**First Measurement of the $\mathbb{E}$ Double-polarisation
Observable for $\gamma n \rightarrow K^+ \Sigma^-$ with CLAS
&
a New Forward Tagging Hodoscope for CLAS12.**

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A thesis submitted for the degree of
Doctor of Philosophy
The University of Edinburgh
30/06/2016

Dedication

For my beloved parents.

Acknowledgements

Firstly, I would like to thank Dan Watts, my supervisor, for all of his insight and expertise shared over these last five years. Instrumental to the work in this thesis was also the guidance of Lorenzo Zana and Derek Glazier, without whom computational headaches would have become computational migraines. Also a relatively new arrival to the group, Nick Zachariou, who was an invaluable source of not just physics knowledge, but squash prowess.

I would like to thank my collaborators at JLab, as well as the University of Glasgow. Particularly Franz Klein for his encyclopaedic knowledge in all matters; Irene Zonta, for her friendship and analysis advice; Mark Anderson, for his friendship and my introduction to Archer; and the resfac staff (particularly Melissa and Rose) who made JLab feel like a home, whether it was for three days or a month.

I am grateful to those who have passed through the department, for their chats, advice, games of chess, squash and general distraction from my work. Similarly my friends in the wider physics department, some from undergrad and others from more recent years.

Thanks to Scott and Lorna for the time we have spent together, as well as my other friends for keeping my spirits up while my work went less than swimmingly. My Dungeons & Dragons group, for all the adventures we have shared, from doing morally questionable things to NPCs, to disintegrating gods.

Of course Brian and Michelle, for their constant support, advice, love and ability to make me believe “the problem is fixable”.

Finally, my darling Alex.

I don't quite know how to sum up all that you've done. You've helped me through illness and days where I couldn't get out of bed. You understood when I spent weekends in the office and made me dinner when I got home at *10pm*. You understood when I flew to America and Italy on three days notice and met me at the airport when I came home.

I could not have done this without you.

Abstract

Establishing the excitation spectrum of the nucleon would be a key advance to further our understanding of nucleon structure and Quantum Chromodynamics (QCD). Recent theoretical advances allow predictions of the excitation spectrum of the nucleon and other nucleon properties directly from QCD in the non-perturbative regime, via numerical methods (such as Lattice QCD), complementing existing constituent quark models. There is an ongoing world programme in meson photoproduction from the nucleon, which has already led to a number of nucleon resonances being discovered and established. This advance has largely been made possible by the first accurate measurement of polarisation observables. Available data has been obtained for proton targets, whereas for a complete picture of meson photoproduction, data from the neutron must also be obtained. This is important, as nucleon resonances can have very different photo-couplings to the proton and neutron.

This thesis presents the first measurement of the $\mathbb{E}$ double-polarisation observable for the exclusive $\gamma n \rightarrow K^+ \Sigma^-$ reaction using a polarised hydrogen-deuterium target from the $g14$ run period at CLAS. Circularly polarised photons of energies between 1.1 and 2.3 GeV were used, with results shown in 200 MeV bins in E_γ and bins of 0.4 in $\cos \theta_{K^+}^{C.M.}$.

Further to this, CLAS has undergone a detector upgrade in order to facilitate electrons of up to 12 GeV from Jefferson Lab's upgraded accelerator. Essential to this, is a new system for tagging quasi-real photons by detecting electrons scattered at very small angles. My work includes significant contributions to the design, realisation and construction of a hodoscope for this forward photon tagging apparatus. Presented in this thesis is a comprehensive overview of my work in developing and constructing the scintillating hodoscope for the CLAS12 Forward Tagger.

Lay Summary

Atoms consist of a positively charged nucleus surrounded by a negatively charged cloud of electrons. Probing deeper, we find that the nucleus is made up of positively charged protons and uncharged neutrons, together referred to as *nucleons*. Probing deeper still, we find that these objects are made of further elementary particles called *quarks*. For decades, scientists have attempted to unravel the interactions of quarks and understand how they combine to make composite particles such as *baryons* (containing three quarks) and *mesons* (containing two quarks). A powerful method to understand such systems is to determine how they can be excited when they absorb energy. As a consequence of the quantum mechanical nature of the objects, the possible energies do not form a continuum, rather discrete (separated) energies. These energies and other properties of the excited states, such as angular momentum and symmetry, give strong constraints on how the quarks interact. Different theoretical models give very different predictions for this spectrum of excited states. My thesis work was an important part of the world programme to provide the first accurate determination of this spectrum experimentally.

To produce the excited nucleon states, we fire an intense beam of high energy photons (γ) at a nucleon target. It is only in recent years that photon beams of sufficient quality have been available to perform these experiments. A key advance is the use of polarised photon beams (having right or left handed rotation of the electric field) and polarised nucleon targets (in which the spin of the nucleons in the target can be oriented with respect to the beam). Once excited, the nucleon decays very quickly (in time-scales of around $\sim 10^{-24}$ s), with the most common decay being back to a nucleon with the emission of a meson, however it has been predicted that many missing excited states would show up strongly in decays to final states which involve *strange* quarks; corresponding to a “Kaon” meson (K)

and a “Sigma” baryon (Σ).

