An experimental study of $\omega$ photoproduction off the proton has been conducted by using the Crystal Ball and TAPS multiphoton spectrometers together with the photon tagging facility at the Mainz Microtron MAMI. The $\gamma p \rightarrow \omega p$ differential cross sections are measured from threshold to the incident-photon energy $E_\gamma = 1.4$ GeV with $\sim 15$ MeV binning and full production-angle coverage. The quality of the present data near threshold gives access to a variety of interesting physics, including an estimation of the $\omega N$ scattering length $a_{\omega N}$.

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Though QCD is generally believed to govern strong interactions, it still can be applied to particular problems only in terms of specific model-dependent approaches, which can be distinguished by their predictions for the resonance spectra. However, such predictions can only be verified in collisions of a very restricted set of hadron pairs. Various constituent quark models (e.g., see Ref. [1] and references therein) predict more baryon resonances than have so far been observed in experiments [2]. Since most known baryon states were discovered in elastic $\pi N$ scattering, some resonances could have been missed because of their weak coupling to the $\pi N$ channels [3]. At the same time, a stronger coupling of those resonances to such channels as $\eta N$, $\omega N$, $K\Lambda$, or $K\Sigma$ cannot be excluded, and, therefore, an extensive study of these channels is very important in searching for the so-called “missing” resonances. Proof of their existence would constitute a strong confirmation of the validity of the constituent quark concept.

The $\omega N$ channel is particularly favorable in searching for missing resonances because, owing to vector-meson dominance (VMD) [4], $\omega$ photoproduction off the nucleon may be directly related to the elastic amplitude for $\omega N$ scattering. Besides, $\omega$ photoproduction provides an “isospin filter” for the nucleon response because $\omega N$ final states can originate only from $N^*$ states with $I = 1/2$, but not from $\Delta^*$s with $I = 3/2$. The $\omega N$ threshold

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region is also especially attractive in searching for new resonances because the reaction threshold is located at the higher-energy edge of the third resonance region, in which the Review of Particle Physics (RPP) [2] shows seven \( N^* \) states with masses between 1650 MeV and 1720 MeV, and then there are no observed \( N^* \) states up to 1860 MeV. It cannot be excluded that this energy range may contain unknown \( N^* \) resonances that are coupled to \( \omega N \) stronger than to other meson-baryon channels. Such an advantage of the threshold region does not exist, for example, for the two most dominant channels, \( \pi N \) and \( \eta N \), which are strongly coupled to their near-threshold resonances, \( \Delta(1232)3/2^+ \) and \( N(1525)1/2^− \).

The photoproduction of \( \omega \) mesons has been under extensive theoretical discussion since the first high-statistics differential cross sections and polarization results were provided from SAPHIR [3], covering a broad interval in center-of-mass (c.m.) energy, up to 2.4 GeV with \( \sim 60\% \) of the full production-angle range. Many models, including coupled channel, effective Lagrangian, and QCD-inspired approaches [4][10], were developed, trying to explain the behavior of the experimental data. Another high-statistics measurement of the \( \gamma p \rightarrow \omega p \) differential cross sections and spin-density matrix elements was recently made by the CLAS Collaboration [11], covering c.m. energies from threshold up to 2.84 GeV. Their binning in c.m. energy was much finer than from SAPHIR [3], but the production-angle coverage was narrower. Unfortunately, for both SAPHIR and CLAS, the data obtained in the energy region near threshold have the poorest quality.

In this work, a new high-statistics measurement of the \( \gamma p \rightarrow \omega p \) differential cross sections near threshold is presented. The results are obtained with \( \sim 15\text{-MeV} \) bins in incident-photon energy, \( E_\gamma \), and full production-angle coverage. The process \( \gamma p \rightarrow \omega p \rightarrow \pi^0\gamma p \rightarrow 3\gamma p \) was measured using the Crystal Ball (CB) [12] as a central spectrometer and TAPS [13] as a forward spectrometer. These detectors were installed at the energy-tagged bremsstrahlung photon beam of the Mainz Microtron (MAMI) [14] incident on a liquid hydrogen target located in the center of the CB. The incident-photon energies were determined by the Glasgow tagging spectrometer [12]. The present analysis is based on the same data set that was used for measuring the \( \gamma p \rightarrow \eta p \) differential cross sections [16]. All details on the experimental resolution of the detectors and other conditions during these measurements are given in Ref. [16, 17] and references therein.

