Photoproduction of Mesons on the Nucleon

B. H. Schoch
Physikalisches Institut, Universität Bonn, Bonn, Germany

Abstract

Experimental studies of the photomeson production on the nucleon provide an abundant amount of data to address key issues of its structure. Depending on the selected channels and kinematics, different aspects can be investigated. The measurements of charged channels at low t constitute a large part of the cross section and exhibit a special sensitivity of the meson cloud. These contributions can be strongly suppressed by using a polarized beam and target. Instead, the excitation of resonances are emphasized in this case. The choice of neutral channels in the final state shows also dominant sensitivities for resonance excitation. The sequential decay of resonances can be studied systematically for the first time.

1. Introduction

The studies of the excitation spectrum of the nucleon enter into a new period of extensive investigations. It has been recognized that several key questions concerning the forming of structure in low energy QCD can be addressed by studying the complete spectrum of excited states. This includes the determination of the quantum numbers and decay branching ratios of these states as well as the extraction of the photocouplings of the states. The identification of the relevant degrees of freedom is one of the most important issues to settle. From the knowledge of the low energy part of the excitation spectrum it can be inferred that the nucleon is built from the degrees of freedom of spin -1/2 fermions confined to a valence qqq system. Further questions wait for answers: Are there, in addition, excitations of the gluonic and sea quark degrees of freedom? Can as many states be found as results from calculations based on symmetric quark models suggest or are degrees of freedom frozen out? The quarks considered in the qqq system are quasiparticles with masses of a third of the nucleon mass. Do the properties of these quasiparticles change when excited to the highest energies? Does the relatively large energy splitting of the parity doublets change to get degenerate at higher excitation energies? An answer to these questions leads to the understanding how QCD makes baryons and provides the basis for a description of the origin of the forces between nucleons. With the study of reactions like $\gamma + N \Rightarrow N + n \cdot mesons$ a comprehensive experimental program can be carried out. Using polarized beams and targets as well as large acceptance detectors the relevant observables can be extracted. Mainly based on data taken recently at ELSA , a general picture of photo - meson production will be presented.

2.Total cross sections

The total photon absorption cross [1] section on the proton (see Fig.1) shows two remarkable features: The pronounced resonance structure at low photon energies ($E_\gamma \leq 1.5GeV$) and the seemingly structureless shape of the cross section at higher energies ($E_\gamma \geq 1.5GeV$). The magnetic and electric dipole excitations of the nucleon are seen in the first and second peak, respectively. The structureless part is well described by an extrapolation of an Regge fit for photon energies with $6GeV \leq E_\gamma \leq 200GeV$ [2]. The successful extrapolation into the resonance region suggests that the same absorption mechanism as in the high energy regime is responsible for this "background" contributions, as this part of the cross section is called in the resonance region. The detailed study of this "background" contribution is interesting by itself, because it constitutes a mayor part of the total absorption cross section which determines via dispersion theory such static properties of the nucleon like the electric and magnetic polarizabilities. These again, provide a fertile ground to test the validity of extended calculations based on the Chiral Perturbation Theory, the low energy realization of QCD. Fig. 2 shows, together with the total photon absorption cross section, the total cross sections of the reactions $\gamma + p \Rightarrow p + \pi^+ + \pi^-$, $\gamma + p \Rightarrow p + \pi^+ + \pi^- + \pi^0$, $\gamma + p \Rightarrow p + \rho^0$, $\gamma + p \Rightarrow p + \omega$ and $\gamma + p \Rightarrow p + K^+ + K^-$ as measured with the SAPHIR detector at ELSA.[3, 4]

