Chapter 1

Introduction

1.1 General introduction

Every observed physical phenomenon is governed by at least one of four types of interactions: Gravitational, Electromagnetic, Weak and Strong interactions. These interactions constitute the fundamental interactions, and are described by the exchange of fundamental particles: gravitons, photons, $W$, $Z$-bosons and gluons. Gravitation is the weakest interaction, however, because it has infinite range, it is quite important in the universe. It is believed that the gravitational interaction would mediate through the exchange of gravitons, however, gravitons are not yet observed experimentally. The electromagnetic interaction occurs between charged particles. This type of interaction can be observed easily in day to day life, for example in the structure of atoms and molecules, telecommunications and so on. The mechanism such as beta decay can be explained on the basis of the weak interaction, which has a very short range. The carriers of the weak interaction are gauge bosons called the $W$ and $Z$ bosons. Hadrons are held together by the force called the strong interaction. The strong interaction is carried by gluons which act between particles that carry colour charge i.e. quarks and gluons. All these four interactions couple to particles with a specific strength, which is characterized by a coupling constant. The coupling constants cover many orders of magnitude and range from about $10^{-39}$ for the gravitational interaction to about 1 for the strong interaction.

In the middle of the last century, experiments revealed that hadrons are not fundamental particles and have an internal structure. This was the beginning of a new era of subatomic physics which describes the nature of hadrons in the context of quarks and gluons. The fundamental laws of quark and gluon interactions are explained by Quantum Chromodynamics (QCD). At low energies (few MeV) the hadrons look like structureless particles. At medium energies the substructure of hadrons can be explored. At very high energies (few hundred GeV)
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the complex nature of quarks and gluons inside the hadrons can be observed. At higher energies the strong coupling constant becomes much smaller than 1. Therefore the QCD theory can be treated perturbatively. At medium excitation energies (about 1 GeV to 3 GeV) where many of the resonant states of the nucleon exist, the coupling constant of the strong interaction is of order 1 and one can not rely on perturbation theory.

More detailed experimental information on the structure of hadrons and in particular of the nucleons can be obtained by understanding its excited states i.e. nucleon resonances. The excitation spectrum of the nucleon reflects its structure and the properties of its constituents. Detailed knowledge on nucleon resonances can be achieved through experiments which involve the transfer of energy to the nucleon by means of a hadronic or electromagnetic probe. Due to this energy transfer, the nucleonic system is left in one of its excited states which decays into the final state. The properties of these final states can be analyzed and provide the information on the complex structure of the nucleon. At present, electron and photon probes are available in the experimental facilities like: ELSA (Bonn) [1], CEBAF (Virginia) [2], MAMI (Mainz) [3], SPring-8 (Hyogo, Japan) [4], GRAAL (Grenoble) [5]. One of the major challenges is extracting reliable information on the properties of the resonances from the available data. The model which explains basic ground state of the baryons is known as constituent quark model. The basics of the quark model are given in section 2.1. Several other models exist which describe the excitation spectrum of baryons, but they all suffer from the problem of predicting far more resonances than have been observed experimentally.

1.2 Missing resonances

Most of the information on the nucleon excitation spectrum has been extracted from pion-induced and pion-production reactions. In the quark model a number of nucleon resonances has been predicted [6] that have not been observed yet experimentally. For example, the predictions of the relativistic quark model [7] is depicted in figure 1.1. Resonances are labeled by their orbital angular momentum $L$ (in the pion channel), by isospin $T$ and spin $J$ with $L^2T, J$. The predictions are compared with the experimentally observed spectrum. It is noticed that the number of predicted resonance states is larger than the experimental findings. There are two explanations for the missing resonances.
1.2. MISSING RESONANCES

