Photoproduction of Vector Mesons

Valentina Vegna

1 Universität Bonn, Physikalisches Institut, Nussallee 12, 53115 Bonn
E-mail: vegna@physik.uni-bonn.de

Abstract. Recent experimental results from $\phi$ and $\omega$ photoproduction off the proton in the third resonance region will be shown. These results are not yet fully understood and leave open questions both from the experimental and from the theoretical point of view. Further experimental investigation could shed new light on the $t$-channel mechanisms responsible for vector meson production and on the role of resonances in case of $\omega$ photoproduction.

1. Introduction

The lightest vector mesons are $\rho(770)$, $\omega(782)$ and $\phi(1020)$. While the $\rho$ has isospin I=1 and a large full width ($\Gamma_\rho = 149.1 \pm 0.8$ MeV), $\omega$ and $\phi$ can be observed in the only neutral charge state and show a much smaller width ($\Gamma_\omega = 8.49 \pm 0.08$ MeV and $\Gamma_\phi = 4.26 \pm 0.04$ MeV) [1]. In Fig.1 the cross sections of $\rho_0$, $\omega$ and $\phi$ photoproduction off the free proton are shown from the corresponding thresholds up to 6 GeV of incoming photon energy (data from Ref.[2]-[6]). The most probable process is the photoproduction of $\rho_0$ meson with a cross section $\sigma_\rho \simeq 20-30 \mu$ barn in the whole energy range. The $\omega$ photoproduction cross section $\sigma_\omega$ is smaller but still comparable with $\sigma_\rho$, showing a maximum of $\simeq 8 \mu$ barn close to threshold. Finally it is observed that the $\phi$ cross section is much smaller with respect to $\sigma_\rho$ and $\sigma_\omega$: more than a factor 10 of difference is observed at $\phi$ threshold. This important difference could be explained in terms of SU(3) representation. In fact, while $\rho_0$ and $\omega$ mesons are described as combinations of up and down quarks and anti-quarks, $\phi$ meson is a pure $s\bar{s}$ state. Due to the Okubo-Zweig-Iizuka (OZI) rule [7], the direct interaction of $\phi$ mesons with particles ”built” by up and down quarks (such as the proton) is strongly inhibited. At the same time $\omega - \phi$ mixing and strangeness content in the proton could be invoked to explain the OZI-violation resulting in a small but still not null cross section.

2. $\phi$ photoproduction

First measurements of cross sections and decay angular distributions for $\phi$ photoproduction off the free proton were performed at the end of the 60’s and during the 70’s ([3], [4], [8] and [9]). More accurate results have been published in the last decade. Examples of recently measured differential cross sections are shown in Fig. 2a and 2b (data are from Ref.[6] and [10], respectively). Results show the typical diffractive behavior, expected for vector meson photoproduction where the $t$-channel exchange mechanism dominates the production process. Data are well fitted by the exponential function $\frac{d\sigma}{dt} = a \cdot e^{-b|t-t_{\text{min}}|}$ for t values corresponding to $\phi$ photoproduction angles up to 90$^\circ$, confirming the dominant role of $t$-channel in this kinematics. From the parameters of the fit, the value of the differential cross section is extrapolated at
Figure 1: Total cross section for $\rho_0$, $\omega$ and $\phi$ photoproduction off free proton up to 6 GeV of incoming photon energy. Data are from references [2]-[6]. Solid, dotted and dashed lines: $\rho_0$, $\omega$ and $\phi$ threshold, respectively.

$|t| = |t_{\text{min}}|$. Results from this procedure are shown in Fig.3. The accurate measurements from LEPS (black points) show an unexpected non-monotonic behavior already visible in data from Ref.[6], with the cross section showing a local maximum at 2.0 GeV. This effect is not yet explained and requires both experimental confirmation and theoretical interpretation.

Accurate measurements of the decay angular distributions were also performed for the decay $\phi \to K^+K^-$ both in the Gottfried-Jackson frame and in the Helicity frame to check $t$-channel and $s$-channel helicity conservation, respectively. In Fig. 4a and 4b angular decay distributions measured by the SAPHIR experiment are shown (Ref.[6]). The behavior expected if helicity is conserved is shown by solid line. Data are well described by the solid line in the Gottfried-Jackson frame indicating the dominance of helicity conserving reactions in the $t$-channel. It is the case of Pomeron exchange mechanism. On the contrary, in the Helicity frame there is evidence of helicity violating production mechanisms. It indicates that also contributions of unnatural parity exchange (e.g. $\pi^0$ exchange) take place in $\phi$ photoproduction off the free proton. A detailed investigation of the decay angular distributions was performed by LEPS in the Gottfried-Jackson frame, looking for a possible explanation of the non-monotonic behavior visible in Fig.3. In fact the angular distributions are measured in the energy range around to the local maximum of the cross section ($E_\gamma = 1.97-2.17$ GeV) and above ($E_\gamma = 2.17-2.37$ GeV) looking for any difference that could be a hint in the understanding of the non-monotonic behavior. Results are shown in Fig.5. The angular distributions show no difference in the two energy bins and it does not allow any conclusion on the origin of the local maximum in the cross section. The non-monotonic behavior still remains an open question.
Figure 2: Differential cross section of $\phi$ photoproduction off free proton. 2a: results from Ref.[6]. 2b: results from Ref.[10].