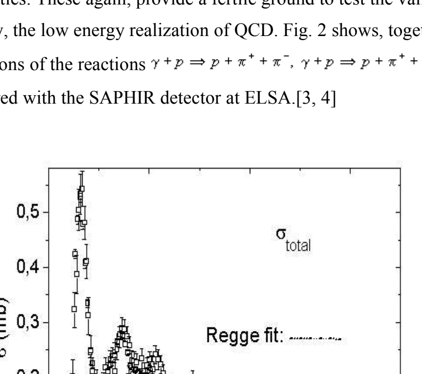

Fig. 1: Total absorption cross section

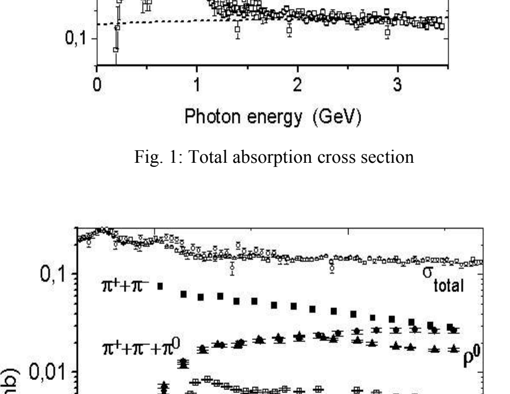

Fig. 2: Total meson production cross sections

These represent a large portion of the total absorption cross section for $E_\gamma \gtrsim 1GeV$. A first step to get insight into the reaction mechanism provides the decomposition of the $\gamma + p \Rightarrow p + \pi^+ + \pi^-$ cross section into the different reaction channels $\gamma + p \Rightarrow p + \rho^0$, $\gamma + p \Rightarrow \Delta^{++} + \pi^-$ and $\gamma + p \Rightarrow \Delta^0 + \pi^+$ which is shown in Fig.3. The dominance of the reactions $\gamma + p \Rightarrow \Delta^{++} + \pi^-$ and $\gamma + p \Rightarrow p + \rho^0$ indicates a diffractive process. More detailed information concerning the reaction mechanism yields the t-dependence of the different reaction channels. A few typical examples in selected γ- energy ranges will be presented.

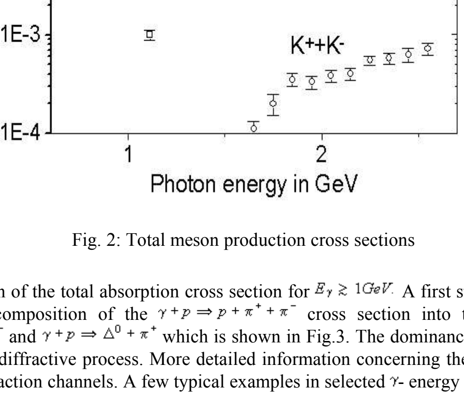

Fig.3: Total two pion production cross sections

3. Differential cross sections

Fig.4 shows the t- dependence of the cross section for the reaction $\gamma + p \Rightarrow \Delta^{++} + \pi^-$. The large cross section at small t and its linear decrease over the whole range as a function of t on a logarithmic scale signifies the dominance of a diffractive process. For the reaction $\gamma + p \Rightarrow p + \omega$, shown in Fig.5, a different behavior of the cross section can be seen: In the low t- range again the diffractive process dominates but in addition, at larger t, the cross section flattens out. This behavior of the differential cross section indicates contributions of certain partial waves due to resonances. Fig. 6 shows as a demonstration the differential cross section of the reaction $\gamma + p \Rightarrow n + \pi^+$ in the first and second resonance region exhibiting very clearly the known resonance contributions from the $\Delta_{33}(1232)$ and the Roper resonance as dominating partial waves.

