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Photoproduction of ω mesons off protons and neutrons

The CBELSA/TAPS Collaboration

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Abstract. ω photoproduction off hydrogen and deuterium has been studied with the tagged photon beam of the ELSA accelerator in Bonn for photon energies up to 2.0 GeV. The ω meson has been identified via the $\omega \rightarrow \pi^0 \gamma \rightarrow \gamma \gamma \gamma$ decay mode, using the combined setup of the Crystal Barrel/TAPS detector systems. Both inclusive and exclusive analyses have been carried out. Differential and total cross-sections have been derived for ω mesons produced off free protons and off protons and neutrons bound in deuterium. The cross-section for the production off the bound neutron is found to be a factor of ≈ 1.3 larger than the one off the bound proton in the incident beam energy region $1.2 \text{ GeV} < E_\gamma < 1.6 \text{ GeV}$. For higher incident beam energies this factor goes down to ≈ 1.1 at 2.0 GeV. The cross-sections of this work have been used as normalization for transparency ratio measurements.

1 Introduction

The study of pion- and photon-induced reactions on nucleons is an important part of modern hadron physics. The information on the baryon resonance spectrum will increase the understanding of the hadron structure and the strong interaction. In addition, it provides information on meson-baryon interactions which is crucial for the investigation of in-medium effects in nuclear media.

At the few-GeV energy scale, where perturbative methods cannot be applied, numerical methods such as lattice gauge theory can be used for describing baryon properties via Quantum Chromodynamics (QCD) [1]. Although it is a slow and resourceful approach, it has had a lot of success determining hadron properties. Still, due to the numerical sign problem (see, *e.g.* [2]), lattice calculations

have difficulties describing QCD at high density, *e.g.* in nuclear matter. Quark models provide a link between experimental observations and QCD. There is, however, no established ground for these models neither when it comes to the number of effective degrees of freedom nor about the residual quark-quark interaction. Various models give rise to different nucleon excitation spectra. However, comparison to experiment has not managed to select one favorable model since all quark models predict more resonant states than have been confirmed by experiments so far. It is thought that these so-called “missing resonances” couple only weakly to the πN channel, which for many years has been the predominant experimental approach to study the excitation energy spectrum of the nucleon. For this reason it is important to study data from other reactions and to have a model that involves other final states.

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Fig. 1. (Color online) The setup of the experiment at ELSA. The beam entered from the left. Scattered electrons were registered by the tagger. The target was mounted at the center of the Crystal Barrel. The forward region was covered by the TAPS detector. The beam intensity was monitored at the end of the beam line.

The photoproduction of ω mesons off the free proton has been measured with the SAPHIR detector at the ELSA facility [3] as well as with CLAS at the Thomas Jefferson National Accelerator Facility [4]. A coupled-channel analysis [5] taking the SAPHIR data into account shows that the ω production off the free proton is dominated by t -channel π^0 exchange at higher incident beam energies ($E_\gamma > 1.3$ GeV). Close to the production threshold a strong contribution from the $P_{11}(1710)$ resonance has been implied. Measurements of polarization observables for ω meson production off the free proton performed by CBELSA/TAPS [6] and GRAAL [7] also indicate s -channel resonance formation in addition to t -channel exchange processes. A partial wave analysis of these data [6,8] indicates important contributions from the $P_{13}(1720)$, $D_{13}(1700)$ and $F_{15}(1680)$ resonances. The experimental progress and theoretical approaches have been summarized in [9, 10].

The cross-section for photoproduction of ω mesons off neutrons, on the other hand, has not been measured so far. It is, however, important for a quantitative understanding of the ω meson-nucleus interaction since it gives insight to the isospin composition of the electromagnetic excitation amplitudes. Measurements of the photoproduction of other mesons like η [11] and η' [12] off neutrons have shown that the cross-sections for production off neutrons and off protons are different. The cross-section for photoproduction of ω mesons off the neutron is an additional experimental constraint for theoretical models for coupled-channel effective Lagrangian calculations aiming at including as many channels and partial waves as possible. Until now, all information on the ω meson-nucleus interaction has come from studying the production off protons.

One of the hot topics in modern hadron physics is the search for in-medium modifications, *i.e.* changes of the properties of hadrons when embedded in a medium other than vacuum (for example, hot and/or dense strongly interacting matter). Various experiments have seen indications for such modifications and a lot of theoretical work has been invested for understanding these changes. For

recent reviews of the field see [13–16]. The present work provides some important input for those studies.

The experimental observable for extracting the in-medium width of mesons is the so-called nuclear transparency ratio [17, 18], which is a measure for the meson absorption in nuclei. Here, the ω production cross-section off the bound proton and neutron are of particular importance as a reference.

The paper has the following structure: a brief description of the CBELSA/TAPS experimental setup is given in sect. 2. Section 3 describes the reconstruction of the ω meson and the identification of the recoil nucleon. In addition, the detector acceptances are shown and the systematic errors are listed. In sect. 4 the results on differential and total cross-sections are presented. In sect. 5 the absorption of ω mesons in larger nuclei is discussed in terms of the transparency ratio, making use of the measured ω photoproduction cross-sections off the bound proton and bound neutron reported in this paper. Conclusions are drawn in sect. 6.

2 Experimental setup

The experiment was performed at the electron stretcher accelerator facility ELSA in Bonn [19, 20] which provides electron beams with intensities of about 1 nA and energies up to 3.5 GeV. For this work, the electron beam energy was 3.2 GeV and 2.6 GeV for the measurements with a liquid hydrogen (LH_2) target and a liquid deuterium (LD_2) target, respectively. Details about the target can be found in [21].

A schematic layout of the beam line is shown in fig. 1. The Bremsstrahlung photons impinging on the target were produced by a radiator and tagged by the tagging spectrometer consisting of 480 scintillating fibers. The unscattered electrons were directed into a beam dump.