Figure 1.1: The nucleon resonance spectrum (taken from [7]). Resonances are classified by total spin and parity $J^\pi$ given in the column on the horizontal axis, the vertical axis indicates the resonance mass. The nucleon resonances predicted by the relativistic quark model are shown in the left part of each column and the experimentally observed spectrum is shown in the right part of each column. The experimental position is indicated by a bar and the corresponding resonance width by the shaded box, which is darker for better established resonances. The status of each resonance is indicated by stars.
The first explanation is that the source of the discrepancy could be found in the relevant degrees of freedom used in the models. The simplest model treats all three quarks inside the baryon on an equal footing. This approach might be wrong, and two of the three quarks could be clustered, forming a quark-diquark pair. This would reduce the number of degrees of freedom in the model and therefore decrease the number of resonances predicted.

A second reason for this discrepancy might be that the unobserved resonances do not couple to the channels that have been investigated. Resonances that have a weak coupling to the studied channels can therefore have gone unnoticed. In particular, reaction channels involving open strangeness have been little studied in the past. Therefore the decay of resonances into strange baryons (hyperons) and strange mesons (e.g. kaons) is of special interest.

In addition, resonances have been postulated in order to solve discrepancies of experimental branching ratios with quark model predictions. One of the postulated resonances is the third $S_{11}$ resonance. In the PDG book [9] two $S_{11}$ resonances are given: the $S_{11}(1535)$ decays through the $N\eta$ channel with 30 to 55 % branching ratio and the $S_{11}(1650)$ decays through the same channel with 3 to 10 % branching ratio. This difference in branching ratios is not understood in the quark models. To solve this discrepancy, Kaiser, Siegel and Weise [10] proposed that the $S_{11}(1535)$ is actually not a three quark resonance state but a quasi-bound $K\Lambda$ or a $K\Sigma$ state. According to Li and Workman [11], this quasi-bound state should be strongly mixed with an additional $S_{11}$ state. In order to study $K^0\Sigma^+$ final states, experimental investigations have been carried out by SAPHIR [12], CLAS [14] and CBELSA/TAPS [15] collaborations. All these data sets show more or less good agreement with each other in the $\gamma p \rightarrow K^0\Sigma^+$ channel.

1.3 The hyperon-nucleon interaction

In order to fully understand the behaviour of the strong interaction, both the nucleon-nucleon (NN) as well as the hyperon-nucleon (YN) interaction need to be investigated. In the case of NN forces an extensive amount of NN scattering data is available to adjust the phenomenological NN force parameters. The knowledge on the YN interaction is still limited because YN scattering experiments are very difficult. Until now, only scarce experimental information is available from hyperon scattering ($\Lambda p \rightarrow \Lambda p$, $\Sigma^\pm p \rightarrow \Sigma^\pm p$), charge exchange
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$(\Sigma^- n \rightarrow \Sigma^0 p)$ and inelastic processes $(\Sigma^- p \rightarrow \Lambda n, \Lambda p \rightarrow \Sigma^0 p)$. One method to extract this information is to study the YN interaction in the framework of final-state interaction (FSI). The reactions which involve the production of a hyperon along with a kaon on light nuclei can provide a significant amount of information on the YN interaction. Since the deuteron has a very simple structure, which consists of one proton and one neutron, and has small binding energy, it is a promising candidate for this study. In their pioneering article Renard and Renard [17, 18], derived the formalism and studied the $\Lambda n$ interaction in kaon photoproduction off the deuteron. Adelseck and Wright [19] have examined the $\Lambda n$ interaction in kaon photoproduction from the deuteron via a distorted-wave formalism by using a simple $\Lambda n$ potential. They concluded that the final-state effects are essential only near threshold and can be neglected at higher energies. In a recent study Yamamura et al. [20] have calculated the YN final state interaction for the $\gamma(d, K^+)YN$ channels by using the more realistic Nijmegen YN potential. They found final-state interaction effects near the $K^+ \Lambda N$ and the $K^+ \Sigma N$ threshold, specially a cusp-like structure close to the $\Sigma$ threshold.