The reaction \( \gamma p \rightarrow \omega p \) was searched for in events reconstructed as \( \gamma p \rightarrow \pi^0\gamma p \rightarrow 3\gamma p \) candidates, having three or four clusters detected in the CB and TAPS together. The selection of event candidates and the reconstruction of the reaction kinematics was based on the kinematic-fit technique. Details on the kinematic-fit parameterization of the detector information and resolution are given in Ref. [17]. Events that satisfied the \( \gamma p \rightarrow \pi^0\gamma p \rightarrow 3\gamma p \) hypothesis with a probability greater than 2% were accepted for further analysis. The largest physical background was found to be due to the reaction \( \gamma p \rightarrow \pi^0\pi^0p \rightarrow 4\gamma p \), which can mimic \( \pi^0\gamma p \) when one of the four final-state photons has not been detected. The determination of the experimental acceptance was based on a Monte Carlo (MC) simulation of \( \gamma p \rightarrow \omega p \rightarrow \pi^0\gamma p \) with an isotropic production angular distribution. The Breit-Wigner parameters of the \( \omega \) meson were taken from the RPP [2]. The background was simulated as \( \gamma p \rightarrow \pi^0\Delta^+(1232) \rightarrow \pi^0\pi^0p \), also with isotropic production angular distributions.

For measuring the \( \gamma p \rightarrow \omega p \) differential cross sections, all event candidates were divided into 20 incident-photon energy bins from the reaction threshold to \( E_\gamma = 1402 \text{ MeV} \). The data within each energy bin were divided into 15 \( \cos \theta \) bins, where \( \theta \) is the angle between the directions of the outgoing \( \pi^0\gamma \) system and the incident photon in the c.m. frame. The number of \( \omega \rightarrow \pi^0\gamma \) decays observed in each \( \cos \theta \) bin was determined by fitting the \( \omega \) peak in the \( m(\pi^0\gamma) \) invariant-mass spectrum above the smooth background, which comes mostly from \( \gamma p \rightarrow \pi^0\pi^0p \). The fitting procedure is illustrated in Fig. 1 for one energy-angle bin. Figure 1(a) depicts the \( m(\pi^0\gamma) \) invariant-mass distribution for the MC simulation of \( \gamma p \rightarrow \omega p \rightarrow \pi^0\gamma p \) fitted with a Gaussian. Figure 1(b) shows a similar distribution for the MC simulation of \( \gamma p \rightarrow \pi^0\pi^0p \) fitted with a polynomial. The experimental distribution fitted with the sum of a Gaussian and a polynomial is shown in Fig. 1(c). The mean value and \( \sigma \) of the Gaussian were fixed to the values ob-

![FIG. 1: \( m(\pi^0\gamma) \) invariant-mass distributions obtained for \( E_\gamma = 1206 \text{ MeV} \) and \( \cos \theta = 0 \): (a) MC simulation of \( \gamma p \rightarrow \omega p \rightarrow \pi^0\gamma p \) with a Gaussian fit; (b) MC simulation of the background reaction \( \gamma p \rightarrow \pi^0\pi^0p \) fitted with a polynomial of order eight; (c) measured spectrum fitted with the sum of a Gaussian and a polynomial of order eight.](image-url)
FIG. 2: (Color online) Differential cross sections for $\gamma p \rightarrow \omega p$ as a function of the $\omega$ production angle in the c.m. frame. The results of this work are shown by blue dots, SAPHIR [5] results by open triangles, CLAS [11] results by open circles, and preliminary results from Ref. [18] by green crosses. Error bars of all results include statistical uncertainties only. The incident-photon energies of the data points shown for previous experiments are within $\pm 5$ MeV of $E_{\gamma}$ indicated in each panel. Model calculations from Ref. [6] are shown by black dashed lines and from Ref. [10] by solid red lines.

tained from the previous fit to the MC simulation for $\gamma p \rightarrow \omega p \rightarrow \pi^0 \gamma p$. The initial parameters for the polynomial were taken from the fit to the MC simulation for $\gamma p \rightarrow \pi^0 \pi^0 p$. The number of $\omega \rightarrow \pi^0 \gamma$ decays was determined from the area under the Gaussian. For consistency, the corresponding detection efficiency was calculated in the same way, instead of using the number of entries in Fig. 1(a). The total number of $\omega$ mesons produced in each bin was obtained by correcting the number of $\omega \rightarrow \pi^0 \gamma$ decays observed with the corresponding detection efficiency and the $\omega \rightarrow \pi^0 \gamma$ branching ratio from the RPP [2]. The $\gamma p \rightarrow \omega p$ differential cross sections were obtained by taking into account the number of protons in the target and the photon-beam flux from the tagging facility. Statistical uncertainties of the results were calculated from the errors given by the Gaussian fits. One contribution to the systematic uncertainty, potentially different for every energy-angle bin, comes from the uncertainty in the shape of the background under the $\omega$ peak; this uncertainty was estimated as 6%. Another contribution, which is practically the same for all bins, comes from the determination of the detector acceptance and the photon-beam flux; it was estimated as 5%.