The reaction products emerging from the target were detected by the combined setup of the Crystal Barrel (CB) [22] and TAPS [23, 24] calorimeter systems, which covered 96% of the full solid angle.

Charged particles were registered by a scintillating fiber detector (the Inner detector) [25] in the CB angular region and by hexagonal plastic veto detectors in front of each TAPS crystal.

The photons that did not interact with the target were counted by the γ -intensity monitor at the end of the beam line and the rate was used to determine the photon flux. The γ -intensity monitor was also used for monitoring the position of the beam.

The hardware trigger selected the interesting events on-line. The trigger conditions for the LD₂ beam time have been explained in detail in [26]. In short, the trigger condition required at least one hit in TAPS over the high energy threshold and two hits in CB OR two hits in TAPS over the low energy threshold. The hardware trigger for the LH₂ beam time was built in a similar way but was less strict [27]. The only difference being that instead of two hits in CB, one hit in CB was sufficient for the trigger to fire. In the analysis a software trigger with stricter and equal conditions for the two beam times was used. The software trigger is described in sect. 3.1.

3 Data analysis

The first step of the analysis, the calibration procedures which transformed the raw data into physical quantities, has been described in [26] and will not be discussed further here. In this section, the focus will be on the specific aspects of the analysis used to obtain the cross-sections published in this paper.

The main emphasis of this work was on the analysis of the LD₂ beam time and the extraction of the cross-section off the neutron. The LH₂ beam time was only analyzed as a cross-check of the analysis, thus the identical analysis was used for the two beam times. The Fermi motion of the bound protons and neutrons prevented the use of methods such as kinematical fitting. An independent analysis of the LH₂ beam time has been carried out and a paper is in preparation [28].

3.1 Software trigger

To enable a direct comparison of the free proton and bound proton acceptances, a software trigger mimicking the stricter conditions of the hardware trigger used for the LD₂ beam time, was implemented. In addition, the aim for a comparison of the reaction off the proton and off the neutron required a software trigger that only allowed for photons to trigger. The software trigger was thus; at least one photon in TAPS over the high energy threshold and two photons in CB OR two photons in TAPS over the low energy threshold.

3.2 Event classes

The ω meson was identified via the $\omega \rightarrow \pi^0 \gamma \rightarrow \gamma \gamma \gamma$ decay channel, which has a branching ratio of 8.28%. Three

partially overlapping event classes have been analysed. Class (a) included events with exactly three neutral hits and one charged hit. This group of events was used for the exclusive analysis where the ω meson was produced off a proton which was detected. The proton was either free in the LH₂ target giving the reaction $\gamma p \rightarrow \omega p$ or bound in the LD₂ target giving the quasi-free reaction $\gamma d \rightarrow \omega p(n)$. Class (b) contained events with exactly four neutral hits and no charged hits. This group of events corresponded to the quasi-free production of ω mesons off a neutron $\gamma d \rightarrow \omega n(p)$ where the recoil neutron was detected in coincidence (exclusive analysis). The last class of events (c) was used for the inclusive analysis where no condition for the recoil nucleon was placed (it may have been detected, but that was not a requirement). It included all events from classes (a) and (b) and, in addition, the events with exactly three neutral hits and no charged hits. For the LH₂ target this class of events corresponded to the reaction $\gamma p \rightarrow \omega(p)$ and for the LD₂ target to the reaction $\gamma d \rightarrow \omega(pn)$.

3.3 Reconstruction of the ω meson

The two photons originating from the π^0 in the $\omega \rightarrow \pi^0 \gamma$ decay were identified with a χ^2 -test minimizing

$$\chi^2 = \frac{(m(\gamma\gamma) - m_{\pi^0})^2}{(\Delta m(\gamma\gamma))^2}, \quad (1)$$

where $m(\gamma\gamma)$ was the invariant mass of all possible combinations of two neutral hits. The term $\Delta m(\gamma\gamma)$ represented the error arising from the detector resolution. Only events with the best candidate with an invariant mass satisfying $110 \text{ MeV}/c^2 < m(\gamma\gamma) < 160 \text{ MeV}/c^2$ were kept for further analysis. For these events the invariant mass was set to the nominal mass of π^0 in order to improve the experimental resolution [26].

For the classes of events where only three neutral hits were detected, the third neutral hit was combined with the already identified π^0 and the ω meson was identified from the $\pi^0 \gamma$ invariant mass. However, for the class of events with four neutral hits (one of them being a neutron candidate) the situation was more complicated. In this case there were two possible solutions for forming the $\pi^0 \gamma$ invariant mass by combining each of the two remaining neutral hits with the already identified π^0 (the true solution where the neutral hit was a photon and the wrong solution where the neutral hit was the neutron). In order to select the true solution the missing mass for both solutions was calculated according to

$$m_{\text{miss}}^n = |\mathbf{P}_\gamma + \mathbf{P}_N - \mathbf{P}_{\pi^0 \gamma}|, \quad (2)$$

where $\mathbf{P}_\gamma$, $\mathbf{P}_N$ and $\mathbf{P}_{\pi^0 \gamma}$ are the four-momenta of the incident photon, the initial state nucleon (assumed to be at rest) and the detected $\pi^0 \gamma$. With a χ^2 -test minimizing

$$\chi^2 \sim (m_{\text{miss}}^n - m_n)^2 \quad (3)$$

the true solution for $m_{\pi^0 \gamma}$ was selected from the two possibilities. To assure the reliability of this method it was

Fig. 2. (Color online) Top: Missing mass spectra for the $\gamma n(p) \rightarrow \omega n(p)$ simulation for two different incident beam energy ranges. Bottom left: The missing mass cut. Bottom right: The invariant mass of $\pi^0 \gamma$ for the LD₂ target data with the class of events with exactly four neutral hits without the missing mass cut (black solid) and with the missing mass cut (red dashed).

tested on a simulation of the $\gamma n(p) \rightarrow \omega n(p)$ reaction. It showed that only in a negligible part of the events the wrong solution was selected and the true solution discarded.