This thesis presents the first measurement of the dependence of the reaction $\gamma n \rightarrow K^+ \Sigma^-$, on the polarisation of the photon beam and neutron target. The experiment detailed was conducted in Hall B of the Thomas Jefferson National Accelerator Facility (*JLab*) in Virginia, USA. This thesis also presents a comprehensive overview of the design and construction of a new detector for the ongoing facility upgrade at JLab. This project was undertaken at the University of Edinburgh, with significant contributions from myself, which in the coming years will further the world programme to isolate further excited nucleon and meson states.

Declaration

The data presented in this thesis were obtained as part of the $g14$ collaboration at the Thomas Jefferson National Accelerator Facility (JLab), Virginia, USA, and the Nuclear Physics Group at the University of Edinburgh. I participated fully in the execution, calibration and analysis of the experiment. The analysis of the experimental data is my own work and this thesis was composed by myself.

Jamie A. Fleming

30/06/2016

Quotes

“There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns - the ones we don't know we don't know.”

Donald Rumsfeld

“To the scientist there is the joy in pursuing truth which nearly counteracts the depressing revelations of the truth.”

H.P. Lovecraft

“In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move.”

Douglas Adams

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Chapter 1

Introduction

The work presented in this thesis shows the first measurement of the $\mathbb{E}$ double-polarisation observable for the reaction $\gamma n \rightarrow K^+ \Sigma^-$ from a HD target, during the $g14$ run period of CLAS; the final period at Jefferson Lab to use an electron beam energy of 6 GeV . The measurement provides key new data for the world programme to constrain the excitation spectrum of the nucleon. In recent years, key advances have been made in this field through **P**artial **W**ave **A**nalysis (PWA) of cross section and polarisation observables in meson photoproduction from the nucleon.

Also contained within this thesis (Chapters 10 and 11) are details of the development and construction of the Forward Tagging Hodoscope, a detector designed for use with post-upgrade Jefferson Lab, which will deliver an electron beam energy of 12 GeV .

This opening chapter discusses the background and motivation for the types of experiment carried out at Jefferson Lab. This will cover the topics directly relevant to the analysis of the HD experiment as well as outlining aspects relevant to the use of the hodoscope at CLAS12.

1.1 Quantum Chromodynamics

Quantum **C**hromo**D**ynamics (QCD) can be summarised as a non-abelian gauge theory which parametrises quarks with symmetry group $SU(3)$ ¹. QCD may be considered as analogous to the more familiar **Q**uantum **E**lectro**D**ynamics (QED),

¹A **S**pecial **U**nitary group.

in that they both describe interactions mediated by a massless *spin* $- 1$ boson (gluons and photons respectively)².

Quarks exist in six flavours, along with their associated anti-particles:

- up (u & $\bar{u}$),
- down (d & $\bar{d}$),
- charm (c & $\bar{c}$),
- strange (s & $\bar{s}$),
- top (t & $\bar{t}$),
- bottom (b & $\bar{b}$).

These elementary particles, omitting the top quark, are able to form composite particles, known as hadrons, using various combinations of two-quark (meson) and three-quark (baryon) states, bound by gluons.

Gluons have no electric charge, like the photon, but instead couple to colour charges, which should be conserved in all strong interactions³. This gives a flavour independence of the strong interaction, i.e. all flavours of quark must have identical strong interactions as they may have the same values of colour states. The crucial difference between QCD and QED is that gluons have the ability to self-interact, as they themselves are bi-coloured, which is what defines QCD as non-abelian. The self-interaction of gluons leads to the ability for three- and four-gluon vertices, examples of which are illustrated in Figure 1.1. Gluonic self-interaction leads to two other important properties; colour confinement and asymptotic freedom.

Figure 1.1: Gluonic self-interaction.

²More comprehensive formulations of QCD, in terms of interactions and mathematics, may be found in [1] [2] [3].

³Colours are defined as red (r), green (g) and blue (b); though not related to the physical perception of colour but a tool to aid with the mathematical complications of QCD.

Colour confinement can effectively be thought of as a condition that states must be colour neutral. Moreover this leads to the requirement that there can be no free quarks, as they have non-zero colour charge and must be contained in a bound system with other quarks. Similarly for gluons, they may not be free but can, in principle, be bound in states with other gluons, inside glueballs⁴.

Asymptotic freedom means that the interaction becomes weaker at shorter distances, and is echoed in the property that the coupling constant is not in fact constant (often called a *running* coupling constant); the evolution of the running coupling constant with energy is shown in Figure 1.2.

Figure 1.2: Summary of measurements of the strong coupling constant, $\alpha_s(Q)$, as a function of the energy scale, Q [4].