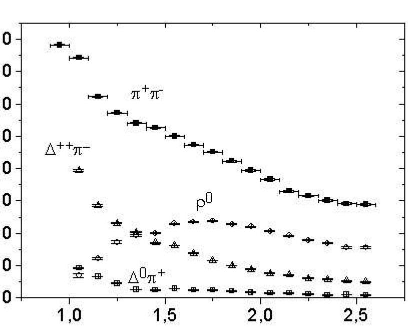

Fig.4: t-dependence: $\gamma + p \rightarrow \Delta^{++} + \pi^-$

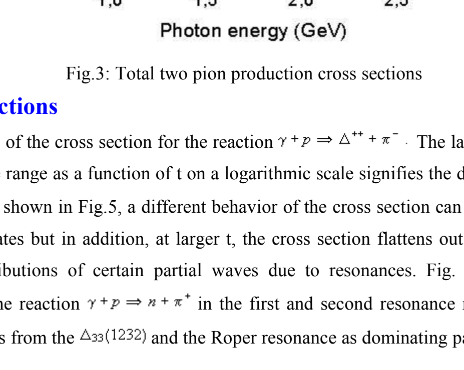

Fig. 5: t-dependence: $\gamma + p \rightarrow p + \omega$

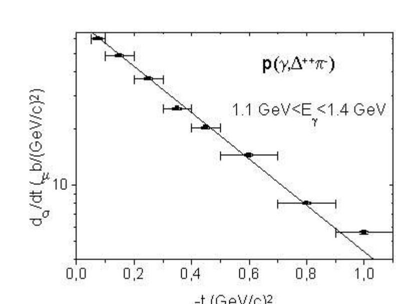

Fig. 6: Differential cross section: $\gamma + p \rightarrow n + \pi^+$, MAID-generated data [5]

The diffractive part at low t- values is due to the pion pole contribution. A similar picture as with the $\gamma + p \Rightarrow p + \omega$ reaction can be seen in the $\gamma + p \Rightarrow p + \rho^0$ reaction, Fig.7. Both reactions hold, therefore, the promise to be very useful channels to find so far unidentified resonances. Remains to be considered (Fig.8) the last vector meson with the quantum numbers of the photon, the Φ -meson. The Φ- meson production is dominated by the diffractive process as expected due to the composition of the Φ -meson by strange quarks. Two directions become visible to use these reactions for investigations of the excitation spectrum of the nucleon. The first one, to perform a partial wave analysis with the identification of the quantum numbers of resonance contributions, is under way. The second one, will be the observation of excited states of the nucleon by using the inelasticity of the diffractive process. As an example [6] the reactions $\gamma + p \Rightarrow Roper + \rho^0 \Rightarrow n + \pi^+ + \pi^+ + \pi^-$ and $\gamma + p \Rightarrow Roper + \omega \Rightarrow n + \pi^+ + \pi^+ + \pi^- + \pi^0$ are considered.

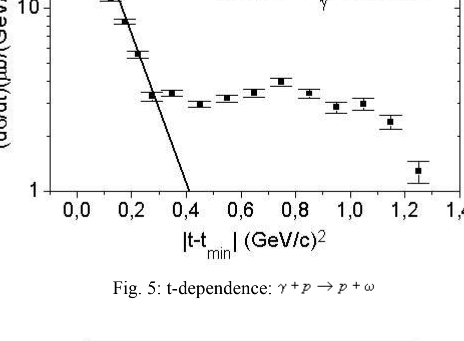

Fig.7: t-dependence: $\gamma + p \rightarrow p + \rho$

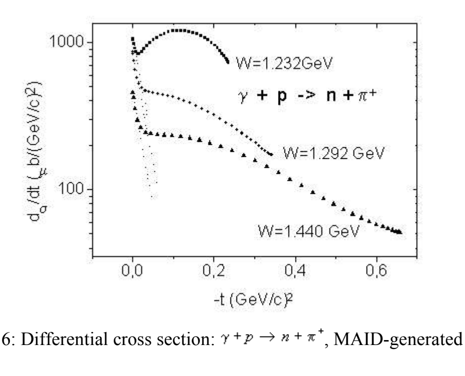

Fig.8: t-dependence: $\gamma + p \rightarrow p + \Phi$

Especially interesting will be a systematic study of scalar excitations as proposed in [6] and a careful examination of the isospin sector due to the "availability" of virtual isovector -and isoscalar vector mesons in the photon beam. Photon beams with photon energies $E_\gamma \gtrsim 3.2GeV$ are mandatory in order to cover the whole excitation spectrum of the nucleon via these unique inelastic vector meson scattering reactions.

