing the measured A-dependence of attenuation in \( \phi \)-meson photoproduction from nuclei. Note that one of these studies takes into account the standard nuclear structure effects, such as Fermi motion, Pauli blocking, nuclear shadowing and quasi elastic scattering processes \([9]\). The enlargement of \( \sigma^{\text{inel}}_{\phi N} \) may be due to nuclear density effect in nuclear matter \([5]\). To clarify the underlying physics, it is essential for us to construct a reliable baseline in a reasonably low density region, using the simplest nucleus—the deuteron—made of one proton and one neutron, where nuclear density effects are minimized.

In the high photon energy region of 45-85 GeV, the \( \phi \)-meson photoproduction yields per nucleon for proton and deuteron targets were found to be the same within a 10% discrepancy \([11]\). The \( \phi \) mesons were produced with large momenta and the results were well described using vector-meson dominance and the additive quark model. In the near-threshold region, the quark exchange processes, other than Pomeron exchange, could contribute, and an interference among them would generate an isospin dependence \([12]\). In this Letter we report the differential cross sections and decay asymmetries of incoherent \( \phi \)-photoproduction with a liquid deuteron target at \( E_\gamma = 1.5-2.4 \) GeV at forward scattering angles.

2. Experiment and analysis

The experiment was carried out at the laser-electron photon facility, SPring-8. Linearly polarized photons were generated by backward Compton scattering of polarized laser light from 8 GeV electrons in the storage ring. The high polarization of photon beams allowed a measurement of the decay asymmetry. Charged particles emitted from the interaction points of photon with a 16-cm long deuteron target were detected at forward angles in the LEPS spectrometer. Particle identification was made by the mass reconstruction using the time of flight and momentum. For more details on the detectors and the quality of the particle identification, see Ref. \([13]\).

Events of \( \phi \)-meson production were selected with a cut on the invariant mass of a \( K^+ K^- \) pair \( |M(K^+ K^-) - M_\phi| < 0.01 \) GeV/c\(^2\). In the invariant mass spectra, assuming the whole deuteron as target, \( \text{MM}_d(\gamma, \phi) \), at \( 1.57 < E_\gamma < 2.37 \) GeV. Each \( \text{MM}_d(\gamma, \phi) \) spectrum is fitted with the sum (solid line) of MC-simulated components of coherent (dotted line) and incoherent (dashed line) events.

![Figure 1: The missing mass spectra assuming the whole deuteron as target, \( \text{MM}_d(\gamma, \phi) \)](image)

\( \text{MM}_d(\gamma, \phi) \) at \( 1.57 < E_\gamma < 2.37 \) GeV. Each \( \text{MM}_d(\gamma, \phi) \) spectrum is fitted with the sum (solid line) of MC-simulated components of coherent (dotted line) and incoherent (dashed line) events.
3. Results

We calculated differential cross sections in the region of $1.57 < E_\gamma < 2.37$ GeV and $|t| < 0.6$ GeV$^2$/c$^2$, where $t = t - t_{\text{min}}$. Here, $t$ is the squared four-momentum transfer between incident photon and nucleon target, and $t_{\text{min}}$ corresponds to the $t$ where the $\phi$ meson is produced at zero degrees. Because of the deuteron form factor, coherent events appear mostly in the small $|t|$ region [18]. The disentanglement fit using MC simulated coherent and incoherent components in MM$_d$($\gamma, \phi$) spectra was performed in the very forward region of $|t| < 0.4$ GeV$^2$/c$^2$, with the bin sizes of 0.1 GeV for $E_\gamma$ and 0.02 GeV$^2$/c$^2$ for $t$. All $\phi$-events with $|t| > 0.4$ GeV$^2$/c$^2$ were counted as incoherent.

With a proper normalization of the photon beam flux, number of target atoms, tagger efficiency, transporting efficiency and branching ratio of charged decay of $\phi$ mesons, differential cross sections of incoherent events $d\sigma/dt$ are displayed in Fig. 2. The error bars shown are statistical only. The differential cross section was fitted with an exponential function convoluted with MC-estimated acceptance efficiency: $d\sigma/dt = a \exp(bt)$, where the fit parameter $a$ is the differential cross section at $t = 0$ (i.e. zero degrees) and $b$ is the exponential slope. Within the error range of the slope $b$ at these $E_\gamma$ bins, no strong energy dependence is observed.

A fit with one common slope parameter for all $E_\gamma$ bins gives a value of $b$ to be $3.23 \pm 0.11$ (stat) $\pm 0.16$ (sys) GeV$^2$/c$^2$ for incoherent events, which is consistent with $3.38 \pm 0.23$ GeV$^2$/c$^2$ for production from a free proton [19]. The zero-degree cross sections of incoherent production from deuteron as a function of the photon energy are shown in Fig. 3(a), together with data from hydrogen [19]. The total error is the square root sum of the statistics and systematic one while the bars represent the range of statistical errors. The systematic uncertainties arise from the disentanglement fit (10-15%), background (5-10%), luminosity (5%) and track reconstruction efficiency (5-10%).

