Beam asymmetries in near-threshold ω photoproduction off the proton

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The photoproduction of ω mesons off protons has been studied at the Bonn ELSA accelerator from threshold to $E_\gamma = 1700$ MeV. Linearly polarized beams were produced via coherent bremsstrahlung. Large photon asymmetries in excess of 50% were obtained. For the first time the pion asymmetries associated with the $\omega \to \pi^0\gamma$ decay were measured and found close to zero. The asymmetries indicate s-channel resonance formation on top of t-channel exchange processes.

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The structure of the nucleon as viewed at very small distances is considered well understood in terms of pointlike light quarks and gluons which mediate the mutual interaction. The mechanism of how the quarks are confined to form the nucleon, how basic properties such as mass and spin emerge in the strongly interacting system, is however only qualitatively understood [1].

One manifestation of the internal nucleon structure is the excitation spectrum. Its description in terms of the basic pointlike quarks and their gluonic interaction in the frame of lattice-QCD is still in its infancy. Hence, quark models (which often attempt to incorporate basic QCD symmetries) provide an important guidance for our understanding. However, they all exhibit a general problem: Many more higher-lying states are predicted than experimentally observed. Since pion-nucleon scattering experiments provided the basis of the investigation of the nucleon excitation spectrum, it was speculated that some excited states may decouple from the pion-nucleon channel and rather couple to nonpionic channels [2]. Hence, the photoproduction of ω mesons was considered as a candidate channel to investigate this issue. The ω threshold is almost ideally located in the higher-lying third resonance region of the nucleon where yet undiscovered states are suspected. Of further advantage are the narrow width of 8 MeV of the ω and its isospin $I = 0$. Any s-channel process will only connect N^* ($I = 1/2$) states with the nucleon ground state, but no Δ^* with $I = 3/2$. This provides a great simplification to the complexity of the contributing excitation spectrum.

Compared to the photoproduction of pseudoscalar mesons it is more difficult to achieve a complete set of observables regarding the decomposition of the reaction amplitudes, due to the vector character of the meson. It is hence essential to measure sufficient polarization observables to constrain the reaction dynamics and to get a hand on possible nucleon resonance contributions.

At high photon energies resonances play no role. The cross section of vector-meson production off nucleons falls off exponentially with the squared recoil momentum, t, corresponding to the range of the mutual interaction. The t dependence of the cross section, which is approximately the same for all sufficiently high photon energies, is characteristic for "diffractive" production. It is associated with the exchange of natural parity quantum numbers (Fig. 1 left) related to the Pomeron, a composite gluonic or hadronic structure. At large $|t|$ deviations from pure diffraction

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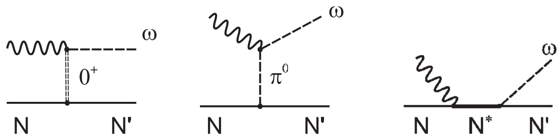

FIG. 1. Contributions to ω photoproduction: natural parity t-channel exchange (left), unnatural parity π^0 t-channel exchange (middle), s-channel intermediate resonance excitation (right).

show up [3]. From the comparison to QCD-inspired models [4] which are also able to describe ϕ and ρ^0 photoproduction, the presence of hard processes in the exchange itself was thus concluded at $|t| > 1\ \text{GeV}^2$.

Because of the sizeable $\omega \to \pi^0\gamma$ decay (8%), significant unnatural parity π^0 exchange has been expected for ω-photoproduction at smaller energies (Fig. 1 middle). It was indeed observed [5] and found dominating close to threshold [6]. However, neither Pomeron nor π^0 exchange are able to reproduce the strong threshold energy dependence of the cross section and the ω decay angular distribution observed in exclusive photoproduction [7] and electroproduction [8]. This was interpreted as possible evidence for s-channel contributions (Fig. 1 right). Complementary experimental support comes from a first measurement of photon-beam asymmetries, Σ, through the GRAAL Collaboration [9]. Recent theoretical coupled-channel analyses yielded, however, inconclusive results [10,11], and a clear-cut evidence is still missing whether s-channel nucleon resonances are at all involved in ω photoproduction.