3.4 Background reduction

3.4.1 Missing mass cut

For all classes of events ((a), (b) and (c)) the missing mass was calculated according to eq. (2). For the exclusive analyses, detection of the recoil nucleon was required. However, since the nucleon did not deposit all its energy in the detector, its mass could not be calculated directly. Instead, it was treated as a missing particle. In the inclusive analysis, for the events where exactly three neutral hits were registered, the recoil nucleon was truly a missing particle.

Simulations of the reaction channels showed that the width of the missing mass peak depended on the incident beam energy. Figure 2 (top) shows the missing mass spectra for the $\gamma n(p) \rightarrow \omega n(p)$ simulation for two different incident beam energies. The missing mass spectra for several different incident beam energies were fitted with Gaussians and the missing mass cut was chosen to be a mean- $3\sigma < m_{\text{miss}}^n < \text{mean} + 2\sigma$ cut around the neutron (or proton) peak varying linearly with the incident beam energy (shown in fig. 2 (bottom left) for the $\gamma n(p) \rightarrow \omega n(p)$ simulation).

The missing mass cut was broader for the LD₂ target data than for the LH₂ target data due to the smearing effect of the Fermi motion of the nucleons in deuterium. For the LH₂ target data the linear missing mass cut implied the condition $835 \text{ MeV}/c^2 < m_{\text{miss}}^p < 1009 \text{ MeV}/c^2$ at an incident beam energy $E_\gamma = 1108 \text{ MeV}$ and $740 \text{ MeV}/c^2 < m_{\text{miss}}^p < 1083 \text{ MeV}/c^2$ at $E_\gamma = 2008 \text{ MeV}$. For the LD₂ target data the width of the missing mass cut varied slightly depending on the event class studied. On average it was $818 \text{ MeV}/c^2 < m_{\text{miss}}^n < 1027 \text{ MeV}/c^2$ for $E_\gamma = 1108 \text{ MeV}$ and $707 \text{ MeV}/c^2 < m_{\text{miss}}^n < 1162 \text{ MeV}/c^2$ for $E_\gamma = 2008 \text{ MeV}$.

Figure 2 (bottom right) shows the effect of the missing mass cut in the LD₂ target data for the class of events with exactly four neutral hits (and no charged hits). A clear improvement of the signal-to-background ratio in the $\pi^0 \gamma$ invariant mass spectrum can be seen. A similar reduction of background for the other event classes was observed when applying the corresponding missing mass cuts.

3.4.2 The $\pi^0 \pi^0$ channel

For class (b) events the dominant background was the $\pi^0 \pi^0$ channel, arising from the reaction $\gamma d \rightarrow \pi^0 \pi^0 (pn)$ when the recoil nucleon went undetected and one of the decay photons was mis-identified as the recoil neutron. To identify this background the four neutral hits (then assumed to be photons) were paired two by two. After calculating the invariant masses, a cut was placed around the $\pi^0 \pi^0$ peak ($115 \text{ MeV}/c^2 < m_{n_1 n_2} < 155 \text{ MeV}/c^2$ and $115 \text{ MeV}/c^2 < m_{n_3 n_4} < 155 \text{ MeV}/c^2$) and all events that fulfilled this condition were discarded.

3.4.3 The π^0 channel

A strong peak at $\approx 550 \text{ MeV}/c^2$ observed in the $\pi^0 \gamma$ invariant mass spectrum for the sub-class of events with exactly three neutral hits (and no additional hits) motivated an additional cut for the inclusive analyses. A comparison between simulation (fig. 3 (upper left)) and data (fig. 3 (upper right)) showed that these background events were clearly separated from the ω events when plotting the opening angle between the π^0 and the γ originating from the ω meson in the center-of-mass system, $\theta_{\text{c.m.}}^{\pi^0 \gamma}$, versus the momentum of the ω meson in the center-of-mass system, $p_{\text{c.m.}}^\omega$. A cut was thus defined according to

$$p_{\text{c.m.}}^\omega < -11.11 \cdot \theta_{\text{c.m.}}^{\pi^0 \gamma} \frac{\text{MeV}/c}{\text{deg}} + 2000 \text{ MeV}/c, \quad (4)$$

and events outside of this cut were discarded. Figure 3 (lower left and right) illustrates that this cut successfully removed the background peak at $\approx 550 \text{ MeV}/c^2$. The cut implied a reduction of the ω signal of $\approx 20\%$ which was taken into account by the detection efficiencies.

Fig. 3. (Color online) Top: The opening angle between the π^0 and γ versus the momentum of the reconstructed ω meson in the center-of-mass system for events with three neutral hits and no further hits for simulation (left) and LD₂ target data (right). The cut is drawn in black. Bottom: The $\pi^0\gamma$ invariant mass before (black solid) and after (red dashed) the opening angle cut for the simulation (left) and for the data (right).

A simulation of the single pion production ($\gamma p \rightarrow \pi^0 p \rightarrow \gamma\gamma p$) showed that this was indeed the background channel responsible for this peak, which originated from events where a proton was mis-identified as a neutral particle and assumed to be the third photon.

3.5 Identification of the recoil nucleon

In the exclusive analyses, detection of the recoil protons or neutrons was required. This was done by selecting the appropriate numbers of charged and neutral hits. Charged and neutral hit separation was achieved using the information from the fiber and veto detectors.

The condition for a charged hit in CB was that two or three of the fibers in the inner detector had fired within a 10° angle to the CsI module which registered energy in CB. The neutral hits were identified as hits when no fiber in the inner detector fired in coincidence with one of the detectors in CB within an angle of 10° . Events where only one fiber fired in the inner detector were discarded.

For a charged hit in TAPS a veto detector must have fired in front of the central BaF₂ detector of the cluster or in front of one of the BaF₂ modules in the ring surrounding the central detector of the cluster. Hits in TAPS not fulfilling these conditions were taken to be neutral.

