The $\gamma p \rightarrow K^0\Sigma^+$ photoproduction reaction$^1$

Hartmut Schmieden
Physikalisches Institut, University of Bonn, Nussallee 12
D-53115 Bonn, Germany
E-mail: schmieden@physik.uni-bonn.de

Abstract. At the electron accelerator facility ELSA of the University of Bonn the photoproduction reaction $\gamma p \rightarrow K^0\Sigma^+$ was investigated using the CBELSA/TAPS experimental setup. A pronounced structure in the cross section is found at the $K^*$ threshold. It is speculated whether this is due to the formation of a $K^*$-hyperon quasibound state below the $K^*$ threshold. The impact of recent polarisation measurements is discussed.

1. Introduction
Excitations of baryons carry information about their inner structure. The effective degrees of freedom are not necessarily just quarks and gluons as may be “simply” expected from the short range nucleon structure revealed, e.g., in deep inelastic lepton scattering. Due to the closeness of the chiral symmetry breaking scale to the nucleon mass/size scale, also the rsp. Goldstone bosons enter as effective “elementary” objects [1, 2]. It is hence no surprise that in some aspects, e.g. the parity ordering of the lowest nucleon excitations [1], models which include the interaction of the light mesons with quarks are more successful than genuine three quark models which attempt to parameterize pure colour interactions. If already meson-quark interactions play a significant role, then meson-baryon interactions appear as a natural extension. Some models indeed assign a leading role in hadronic excitations to meson-baryon interactions [3, 4, 5, 6, 7], and some of the states which persistingly resisted a conventional three-quark explanation in the meanwhile are speculated to predominantly exhibit meson-baryon dynamics, e.g. the $\Lambda(1405)$ [8]. In addition to the interaction of pseudoscalar mesons with baryons also vector mesons are considered for dynamical resonance generation [9, 10, 11]. Degenerate states of $J^P = 1/2^-, 3/2^-$ are expected, in particular in the mass region around 2 GeV [12].

$K^0$ photoproduction off the proton provides a very interesting channel for several reasons [8]. For the study presented here it is of particular interest that, compared to the extensively measured charged kaon channels, $t$-exchange is suppressed in the production mechanism. Hence, a cleaner probe to $s$-channel contributions is provided. On the other hand, $t$-exchange is not strictly forbidden despite the zero charge of the $K^0$, because the photon may magnetically couple to a $K^{0*}$ vector meson as is shown in Figure 1(e). If vectormeson-baryon dynamics was significant in the production process, then diagrams of the type Figure 1(f) should play a role and differently affect $K^0$ photoproduction above and below the $K^{0*}$ threshold, unobstructed by the strong charge-dominated $t$-exchange in $K^+$ production. While previous $K^0\Sigma^+$ data of Crystal Barrel [13] and SAPHIR [14] agree rather well in general, differences show up just in the

$^1$ Supported by the Deutsche Forschungsgemeinschaft (DFG) within SFB/TR-16.
energy region of the $K^*$ threshold. This prohibits a clear conclusion on the role of $K^*$-hyperon dynamics. The new data discussed here improve this unsatisfactory situation.

2. Experiment
The experiment was performed at the Electron Stretcher Accelerator ELSA [15] of the University of Bonn using the combined Crystal Barrel [16] and TAPS [17, 18] detector system. At an electron beam energy of $E_0 = 3.2$ GeV tagged photon beams were generated by coherent bremsstrahlung from a 500 $\mu$m thick diamond radiator [19]. The bremsstrahlung electrons were momentum analysed in a magnetic “tagging” spectrometer. A photon energy range of $E_\gamma = 0.18$–0.92 $E_0$ was covered. The tagging system provided an energy resolution between 10 and 25 MeV. It was run at electron rates up to $10^7$ Hz. The absolute photon flux was determined from the tagged electron spectrum in combination with a fast total absorbing PbWO$_4$ detector to measure the energy dependent tagging efficiency.

The photon beam impinged on liquid hydrogen contained in a 5.3 cm long target cell with 80 $\mu$m Kapton windows. The reaction products were observed in the Crystal Barrel and TAPS spectrometers, complemented by a three layer scintillating fibre detector [20]. In total, the detector system covered a polar angular range of 5.8 – 165 degree. Further details of setup and readout are given in Ref. [21].