Since the slope parameters of differential cross sections in the production from deuteron and hydrogen are rather close, the nuclear transparency ratios for deuteron, $T_d = \sigma_d/(2\sigma_p)$, can be evaluated by the ratio of cross sections at zero degrees and are shown in Fig. 3(b). Compared to the $\phi$ production from a free proton, a significant 25-30% reduction of the $\phi$ yield per nucleon is observed for incoherent production from deuteron. We confirmed that the cross sections of $\gamma_d \rightarrow \phi p$ obtained from runs off hydrogen in the present experiment are in agreement with the reported value in Ref. [19], thus checking the consistency of the beam and target normalization and the related efficiency factors.

Because the normalization used in the nuclear transparency ratio is associated with the production from protons, it is straightforward to speculate that the observed suppression of nuclear transparency ratio for deuteron stems from a reduction in $\phi$-mesons produced from neutrons. For example, Titov et al. [12] suggested that such a reduction happens because of a destructive interference effect between unnatural-parity isovector $\pi$ and isoscalar $\eta$ exchange. However, it is known that $\phi$-meson photoproduction from hydrogen is dominated by the processes of natural-parity $t$-channel exchange [19]. A possible interference
effect in the unnatural-parity sector is unlikely to induce significant differences in the cross sections from the proton or the neutron.

We examined the isospin dependence of $\phi$ photoproduction by studying the exclusive $\phi$ events whose final state of a $K^+K^-$ pair and a proton is fully detected in the spectrometer; the kinematics of these events is dominated by interactions with the proton inside deuterium. Though limited by statistics, Fig. 4(a) clearly shows a similar degree of reduction for quasi-free events from the proton as compared with inclusive reactions, see Fig. 5(b). Therefore the reduction in $\phi$ yields occurs in a similar scale for the incoherent production from both the proton and the neutron inside deuterium. It also suggests that the $\pi$-$J$ interference effect, which makes a difference in the production from proton and neutron, is small.

Further information on isospin effects comes from the decay angular distributions of $W(\Phi - \Psi)$. These distributions were obtained in the Gottfried-Jackson frame and in the region of $|t| < 0.1$ GeV$^2$/c$^2$ at $1.87 < E_\gamma < 2.37$ GeV. Here, $\Phi$ denotes the decay azimuthal angles of the $K^+$ in the $\phi$-meson rest frame. The azimuthal angle between the photon polarization and the production plane is $\Psi$. Events with photon energies below 1.9 GeV were excluded due to insufficient statistics in the angular bins.

The decay angular distribution of $W(\Phi - \Psi)$ is parametrized as $1 + 2P_s\rho_1 \cos[2(\Phi - \Psi)]$, where $P_s$ is the polarization degree of the photon beams $[20]$. In the case of helicity-conservation, the decay asymmetry $\rho_1$ reflects the relative contributions of natural- ($|I_0^\Psi|^2$) and unnatural-parity processes ($|I_0^{\tilde{\Psi}}|^2$): $\rho_1 = 0.5(|I_0^{\Psi}|^2 - |I_0^{\tilde{\Psi}}|^2)/(|I_0^{\Psi}|^2 + |I_0^{\tilde{\Psi}}|^2)$ [20]. In two separated regions of missing mass, the decay asymmetry $\rho_1$ and the percentage of incoherent events ($R$) were determined respectively.

The individual decay asymmetry of incoherent ($\rho_{1\text{ inc}}$) and coherent ($\rho_{1\text{ co}}$) events were extracted from the difference of measured decay asymmetries and relative weights of two kinds of events in these two regions, assuming a linear weighting of each component, $\rho_1 = R\rho_{1\text{ inc}} + (1 - R)\rho_{1\text{ co}}$. Figure 2(b) shows the decay asymmetries $\rho_{1\text{ inc}}$, as a function of photon energy at $E_\gamma = 1.67-2.37$ GeV. Compared with those for $\gamma p \rightarrow \phi p$ reaction, the decay asymmetries for the $\gamma d \rightarrow \phi pn$ reaction is slightly larger in the region of $2.17 < E_\gamma < 2.37$ GeV, and agrees well in the region of $1.97 < E_\gamma < 2.17$ GeV.

Given a value of 0.25 for $\rho_{1\text{ inc}}$, the $\rho_1$ for the $\gamma n \rightarrow \phi n$ interaction would be 0.3 assuming an equal production from either the proton or the neutron. One theoretical model gives a compatible prediction of 0.3-0.35 [21]. Constrained by the measurement of decay asymmetries, the possible target isospin asymmetry is less than 15% and, the reduction in the $\phi$ yield per nucleon for incoherent production from deuterium is at most 8% within the scenario of interference effect between unnatural-parity parts. The closeness of decay asymmetries in the interactions with nucleons and with free protons actually hints at the weakness of the isoscalar component $\eta$-exchange in the unnatural-parity exchange processes. This interpretation is supported by a complete dominance of the natural-parity Pomeron exchange processes in the coherent production, where the isovector $\pi$-exchange is forbidden [18].