A missing mass cut required the nucleon candidate to be close to the proton or neutron mass. Two additional steps were done to assure the correct identification of protons and neutrons.

Fig. 4. (Color online) Polar angle of the neutron versus incident beam energy [fiber numbers] for simulation (upper left) and for data (upper right). The cut used is drawn (solid curve) in both figures. Lower left: Projection onto the θ_{lab}^n -axis for simulation (black solid) and data (red dashed). Lower right: The invariant mass of $\pi^0\gamma$ for events inside the cut (red solid) and for events outside the cut (black dashed) for the data.

3.5.1 Kinematical constraints

The available kinematics put constraints on the maximum θ_{lab} -angle allowed for the recoil nucleon, the allowed angle being smaller at lower incident beam energies. A cut was determined according to simulations (see fig. 4 (upper left)) and the events outside of the red-bounded area were discarded. This cut was important in the case of the ω meson being produced off the neutron, but for consistency it was placed also in the case of the ω meson being produced off the proton. In the latter case, this resulted in a reduction of background. For the neutron identification, however, this cut was crucial. Figure 4 (upper right) and fig. 4 (lower left) illustrate that a substantial part of the neutron candidates in the data were seen at angles much larger than the maximal angle allowed by kinematics. Figure 4 (lower right) shows that this cut not only reduced the background in the $\pi^0\gamma$ invariant mass spectra, it also implied a reduction of yield in the ω meson signal. These events had to be discarded though, since they could obviously not belong to ω mesons produced off neutrons.

3.5.2 Proton and neutron mis-identification

For the exclusive analyses the ω yield had to be corrected for the mis-identification of the recoil nucleons due to inefficiencies of the fiber and veto detectors.

When studying the reaction of the ω meson produced off the neutron the events with protons mis-identified as neutrons had to be removed. Factors correcting for this

mis-identification were determined for each angular bin by studying the LH₂ target data and checking how large a fraction of the detected protons were mis-identified as neutrons. For $0.9 < \cos(\theta_{c.m.}^\omega) < 1.0$ at incident beam energies $E_\gamma > 1550$ MeV no correction factors could be determined due to the zero proton detection efficiency in this range. These angular bins were excluded and the differential cross-sections off the neutron had to be extrapolated into this region. The correction factors were on average $\approx 15\%$ for incident beam energies $E_\gamma = 1150$ – 1300 MeV and steeply decreasing to $< 5\%$ for $E_\gamma = 1500$ – 2000 MeV. The removal of protons mis-identified as neutrons was crucial for incident beam energies $E_\gamma < 1300$ MeV. At $E_\gamma \approx 1250$ MeV the cross-section off the neutron was reduced by $\approx 40\%$. For higher incident beam energies the effect on the cross-section was $< 5\%$.

Correspondingly, correction factors for removing neutrons mis-identified as protons when studying the ω meson production off the proton bound in the LD₂ target were determined from the $\gamma n(p) \rightarrow \omega n(p)$ simulation.

Correction factors of $\approx 15\%$ were obtained. However, since these factors were related to the relatively small number of detected neutrons, the effect on the cross-section from this correction was only on the few percent level.

The events with protons mis-identified as neutrons, known to be protons from the LH₂ target data, were added to the number of events contributing to the cross-section off the proton. Therefore, extrapolation of the differential cross-sections off the proton had to be used in the same area as for the exclusive analysis off the neutron.

When studying the ω meson production off the free proton the problem of mis-identifying neutrons as protons did not occur, since only protons were present in the LH₂ target.

3.6 Determination of the ω yield

The ω yield was determined by fitting the $\pi^0\gamma$ invariant mass spectra with a five parameter function for describing the background and a Gaussian function describing the signal

$$f(x) = \gamma(x - x_L)^\alpha(x - x_H)^\beta + \text{Gaussian}. \quad (5)$$

Figure 5 shows a few examples of fitted spectra for three different incident beam energies for the LH₂ target with the event selection three neutral hits and one charged hit (top row), for the LD₂ target with the event selection of three neutral hits and one charged hit (middle row) and the LD₂ target with the event selection four neutral hits and no charged hits (bottom row). Close to the ω production threshold ($E_\gamma = 1108$ MeV) the fitting was difficult due to the fact that the background did not extend to the higher mass side. In addition, for the LD₂ target the signal-to-background ratio was not that good close to threshold. For that reason, the energy bin $E_\gamma = 1108$ – 1158 MeV for the production off the LD₂ target could not be used and no cross-sections were deter-

Fig. 5. (Color online) $\pi^0\gamma$ invariant mass spectra at three different incident beam energy ranges for the event selections three neutral hits and one charged hit for LH₂ target data (top row), three neutral hits and one charged hit for LD₂ target data (middle row) and four neutral hits and no charged hits for the LD₂ target data (bottom row).

Fig. 6. (Color online) $\pi^0\gamma$ invariant mass spectra for different bins of $\cos(\theta_{c.m.}^\omega)$ for incident beam energy $E_\gamma = 1708$ – 1808 MeV for the events with four neutral hits for the LD₂ target data.

mined for that bin. For the LH₂ target data a finer energy binning was used than for the LD₂ target data. The binning was chosen to be the same as the one used by SAPHIR [3] to enable a direct comparison of results.

The angular distributions for the ω mesons indicate a non-isotropic production. Figure 6 shows the $\pi^0\gamma$ invariant mass spectra for different bins of $\cos(\theta_{c.m.}^\omega)$ for the

Fig. 7. (Color online) Acceptances for detecting a proton without Fermi motion (blue diamonds), a proton with Fermi motion (open squares), a neutron with Fermi motion (red triangles) and for reconstructing the $\omega \rightarrow \pi^0 \gamma$ decay (green circles), obtained from simulations.

incident beam energy range $E_\gamma = 1708\text{--}1808\text{ MeV}$ for the LD₂ target with the event selection of four neutral hits. The production of ω mesons going in forward direction was strongly enhanced. However, for the LH₂ target, at higher incident beam energies ($E_\gamma > 1550\text{ MeV}$), basically no ω mesons in coincidence with a proton were seen in the most forward bin. The forward going ω mesons in this energy region were correlated with protons going backward in the c.m. system, *i.e.* slow protons that did not have enough energy in order to be detected. For this reason the most forward bin could not be used for extracting exclusive cross-sections off the free proton for incident beam energies $E_\gamma > 1550\text{ MeV}$. The differential cross-section had to be extrapolated into this region with a fit.