4. The case for polarization

With the development and implementation of polarized targets and beams for γ- induced reactions new classes of experiments become possible. The spin structure in the resonance region can be investigated in a more direct way by using longitudinally polarized γ- beams in combination with longitudinal polarized targets. A mayor experimental achievement has been the development of polarized targets [10] which are suitable to be used in the whole angular acceptance range of 4π-detectors. Linearly polarized γ-beams, prepared by using coherent bremsstrahlung, are suitable to investigate transitions due to convection currents and allow to separate parity even and parity odd transitions. For the first time the total absorption cross section for circular polarized photons has been determined by performing double polarization experiments. By measuring the difference of the spin projected cross sections $\sigma_{3/2} - \sigma_{1/2}$ the spin response of the nucleon excitation spectrum up to $E_\gamma = 3GeV$ has been extracted. Fig.9 shows the total photon absorption cross section difference $\sigma_{3/2} - \sigma_{1/2}$ in the photon energy range

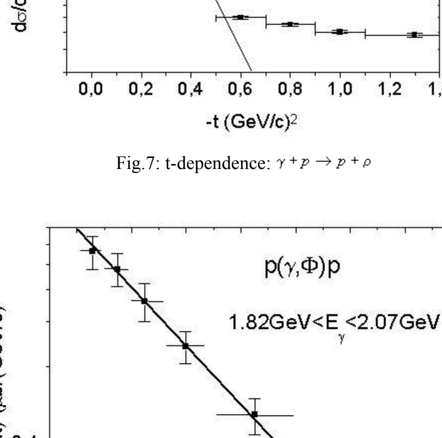

Fig. 9: Difference of the total cross sections $\sigma_{3/2} - \sigma_{1/2}$

$.2GeV \leq E_\gamma \leq 3GeV$ as has been measured in a double polarization experiment at MAMI ($0.2GeV \leq E_\gamma \leq 0.8GeV$) [7] and ELSA ($0.75GeV \leq E_\gamma \leq 3GeV$) [8,9].

At a first glance by looking at the cross section the very pronounced peaks in the resonance region become apparent. The missing of the above mentioned "background" terms constitutes the second remarkable feature. This signifies the suppression, especially of the diffractive or peripheral contributions to the cross section, by performing double polarization experiments. With these data the GDH - sum rule has been checked, a fundamental relation between the total absorption cross section for circular polarized photons on longitudinal polarized protons and the anomalous magnetic moment of the proton.

5.The observation of multi photon states in the final state

A decomposition of the total γ-absorption cross section into its final states exhibits a strong dominance of charged mesonic states as can be seen e.g. in Fig.2. Because of large "background" contributions no obvious resonance structures are seen in the total cross sections. However, by choosing reactions like $\gamma + p \Rightarrow p + \eta$, $\gamma + p \Rightarrow p + \eta'$, $\gamma + p \Rightarrow p + \pi^0 + \pi^0$, $\gamma + p \Rightarrow p + \eta + \pi^0$ resonances are expected to stand out of the background very clearly as the example of experimental studies on the $S_{11}(1535)$ have demonstrated,e.g. [11]. At ELSA an experimental program has been started to investigate, in a first round of experiments, the multi photon decay channels. The high segmented (1380 CsJ- crystals) CRYSTAL BARREL[12] detector serves as the main instrument in an experimental set-up with a photon tagger, a forward time of flight wall and fiber detectors inside the barrel. Fig.10-12 show spectra of 2, 4 and 6 photons in the final state, respectively.