The $K^0 \Sigma^+$ reaction was investigated in the neutral decay modes $K^0 \rightarrow \pi^0 \pi^0$ (B.R. 31.4 %) and $\Sigma^+ \rightarrow p\pi^0$ (B.R. 51.6 %), yielding 6 photons and the proton. The identification of the $K^0 \Sigma^+$ reaction channel was based on a kinematic fit to the $\gamma p \rightarrow p 3\pi^0$ reaction. Energy and angle parameters for the fit were provided by the final state photon hits, the photon energy by the tagging spectrometer. Due to the hermetic and even acceptance, cross sections and polarisation observables were obtained over the full angular range. Total cross sections could be extracted without any extrapolations.

3. Cross sections
After the kinematic fit two-dimensional invariant mass distributions are obtained as shown in Figure 2. The $K^0 \Sigma^+$ events are selected from the appropriate region in Figure 2. Background is subtracted through simulation of various channels which may lead to the 6 $\gamma$ event topology.
Figure 2. $\pi^0\pi^0$ against $p\pi^0$ invariant mass distribution after event preselection and kinematic cut, showing a concentration of events in the $K^0\Sigma^+$ final state.

and tuning to the observed one-dimensional invariant mass distributions. The most severe background is found to come from uncorrelated $3\pi^0$ photoproduction. The decay $\eta \rightarrow 3\pi^0$ is suppressed by an appropriate anti-cut in the $6\gamma$ invariant mass distribution. Upon flux normalisation and acceptance correction then differential cross sections are obtained (for details see [21]).

Figure 3 shows the results in comparison to previous measurements of Crystal Barrel [13] and SAPHIR [14]. The data sets agree rather well in general. Discrepancies are however observed in forward directions and in the energy range of the $K^*$ threshold ($E_\gamma = 1750 – 1850$ MeV bin). These discrepancies are resolved by the new data. Below the $K^*$ threshold mostly the SAPHIR data is favored. At the $K^*$ threshold and higher energies the previous Crystal Barrel data is supported.

Directly above the $K^0\Sigma^+$ threshold a differential cross section of $\simeq 0.02\mu$barn/sr is obtained with flat angular dependence, typical for $s$-wave production. The cross section rises with increasing photon energy and also develops an increasing forward peaking, suggesting increasing $t$-channel contributions. This forward peaking is most pronounced in the $E_\gamma = 1700 \pm 50$ MeV bin. The next energy bin exhibits an entirely flat distribution again and the cross section drops back to $\simeq 0.02\mu$barn/sr. This is at $E_\gamma = 1800$ MeV, i.e. between the thresholds of $K^*\Lambda$ and $K^*\Sigma$ photoproduction. The effect is strong enough to be clearly visible also in the total cross section, cf. Figure 4, but it is most pronounced in the most forward angular bin where the cross section drops by a factor of four. This is shown in Figure 5. Above the $K^*$ threshold the differential cross section remains almost flat and practically constant up to the highest measured energies.

4. Polarisation Observables
In order to achieve full experimental account of meson photoproduction reactions the measurement of polarisation observables is mandatory. The most basic one is the photon beam
Figure 3. Measured differential cross sections for $K^0\Sigma^+$ photoproduction as a function of the kaon center-of-mass angle in ±50 MeV wide bins of photon energy from 1100 to 2200 MeV. The present results (full squares) are compared to previous measurements of Crystal Barrel (open squares) [13] and SAPHIR (triangles) [14]. The error bars are purely statistical. An estimate of the systematic uncertainty is given by the bars on the x-axis.

asymmetry. It measures the asymmetry of the azimuthal orientation of the reaction plane relative to the plane of photon linear polarisation. In associated photoproduction of strange mesons with hyperons the polarisation of the recoiling baryon is also easily accessible due to the self analysing weak decay. Both observables were analysed in addition to the cross sections.

