After the discovery of the ground state baryons, a classification scheme was proposed by Gell-Mann and Zweig. They proposed that all baryons consist of three quarks, each carrying a fractional charge and baryon number $1/3$. This classification, producing the ground state octet and decuplet (see figure 1.1), created a problem. In the decuplet, the three quarks forming the $\Delta^{++}$ state would need to have the same quantum numbers. Since the quarks are fermions, this constitutes a violation of the Pauli principle. The riddle was solved by the introduction of an additional quantum number, color, which in turn led to the development of Quantum Chromodynamics (QCD), the theory of the color force between the quarks, mediated by massless gluons.

### 1.1 Quark models

![Figure 1.1: The ground state octet and decuplet of the baryons with spin-parity $\frac{1}{2}^+$ and $\frac{3}{2}^+$ respectively. The numbers in brackets give the masses in MeV.](image-url)
Nowadays, QCD has been extensively tested in high-energy experiments conducted, among others, at DESY (Hamburg), and LEP (CERN), and the Lagrangian describing the force is well known. At high energies the theory can be treated perturbatively due to the fact that the strong coupling constant $\alpha_S$ becomes much smaller than 1. At lower energies (around 1\(\text{-} 3\) GeV) this approach breaks down due to the fact that the value of the running coupling constant $\alpha_S$ becomes too large to allow perturbative treatments of QCD.

As energies between 1 and 3 GeV constitute the range where many of the resonant states of the nucleon exist, there is no practical way to exploit the QCD Lagrangian for a complete description of all baryon resonances and their properties. Numerical methods may be used to solve the QCD Lagrangian (so called Lattice QCD), but this requires large amounts of computing power. These calculations are, at present, typically done with much higher quark masses, using extrapolations to get results at the true quark masses. Nevertheless, Lattice QCD holds great promise for the future.

Meanwhile, the simple model used to classify the ground state baryons has been developed further and models of this class have become known as quark models. The basics of such models are described in section 2.1.1, but in principle all start from the triplet of light quarks: $u$, $d$, and $s$. Many different models exist, using different QCD-based dynamics to describe the possible excited states of the baryon, but all suffer from the problem of predicting far more resonances than have been observed experimentally.

1.2 Missing resonances

The predicted resonant states that have so far not been seen experimentally are usually referred to as the missing resonances. To explain this discrepancy between prediction and observation, two explanations have been proposed. The first explanation is that the source of the discrepancy could be found in shortcomings of the models. The first models treated all three quarks inside the baryon on an equal footing. This approach might be wrong, and two of the three quarks could be clustered [1], forming a quark-diquark pair. This would reduce the number of degrees of freedom in the models and therefore decrease the number of resonances predicted in the energy range between 1 and 3 GeV. However, lattice QCD calculations [2] find no evidence for such a quark-diquark structure.

Another possibility is that these states have not been observed because they do not couple to the channels that have been investigated so far. Most resonances have been observed in $\pi N$ elastic scattering. Resonances that
have a weak coupling to this channel can therefore have gone unnoticed.

Recently two different quark models ([3], [4]) have predicted substantial branching ratios into final states containing $K\Lambda$ and $K\Sigma$. A measurement which obtains precise cross section data in those channels may therefore be an important tool to aid in the search for these missing resonances.

1.2.1 Specific predictions for resonances

Such a missing resonance about which some predictions have appeared is the third $S_{11}$ resonance. The PDG book [5] lists two known $S_{11}$ resonances. The first is the $S_{11}(1535)$ which has a branching ratio into the $N\eta$ decay mode of 30-55%, and the second is the $S_{11}(1650)$, which has a branching ratio into the same decay mode of 3-10%. This difference has not been satisfactorily explained within quark models, although some effort has been made to explain the effect from resonance mixing. Glozman and Riska explain the difference in branching ratio using a quark model based on Goldstone boson (pion) exchange [8]. A discussion between both sides of this argument can be found in [6] and [7].

Another solution, proposed by Kaiser, Siegel, and Weise [9], is that the $S_{11}(1535)$ is actually not a three quark resonance at all, but rather a quasi-bound $K\Lambda$ or a $K\Sigma$ state which they show to have properties similar to the $S_{11}(1535)$. If this is true, this quasi-bound state should be strongly mixed with an additional $S_{11}$ state according to Workman and Li [10], as the $Q^2$-dependence of the helicity amplitude of the $S_{11}(1535)$ shows it is predominantly a three quark state, while a $K\Lambda$ or $K\Sigma$ quasi-bound state should show up as a five quark state. They expect this additional $S_{11}$ to couple strongly to the $K\Sigma$ channel based on a partial-wave analysis by Deans et al. [11].