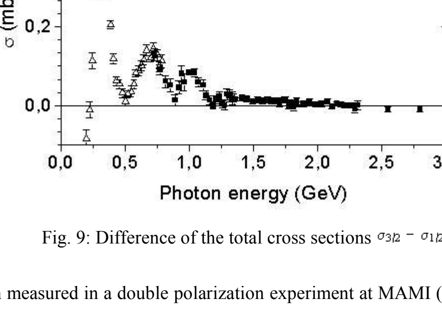

Fig.10 Two photon spectrum

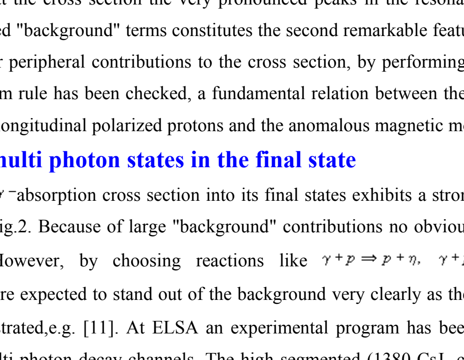

Fig.11 Four photon spectrum

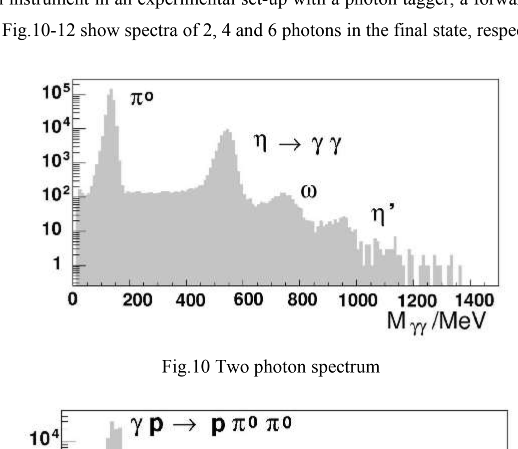

Fig.12: Six photon spectrum

By identifying the hit pattern and adding up the collected energy, the expected mesonic final states stand up very clearly. The ω- meson is seen in the two photon channel because one of of the decay photons escaped identification. A good check for the calibration of the efficiencies provides the comparison of the two photon with the six photon cannel by considering the η channel. These many photon final states can be measured almost background free. Besides transitions from excited states leading to the ground state, cascade transitions can be observed for the first time in a systematic way. Fig.13 shows a cascade decay, as indicated in Fig.14, for the two pion channel; photo excited up to $\sqrt{s} = 2100MeV$. The excited state decays via intermediate states to the ground state. Clearly visible are in this example the $\Delta_{33}(1232)$ and the $D_{13}(1520)$ as intermediate states.

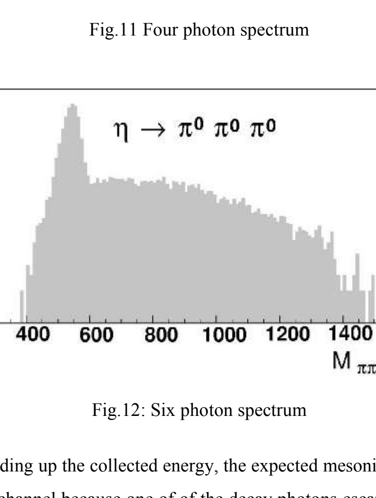

Fig.13: Two π^0 decay

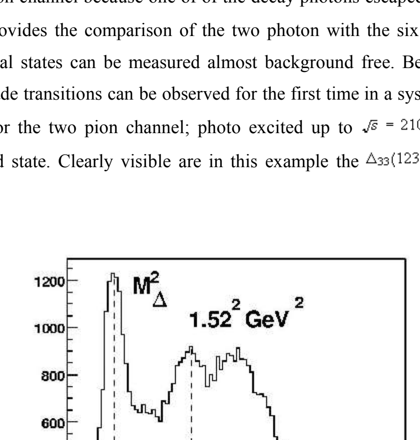

Fig.14: Decay scheme for two π^0 decay

A similar cascade decay can be observed, Fig.15, in the $\gamma + p \Rightarrow p + \eta + \pi^0$ channel; excited to an energy $\sqrt{s} = 2.25GeV$ the decay takes place via the S_{11} resonance, Fig.16, which subsequently decays via an η-decay. This connection of the decay of so far not seen or not well studied resonances allows a deepened study of the structure of the resonances.