Figure 3: Values of the differential cross section extrapolated at the minimum possible value of transferred 4-momentum $t$ (Fig.3 from Ref.[10]).
Figure 4: Decay angular distributions measured at SAPHIR in the Gottfried-Jackson frame and in the Helicity frame. Solid line: expected behavior if helicity is conserved.

Figure 5: Decay angular distributions measured at LEPS in the Gottfried-Jackson frame.

3. $\omega$ photoproduction
The $\omega$ meson is described in the SU(3) representation as $\omega = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d})$. Due to this, also contributions from $s$- and $u$-channels are supposed to play an important role in the $\omega$ photoproduction off the nucleon. As a consequence, while $\phi$ photoproduction is a powerful tool for the study of the $t$-channel reaction mechanisms, $\omega$ photoproduction is important in the study of the baryonic spectrum and in the investigation of the open issue of the missing resonances. Since it has isospin $I = 0$ and due to isospin conservation in strong interaction, the study of $\omega$ photoproduction allows to access only $N^*$ nucleon resonances, which are the resonances with isospin $I = \frac{1}{2}$. The important role of the $t$-channel exchange contribution and the influence of resonant channels in $\omega$ photoproduction off the free proton is visible in the differential cross
section, as it is shown in Fig. 6 (Fig 2 of Ref.[11]). $t$-channel exchange mechanisms dominate the differential cross section in the whole energy range for $t$ up to 0.5 GeV$^2$. For higher values of the transfer momentum $t$, resonant contributions become visible.

![Graphs showing differential cross sections](image)

Figure 6: See Ref.[11].

In order to better appreciate the resonances involved in the photoproduction of the $\omega$ meson, the beam asymmetry $\Sigma$ should be measured. The asymmetry should be null if only contributions from $t$ channel exchange are responsible of the production reaction. Any deviation is a strong indication of the role of the resonances. Figs. 7a and 7b show the already published results and theoretical descriptions for $\omega$ beam asymmetry. Experimental data suggested an important role of the resonance $P_{13}(1720)$ in $\omega$ photoproduction. The actual status is still confusing. New results from GRAAL and CB-ELSA collaborations should be published in the next future.
Figure 7: Experimental and theoretical results for the reaction $\gamma + p \rightarrow \omega + p$.

Fig.7a Green squared and black stars are results from Ref.[12] and [13], respectively.
Fig.7b Black and light-blue lines from Ref.[14]. Purple line from Ref.[15]. Red line from Ref.[16].
Green line from Ref.[13]. Blue line from Ref.[17].

4. Perspectives
The new BGO-OD experiment installed at the ELSA facility in Bonn could give new results useful for a better understanding of $\omega$ and $\phi$ photoproduction off the nucleon. The experiment will use an unpolarized or linearly polarized photon beam produced by Bremsstrahlung from the ELSA electron beam. Photons will give rise to photonuclear reactions by impinging on an unpolarized target (e.g. Hydrogen, Deuterium or light nuclei). A large acceptance detector will allow photon detection and charged particle detection and identification. The central part of the detector consists of two cylindrical wire chambers for charged particle tracking, a barrel of plastic scintillating bars for charged/neutral particle discrimination and a BGO calorimeter optimized for photon detection. This set-up was already used in the GRAAL experiment (see Ref.[18] for more details on the central detector), giving high quality results in the study of several reactions (e.g. $\pi^0$ and $\eta$ photoproduction off proton and neutron, $K\Lambda$ photoproduction off proton, etc.). The forward detector consists of detectors for charged particle tracking, an open dipole magnet and 8 drift chambers for charged particle identification (on the base of momentum reconstruction) and a time-of-flight detector for charged and neutral particle detection in the forward direction. The combination of the central detector - optimized for photon detection - and of the forward spectrometer will allow a detailed analysis of several photonuclear reactions by the study both of charged particle final states and multi-photons final states.

The detector could be used for a new measurement of the differential cross section of $\phi$ photoproduction at small values of the transfer 4-momentum $t$ with $\phi$ identified by the decay $\phi \rightarrow K^+ + K^-$. In fact charged kaons can be detected and identified at small polar angle $\theta$ in the laboratory frame by the forward spectrometer and a new measurement of the differential cross section can be performed in the energy region corresponding to the local maximum of LEPS data. If the non-monotonic behavior will be confirmed, efforts will be needed to understand
the origin of this effect. For the first time, also the measurement of the cross section of φ photoproduction off the neutron could be performed using a Deuterium target. If the results from LEPS will be confirmed, a new measurement of the cross section of ω photoproduction should also be performed to verify the presence of a local maximum in this case. First measurement of the cross section of ω photoproduction off the neutron could also be performed. With the polarized photon beam, new measurements of beam asymmetries and decay angular distributions could be performed both for φ photoproduction (with φ → K⁺K⁻) and for ω photoproduction (with ω → π⁺ + π⁻ + π⁰ and ω → π⁰γ).

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