3.7 Flux determination

The flux determination has been described in [29] and will only be discussed briefly here. The photon flux was determined from the number of scattered electrons reaching the tagging system which was counted by scalars. The scalars

recorded during the spill time, whereas the data acquisition was running during the life time, hence, the number had to be corrected for dead time effects. The life time was monitored to be $\approx 40\%$.

Due to the beam dispersion (and consequently, the usage of a collimator placed behind the bending magnet) the number of electrons recorded by the scalars did not directly correspond to the number of photons that reached the target. This was corrected for by the tagging efficiency. The measured tagging efficiencies were on average 72% for the data with LH₂ target and 85% for the data with LD₂ target [26].

3.8 Monte Carlo simulations and detector acceptances

The detection efficiencies were obtained from simulations using the GEANT3 package [30] with the dimensions and materials of the detector implemented giving a realistic response of the detector to the generated particles. In order to describe low energy neutron interactions, the GCALEOR package was used for the simulations [31].

For the acceptance determination, the production off the free proton $\gamma p \rightarrow \omega p$ and the quasi-free productions off deuterium $\gamma d \rightarrow \omega p(n)$ as well as $\gamma d \rightarrow \omega n(p)$ were simulated. The protons and neutrons bound in deuterium were simulated as having a momentum distribution corresponding to their Fermi motion in the nucleus which was calculated from the Paris potential wave function [32]. For deuterium the most probable momentum was $\approx 40 \text{ MeV}/c$. The spectator nucleon was not registered in the reaction. The start distribution of the generated ω mesons was flat in $\cos(\theta_{\text{c.m.}}^\omega)$ and the decay mode was $\omega \rightarrow \pi^0 \gamma \rightarrow \gamma \gamma \gamma$. Assuming a forward peaked angular distribution did not change the angle differential acceptance within errors.

For the inclusive analyses, an additional method independent of reaction kinematics was used. This method implied an event-by-event efficiency correction depending on the kinetic energy (T_{lab}^ω) and the polar angle ($\theta_{\text{lab}}^\omega$) of the ω meson. This so-called grid efficiency was obtained from a GEANT simulation where ω mesons were generated with a flat $(\theta_{\text{lab}}, T_{\text{lab}})$ -distribution and reconstructed by the analysis. The signal losses due to the cuts in the missing mass and opening angle were not taken into account by the grid efficiency. They had to be estimated from simulations and corrected for at a later stage. The difference in the obtained cross-sections from the two different methods indicates the systematic uncertainties.

Figure 7 shows the acceptances for protons (bound and free), neutrons and the probability for reconstructing the $\pi^0 \gamma$ decay of ω mesons as a function of $\cos(\theta_{\text{c.m.}}^\omega)$. The proton and neutron acceptances can be seen to drop at high $\cos(\theta_{\text{c.m.}}^\omega)$ values. The ω mesons in this region are correlated with nucleons going backward in the c.m.-system which implies slow nucleons in the laboratory system that do not have enough energy to be detected. When the ω meson is produced off the free proton the efficiency is even zero in the most forward bin, $0.9 < \cos(\theta_{\text{c.m.}}^\omega) < 1.0$ for $E_\gamma > 1550 \text{ MeV}$. For the nucleons bound in deuterium the smearing due to the Fermi motion allows some protons to be detected so that the efficiency is small in this most forward bin, but non-zero. Figure 8 shows the angle integrated acceptances of fig. 7 as a function of incident beam energy.

3.9 Systematic uncertainties

Systematic uncertainties which affect the overall normalization of the cross-sections have been estimated to $\approx 10\%$ [26]. This uncertainty stems mainly from the photon flux determination. The uncertainty of the target thickness is comparably small (few percent) and the uncertainty of the decay branching ratio is negligible. This type of systematic uncertainty cancels out when comparing the cross-section off the bound proton with the one off the bound neutron.

Comparison between the two different methods used to determine the inclusive cross-sections indicate a $\approx 6\%$ systematic uncertainty arising from the ω acceptance. Systematic uncertainties from fits and analysis cuts were estimated to be in the range $\approx 5\text{--}10\%$ giving a total systematic error of $\approx 10\text{--}15\%$ for the ω meson reconstruction.

Fig. 8. (Color online) Angle integrated efficiencies as a function of the incident photon energy for detecting a proton without Fermi motion (blue diamonds), a proton with Fermi motion (open squares), a neutron with Fermi motion (red triangles) and for reconstructing the $\omega \rightarrow \pi^0 \gamma$ decay (green circles), obtained from simulations.

Table 1. Sources of systematic errors.

Source	$\gamma d \rightarrow \omega p(n)$	$\gamma d \rightarrow \omega n(p)$
Analysis:		
Signal fits and cuts	$\approx 5\text{--}10\%$	$\approx 5\text{--}10\%$
Exponential fits	$\approx 5\%$	$\approx 5\%$
Extrapolation ($E_\gamma > 1.5 \text{ GeV}$)	$< 10\%$	$< 10\%$
ω acceptance	$\approx 6\%$	$\approx 6\%$
Recoil nucleon detection	$\approx 5\text{--}10\%$	$\approx 10\text{--}30\%$
Overall normalization	$\approx 10\%$	$\approx 10\%$
Total	$\approx 15\text{--}20\%$	$\approx 20\text{--}35\%$

The extrapolation needed in the exclusive analyses in the small momentum transfer region for incident beam energies $E_\gamma < 1.5 \text{ GeV}$ also introduced a systematic uncertainty. Deliberately removing the most forward point (small t) in the inclusive differential cross-section and using extrapolation showed that the systematic error introduced was at most 10%. For incident beam energies $E_\gamma > 1.7 \text{ GeV}$ the cross-section obtained by extrapolation was 10% lower than the one where the full angular range was used.