This provided our motivation to measure for the first time the pion asymmetry, Σ_π, associated with the $\omega \to \pi^0\gamma$ decay in the reaction $\gamma p \to p\omega$ with linearly polarized photon beams. Σ_π provides new information on the mechanism of ω photoproduction. It is measured in the laboratory frame relative to the plane of polarization of the incident photon beam, and related to the decay asymmetry in the vector-meson rest frame by a corresponding Lorentz boost. In the case of a pure π^0 exchange mechanism $\Sigma_\pi \simeq -0.5$ is expected, $+0.5$ for pure Pomeron exchange [12]. The large values of ± 0.5 correspond to fixed parity exchange. If s-channel resonances contribute in a manner compatible with the partial wave decomposition of the available cross section data [12,13], Σ_π should be close to zero.

In contrast, the standard photon asymmetry Σ is expected to be zero or very close to zero for a pure t-channel mechanism, i.e. pure π^0 exchange, pure Pomeron exchange, and in case of interference of both. It should become large with s-channel resonance contributions [12,14,15]. In addition to the measurement of Σ_π we also extended the energy range of previous photon asymmetry measurements.

Exploiting linearly polarized photon beams, the photoproduction cross section off a nucleon can be cast into the form

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 - P_\gamma \Sigma_{(\pi)} \cos 2\Phi_{(\pi)}), \tag{1}$$

where σ_0 denotes the polarization independent cross section, P_γ the degree of linear polarization of the incident photon beam, and Φ the azimuthal orientation of the reaction plane with respect to the plane of linear polarization. The pion asymmetry is obtained if in Eq. (1) the azimuthal angle of the ω meson, Φ, is replaced by the angle Φ_π of the decay π^0. This convention gives Σ_π a sign equivalent to Σ, but opposite to the (charged) decay asymmetry as defined in e.g. [16].

The experiment was performed at the tagged photon beam of the ELSA electron accelerator of the University of Bonn. Using electron beams of $E_0 = 3.2$ GeV coherent bremsstrahlung was produced from a 500 μm thick diamond crystal. After radiating a photon the electrons were momentum analyzed in a magnetic dipole (tagging) spectrometer, covering a photon energy range of $E_\gamma = 0.18$–$0.92 E_0$. The photon beam, linearly polarized along the vertical direction, was incident on a 5.3-cm long liquid hydrogen target with 80 μm Kapton windows. A three layer scintillating fiber detector [17] surrounded the target within the polar angular range from 15° to 165°. It determined a point-coordinate for charged particles.

Both, charged particles and photons were detected in the Crystal Barrel detector [18]. It was cylindrically arranged around the target with 1290 individual CsI(Tl) crystals of 16 radiation lengths in 23 rings, covering a polar angular range of 30°–168°. For photons an energy resolution of $\sigma_E/E = 2.5\%/\sqrt[4]{E/\text{GeV}}$ and an angular resolution of $\sigma_{\text{angle}} \simeq 1.1°$ was obtained.

The 5.8°–30° forward cone was covered by the TAPS detector [19], set up in one hexagonally shaped wall of 528 BaF_2 modules at a distance of 118.7 cm from the target. For photons between 45 and 790 MeV, the energy resolution is $\sigma_E/E = (0.59/\sqrt{E/\text{GeV}} + 1.9)\%$ [20]. The position of photon incidence could be resolved within 20 mm. To discriminate charged particles each TAPS module has a 5 mm plastic scintillator in front of it. The TAPS detectors are individually equipped with photomultiplier readout. The first level trigger was derived from TAPS. A cluster recognition for the Crystal Barrel provided a second level trigger.