Recently Kerbikov [21] has investigated the YN interaction in kaon photoproduction off the deuteron in a covariant reaction formalism. The elementary amplitudes were derived from a tree-level effective Lagrangian taking into account several resonances in the s, t and u channel [22]. As compared to the plane wave result without FSI, the YN interaction has a significant effect near the $\Sigma N$ threshold at $E_\gamma = 1.49$ GeV (see figure 2.8). This is in contrast with a previous analysis by Adelseck and Wright [19], in which they concluded that FSI was only important near the $\Lambda N$ threshold and insignificant at higher energies.

Very recently A. Salam et al. [23] have published the cross section for kaon photoproduction off the deuteron in $\gamma(d, K^+)YN$ and $\gamma(d, K^0)YN$ channels. In their results they have shown the effect of YN interaction, KN interaction and the effects due to the $\pi N \rightarrow KY$ process (two-step process). They found a strong enhancement in the total cross section due to the two-step process as compared to that of YN and KN interaction.

To verify the predictions from different models, the experimental data obtained in this thesis are essential. For the first time, exclusive data in the $K^0 \Sigma^+ n$ channel are obtained from photoproduction off the deuteron.
1.4 The present work

The knowledge about the YN interaction is far from complete and it requires more attention. There are some predictions on the YN interaction as discussed in the previous section but these models have not been tested because of lack of experimental data. To this end we have studied the kaon photoproduction on the deuteron target in the $\gamma d \rightarrow K^0\Sigma^+ n$ channel [24]. In this experiment we measured the neutral decay products of the final unstable particles. The $K^0$ decays into $\pi^0\pi^0$ with a branching ratio of 31% and the $\Sigma^+$ decays into $\pi^0 p$ with a branching ratio of 52% (for other decay modes see table 2.2). The experiment has been carried out at the ELSA facility at Bonn in Germany which is capable of delivering a tagged photon beam up to 3 GeV. The reaction is schematically shown in figure 1.2. The decay particles in the final state were measured by the Crystal Barrel detector in combination with the TAPS\textsuperscript{1} photon spectrometer (see chapter 3). The setup at ELSA was very well suited to measure the reaction in the neutral decay channel:

$$\gamma d \rightarrow K^0\Sigma^+ n \rightarrow \pi^0\pi^0\pi^0 pn \rightarrow 6\gamma pn$$ (1.1)

in which the final state consists of 6γ’s, a proton and a neutron. 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 6γ’s, a proton and a neutron. In this experiment reaction events containing 6γ’s and a proton were measured and the neutron energy and momentum have been calculated using the energy and momentum balance equations. The most important background originates from the $\eta$ production and sequential resonance decay:

$$\gamma d \rightarrow \eta pn \rightarrow \pi^0\pi^0\pi^0 pn \rightarrow 6\gamma pn$$

$$\gamma d \rightarrow \pi^0\pi^0\pi^0 pn \rightarrow 6\gamma pn$$ (1.2)

The background from the $\eta$ channel can be removed by applying a cut on the $\eta$-mass, while the background stemming from sequential resonance decay has to be estimated by a background subtraction procedure (explained in chapter 6).

A good measurement of a reaction with seven particles in the final-state, 6γ’s and a proton, requires a large geometrical acceptance. If the setup is not able to detect particles over the entire solid angle, the acceptance for detecting all final-

\textsuperscript{1}Two Arm Photon Spectrometer
state particles can easily become very small. The advantage of using the TAPS and Crystal Barrel detector set up is that the combination covers about 98% of the full solid angle.

The granularity of the detector is also an important requirement for this reaction, which involves a large number of final-state particles, to avoid an overlap of the electromagnetic showers created by the photons. The high total number of detector elements allowed to fulfill this requirement. The 528 crystals of the TAPS detector, placed at forward angles, covered on average 1.4 msr per detector. The 1290 Crystal Barrel crystals covered on average 8.8 msr per detector. Thus, a good coverage and high granularity can be achieved with both Crystal Barrel and TAPS detector together.