In addition, the systematic uncertainty due to the use of the exponential fit to the differential cross-section (integral of which gave the total cross-section) was estimated to be $\approx 5\%$ in the full incident beam energy range.

Apart from incident photon energies near the production threshold the systematic uncertainty of the proton detection, derived from the comparison between the inclu-

Fig. 9. (Color online) Differential cross-sections of ω mesons produced off the free proton *versus* the momentum transfer to the nucleon, t . The results of this work from the exclusive analysis (blue diamonds) and from the inclusive analysis (green stars) are compared to results from SAPHIR (open circles) [3] and CLAS (magenta circles) [4]. Since the incident energy binning of the present work does not coincide with that in [4] several CLAS data sets are shown for the incident energy intervals given in this figure. The lines are fits to the CBELSA/TAPS data (solid) and SAPHIR data (black dashed) according to eq. (6). For four incident beam energies theoretical curves are shown calculated with (red solid line) and without (red dotted line) N^* contributions [33].

sive and exclusive cross-sections off the free proton target, is ≈ 10 –15%. The comparison between the cross-section off the neutron from the exclusive analysis and calculated by subtraction of the cross-section off the proton from the inclusive cross-section (see fig. 17) indicate a systematic uncertainty of the neutron detection of ≈ 10 –30%.

Table 1 summarizes the sources of systematic errors. They add up to a total systematic uncertainty averaged for all incident beam energies of ≈ 15 –20% and ≈ 20 –35% in the cross-section determination off protons and neutrons, respectively. The systematic uncertainties related to the data analysis and the overall normalization are shown

Fig. 10. (Color online) Total cross-section as a function of the incident photon energy for ω mesons produced off the free proton. The results of this work for the exclusive analysis (blue diamonds) and for the inclusive analysis (green stars) are compared to results from SAPHIR (open circles) [3]. The systematic errors of the present analysis which affect the overall normalization are shown as bar histogram. The bands indicate the systematic errors in the data analysis.

separately as bands and bar histograms, respectively, in figs. 10 and 17.

4 Results and discussion

A strong exponential rise, characteristic of t -channel exchange, is observed in the differential cross-sections $d\sigma/d\cos(\theta_{c.m.}^\omega)$ for forward going ω mesons at higher incident beam energies. This motivates a scaling with the momentum transfer to the nucleon, t . In this paper the differential cross-sections are exclusively shown as $d\sigma/dt$. They have been fitted with the function

$$F(|t - t_{\min}|) = a + \exp(b + c \cdot |t - t_{\min}|). \quad (6)$$

The parameter c quantifies the t -channel contribution and a quantifies the contributions predominately due to resonances (dominant at larger momentum transfers). Integration of these fits up to $t_{\max}$ gives the total cross-sections as a function of incident beam energy.

4.1 The reaction off the free proton $\gamma p \rightarrow \omega p$

The differential cross-sections $d\sigma/dt$ for ω meson production off the free proton from this work are shown in fig. 9 and compared to previously published data from SAPHIR [3] and CLAS [4]. In general, they come close

to each other, however, CBELSA/TAPS data can be seen to lie above the previously published data in the small momentum transfer region for almost all incident photon energy bins.

The exponential slopes agree within the uncertainty of determination due to the shape of the fitting function and the lack of a well defined border in t where the t -channel exchange no longer contributes to the cross-section. At energies $E_\gamma > 1.55$ GeV the inclusive analysis gives somewhat steeper slopes than the exclusive analysis. In this energy region, the differential cross-section for the most forward-going ω mesons, $0.9 \leq \cos(\theta_{c.m.}^\omega) \leq 1.0$, could not be determined in the exclusive analysis due to vanishing acceptance. In this region, an extrapolation had to be used which could explain the discrepancy in slopes.

The horizontal level in $d\sigma/dt$, which is related to the ω meson production via resonances, can be seen to be in good agreement with the previously published data. For $E_\gamma > 1.6$ GeV the horizontal level seen in the CLAS data lies slightly above the SAPHIR data. The present data comes close to the CLAS data in this region.

The differential cross-section in fig. 9 is compared to theoretical calculations at four incident beam energies $E_\gamma = 1.23, 1.45, 1.68$ and 1.92 GeV [33]. In the small momentum transfer region, where pseudoscalar-meson exchange and Pomeron exchange dominate, the calculations agree with the data. In the large momentum transfer region, nucleon resonance contributions seem to play a role. However, it appears to be underestimated in the calculations, especially at lower incident beam energies.

The total cross-sections for ω mesons produced off the free proton are shown in fig. 10. For incident beam energies < 1.3 GeV agreement is found between the present data and the SAPHIR data, within the systematic errors. However, at higher incident beam energies the total cross-sections from the exclusive analysis lies generally $1\text{--}2\ \mu\text{b}$ above the data published by SAPHIR. For incident beam energies $E_\gamma > 1.7$ GeV the cross-section from the inclusive analysis tend to be larger than the exclusive cross-section by $\approx 10\%$. This difference is attributed to the extrapolation of the fits in the small momentum transfer region, which was necessary for the exclusive analysis. Within the systematic errors quoted, the inclusive and exclusive cross-sections are in agreement.

4.2 The quasi-free reaction off the bound proton $\gamma d \rightarrow \omega p(n)$

Figure 11 shows the differential cross-section $d\sigma/dt$ off the bound proton compared to the exclusive differential cross-section off the free proton. In the low-energy region, where production via resonances makes a substantial contribution to the cross-section, the differential cross-section off the bound proton lies below the one off the free proton. At higher incident beam energies the differential cross-sections off bound and off free protons come close to each other.