The ω was identified through its decay into $\pi^0\gamma$. Four detector hits were required during the offline analysis, corresponding to three photons and the proton. Basic kinematic cuts were applied in order to ensure longitudinal and transverse momentum conservation. In the analysis we consider all combinatorial possibilities of the detector hits. For the proton candidate the detected angles directly enter the analysis; the energy information is not used. In addition, it turned out important to *not* positively require proton identification through the signals of the inner scintillating fiber detector of the barrel or the veto detectors of TAPS, in order to reduce the bias from detector inefficiencies on the azimuthal distributions.

Figure 2 shows the $\pi^0\gamma$ invariant mass distribution for the full photon energy and angular range. The main source of background is $2\pi^0$ production where one of the decay photons escaped detection, either through the (small) detector leaks in extreme forward/backward direction, or because one energy deposit remained below the $\simeq$ 25 MeV threshold—in which case the three detected photons practically carry the full kinematic information of the $2\pi^0$ event. Additional non-$2\pi^0$ background was bin-wise fitted by a polynomial as shown in Fig. 2.

In the invariant mass spectra events were selected in a ± 50 MeV range around the nominal ω mass. The photon-beam asymmetry was determined according to Eq. (1). Fits of the azimuthal event distribution in the individual bins of energy and angle were performed (see example in Fig. 3),

$$f(\Phi'_{(\pi)}) = A + B\cos 2\Phi'_{(\pi)}, \tag{2}$$

of both the directions of the reconstructed ω and the decay π^0 with respect to the horizontal lab plane ($\Phi' = \Phi + \frac{\pi}{2}$). The ratio B/A of the fit determines the product of beam (pion) asymmetry and photon polarization, $P_\gamma \Sigma_{(\pi)}$, of Eq. (1). The asymmetries are based on all events within the mass range indicated in Fig. 2. The background can not be subtracted on an event-by-event basis. Instead we corrected the experimental asymmetry according to the fractional background contribution and background asymmetry.

Of particular importance is the $2\pi^0$ background, because the associated events potentially carry sizeable beam asymmetry [21]. Fortunately, in the $\pi^0\gamma$ invariant mass range considered here, the remaining asymmetries turn out relatively small, typically in the range of 0.1 [22,23]. For the non-$2\pi^0$ (polynomial) background zero asymmetry was assumed. To estimate the systematic error associated with the subtraction method, the magnitude of the $2\pi^0$ and non-$2\pi^0$ backgrounds in the invariant mass distributions were varied from 0%–100% (relative) in the fit of the invariant mass distribution. In addition, both background asymmetries were assigned errors of $\delta a \simeq \pm 0.11$.

The second important source of systematic errors is the angular dependent variation of detector efficiencies. Those may affect the measured Φ distributions in spite of the azimuthally symmetric layout of the detector setup. To estimate the associated systematic error, use was made of the fact that, due to the $\cos 2\Phi$ dependence, the azimuthal modulation over the full azimuth carries a twofold redundancy. Any deviation in separate left/right fits (where one example is shown in Fig. 3) in excess of a 1σ statistical fluctuation was assigned to systematics.

The total systematic error varies over the individual bins of energy and angle. In average, $\delta_{\text{syst}}\Sigma = 0.09$ and $\delta_{\text{syst}}\Sigma_\pi = 0.08$ are obtained for Σ and Σ_π, respectively. This also includes the uncertainty in the absolute degree of beam polarization of $\delta P_\gamma < 0.02$ [24] which, however, is practically negligible.