In Fig. 2 the results of this work for the $\gamma p \rightarrow \omega p$ differential cross sections are compared to previous measurements at similar energies (from SAPHIR [5], CLAS [11], and Ref. [18]) and to model calculations from Refs. [6, 10]. The error bars shown for all data points in Fig. 2 include statistical uncertainties only. As seen, the data points of this work cover the full production-angle range and have quite small statistical uncertainties. Thus, combining these features of the present results with fairly small energy binning ($\sim 15$ MeV in $E_{\gamma}$) makes it possible to study the threshold-region dynamics with much better accuracy than before. As also seen, the present results are in general agreement with previous measurements in the angular range where they overlap. Deviations at some energies from the results of CLAS and Ref. [18] can be explained by a slight difference in $E_{\gamma}$. The results from SAPHIR for backward
angles are smaller than all other measurements. The impact of the SAPHIR data on the models can be seen in the calculations from the Giessen group [10], the predictions of which for backward angles follow the behavior of the SAPHIR results. The quark-model calculations from Ref. [6] are in good agreement with the present data at higher energies. At lower energies, the quark-model predictions are larger than experiment, especially for backward angles. It seems that the role of the N(1720)3/2+ and N(1680)5/2+ states, dominating near the ω threshold, is overestimated in the model of Ref. [6].

Near-threshold cross sections of good accuracy allow the extraction of various useful parameters, including resonance masses. For instance, the near-threshold behavior of the reaction e+e− → W+W− was used to measure the W-boson mass [19, 20]. In general, the total cross section for an inelastic reaction a → b + c + d with the particle masses m(a) + m(b) < m(c) + m(d) can be written as

$$\sigma_t = (q/W) \cdot F(W^2),$$

where W is the c.m. energy and q is the c.m. momentum of the final-state particles. The factor $F(W^2)$, not vanishing at threshold, comes from the sum of production amplitudes squared, and (q/W) from the integration over the final-state phase space. Because $W^2$ is linearly related to $E_\gamma$ for meson photoproduction, the value $\sigma_t^2$ as a function of $E_\gamma = E_{th}$ reaches zero at the threshold energy $E_\gamma = E_{th}$ without any singularity (i.e., linearly, if the final-state $S$ wave does not vanish at threshold).

The results of this work for $\sigma_t^2(\gamma p \to \omega p)$ are shown as a function of $E_\gamma$ in Fig. 3(a). In the same figure, the present results are also compared to model calculations from Refs. [6, 10] and to the preliminary results from Ref. [18], the full angular coverage of which made direct measurement of the total cross sections possible. The fit of the present $\sigma_t^2$ data with the formula

$$\sigma_t^2(E_\gamma) = b_1 d + b_2 d^2 + b_3 d^3,$$  \hspace{1cm} (1)

containing four free parameters, is shown in Fig. 3(a) by a solid red line. For the parameter $E_{th}^\omega$, the fit results in the value $(1109.90\pm0.73)$ MeV, corresponding to the mass $m_\omega = (783.10\pm0.40)$ MeV/c^2, which is in good agreement with the RPP value $m_\omega = (782.65\pm0.12)$ MeV/c^2 [2]. Although the estimate made here for the $\omega$-meson mass cannot compete in precision with the known RPP value, the agreement observed indicates the good quality of the present data and the correctness of the photon-beam energy calibration, the systematic uncertainty in which was determined as 0.5 MeV [15].

More traditionally, the $\sigma_t$ behavior of a binary inelastic reaction near threshold can be described as a series of odd powers of q. The results of this work for $\sigma_t(q)$ are shown in Fig. 3(b). In the present energy range, the formula

$$\sigma_t(q) = a_1 q + a_3 q^3 + a_5 q^5$$  \hspace{1cm} (2)

is enough to describe well all experimental points for $\sigma_t(q)$. The fit of the present $\sigma_t(q)$ data with Eq. (2) is shown in Fig. 3(b) by a solid red line, resulting in $a_1 = (4.42\pm0.12) \cdot 10^{-2} \mu b/(MeV/c)$, $a_3 = -1.06 \pm 0.34 \cdot 10^{-2} \mu b/(MeV/c)^3$, and $a_5 = -1.22 \pm 2.18 \cdot 10^{-13} \mu b/(MeV/c)^5$. The linear term is determined here by the $S$ waves only (with the total spin 1/2 and/or 3/2), while the contributions to the cubic term come from both the $P$-wave amplitudes and the $W$ dependence of the $S$-wave amplitudes, and the fifth-order term arises from the $D$ waves and the $W$ dependences of the $S$ and the $P$ waves.