Effects of possible final-state interactions and Fermi momentum are explored by investigating quasi-free incoherent events using the “minimum momentum spectator approximation” developed in Ref. [22]. In our acceptance, the Fermi momentum is well approximated by the so-called “minimum momentum of spectator” $p_{\text{min}}^{\text{spec}}$, defined as the component of the spectator momentum in the direction of the momentum of the $np$ pair. The magnitude of $p_{\text{min}}^{\text{spec}}$ is about $70/\sqrt{3}$ MeV/c. Fig. 5 shows the $p_{\text{min}}^{\text{spec}}$ distributions for $\phi$ events in eight bins of $1.57 < E_\gamma < 2.37$ GeV. The main contribution with a peak near zero comes from incoherent events. Contributions from coherent events with a deuteron in the final state is characterized by a positive $p_{\text{min}}^{\text{spec}}$ around 0.15-0.2 GeV/c, which is approximately equal to half of the momentum of the $np$ pair.

For incoherent $\pi^0$ photoproduction from deuterium, final-state interactions play a significant role because the final NN state strongly overlaps with deuteron bound state [23]. A large reduction is found in the differential cross section of incoherent production from deuterons at forward angles, compared to that of production from free protons. However the situation is rather different in the case of $\phi$ production: the large mass of the $\phi$ meson results in a large momentum transfer between the incident photon and the participant nucleon in the near-threshold production. The minimum momentum of a rescattered nucleon in the lab system ranges from 700 MeV/c at threshold to 250 MeV/c at $E_\gamma = 2.5$ GeV. With such a large momentum for the recoiled nucleon, the overlapping of final NN state with deuteron bound state is rather limited. Therefore the effect of final-state interactions is greatly reduced. As mentioned earlier, the slope parameters of differential cross sections for deuteron and proton targets in the forward direction agree well. There also exists an overall agreement between the distribution of incoherent events and the overlaid curve representing the MC-simulated distribution of incoherent events without any final-state interactions shown in Fig. 5. It is noted that the discrepancy between the real distribution and the MC simulation around $p_{\text{min}}^{\text{spec}} = 0.1$ GeV/c cannot be fully resolved even with the inclusion of final-state interactions.
Events which are associated with quasi-free processes can be selected with a small $p_{\text{spec}}/p_{\text{min}}$ value. The nuclear transparency ratios, for events with the magnitude of $p_{\text{spec}}$ below 90 MeV, agree well with those obtained using the disentanglement method. Thus we exclude both final-state interactions (between participants and spectator nucleons) and Fermi momentum of target nucleons from the dominating mechanism in generating the observed reduction.

4. Discussion

A target mass number dependence of $A^{-0.28}$ in the nuclear transparency of $\phi$ mesons was found in the incoherent photoproduction with nuclei [6]. According to this dependency, the expected nuclear transparency ratio for deuterium is 0.82, which is even slightly above the energy-averaged value $0.73 \pm 0.058$, obtained from the ratios shown in Fig. 3(b). Since the deuteron is composed of a loosely bound proton and neutron, where the nuclear medium effect is minimal, the present observations strongly suggest that some effect other than nuclear density is necessary to achieve a complete understanding the reduction of $\phi$ production in the nuclear medium [3]. For example, since the present results are obtained near the production threshold, the momenta of produced $\phi$ mesons are relatively small in the range of 1-2 GeV/c. The $\phi$ meson, which could fluctuate to either a $K^+K^-$ pair or an $\omega$ meson [10], is likely to have a larger cross section with nucleons nearby. In the low-energy region, a two-step processes and/or coupled-channel effects might induce a more significant loss of $\phi$-mesons in nuclei than the current theoretical estimates.

5. Summary

In summary, differential cross sections and decay asymmetries of incoherent $\phi$-meson photoproduction from deuterons were measured at forward scattering angles near threshold. In comparison with those from proton, the decay asymmetry is similar, but the production cross section per nucleon shows a significant reduction. The reduction is common in incoherent production from both the proton and the neutron inside deuterium. The target isospin asymmetry is found to be small and cannot account for the large suppression of the nuclear transparency ratio for the deuteron. The present work suggests that the nuclear transparency ratio of $\phi$-meson photoproduction is sensitive to the details of the nuclear structure. It should also be an important baseline to differentiate nuclear density effects. Further theoretical work on refining the $\phi$-N interaction within a nucleus is required to explain such a large reduction near threshold from deuteron. Hence the existence of nuclear medium effects, or any other interesting mechanisms, can be identified in a future study of $\phi$-meson production from nuclei.

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