The main results of our measurements are shown in Fig. 4. All energy bins are included in each part of the figure as described in the caption. The left part shows Σ as a function of $|t|$. Unlike the cross section in the diffractive regime the beam asymmetry does not show a universal, i.e. energy independent, $|t|$ dependence. This is to be expected for a purely kinematic reason. Because of the intrinsic

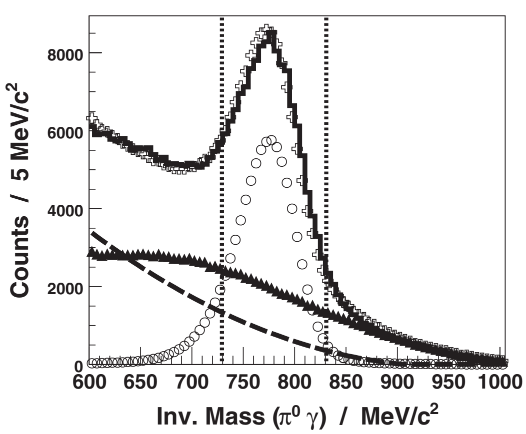

FIG. 2. The $\pi^0\gamma$ invariant mass distribution around the ω signal from the full energy and angular range. The full histogram represents the experimental distribution. Monte Carlo simulations are shown for the ω signal (circles) and the $2\pi^0$ background (triangles). The dashed line is the additional polynomial background (see text), and the crosses show the sum of backgrounds and signal. The mass range accepted in the analysis is indicated by the vertical lines.

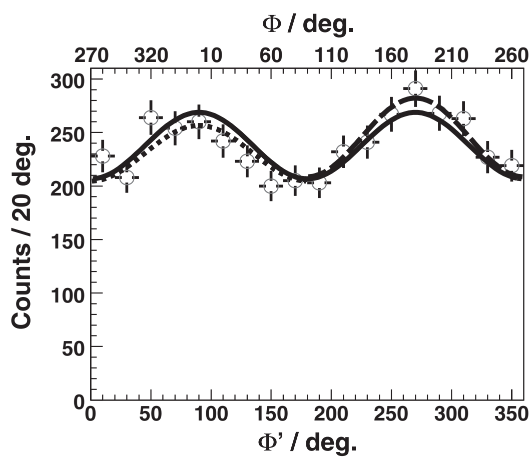

FIG. 3. Azimuthal distribution of the reconstructed ω direction with respect to the plane of photon linear polarization (Φ, top abscissa) and to the horizontal x axis of the standard laboratory frame (Φ', bottom abscissa) within the bin $E_\gamma =$ 1200–1300 MeV and $\Theta = 85°$–$100°$ (ω polar angle in the center-of-mass frame of the reaction). The solid curve represents the full fit. The separate fits of the left and right region are denoted dashed line and dotted line (see text).

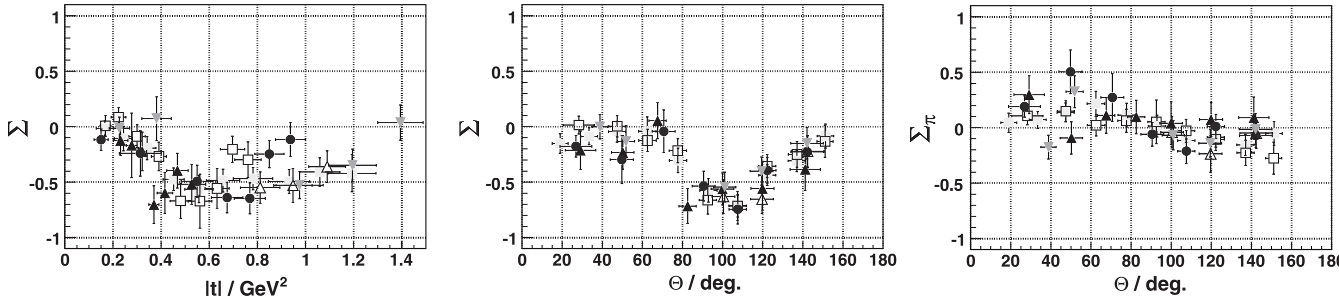

FIG. 4. Photon-beam asymmetries and pion asymmetries with total error bars (statistical and systematic errors added in quadrature). In each figure all different energy bins are included: 1108–1200 MeV (full triangles tip up), 1200–1300 MeV (open squares), 1300–1400 MeV (circles), 1400–1500 MeV (open triangles), and 1500–1700 MeV (full triangles tip down). The full squares represent the full energy range. On the left Σ is shown as a function of $|t|$, in the middle Σ as a function of Θ, and on the right Σ_π as a function of Θ (ω polar angle in the center of mass of the reaction).

