Status and perspectives in strangeness photoproduction

T C Jude
Physikalisches Institut, Universität Bonn
E-mail: jude@physik.uni-bonn.de

Abstract.
A review of recent results in strangeness photoproduction is presented, in preparation for experimental proposals for the new BGO-OD experiment at the ELSA facility, Bonn. Cross section measurements and polarisation observables in $\gamma (p, K^+)\Lambda$ are discussed, and the relation to these measurements and what can be gleaned from neutral kaon photoproduction. Recent cross section data for $\gamma (p, K^0)\Sigma^+$ and $\gamma (n, K^0)\Lambda$ is presented, and measurement of the $\Lambda(1405)$ lineshape from $\Sigma\pi$ decays and comparison to theory. Hypernuclei are introduced, and what could be achieved using a real photon beam.

1. Introduction
Over the last 20 years, increases in electron beam energy and intensity at accelerator facilities has markedly increased statistics for the photoproduction of mesons and baryons with non-zero strangeness. The intention of this paper is to highlight recent progress and areas where further research is required. This is expected to form the basis of experimental proposals in open strangeness for the newly commissioned BGO-OD experiment [1] at the ELSA accelerator facility [2], Bonn. The experiment uses a real, bremsstrahlung photon beam to an energy of 3.5 GeV, which impinges upon a static target at the centre of the BGO Ball. The BGO Ball, a highly segmented calorimeter, covers polar angles from 155$^\circ$ to 25$^\circ$ degrees. A momentum spectrometer, consisting of a series of tracking detectors and a large magnetic field covers more forward angles. The excellent momentum reconstruction makes the experiment ideally suited to strangeness photoproduction, where for example, t-channel exchange is expected to be dominant, and so acceptance at forward centre of mass angles is crucial in understanding the photoproduction mechanism. For further details see [3].

The reviews in this paper are not exhaustive, rather it is intended to provide a platform for further discussion. The paper is organised as follows. Progress in charged strangeness photoproduction is presented in section 2. Comparison and relation to neutral kaon photoproduction and discussion of recent results is in section 3. Section 4 describes theory and measurement of the $\Lambda(1405)$. Section 5 briefly describes progress in hypernuclei research and what can could be achieved using a real photon beam as a production mechanism.

2. $K^+\Lambda$ photoproduction
Due to the absence of analytical solutions to QCD, constituent quark models have often been used to describe the photoproduction mechanism. Many models have predicted resonance
states however which have not been observed in the excitation spectrum of non-strange photoproduction channels. It has been argued that this may be that the degrees of freedom that have been used are incorrect (for example, di-quark models have been proposed, where there are two tightly bound constituent quarks with antisymmetric wave functions [4]), or alternatively that experiments have been insensitive to these resonance contributions. Capstick and Roberts [5] suggested that many so called “missing resonances” may couple strongly to photoproduction channels with open strangeness.

The photoproduction mechanism can be described as a series of transversity or helicity amplitudes. An understanding of the relative phases and magnitudes allows a complete, model independent measurement. These amplitudes can be extracted from combinations of the polarisation of the beam, target and recoil nucleon. A judiciously selected set of these polarisation observables allows a complete measurement of all amplitudes and phases [7].

There is currently a global effort for complete measurements of photoproduction channels, and $\gamma(p, K^+)\Lambda$ offers one of the best possibilities. The pseudoscaler $K^+$ with zero spin limits the required number of polarisation observables (compared to vector mesons), and the self analysing weak decay of the $\Lambda$ allows access to the recoil nucleon polarisation via the distribution of decay particles (to determine the polarisation of a recoil proton, for example, requires the secondary scattering of the proton from material surrounding the reaction vertex).

The search for missing resonances and the goal of a complete model independent measurement have provided motivation for the most extensively measured strangeness channel, $\gamma(p, K^+)\Lambda$. Differential cross section data with high statistics have been measured with the SAPHIR detector [8, 9] at ELSA and CLAS detector [10, 12] at Jefferson Lab. Discrepancies between the SAPHIR and CLAS data (fig. 1) however leave ambiguities to the contributing s-channel resonances. The most notable difference is around the structure at approximately $\sqrt{s} = 1.9$ GeV. Different partial wave analyses, constituent quark models and isobar models cannot agree which resonances contribute. This is despite the extensive data set of polarisation observables (see below). For example, an isobar model of Mart and Bennhold predicted a contribution from $D_{13}(1900)$ [13]. A model of Saghai suggested that $D_{13}(1900)$ was not required to fit to data if $P_{01}(1810)$ and $P_{03}(1890)$ hyperonic resonances were included. A coupled channel approach by Julia-Diaz et al. (where intermediate states, $\gamma p \rightarrow \pi N \rightarrow KY$ are also included), suggested large contributions from $S_{11}$ states.