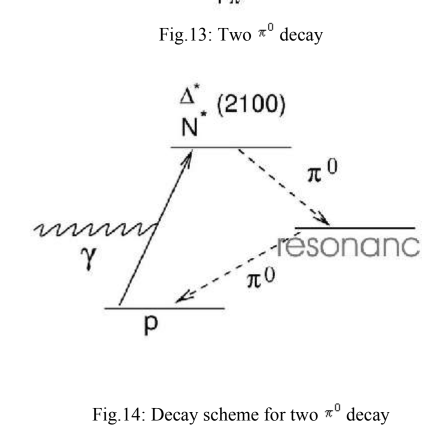

Fig.15: $\pi^0 - \eta$ decay spectrum

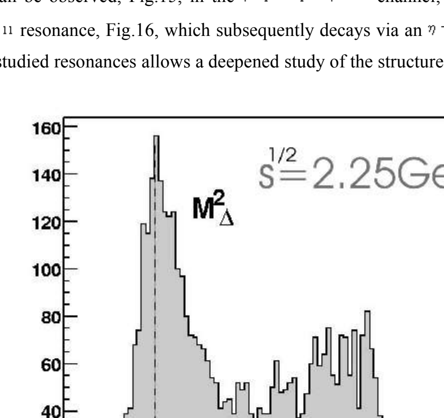

Fig.16: $\eta - \pi^0$ decay scheme

The high energy part of the excitation spectrum, which can be investigated in an optimal way via these cascade decays, are of great interest for studies of chiral symmetry restoration [13,14]. Several doublets are predicted if this conjecture should hold.

6. Summary

The study of the various meson production channels in photoproduction reactions on the nucleon reveals and continues to reveal essential informations concerning the excitation spectrum of the nucleon. Diffractive processes provide the largest contributions to the total unpolarized cross section for $E_\gamma \succ 0.9GeV$. These contributions disappear almost completely in the case of the spin polarized cross section difference $\sigma_{3/2} - \sigma_{1/2}$. This recent result and previous measurements with linearly polarized photons underscore the importance of the exploitation of polarization degrees of freedom in exploring the excitation spectrum of the nucleon. Other promising options open up by the investigation of special decay channels like $\pi^0\pi^0$ and $\eta\pi^0$. The reconstruction of cascade decays paves the way for the study of so far not accessible observables between excited states. Even $\eta\ \eta$ events in the final state have been reconstructed and identified as signals of cascade decays. Thereby, isolated resonances in the higher part of the excitation spectrum of the nucleon have been seen. However, it becomes clear that the decay branching ratios are very small and high luminosity set-ups are mandatory for a systematic exploration of these transitions. Besides the tremendous progress in the development of beams, targets and detectors an adequate effort in analyzing procedures are necessary in order to extract the relevant information out of the data. First results in this respect look quite promising. Today, the situation concerning the investigation of the excitation spectrum of the nucleon shows similarities with the spectroscopy of atoms in the early 20th century. Sommerfeld wrote in 1919 [15] that the problem of the atom would undoubtedly be solved once physicists had learned to understand the language of spectra [16].

Acknowledgements

Many fruitful discussions with M. Ostrick, W. Schwille, F. Klein and E. Klempt are acknowledged.

References

[1] K. Hagiwara et al., Phys. Rev. D 66, 010001 (2002)
[2] A. Donnachie and P.V. Landshoff, Particle World, 2, 1 (1991) 7
[3] J. Barth, PhD-Thesis, Physikalisches Institut, University Bonn, 2002, to be published
[4] Ch. Wu, private communication
[5] D. Drechsel et al. Nucl.Phys.A645 (1999) 145
[6] M. Soyeur, Nucl.Phys.A671 (2000) 532
[7] J. Ahrens et al., Phys.Rev.Lett. 87, 022003, 2001
[8] T. Speckner, PhD-Thesis, Physikalisches Institut, University Erlangen, 2002, to be published
[9] G. Zeitler, PhD-Thesis, Physikalisches Institut, University Erlangen, 2002, to be published
[10] C. Bradke et al., Nucl.Instr.&Meth.A 436 (1999) 430
[11] B. Schoch, Progr.Part.Nucl.Phys. 34, (1995) 43
[12] E. Aker et al.,Nucl.Instr&Meth.A 321, (1992) 69
[13] L. Glozman, contribution to this volume
[14] E. Klempt, Phys.Rev.C, 66 ,052002 (2002)
[15] A. Sommerfeld, Atombau und Spektrallinien, first edition, 1919
[16] G. Gibson et al., Physics Today, 2002, 42