Evidence for such an additional $S_{11}$ was discussed by Saghai and Li [12] who analyzed the $\gamma p \rightarrow n p$ cross sections obtained in the GRAAL [13] experiment. They claim that within their chiral quark model, an additional $S_{11}$ is indeed needed to describe the data.
1.3 Strangeness photoproduction

1.3.1 Existing data

At the time the experiment described in this work was proposed and conducted, only two measurements for the photoproduction of $K^0\Sigma^+$ had been published. The first was a result from the ABBHHM Collaboration published in 1969 [14]. In the ABBHHM experiments, conducted at DESY, a hydrogen bubble chamber was used together with a bremsstrahlung photon beam to look at photoproduction reactions with three or more outgoing particles. The published data points consist of two data points for the excitation function, covering the range of photon energies between 1 and 2 GeV, shown in figure 1.2 as open circles.

The second available data set was published by the SAPHIR collaboration in 1999 [15]. In their experiments the SAPHIR collaboration impinged a bremsstrahlung photon beam on a liquid hydrogen target at the ELSA...
electron accelerator in Bonn. A magnetic spectrometer was used to measure the reaction products.

The $K^0\Sigma^+$ final state was obtained through the reactions:

$$\gamma p \rightarrow K^0\Sigma^+ \rightarrow (\pi^+\pi^-)(p\pi^0)$$  \hspace{1cm} (1.1)

$$\gamma p \rightarrow K^0\Sigma^+ \rightarrow (\pi^+\pi^-)(n\pi^+)$$

In these reactions either the neutron or the neutral pion is treated as a missing particle. In addition to obtaining a much greater accuracy in the measurement of the excitation function, the SAPHIR collaboration measured angular distributions and the $\Sigma^+$ recoil polarization. The results for the excitation function are shown in figure 1.2 as squares.

During the course of this work, a more detailed analysis of the SAPHIR data has followed, using a much larger data set and performing a more exact subtraction of the background. The results from this analysis have been published in [16] and are shown in figure 1.2 as triangles.

### 1.3.2 The present work

The available data in the $K^0\Sigma^+$ channel were of lower quality, compared with other strange decay channels such as $K^+\Sigma^0$ or $K^+\Lambda$ (data sets are available from CLAS [17], SAPHIR [18], and SPRING8 [19]). This is due to the fact that the experiments that have measured these reactions were set up to detect charged particles in the final state.

For the reaction $K^0\Sigma^+ \rightarrow \pi^-\pi^+\rho\pi^0$, combining the branching ratios that lead to the final state yields only 17% compared to 63% for the reaction $K^+\Lambda \rightarrow K^+\rho\pi^-$. In addition the cross sections for $K^0\Sigma^+$ productions are a factor 4 lower than the reactions producing charged kaons. To compare the data in the $K^0\Sigma^+$ channel with predictions such as put forth in section 1.2.1 more sensitivity in was therefore definitely needed.

Therefore, the combination of the two photon-spectrometers Crystal Barrel and TAPS in the tagged photon beam facility of the ELSA accelerator, the CBELSA / TAPS experiment, presented an excellent opportunity to improve the results for $K^0\Sigma^+$ production. The setup at ELSA was very well suited to measure the reaction in the neutral decay channel:

$$\gamma p \rightarrow K^0\Sigma^+ \rightarrow (\pi^0\pi^0)(p\pi^0) \rightarrow 6\gamma p$$  \hspace{1cm} (1.2)

The branching ratios for the decays involved in this channel are shown in figure 1.3, in total only 7.8% of all produced $K^0\Sigma^+$ pairs decay into 6$\gamma$s and a proton. In the experiment all seven final-state particles were
Figure 1.3: The branching ratios involved in the decay of the $K^0\Sigma^+$ pair into the measured final state. The $K^0$ can decay into a $K_L$ and a $K_S$ with equal probability. The $K_S$ predominantly decays into a $\pi^+\pi^-$ pair, but has a significant branching ratio into the neutral pion channel. The $\Sigma^+$ can decay into $\pi^+n$ or $\pi^0p$ with almost equal probability.

measured, so that the measurement was over-constrained, which gives possibilities to reject any background channel with the same final state. The most important physical background originates from the $\eta$ production channel and sequential resonance decay:

$$\gamma p \rightarrow \eta p \rightarrow \pi^0\pi^0\pi^0 p \rightarrow 6\gamma p \quad (1.3)$$

After applying all possible cuts only the last reaction, sequential resonance decay, will be shown to be an important factor. Using background subtraction it is then easy to cleanly separate the signal from the background, as will be shown in section 6.4.4. In addition to these advantages, the acceptance of this setup for the $K^0\Sigma^+$ is very flat over the entire solid angle (see section 6.3.2), which simplifies the analysis considerably. By running the experiment in parallel with other investigations performed with the same setup roughly 1000 hours of measurement time was available, which allows us to obtain error bars which are a factor two smaller than those of the existing data of [15].