4.1. Recoil polarisation
In meson photoproduction the recoiling spin 1/2 baryon generally carries polarisation. The origin is twofold: (i) polarisation transfer from the linearly or circularly polarised photon field, and (ii) spin-orbit coupling in final state interactions [25]. The present experiment used linearly polarised photon beams. In this case, angular momentum transfer results in $\sin 2\phi$ and $\cos 2\phi$ modulations of the recoil polarisation within the reaction plane [26], which is spanned by the ejected kaons and hyperons. The angle $\phi$ denotes the azimuth between the plane of linear polarisation and the reaction plane. Integrating over all possible orientations which, effectively, corresponds to unpolarised photons, solely leaves the polarisation component (ii) non-zero. That
**Figure 4.** Total cross section for $K^0\Sigma^+$ photoproduction as a function of the centre-of-mass energy from the present experiment (full squares) in comparison to the previous Crystal Barrel (open squares) [13] and SAPHIR (triangles) [14] data. The vertical lines indicate the $K^\ast\Lambda$ and $K^\ast\Sigma^+$ thresholds at $W = 2007.4$ and $2085.5$ MeV, respectively. The SAID parameterisation [29] is represented by the dashed-dotted curve. A K-MAID calculation [23] with standard parameters yields the dashed curve. The full curve is obtained with the modifications described in the text. Above the $K^\ast$ threshold the grey circles represent the sum of the $K^0\Sigma^+$ cross section of the present experiment and the $K^0\Sigma^+$ cross section of the work of Nanova et al. [24]. The vertical bars on the abscissa again indicate the experimental systematic errors, the errors plotted with the data symbols are purely statistical.

**Figure 5.** Cross section for $K^0\Sigma^+$ photoproduction as a function of the centre-of-mass energy from the present (full squares) and a previous (open squares) [13] Crystal Barrel experiment in the most forward angular bin of Figure 3.
one is usually called the recoil polarisation, $P$. Due to parity conservation it is oriented normal to the reaction plane.

In the studied reaction, the weak decay of the final state $\Sigma^+$ enables the reconstruction of the recoil polarisation $P$ of the hyperon. The decay angular distribution has the form

$$W(\theta_p) = \frac{1}{2} \left( 1 + \alpha_0 P \cos \theta_p \right)$$

with $\alpha_0$ denoting the so-called decay parameter, and $\theta_p$ the angle between the decay proton direction and the normal of the reaction plane. In consequence, the count rate asymmetry

$$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{1}{2} \alpha_0 P$$

is obtained relative to the reaction plane, where $N_\uparrow$ and $N_\downarrow$ represent the event numbers above and below the reaction plane, respectively. A particular benefit of the $\Sigma^+ \to \pi^0 p$ decay observed in the present experiment is the large decay parameter $\alpha_0 = -0.980$ [27]. According to Eq. 2 it results in large asymmetries from which the recoil polarisation is then determined.

In order to facilitate the comparison to previous measurements, the results are presented in two different sets of binnings, Fig. 6 and Fig. 7. In both cases the errors attached to the data

Figure 6. Recoil polarisation of the $\Sigma^+$ in the four bins of photon energy indicated in the diagrams. The results of the present measurement are compared to the parameterisations of SAID [29] (blue curve) and K-MAID [23] (red curve). Attached to the data points are the statistical errors and, as horizontal lines, the bin widths in $\cos \theta$. The systematic errors are indicated by the grey bars on the abscissa.
Figure 7. The dots represent the same recoil polarisation data as in Fig. 6 now rebinned into two bins of photon energy to allow better comparison to the previous SAPHIR data (squares). Errors and bin widths are indicated as in Fig. 6.

points are purely statistical. The grey bars on the abscissa give an estimate of the systematic uncertainties. Since according to Eq. 2 the recoil polarisation is determined from a ratio of event rates, some of the systematic effects cancel out which may affect cross section or beam asymmetry measurements. Among those are photon flux, detector inefficiencies and beam polarisation. Remaining systematic errors were studied by variations of the cuts applied in the analysis as described in Ref. [21] for the cross section analysis.

Fig. 6 shows the polar angle dependence of the recoil polarisation in four ±150 MeV wide bins from $E_\gamma = 1050$ to 2250 MeV along with a previous measurement of the CBELSA/TAPS collaboration [13] where a similar detector setup but unpolarised beam was used. The general agreement between the data sets seems fair. The errors of the present measurement represent a significant improvement in particular at lower energies. Fig. 7 shows the same data binned in the way of the previous SAPHIR measurements [14]. Within the errors excellent agreement is obtained.