Fig. 11. (Color online) Differential cross-section *versus* the momentum transfer to the nucleon for ω mesons produced off the bound proton (open squares) and for ω mesons produced off the free proton (blue diamonds). The curves are fits to the data according to eq. (6).

The parameters of the fits (eq. (6)) to the differential cross-sections shown in fig. 12 confirm that at higher energies ($E_\gamma > 1.4$ GeV) the bound proton becomes quasi-free and the production mechanism is almost the same as off a free proton giving equal slopes and horizontal levels.

At low energies the proton-neutron interaction becomes particularly relevant. In this energy region the exponential slope is difficult to determine because of the strong resonance contributions. The horizontal levels in this energy region indicate stronger resonance contribution for ω production off the free proton compared to off the bound proton. This can partly be explained by a smearing due to the Fermi motion of a bound proton. However, fig. 13 illustrates that folding the total cross-section off the free proton with the Fermi motion of nucleons in deuterium is not enough to explain the difference in cross-sections which amounts to $\approx 20\%$. The folding was done statistically by recalculating the initial state energy using impulse approximation where the target proton was given a randomly generated momentum from the Fermi distribution for a nucleon in the deuteron.

Fig. 12. (Color online) (Left) slope parameter and (right) horizontal level from the fit of eq. (6) to $d\sigma/dt$ for ω mesons produced off the bound proton (open squares) and for ω mesons produced off the free proton (blue diamonds).

Fig. 13. (Color online) Total cross-sections as a function of the incident photon energy for ω mesons produced off the free proton from exclusive analysis (blue diamonds) and off the bound proton (open squares). Folding the cross-section off the free proton, fitted by the solid blue curve, with the Fermi motion of nucleons in deuterium leads to the dashed black curve.

4.3 The quasi-free reaction off the bound neutron $\gamma d \rightarrow \omega n(p)$

Figure 14 shows the differential cross-section off the bound neutron compared to the one off the bound proton. For incident beam energies $E_\gamma < 1.4$ GeV the differential cross-section off the bound neutron is larger than the differential cross-section off the bound proton. For higher incident beam energies the difference in the differential cross-sections off protons and off neutrons becomes smaller.

The differential cross-sections were fitted (eq. (6)) and for incident beam energies $E_\gamma > 1.5$ GeV the fits were used to extrapolate the differential cross-sections in the small momentum transfer region, where a proper neutron identification was not achievable, as discussed in sect. 3.5.2. The parameters of the fits are shown in fig. 15. The exponential slopes, which characterize the t -channel exchange, can be seen to agree within the precision of determination for ω mesons produced off the bound neutron and off the bound proton.

The comparison of the horizontal levels show stronger resonance contribution for ω meson production off the neutron than for the production off the proton for incident beam energies $E_\gamma < 1.4$ GeV. At higher incident beam energies both slopes and horizontal levels become identical, indicating a production mechanism independent of isospin.

These differences in differential cross-sections off protons and off neutrons are also reflected in the angle integrated cross-sections which are shown in fig. 17. For incident beam energies $E_\gamma < 1.6$ GeV the cross-section off the bound neutron is on average a factor ≈ 1.3 larger than the cross-section off the bound proton. At higher energies, this difference becomes smaller.

4.4 The quasi-free inclusive reaction off deuterium $\gamma d \rightarrow \omega(np)$

A comparison of the inclusive differential cross-section off deuterium to the sum of the two exclusive differential cross-sections was made in order to check the validity of the cross-sections determined by the exclusive analysis. The sum of the two exclusive cross-sections should not exceed the inclusive cross-section. As shown in fig. 16 both cross-sections agree within errors. Only for incident beam energies $E_\gamma > 1.6$ GeV a slight discrepancy in the exponential slopes for small momentum transfers is seen. For the lowest point in t a reliable neutron identification was not ensured, thus the exclusive differential cross-sections had to be extrapolated, which could possibly explain the observed discrepancy.

Figure 17 shows that the sum of the angle integrated cross-sections for exclusive ω production off the bound proton and bound neutron agrees, within errors, with the inclusive cross-section. For energies $E_\gamma > 1.6$ GeV the inclusive cross-section is slightly larger than the sum of the two exclusive cross-sections. This difference may be due to the extrapolation of the differential cross-section at low momentum for the exclusive analyses.

An alternative determination of the cross-section off the neutron was made by subtracting the cross-section off the bound proton from the inclusive cross-section. The resulting cross-section, which is independent of the neutron detection efficiency, is also shown in fig. 17. This cross-section is seen to be larger than the cross-section off the bound proton, consistent with the exclusively determined cross-section off the neutron. The difference in the two determinations of the production cross-section off the bound neutron mainly reflects the systematic error in the neutron identification.

5 Transparency ratio for the ω meson normalized to the cross-sections off the bound proton and neutron

With the measurement of the photoproduction cross-section off the bound proton and neutron, presented in this work, it has become possible to take the difference in these cross-sections into account in the study of the ω transparency ratio. The transparency ratio [34]

$$T = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}} \quad (7)$$

is a measure for the absorption of a meson in a nucleus. It compares the cross-section per nucleon for the production

Fig. 14. (Color online) Differential cross-section *versus* the momentum transfer to the nucleon for ω mesons produced off the bound proton (open squares) and for ω mesons produced off the bound neutron (red triangles). The curves are fits to the data according to eq. (6).

Fig. 15. (Color online) (Left) slope parameter and (right) horizontal level from the fit of eq. (6) to $d\sigma/dt$ for ω mesons produced off the bound proton (open squares) and off the bound neutron (red triangles).

of a meson off a nucleus with the production off the free nucleon. Here, the nucleus serves as a target and as an absorber at the same time. If there were no absorption, the transparency ratio would be equal to 1.0. The meson

absorption is due to the removal of the meson by inelastic reaction channels within the nuclear medium. Due to this absorption-related decrease of the meson lifetime, its in-medium width is correspondingly increased.