The $\sigma_t(\gamma p \to \omega p)$ data near threshold can also be used for determining the $\omega N$ scattering length $a_{\omega p}$, defined by the threshold relation $d\sigma(\omega p \to \omega p)/d\Omega|_{th} = |a_{\omega p}|^2$ (in reality, it is a combination of two independent $S$-wave scattering lengths with total spins 1/2 and 3/2). In the VMD framework, $a_{\omega p}$ appears also in $\sigma_t(\gamma p \to \omega p)$ near threshold [21]

$$\sigma_t(\gamma p \to \omega p)|_{th} = \frac{q}{k} \cdot \frac{4\alpha \pi^2}{\gamma^2} \cdot |a_{\omega p}|^2,$$ \hspace{1cm} (3)

where $k$ is the c.m. momentum of the incident photon at the $\gamma p \to \omega p$ threshold, $\alpha$ is the fine-structure constant, and $\gamma = 8.53 \pm 0.14$ is the $\gamma - \omega$ coupling, as determined from the $\omega \to e^+e^-$ decay width [2]. Combining Eq. (3) with the $a_1$ value from fitting Eq. (2) to the present $\sigma_t(\gamma p \to \omega p)$ data results in

$$|a_{\omega p}| = \frac{\gamma}{2 \pi} \sqrt{\frac{k a_1}{\alpha}} = (0.82 \pm 0.03) \text{ fm},$$ \hspace{1cm} (4)

which should be considered only as an estimate assuming only the sequence $\gamma \to \rho^0$, $\rho^0 p \to \omega p$, containing in particular $\pi^0$ exchange, and from a similar transition $\gamma \to \phi$. 

FIG. 3: (Color online) Results of this work (blue dots) for the $\gamma p \to \omega p$ total cross sections $\sigma_t$ are shown in (a) for $\sigma_t^2$ as a function of the incident-photon energy $E_\gamma$ and in (b) for $\sigma_t$ as a function of the c.m. momentum q of the final-state particles. The preliminary $\sigma_t$ results from Ref. [18] are depicted by green crosses. The vertical error bars represent the total uncertainties of the results. The horizontal error bars reflect the energy binning. The red solid line shows the fit of the present data (a) with Eq. (1) and (b) with Eq. (2). The result from the calculation in Ref. [8] is shown by a black short-dashed line and in Ref. [14] by a magenta long-dashed line.
Note that the present estimate for $|\alpha_{\omega p}|$ is on a similar level with other $\alpha_{\omega p}$ values available in the literature: $(-0.026 + i \ 0.28)$ fm from the coupled-channel analysis of the $\omega$ production in $pN$ and $\gamma N$ interactions [10], $(0.41 \pm 0.05)$ fm from the QCD sum-rule analysis [22], $(1.6 + i \ 0.30)$ fm from the effective Lagrangian approach based on chiral symmetry [23], and $(-0.44 + i \ 0.20)$ fm from the coupled-channel unitary approach [24].

Good-quality data on $\omega$ photoproduction near threshold also allow further analysis for extracting contributions from the pion-exchange and the Born nucleon diagrams. The latter diagrams contain the coupling vertex $\omega NN$, which determines the $\omega$-exchange contribution to $NN$ forces and was extracted earlier in the phenomenological analysis of Ref. [25]. Thus, one can check the current understanding of the $NN$ potential. Threshold data are important here because, at higher energies, the Born contributions become nonessential with respect to the Pomeron-exchange contribution.

In summary, an experimental study of $\omega$ photoproduction off the proton has been conducted by the A2 Collaboration at MAMI. The $\gamma p \rightarrow \omega p$ differential cross sections are measured from threshold to $E_{\gamma} = 1.4$ GeV with $\sim 15$ MeV binning and full production-angle coverage, improving significantly the data available for this energy range. The quality of the present data near threshold gives access to a variety of interesting physics that can be extracted by studying the $\omega N$ system. In particular, our estimate for the $\omega N$ scattering length is consistent with previous theoretical results. The present data are expected to be invaluable for future partial-wave and coupled-channel analyses, which could provide much stronger constraints on the properties of nucleon states known in this energy range and even reveal new resonances.

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