4.2. Photon beam asymmetry
Accounting for a linearly polarised photon beam, the cross section of photoproduction of pseudoscalar mesons off a nucleon can be written in the form [28]

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_{\text{lin}} \Sigma \cos 2\phi\right).$$

(3)
Figure 8. Angular distribution of the photon beam asymmetry $\Sigma$ in the three bins of photon energy indicated in the diagrams. Attached to the data points are the statistical errors and, as horizontal lines, the bin widths in $\cos \theta$. The systematic errors are indicated by the grey bars on the abscissa. The curves represent: SAID [29] (full blue), K-MAID [23] (full red), and variants of the Gent model [31] (dashed).

Here, $(d\sigma/d\Omega)_{0}$ is the polarisation independent cross section, $P_{\text{lin}}$ the degree of linear polarisation, and $\Sigma$ denotes the photon beam asymmetry. The product $P_{\text{lin}}\Sigma$ determines the magnitude of modulation of the cross section with the azimuthal angle $\phi$. Vice versa, it is obtained from the measured modulation by a fit of the function

$$ f(\phi) = A \left(1 - \frac{B}{2A} \cos 2\phi \right) $$

(4)

to the $K^{0}$ yield. $\Sigma$ can then be determined once the beam polarisation is determined as described in Ref. [19]. The method is exactly the same as described in Ref. [22] for $\eta$ photoproduction. The results for the beam asymmetries are shown in Fig. 8.

5. Discussion
Both K-MAID [23] and SAID [29] disagree with the measured cross section data. This can clearly be seen in Figures 4 and 5. Neither parameterisation describes the observed dip in the total cross section. Due to the vicinity of the dip to the $K^{*}$ threshold, it seems likely related to $K^{*}$ exchange in the $t$-channel according to Figure 1(e).

The role of this $t$-exchange was tested with the K-MAID parameterisation, where it is possible to manually change the $K^{*}$ exchange strength. In addition to some modifications
of couplings below the $K^*$ thresholds to improve the overall description of the data (cf. [21]), mainly the $K^{0*}$ exchange was retained below the $K^*\Sigma^+$ threshold but manually set to zero above. As is demonstrated by the full curve in Figure 4, with these modifications K-MAID yields a significantly improved description of the cross section, including the structure at the $K^*$ thresholds. In forward directions (cf. Figure 5) the modified K-MAID still compares only modestly with the data at smaller energies. The drop of the cross section at the $K^*$ thresholds is however rather well reproduced by switching off the $K^{0*}$ exchange contribution.

From this it is concluded that below $K^*$ threshold there may happen a transition in $t$-exchange from $K^*$ vector to pseudoscalar $K^0$. Close to the $K^*$ threshold the vector meson is almost on mass shell in a relative $s$-wave. It subsequently decays into a pion, which rescatters with the hyperon, and the final state $K^0$. Such a process is depicted in Fig. 1 (f). It resembles the formation of a vector meson-baryon quasibound state. Above $K^*$ threshold the vector meson is produced as a free particle. Hence, this process no longer feeds the $K^0\Sigma^+$ final state, leading to the sharp drop of the $K^{0*}\Sigma^+$ cross section. It speaks in favour of this hypothesis that corresponding strength is indeed found in the $K^{0*}$ total cross section [24]. This is illustrated in Figure 4. With the sum of $K^{0*}_0$ and $K^{0*}$ cross sections a smooth transition is obtained at the $K^*$ threshold.

Besides the cross sections, both photon beam asymmetry and recoil polarisation are indispensable observables to unambiguously extract the reaction amplitudes [30], and hence partial wave amplitudes, in a reliable manner. The curves in Figures 6 and 8 demonstrate the level of agreement with the present polarisation data which can be obtained within the K-MAID and SAID parameterisations, as well as with the Gent model [31] for the photon beam asymmetry.