The transparency ratio has been measured for the ω [35, 36], η' [37], and ϕ [36, 38, 39] meson. In most cases the transparency ratio has not been normalized to the production off the free nucleon but off a nucleon in a light nucleus like carbon or lithium because the production cross-section off a neutron was not always known. Furthermore, by this normalization distortions due to meson production and absorption on two or more nucleons are reduced which may occur in heavy nuclei as well as in carbon but not on a free nucleon.

In fig. 18 we nevertheless present a plot of ω transparency ratios normalized to the cross-section off the proton and neutron, both bound in deuterium, according to

$$T_A^D = \frac{\sigma_{\gamma A \rightarrow \omega X}}{Z_{\text{eff}} \cdot \sigma(\gamma p_{\text{bound}} \rightarrow \omega p) + N_{\text{eff}} \cdot \sigma(\gamma n_{\text{bound}} \rightarrow \omega n)}. \quad (8)$$

Fig. 16. (Color online) Differential cross-section *versus* the momentum transfer to the nucleon for the quasi-free inclusive channel off deuterium (green circles) compared to the sum of the two exclusive production channels, $\sigma_p^{\text{bound}}/dt + \sigma_n^{\text{bound}}/dt$ (purple crosses).

Here, Z_{eff} and N_{eff} are the effective number of protons and neutrons seen by the incident photons which are reduced relative to the total number of protons and neutrons because of photon shadowing [40]. According to fig. 17, the average cross-sections for the production of ω mesons off the proton and neutron are $6.6 \pm 0.1 \mu\text{b}$ and $8.4 \pm 0.2 \mu\text{b}$, respectively, in the incident photon energy range 1200–2000 MeV.

The CBELSA/TAPS data are well reproduced by the GiBUU transport calculations assuming an in-medium width of the ω meson of 140 MeV at normal nuclear matter density [17]. Corresponding data by the CLAS Collaboration [36] for Fe/Ni and Pb —also normalized to deuterium— are consistent with this calculation as well. There is, however, a discrepancy between the CLAS and CBELSA/TAPS data for carbon. The normalization of the transparency ratios to the respective carbon values in the earlier publications [35,36] may at least partially account for the difference in ω absorption discussed in [36] apart from the difference in ω recoil momenta and possible ω - ρ interference effects in the $\omega, \rho \rightarrow e^+e^-$ decay channel.

It is remarkable that also after normalizing the transparency ratio measurements to the cross-section off the bound proton and neutron, the data are still well described by the GiBUU simulation over the full range of nuclear masses. In [37] it had been argued that a normalization to a light nucleus like Li or C is advisable to suppress distortions of the transparency ratio due to meson production and absorption on two or more nucleons. These processes are not included in GiBUU simulations [41] which only treat absorption on single nucleons. The fact that GiBUU simulations still describe the data may be taken as an indication that two-body absorption processes do not play a dominant role for the ω meson, consistent with recent calculations of the density and momentum dependence of the in-medium ω width [42, 43].

6 Conclusions

The cross-section for photoproduction of ω mesons off the free proton and off the proton and neutron bound in deu-

Fig. 17. (Color online) Total cross-section as a function of the incident photon energy for ω mesons produced off the bound proton (open squares) and off the bound neutron (red triangles), the sum of the two exclusive cross-sections $\sigma_p^{\text{bound}} + \sigma_n^{\text{bound}}$ (purple crosses), the quasi-free inclusive cross-section σ_{incl} (green circles) and the cross-section off the neutron calculated by $\sigma_{\text{incl}} - \sigma_p^{\text{bound}}$ (black circles). The systematic errors which affect the overall normalization are shown as bar histograms. The bands indicate the systematic errors in the data analysis.

Fig. 18. (Color online) Transparency ratio for the ω meson as a function of the nuclear mass number $A_{\text{eff}} = Z_{\text{eff}} + N_{\text{eff}}$. The blue full circles represent data of the CBELSA/TAPS Collaboration [35] normalized to the ω photoproduction cross-sections on the bound proton and the bound neutron in the energy range 1.2–2.0 GeV, reported in this work. Open squares are data taken by the CLAS Collaboration in the energy range 0.6–3.8 GeV [36]—also normalized to deuterium. The solid curve represents the result of a GiBUU transport calculation for an in-medium width of the ω meson of 140 MeV at nuclear saturation density [17].

terium as well as the cross-section for inclusive ω production off deuterium have been measured for incident photon energies from threshold up to 2 GeV. For all cases, a strong forward rise of the differential cross-section, indicative of t -channel production processes, is observed.

The cross-section off the bound proton is smaller than the one off the free proton. This difference cannot be attributed to a mere smearing due to the Fermi motion. At energies close to the production threshold the interaction with the neutron plays a role. Only at higher energies the ω mesons production cross-sections come close to the ones off the free proton.

For photon energies $1.2 \text{ GeV} < E_\gamma < 1.6 \text{ GeV}$ the production cross-section off the bound neutron is larger than that off the bound proton by about a factor 1.3. In this energy region the excitation and decay of nucleon resonances plays a dominant role. A stronger resonance contribution to the cross-section for ω production off the bound neutron compared to off the bound proton is observed. At higher energies $E_\gamma > 1.7 \text{ GeV}$ the cross-sections come close to each other, indicating production mechanisms independent of isospin. A deeper understanding of the results would require more detailed model calculations. It is hoped that the present work will motivate further theoretical studies.

Further experimental progress will require the measurement of polarization observables. On the free proton, a first step has been made with the study of beam asymmetries in ω photoproduction [6, 7].

The average cross-sections for photoproduction of ω mesons off the bound proton and neutron have been used for normalizing previous transparency ratio measurements. Transport calculations with the GiBUU code provide a description of the data over the full range of nuclear masses, indicating that for ω mesons many-body absorption processes—not included in GiBUU—do not seem to play a dominant role.

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