Figure 1. $\gamma(p, K^+)\Lambda$ cross section data from CLAS (blue points) [10] and SAPHIR (red points) [8, 9] detectors. Fitted models are referenced in [10].
Data will soon be published from the Crystal Ball experiment at MAMI [6], which will add a third data set with high statistics and beam energy resolution, and will constrain the excitation spectrum further (fig. 2). This will increase statistical accuracy particularly near threshold, which is important for the testing of models based upon chiral effective Lagrangians ([18], for example). Due to the large strange quark mass, chiral symmetry breaking limits these models further than when applying them to non-strange final states. It will also allow the search for narrow structure, which previous data with beam energy resolutions of the order of 20 MeV would have been unable to resolve.

![Figure 2. Preliminary differential cross section data for $\gamma(p, K^+)$Λ measured at the Crystal Ball detector [6]. Dark blue and black points are data measured from two different data taking periods (inset). Red and light blue data were measured at SAPHIR [9] and CLAS [10] respectively. Angular range, $\theta_{CM}$, is the centre of mass polar angle of $K^+$ detection.](image)

Polarisation observables have been extensively measured for this channel. This includes, for example, beam asymmetry, $\Sigma$ [15, 16], beam-recoil polarisation ($C_Z$ and $C_X$) [17] (fig. 3(a)) and recoil polarisation, $P_\Lambda$ [15, 16] (fig. 3(b)).

![Figure 3. (a) Beam-recoil polarisation, $C_Z$ (top) and $C_X$ (bottom) for $\gamma(p, K^+)$Λ. Taken from, and model fits described in [17]. (b) Recoil polarisation, $P$ for $\gamma(p, K^+)$Λ. Taken from [15].](image)

Data from recoil nucleon polarisation exhibit unexpected behaviour. The magnitude of the
hyperon polarisation, $R_\Lambda$, can be described by the recoil polarisation, $P$, and the beam-recoil polarisations, $C_X$ and $C_Z$ (eq. 1).

$$|R_\Lambda| \equiv \sqrt{P^2 + C_X^2 + C_Z^2}$$  \hspace{1cm} (1)

$R_\Lambda$ must be equal or less than one, with the polarisation shared between $R_\Lambda$ and the relative orbital angular momentum of the $K^{+}$ and $\Lambda$. Fig. 4(a) [11] shows the surprising result that $R_\Lambda$ is nearly one over all energies and angles. This would occur if $K^{+}$ and $\Lambda$ were in a relative s-wave, however this was not predicted by any partial wave analysis before the measurement. It was suggested that this may hint at more fundamental dynamics of the photoproduction reaction [11]. Schumacher [11] suggested a “toy” model, where the incoming photon fluctuates to an $s\bar{s}$ pair and the $s$ quark retains the full polarisation which is transfered to the $\Lambda$ (fig. 4(b)).

Figure 4. (a) Hyperon polarisation, $R_\Lambda$ versus the cosine of the $K^{+}$ centre of mass polar angle for different centre of mass energies, $W$. Taken from [17]. (b) “Toy” model of polarisation transfer to the recoiling hyperon [11]. Description in the text.

3. Neutral kaon photoproduction
Determining s-channel resonances which contribute to the $\gamma(p,K^{+})\Lambda$ spectrum is further complicated by large t-channel contributions. These contributions must be understood before a partial wave analysis of s-channel resonances can be performed. In this sense, neutral kaon photoproduction (for example, $\gamma(p,K^{0})\Sigma^{+}$ and $\gamma(n,K^{0})\Lambda$) are easier channels to understand. The t-channel exchange (fig. 5(c)) no longer contributes as the photon cannot couple to the neutral $K^{0}$. However, $K^{+}$ t-channel exchange is still expected to contribute (with the photon coupling magnetically to the spin one vector meson, fig. 5(e)). As well as clarifying the contributions of s-channel resonances, neutral kaon photoproduction therefore also provides an insight into contributions from vector meson t-channel exchange.