The recoil polarisation neither is satisfactorily described by SAID nor by K-MAID (cf. Figure 6). Since, through interfences, the recoil polarisation is very sensitive to even small resonances, this points to a yet incomplete resonance basis for $K^0\Sigma^+$ photoproduction in these parameterisations. Either there are other $s$-channel resonances involved than included in the models, or the decomposition into $s$- and $t$-channel is different than assumed.

In contrast to the Gent model, the K-MAID and SAID parameterisations of the photon beam asymmetry show reasonable agreement with the data, except in forward directions in the highest energy bin. Similar to the recoil polarisation, also the beam asymmetry is sensitive to interfences of partial waves, and in $s$-channel production therefore a large sensitivity is obtained to even small resonance contributions. In $t$-channel processes, however, the photon beam asymmetry reflects the character of the $t$ exchange. In the transition amplitudes the dominant pieces of the electromagnetic coupling with the $t$-exchange can be written [32]

$$T \propto (\epsilon \times \vec{q}) \cdot \vec{p}_f$$
$$T \propto \epsilon \cdot (\vec{q} + \vec{p}_f)$$

for $K^*$ and $K$ exchange, respectively. Here, $\epsilon$ denotes the photon polarisation vector, and $\vec{q}$ and $\vec{p}_f$ the momenta of the exchanged (intermediate) and final-state kaons, respectively. The scattered kaon and hyperon in the final state are produced most likely perpendicular to the plane of photon polarization when a $K^*$ is exchanged, and parallel to it in the case of an intermediate $K$. The photon beam asymmetry is determined by

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}$$

with $\sigma_\perp$ and $\sigma_\parallel$ denoting the cross sections perpendicular and parallel to the photon polarisation plane, respectively. Therefore, in case of a $K^*$ exchange the asymmetry is expected to be positive and, oppositely, negative for a pseudoscalar $K$ exchange.
In this light the beam asymmetry shows an interesting behaviour in the highest energy bin where the differential cross sections already exhibit forward peaking, suggesting significant $t$-channel contributions. In the case of $K^0$ production the exchange particle is a $K^{*0}$ as depicted in Fig. 1(e). The reaction mechanism suggested above requires a flip-over from $K^*$ to $K$ exchange in the vicinity of the $K^*$ thresholds. The generally positive beam asymmetry is compatible with $K^*$-exchange. In forward directions of the 1450–1650 MeV bin, however, it turns significantly negative. This indeed seems especially here to indicate the predominant exchange of a pseudoscalar $K$ -- as it would be expected, if a $K^*$-hyperon molecular state was generated via diagram Fig. 1(f). Unfortunately, the energy range of the present beam asymmetry data is still restricted to somewhat below the $K^*$ threshold. It is necessary to extend the data base over and beyond the $K^*$ threshold, in order to further clarify the reaction mechanism.

In chiral unitary approaches quasibound $K^*$-hyperon states are indeed theoretically expected close the $K^*$ threshold through the interaction of the nonet of vector mesons with the octet of baryons [33].

6. Summary and outlook
Cross sections and single polarisation observables of $K^0\Sigma^+$ photoproduction off the proton were discussed. The differential and total cross sections exhibit a dip structure at the $K^*$ threshold which isn’t described in any of of the standard parameterisations of the reaction. It is speculated whether a transition is seen from $t$-channel $K^*$-exchange to $K^0$ exchange. In the latter case a $K^*$ is produced off mass shell, subsequently decaying into a $\pi^0$, which rescatters with the hyperon, and the $K^0$ which is observed in the final state. A $K^*\Sigma$ intermediate state may be dynamically generated.

The recoil polarisation $P$ could be determined from threshold to $E_\gamma = 2250$ MeV. It agrees well with previous measurements. The model descriptions remain unsatisfactory as well, pointing to yet unresolved resonance contributions.

The photon beam asymmetry was measured for the first time in $K^0\Sigma^+$ photoproduction. Again, SAID and K-MAID are not able to reproduce the data. The beam asymmetry shows the interesting feature that it turns strongly negative in forward directions just below $K^*$ threshold. This is expected if, close to $K^*$-threshold, a dominating $t$-exchange mechanism flips from $K^*$ to pseudoscalar $K$ exchange. Hence, the beam asymmetry is in agreement with the reaction mechanism hypothesised to explain the observed anomaly of the $K^0$ photoproduction cross section at the $K^*$ threshold. However, before definite conclusions can be drawn it appears important to extend the beam asymmetry measurements across the $K^*$ threshold. This will be subject to future investigations. The reduced photon flux and beam polarisations at higher photon energies can be compensated by exploiting the charged decay channels in addition to the neutral ones used here. This will be made possible by the new BGO-OD detector setup [34] at ELSA.