This experiment aims to measure the excitation function for $K^0$ photoproduction on the deuteron target in the $\gamma d \rightarrow K^0\Sigma^+ n$ channel. This channel is also capable to possibly shine some light on the $\Sigma^+ n$ final-state interaction.

An overview of the data taking periods using a Liquid Deuterium target is given in table 1.1. The data were taken with 3.2 GeV and 2.6 GeV electron beam energy.

1.5 Other experiments running in parallel

The TAPS and Crystal Barrel detector setup at ELSA started data taking in October 2002 and lasted until December 2003. During this time apart from the experiment described in this work, other experiments with different nuclear targets have been carried out. A large amount of data has in addition been gathered to study the highly debated five-quark state $\Theta^+$ [25]. The major part of the beam time was devoted to $K^0$ photoproduction on the free proton target [15].
Figure 1.3: The branching ratios of $K^0\Sigma^+$ decay into the multiphoton 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. The $\pi^0$ decay into $2\gamma$ with highest probability.

Table 1.1: Overview of the data taking periods using the Liquid Deuterium target.

<table>
<thead>
<tr>
<th>Data taking period</th>
<th>Target</th>
<th>e$^-$ Beam Energy</th>
<th>Total Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 2003</td>
<td>LD$_2$</td>
<td>3.2 GeV</td>
<td>3421</td>
</tr>
<tr>
<td>Feb 2003</td>
<td>LD$_2$</td>
<td>3.2 GeV, 2.6 GeV</td>
<td>1934, 3008</td>
</tr>
</tbody>
</table>

Another beam time was used to study the in-medium behavior of the $\omega$ meson, using solid targets [26]. The recorded data set was also used to study the $\eta$ and $\eta'$ cross section off the proton, deuteron [34] and solid targets [35].

1.6 Outline of the thesis

Chapter 2 gives a brief description of the theoretical tools and predictions which are important for this work. Two different models the Isobar model and the P-matrix approach, which include the YN final-state interaction, are explained in this chapter.

Chapter 3 deals with the experimental set up used to study the reaction discussed in this thesis. The detector systems: Crystal Barrel, TAPS, tagger system
(which tag the photon beam passing through the target) are discussed in this chapter.

Chapter 4 explains the procedures used to calibrate the different detector components and to monitor the stability of the calibration. This involves the calibration of the energy and time measurements for the Crystal Barrel, TAPS and the tagger system.

Chapter 5 describes the methods used to reconstruct the particle energy and momentum from the measured energy and time values. An important tool for the reconstruction of the events was the kinematic fit. This technique improves the resolution of the measured invariant mass of the reconstructed particles. The analysis procedure used to study the reaction in this thesis is given in this chapter.

The result of the analysis and the kinematical fit are described in chapter 6. The procedure to subtract the background and extract the number of \( K^0 \) events are given in this chapter. The experimental cross sections obtained from this work are also mentioned in this chapter.

In the end, the experimental cross sections obtained from this work are compared with the predictions made by A. Salam et al. [42], who performed the calculations using the Isobar model.
1.7 Used units

**Energy:** In atomic physics and particle physics the unit of energy is the *electron volt (eV)*, defined as the energy gained by one unit charge (i.e. electron) passing through the potential difference of 1 Volt. \(1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}\).

**Mass:** The equation \(E = m \cdot c^2\) implies that the unit of mass is \(\text{eV}/c^2\), where \(c\) is the speed of light. But in practice the natural unit system is used which sets \(\hbar = c = 1\). The unit used for mass is eV.

**Momentum:** The unit used for momentum is eV/c.

The coordinate system used in this thesis is shown in figure 1.4. The direction of the beam is along the z-axis. The momentum of the \(K^0\) and \(\Sigma^+\) are measured with respect to the z-axis in laboratory system.