Furthermore, charged and neutral strangeness channels are intrinsically related via SU(3) symmetry. Eq. 2 shows how this leads to a relation between hadronic coupling constants. For isobar models, where effective Lagrangians use a series of Feynman diagrams to fit to data sets, this can be extended to predict cross sections and polarisation observables of the unmeasured
**Figure 5.** Diagrams contributing to charged and neutral strangeness photoproduction. Resonance contributions can contribute in s- and u-channels ((a) and (b)). t-channel pseudoscaler meson exchange, (c) and the contact term, (d) are proportional to the kaon charge. Vector meson t-channel exchange, (e) can occur in charged and neutral kaon photoproduction. Diagram (f) is sub-threshold $K^*$ production, which couples to $K^0$ and the pion is reabsorped by the hyperon. See the text for details.

SU(3) partner. Fig. 6 demonstrates how an isobar model fitted to $\gamma(p,K^+)^{\Lambda}$ data was used to determine hadronic coupling strengths and predict the $\gamma(n,K^0)^{\Lambda}$ cross section [14].

\[
g_{K^+ \Lambda p} = g_{K^0 \Lambda n} \\
g_{K^+ \Sigma_0^p} = -g_{K^0 \Sigma_0^n} \\
g_{V,T} = g_{V,T}^{\Lambda} \\
g_{K^*+ \Lambda p} = g_{K^*0 \Lambda n}
\]  

**Figure 6.** A fitted isobar model to $K^+\Lambda$ photoproduction (left). Relating hadronic coupling constants from eq. 2 allowed the prediction of the $n(\gamma,K^0)^{\Lambda}$ cross section (right). Taken from [14].
Despite the fact that neutral kaon photoproduction is so crucial in understanding the photoproduction process, there is surprisingly little data available. The remainder of this section highlights two recent experiments; $\gamma(p, K^0)\Sigma^+$ cross section [22, 23] and $\gamma(n, K^0)\Lambda$ cross section [28] measurements.

3.1. $\gamma(p, K^0)\Sigma^+$ cross section

The experiment was performed with the Crystal Barrel and TAPS experiment at the ELSA facility, Bonn. The Crystal Barrel [19] is a highly segmented NaI calorimeter, with the TAPS detector [20, 21]—a wall of BaF2 crystals, at forward angles. The ELSA accelerator produced an electron beam to an energy of 3.2 GeV. Bremsstrahlung photons were produced to an energy of 2.94 GeV and were incident upon a liquid hydrogen target at the centre of the Crystal Barrel.

The channel was identified from six neutral and one charged particle, from the decays: $K^0 \rightarrow \pi^0\pi^0$ and $\Sigma^+ \rightarrow p\pi^0$. A kinematic fit tested event by event the hypothesis: $\gamma p \rightarrow p\pi^0\pi^0\pi^0$. Events were selected which were consistent with $K^0$ and $\Sigma^+$ reconstructed invariant masses (fig. 7). The nearly uniform, 4$\pi$ acceptance made the analysis ideal for the extraction of differential cross sections. For further description of the experiment and analysis, see [22, 23].

![Figure 7](image_url)

**Figure 7.** (a) Reconstructed $K^0$ mass (from the momenta of two decay $\pi^0$) versus $\Sigma^+$ (from the momenta of a decay proton and $\pi^0$). A peak at the expected masses is visible. (b) $2\pi^0$ invariant mass selected over the region of the $\Sigma^+$ mass on the x-axis from (b). A peak at the $K^0$ mass (red hatched region) is evident above a background. The background is mainly from uncorrelated $2\pi^0$ and is described well by simulation (green hatched region). Taken from [23].