$\sin^2\Theta$ dependence of Σ, it is bound to zero in each energy bin at the smallest and largest possible $|t|$ which correspond to forward and backward production, respectively. It is, however, found that Σ exhibits a universal dependence on the ωp center-of-mass angle Θ (Fig. 4 middle). This may be associated with intermediate s-channel excitations with specific decay patterns. Also the large magnitude of the beam asymmetries at $\Theta > 80°$ seems hardly reconcilable with pure t-channel processes [12,14,15].

An essential new piece of information is provided through the pion asymmetry, Σ_π (Fig. 4 right). In the angular region beyond $\Theta = 80°$ where Σ is large, Σ_π is close to zero. According to the introductory discussion, such a behavior is not expected with t-channel processes dominating. It provides a new indication for significant s-channel resonance contributions. In the forward angular region, $\Theta < 80°$, Σ_π exhibits larger spreads around 0, consistent with increasing t-exchange contributions in forward production.

The above findings are further corroborated through quantitative comparison of our new data to the Bonn-Gatchina partial wave analysis [12,13] shown in Fig. 5. In addition to the pseudoscalar channels, the PWA is based on the SAPHIR [7] and GRAAL [9] ω photoproduction data. Our new data are *not* yet incorporated. Good agreement is only achieved, if, on top of t exchange, the PWA includes resonant partial waves. The far dominating $3/2^+$ wave is associated with the $P_{13}(1720)$.

In summary, we have measured for the first time the pion asymmetry Σ_π related the $\omega \to \pi^0\gamma$ decay in ω photoproduction off the proton from threshold to $E_\gamma = 1700$ MeV. It provides a new indication that baryonic resonances play an important role in the production process, further supporting our present and previous other findings based on the photon-beam asymmetry Σ. The photoproduction of ω mesons thus continues to be a promising channel to find so far undetected baryonic resonances predicted by current quark models. Ongoing measurements of further double polarization observables will be indispensable to fully disentangle the process.

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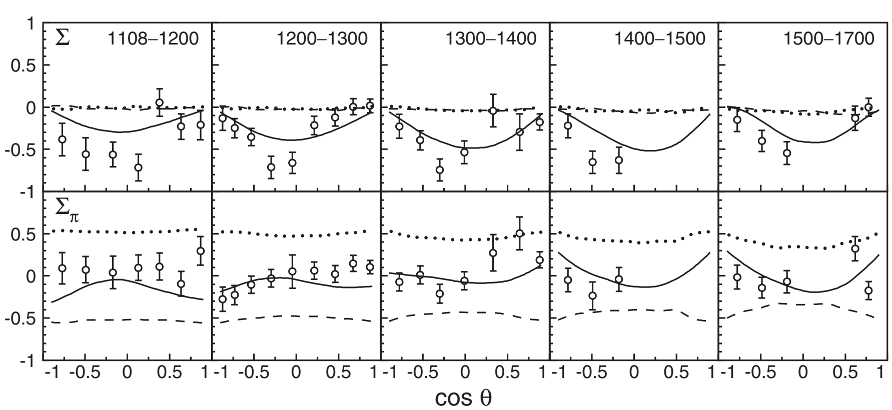

FIG. 5. Comparison of the experimental data for Σ (upper row) and Σ_π (lower row) to the Bonn-Gatchina PWA. The PWA uses the experimental binning in E_γ from 1108 to 1700 MeV. Three versions of the PWA are shown: pure π^0 exchange (dashed line), pure pomeron exchange (dotted line), and the full solution (based on a fit to unpolarized data and the GRAAL beam asymmetry; the experimental data presented here were *not* included).

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