Detecting all seven final-state particles, the six photons and the proton, places severe requirements on the experimental setup. The combination of the two photon-spectrometers, TAPS and Crystal Barrel, was needed for providing sufficient geometrical acceptance. If the setup is not able to detect particles over the entire solid angle, the acceptance for detecting all final-state particles can easily become very small, as is illustrated in table 1.1. The setup at ELSA in Bonn provided a coverage of 98% of the
Table 1.1: The fraction of reconstructed events for different numbers of (uncorrelated) particles in the final state and for different coverage of the full (4π) solid angle. For seven final-state particles it is very important to cover as large a solid angle as possible.

<table>
<thead>
<tr>
<th>Coverage of the full solid angle</th>
<th>TAPS Crystal Barrel</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 particles</td>
<td>3.60 · 10^{-3}</td>
<td>0.85</td>
</tr>
<tr>
<td>3 particles</td>
<td>2.16 · 10^{-4}</td>
<td>0.78</td>
</tr>
<tr>
<td>4 particles</td>
<td>1.30 · 10^{-5}</td>
<td>0.72</td>
</tr>
<tr>
<td>5 particles</td>
<td>7.78 · 10^{-7}</td>
<td>0.66</td>
</tr>
<tr>
<td>6 particles</td>
<td>4.66 · 10^{-8}</td>
<td>0.61</td>
</tr>
<tr>
<td>7 particles</td>
<td>2.80 · 10^{-9}</td>
<td>0.55</td>
</tr>
</tbody>
</table>

full solid angle, enough to keep the combined acceptance for all seven particles well above 50%.

Another important requirement that stems from the large number of final-state particles is the high granularity of the detector, which is needed to avoid overlap of the electromagnetic showers created by the photons. The high total number of detector elements (almost 2000) allowed to fulfill this requirement. The 528 crystals of the TAPS detector, placed at forward angles, covered on average 1.4 msr per detector, and the 1290 Crystal Barrel crystals covered on average 8.8 msr per detector. In this way, a high granularity was provided at forward angles, where the density of detected particles was also expected to be high.

1.4 Other experiments running in parallel

The experiment described in this work is part of a larger campaign conducted with TAPS and the Crystal Barrel at ELSA, aiming to increase our understanding of the structure of baryons. Apart from the experiments described in this work, a polarized photon beam was used to study ω and K⁰ production and investigate the hypothetical five-quark state Θ⁺. Another beam period, using a deuterium target, was aimed at investigating the channel γd → K⁰Σ⁺n in order to determine the coupling constant g_{NΣ}. A third beam period was used to study the in-medium behavior of the ω meson, using solid-state targets [20].
1.5 Outline of this work

Chapter 2 gives a short theoretical background of the models important to this work. It will explain the basics of the quark models used to predict the possible resonant states of three quarks inside the nucleon. In an experimental situation, such a bound state is never tested in isolation, but rather as a contribution to a reaction channel. Therefore all other possible contributions to the reaction channel under investigation need to be considered when making a comparison between theory and measurement. This can be done within the K-matrix approach, which is explained in this chapter. Chapter 3 gives a description of the experimental setup used in this work. The ELSA accelerator is described, as well as the photon-tagger (which was used to obtain a beam of photons of known energies) and the photon spectrometers Crystal Barrel and TAPS.

Chapter 4 explains the procedures used to calibrate the different detector components and monitor the stability of the calibration constants. This entailed calibration of the energy and time measurements for the Crystal Barrel, TAPS, and the subsystem measuring the incoming beam energy.

Chapter 5 describes the methods used to reconstruct the particle properties from the measured energy and time values. An important step in the reconstruction of the events was the kinematic fit. This technique improved the resolution of the measured invariant-mass signal by changing the measured angles and energies of each particle in order to minimize certain constraints such as conservation of momentum and energy.

The next step in the analysis, described in chapter 6, was to select the events with a $\Sigma^+$ hyperon via a cut on the $\pi^0 p$ invariant-mass. Finally the signal is extracted from the kaon peak in the $\pi^0 \pi^0$ invariant mass spectrum. The rest of this chapter is devoted to the normalization procedure, which uses the channel $\gamma p \rightarrow \eta p$ for which accurate cross sections are already published (see reference [21], [22], and [13]).

In the final chapter, the results obtained in this work are compared with other recent results in the $K^0 \Sigma^+$ channel, obtained by B. Carnahan with the CLAS detector at JLAB ([23]) and by R. Lawall who conducted a reanalysis of the SAPHIR data from Bonn [16]. The results will also be compared with the predictions made by A. Usov and O. Scholten, who performed calculations within the K-matrix approach described in Chapter 2. The agreement of their predictions improves considerably with the inclusion of an additional $P_{13}(1830)$ resonance.