Fig. 8 shows the differential cross section versus centre of mass polar angle for different $\sqrt{s}$ energy bins. Near threshold, the cross section is flat, suggesting only s-channel contributions. This becomes increasingly forward peaked with energy, suggesting increased contributions from t-channel mechanisms. There is a large “cusp” effect however around 1800 MeV, where the cross section reduces approximately by a factor of four at forward angles. Beyond this energy, the cross section remains flat. It was suggested that $K^*$ t-channel exchange (fig. 5(e)) contributes to the reaction mechanism below this energy. Above the energy where $K^*$ exchange can be produced on-shell, this t-channel mechanism no longer contributes. Fig. 9 shows the total cross section, where the cusp effect at forward angles is still evident. It is clear that the existing Kaon-MAID parameterisation [33] does not describe the data well. The fit to data below $K^*$ threshold is improved by changing the coupling to the $S_{31}(1900)$ state to $G_1 = 0.3$ and $G_2 = 0.3$, and reducing the Born couplings from 1.0 to 0.7. Beyond $K^*$ threshold, the $K^*$ t-channel exchange has been "switched off", matching the data well.

It was speculated that below threshold, the diagram fig. 5(f) contributes to the $K^0\Sigma^+$ channel. $K^*$ couples to a $K^0$ and a $\pi$, and the $\pi$ is subsequently reabsorbed by the hyperon. Above $K^*$ production threshold however, the $K^*$ is produced as a free particle. In this sense, the $K^0\Sigma^+$
Figure 8. $\gamma(p,K^0)\Sigma^+$ differential cross section as a function of $K^0$ centre of mass polar angle for 100 MeV bins of photon energy (values inset). Red, down pointing triangles are for data with six neutral particles and one charged particle identified. Green, up pointing triangles are for only six neutral particles identified. Black circles are for all data. Taken from [22].

feeds off the $K^*\Sigma^0$ channel below threshold. Above $K^*$ threshold, the dip in the cross section for $K^0\Sigma^+$ contributes to the $K^*\Sigma^0$ cross section. There is evidence of this in fig. 9, where summing the cross sections of the two channels agrees well with the standard Kaon-MAID parameterisation [33].

Fig. 5(f) could be interpreted as a strong meson-baryon interaction in a relative s-wave. If the reduction in cross section occurs between the $K^*\Lambda$ and $K^*\Sigma^0$ thresholds, there maybe an intermediate strongly bound $K^*\Sigma^0$ state, with $J^\pi (1/2)^-$ or $(3/2)^-$. Dynamically generated resonances have recently been investigated via the interaction of the nonet of vector mesons and baryon octet [30, 31]. Using a coupled channeled, chiral unitary approach, an isospin 1/2 doublet was predicted close to the $K^*$ threshold [31].

To further understand $K^0\Sigma^+$ photoproduction mechanism, further polarisation observables are required. For example, the beam-target double polarisation observable, $E$, is sensitive to changes in s-channel contributions. The introduction of a meson-baryon dynamically generated resonance at a given $\sqrt{s}$ could potentially change the sign of $E$. Furthermore, the loss or addition of a large t-channel contribution would change the magnitude of $E$, as a pure t-channel
mechanism would exhibit zero asymmetry.

3.2. $\gamma(n, K^0)\Lambda$ cross section

The first cross section data for $\gamma(n, K^0)\Lambda$ using a deuterium target was measured with the Neutral Kaon Spectrometer at the Laboratory of Nuclear Science (LNS) at Tohoku University [28] (a previous measurement used a carbon target [32], but was limited due to the many body nature of the target). Bremsstrahlung photons with an energy range of 0.8-1.1 GeV and a measured energy resolution of 10 MeV were incident upon the target. The NKS identified and measured the momenta of particles using a 0.5 T magnetic dipole and a series of drift chambers, hodoscopes and electron veto scintillation counters (see [28, 29] for more details). The experiment had an acceptance of approximately $\pi$ steradians, covering forward angles. $K^0$ were identified via the decay $K^0 \rightarrow \pi^+\pi^-$, where the $K^0$ invariant mass was reconstructed from the pion momenta.