Acknowledgements
The data discussed are obtained within the frame of the CBELSA/TAPS collaboration and I thank all collaborators for their support. Ralf Ewald deserves the biggest share of credit for performing the data analysis within his doctoral thesis. The project is supported by the Deutsche Forschungsgemeinschaft DFG within the SFB/TR-16 and by the Federal State of Northrhine Westphalia.
References

[1] L.Ya. Glozman and D.O. Riska, Physics Reports 268 (1996) 263
[2] A. Manohar and H. Georgi, Nucl. Phys. B 234 (1984) 189
[3] R.H. Dalitz and J.G. McGinley, in Low and Intermediate Energy Kaon-Nucleon Physics, ed. by E. Ferrari and G. Violini, Reidel, Boston (1981) 381; R. H. Dalitz, T.C. Wong, and G. Rajasekaran, Phys. Rev 153 (1967) 1617
[4] P.B. Siegel, and W. Weise, Phys. Rev C 38 (1988) 2221
[5] N. Kaiser, T. Waas, and W. Weise, Nucl. Phys. A 612 (1997) 297
[6] C. García-Recio, M.F.M. Lutz, and J. Nieves, Phys. Lett B 582 (2004) 49
[7] M.F.M. Lutz and E.E. Kolomeitsev, Phys. Lett. B 585 (2004) 243
[8] T. Jude, these proceedings
[9] P. Gonzalez, E. Oset and J. Vijande, Phys. Rev C 79 (2009) 025209
[10] S. Sarkar et al., Eur. Phys. J. A 44 (2010) 431
[11] E. Oset and A. Ramos, Eur. Phys. J. A 44 (2010) 445
[12] E. Oset et al., arXiv:1103.0807v1 [nucl-th]
[13] R. Castelijns et al., Eur. Phys. J. A 35 (2008) 39
[14] R. Lawall et al., Eur. Phys. J. A 24 (2005) 275
[15] W. Hillert, Eur. Phys. J. A 28, s01 (2006) 139
[16] E. Aker et al., Nucl. Instrum. Methods A 321 (1992) 69
[17] R. Novotny et al., IEEE Trans. Nucl. Sci. 38 (1991) 379
[18] A.R. Gahler et al., Nucl. Instrum. Methods A 346 (1994) 168
[19] D. Elsner et al., Eur. Phys. J. A 39 (2009) 373
[20] G. Suft et al., Nucl. Instrum. Methods A 538 (2005) 416
[21] R. Ewald et al., arXiv:1112.0811v1 [nucl-ex]
[22] D. Elsner et al., Eur. Phys. J. A33 (2007) 147-155
[23] D. Drechsel et al., http://www.kph.uni-mainz.de/MAID/ (Version 29.3.2007)
[24] M. Nanova et al. (Crystal-Barrel/TAPS Collab.), Eur. Phys. J. A35 (2008) 333
[25] Chinese Physics C 33 (2009) 1146 (Proceedings of NSTAR09, Beijing)
[26] D. Drechsel and L. Tiator, Journal of Physics G 18 (1992) 449
[27] K. Nakamura et al. (Particle Data Group), Journal of Physics G 37 (2010) 075021
[28] G. Knöchlein, D. Drechsel and L. Tiator, Z. Phys. A352 (1995) 327
[29] R.A. Arndt et al., http://gwdac.phys.gwu.edu
[30] W.-T. Chiang and F. Tabakin, Phys. Rev. C55 (1997) 2054
[31] S. Janssen et al., Phys. Rev. C66 (2002) 035202
[32] S. Nam et al., Phys. Rev. D 75 (2007) 014027
[33] E. Oset and A. Ramos, Eur. Phys. J. A 44 (2010) 445
[34] H. Schmieden, Int. J. Mod. Phys. 15 (2010) 1043