Fig. 10 shows the measured inclusive spectra for $K^0 Y$ (where $Y$ is predominantly $\Lambda$ but also $\Sigma^0$ and $\Sigma^+$). Three different models were fitted to the data; Kaon-MAID [33], Saclay-Lyon A isobar model [34], and a phenomenological model which fitted Legendre polynomials. The isobar models assumed isospin symmetry to extract the hadronic coupling constants. Kaon-MAID used a simultaneous fit to $K^0\Sigma^+$ data as a constraint. Couplings to t-channel $K_1$ and $K_2$ mesons were left as free parameters. It is clear that the Kaon-MAID solution over estimates the cross section and near threshold is more forward peaked. The SLA model, which only fixed the $K_1$ and $K_2$ couplings from the lower energy plot has a better agreement. The differences between these two models is predominantly due to different angular distributions, with the SLA model more backward peaked. The PH1 model is a fit to data of a series of Legendre polynomials. PH2 is the same model but with the lowest order term given the opposite sign, producing the opposite angular distribution. The PH2 model is seen to match the Kaon-MAID solution more closely.
Figure 10. $\gamma(n, K^0)\Lambda$ differential cross section as a function of $K^0$ momentum for photon beam energy (a) 0.9-1.0 GeV and (b) 1.0-1.1 GeV, for laboratory frame polar angles smaller than 25°. Solid black line is a Kaon-MAID fit [33], dotted black line the Saclay-Lyon A isobar model [34], dotted red and dot-dashed red are phenomenological models described in the text, and the blue dashed and dot dashed lines are Kaon-MAID fits to $K^0\Sigma^0$ and $K^0\Sigma^+$. Taken from [28].

In conclusion, the data suggests a more backward peaking angular distribution than what was predicted with the Kaon-MAID parameterisation, however the region of acceptance and statistics (and separating the reaction channels) can still be greatly improved in an attempt to understand a crucial channel in strangeness photoproduction.

4. Properties of the $\Lambda(1405)$

The $\Lambda(1405)$ was established in the 1960s between the $\pi\Sigma$ and $N\bar{K}$ thresholds, however the nature of the state is still not well understood. It is difficult to describe in a constituent quark model as it has a lighter mass than the non-strange $N(1535)$, and the mass difference to the spin-orbit partner, $\Lambda(1520)$, is too large.

Recent advances in chiral unitary formulism for meson-baryon interactions [36, 35, 37] described the $\Lambda(1405)$ as a two-pole structure, with the contributions interfering on the real energy axis (fig. 11). The $\Lambda(1405)$ can only be observed via the decays: $\Lambda(1405) \rightarrow \pi\Sigma$ with $I = 0$, however it was found that the coupling of the two poles to different meson-baryon channels are of different strength, leading to a difference in the $\Lambda(1405)$ line shape depending upon the decay it is observed via (fig 12(a)).

Recent data from CLAS at Jefferson Lab was able to reconstruct the $\Lambda(1405)$ from all three decay modes [38] (fig. 12(b)). It is clear that the line shape differs depending upon the decay mode, however they do not agree with the theoretical prediction in fig. 11, where the $\Sigma^-\pi^+$ line shape is at a higher mass. Resolving this, and understanding the cross section dependence upon the momentum transfer are still open questions.

5. Hypernuclei

Hypernuclei provide a "natural laboratory", where nucleon-nucleon and nucleon-hyperon interactions can be directly observed. Analysis of the bound hyperon also gives a unique insight into the nucleon interior as it is not bound by the Pauli exclusion principle to specific quantum states as with other nucleons. Most hypernuclei have been produced by stopping $K^+$ or $K^-$ in flight. Recently however, hyperon spectroscopy has been performed with electron beams at Jefferson Lab [39]. Electromagnetic probes allows the creation of neutron rich hypernuclei.
Figure 11. The two pole structure of the Λ(1405). Predicted by a chiral unitary formulism [36, 35, 37], the absolute value of the scattering matrix, |T|, is plotted in the second Riemann sheet, with poles close together on the real energy axis. Taken from [36].

Figure 12. (a) The predicted Λ(1405) lineshape for different decay channels (inset) as predicted by a chiral unitary formulism [36, 35, 37]. Taken from [37]. (b) The measured Λ(1405) line shape for all decay channels (inset) with the CLAS detector [38]. The dashed line is a relativistic Breit-Wigner shape using mass and width values from the PDG. Taken from [38].

(potentially with halo structure), and due to contributions of spin flip amplitudes, excites states with significant cross sections which are hard to observe using hadronic probes. It was proposed by Shyam, Lenske and Mosel [40] that for these reasons, and also that a photon can penetrate deep into the nuclear medium to create deeply bound hypernuclei, that the
photoproduction of hypernuclei would be an important addition to existing analysis. This would allow further investigation of the spin flip amplitude and impose constraints upon the nucleon-hyperon interaction.

It is reasonable to assume that the BGO-OD experiment would be able to provide data with significant statistics and accuracy to improve or consolidate all previous results discussed in this paper. It is therefore worth considering what can be achieved with the BGO-OD experiment in hypernuclei research.

After the production of a hypernuclei, the hyperon usually occupies an excited state within the nucleus. For the hyperon to reach the ground state, photons and nucleons may be emitted. At the ground state, the hyperon will decay weakly. Within the nuclear medium, the decay can be observed as mesonic ($\Lambda \rightarrow \pi N$), which is equivalent to what is observed for free unbound $\Lambda$, or non-mesonic, $\Lambda N \rightarrow NN$, where the pion is reabsorbed by a nucleon. The ratio of the two decay modes is shown as a function of atomic number in fig. 13(a).

To identify a hypernuclei state using the BGO-OD, the first step should be to identify the $K^+$. For the $\Lambda$ to be bound in the nucleus, the $K^+$ must have nearly all available momentum and therefore should be detected in the forward spectrometer. The weak decay of the $\Lambda$ within the nucleus could be observed via the mesonic mode, where the baron and meson can be detected and the $\Lambda$ invariant mass reconstructed. A further selection cut could reject events where momentum is conserved between the incident momentum and the sum of the $K^+$ and $\Lambda$ momenta, in order to reject events where the $\Lambda$ was not bound in the nucleus. To verify the hypernucleus, and to identify the state occupied by the hyperon, the BGO-Ball would identify a low energy photon in timing coincidence with the $\Lambda$ weak decay. This photon is from the de-excitation of the hyperon and would be of the order of 1-10 MeV. The resolution would not be sufficient to search for new states, but if a state was already known it could be identified. A similar approach was used recently by Tarbert and Watts et al. with the Crystal Ball detector [42], where $\pi^0$ photoproduction from a $^{12}\text{C}$ target, leaving the $^{12}\text{C}$ nucleus in 4.4 MeV state was observed (incoherent neutral pion photoproduction). Fig. 13(b) shows the angle of the reconstructed pion and the energy deposition of a third photon (not the two $\pi^0$ decay photons). There is a low energy tail arising from misidentified electromagnetic showers from the pion decay photons, however there is also a clear signal from the 4.4 MeV photon from the de-excitation of the $^{12}\text{C}$ nucleus.

![Figure 13](image.png)

**Figure 13.** (a) Mesonic and non-mesonic decay widths of bound $\Lambda$ within a hypernuclei, compared to a free $\Lambda$ decay as a function of nucleon number. Taken from [41]. (b) Identification of a 4.4 MeV photon from the de-excitation of a $^{12}\text{C}$ following $\pi^0$ photoproduction. Further description in the text. Taken from [42].
From fig. 13(b), it is clear that a low atomic mass nucleus is favourable if the mesonic decay mode is used to identify hypernuclei. Rather than calculating absolute cross sections, ratios of yields of different hyperon states could be observed. This could be compared to ratios and cross sections of the same states created with hadronic and electron probes and provide further constraints upon spin flip transitions and hyperon-nucleon interactions.

6. Summary and conclusions
The abundance of recently accrued data imposes large constraints upon strangeness photoproduction mechanisms. It is expected that further analysis of recently published data will narrow down resonances which contribute to the excitation spectrum in \(K^+\Lambda\) photoproduction. Neutral kaon photoproduction is still in its infancy in comparison, but is crucial in our understanding of resonance structure, given the SU(3) symmetry with charged photoproduction, and the contribution from vector meson t-channel exchange. The nature of the \(\Lambda(1405)\) is beginning to reveal itself to experiment, however at present there is very little understood with how the cross section varies with respect to momentum transfer.

Many results presented were measured from only a few experiments. Consequentially, certain kinematic regions have poor or no statistics due to the acceptance regions of experimental setups. It is therefore paramount to consolidate and add to existing data sets where possible with new experiments and to extend the data sets of polarisation observables where possible.

Hypernuclei research with the BGO-Ball could potentially provide unique measurements which are unattainable at any other accelerator facility. Practical issues, such as whether the cross section is sufficient for reasonable statistics, or low energy photons from the beam dump contaminating the event selection remain open questions.

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