As the distance increases ($> 1 \text{ fm}$) the higher order corrections of interactions become more important. In this regime there are two main approaches:

1. Phenomenological models which include aspects expected from QCD but

⁴The existence of the glueball remains to be established experimentally.

employing effective degrees of freedom. Such approaches are discussed further in Section 1.5.0.1.

2. Obtaining solutions based on calculations using powerful computational tools. Probably the most successful technique to date is that of **Lattice QCD** (LQCD)⁵. This approach is discussed further in Section 1.5.1.

It is also important to consider the effect of gluonic interactions within hadrons. If we consider the proton, the constituent quark rest masses only account for $\sim 1\%$ of the total mass. This means that $\sim 99\%$ of the mass is dynamically generated from the non-perturbative interactions of quarks via the exchange of gluons. These can self couple and interact with the vacuum to produce quark-antiquark pairs. The net energy of all these processes then produces the mass, from the equivalence between mass and energy ($E = mc^2$). An artistic representation of this is shown in Figure 1.3. This demonstrates why the internal dynamics of the proton and other hadrons are far from trivial.

Figure 1.3: A representation of quark and gluon interactions inside the nucleon [7].

1.2 Particle Multiplets

After the discovery of the proton and neutron, it was postulated that they could be considered as two states of the same particle, called the *Nucleon* [1]. At a

⁵A more complete formalism of LQCD may be found in [5] [6].

cursory glance it can be seen that throughout the existing hadrons there are sub-groups which seem to form families of particles with similar masses⁶. For example, the nucleons:

$$\begin{aligned} p(938) &= uud, \\ n(940) &= udd, \end{aligned} \tag{1.1}$$

and the family of kaons:

$$\begin{aligned} K^\pm(494) &= u\bar{s}, \\ K^0(498) &= d\bar{s}. \end{aligned} \tag{1.2}$$

These families are labelled *Isospin Multiplets* [1].

1.2.1 Isospin

Isospin, I , is a spin quantum number, which has its definition based in the construction of these multiplets. Another quantum number can be introduced, *hypercharge* Y :

$$Y = B + S + C + \tilde{B} + T, \tag{1.3}$$

where B , S , C , $\tilde{B}$ and T are the baryon number, strangeness, charm, beauty and truth respectively. If we consider the members of a multiplet it can be seen that these individual quantum numbers do not change, therefore neither does the hypercharge. Here we see the third component of isospin, I_3 , defined in terms of hypercharge and the electric charge, Q :

$$I_3 = Q - \frac{Y}{2}. \tag{1.4}$$

For the case of the nucleon, only the baryon number contributes to hypercharge ($Y = 1$), from Equation 1.4 this gives the values of $I_3 = +1/2$ and $I_3 = -1/2$ for the proton and neutron respectively.

⁶Other interesting properties which these families display are identical spin, parity, baryon number, strangeness, charm and beauty.

The values of I_3 for a multiplet run from $\pm I$:

$$I_3 = I, I - 1, \dots, -I. \quad (1.5)$$

If we extend our earlier example of nucleons and kaons, the quantum numbers can be shown simply in Table 1.1 as:

Particle	B	Y	Q	I_3	I
$p(938)$	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$
$n(940)$	1	1	0	$-\frac{1}{2}$	$\frac{1}{2}$
$K^+(494)$	0	1	1	$\frac{1}{2}$	$\frac{1}{2}$
$K^0(498)$	0	1	0	$-\frac{1}{2}$	$\frac{1}{2}$

Table 1.1: Summary of nucleon and kaon properties.

We have only considered the variable of isospin, but these multiplets can be extended in hypercharge space, giving rise to further families. This can be done for mesons, as in Figure 1.4, and equivalently for baryons, as in Figure 1.5.

Figure 1.4: Meson nonet ($B = 0$) shown in terms of charge, Q , and strangeness, S [8].

Figure 1.5: Baryon octet ($B = 1$) shown in terms of charge, Q , and strangeness S [9].

1.3 Hadron Spectroscopy

The internal structure of the nucleon and its interactions are key areas of interest within the nuclear physics community. The excitation spectrum of the nucleon is a very effective way to constrain nucleon dynamics; spectroscopy is the study of these excited states. The excited states of the nucleon are resolvable in a limited mass range, typically $\sim 1\text{-}2\text{ GeV}$ [10] [11]. As shown in Figure 1.2, the running coupling constant is extremely large in this region, therefore perturbation theory is no longer valid; this is shown explicitly in Figure 1.6 in terms of interaction distance.

Figure 1.6: Evolution of the strong coupling constant, $\alpha_s(Q)$, as a function of the interaction distance [12].

Decays from resonances of excited nucleon states predominantly proceed via the strong force. Intrinsically, strong processes occur over very short times, leading to large peak widths, as expected from the uncertainty principle;

$$\Delta E \Delta t \geq \frac{\hbar}{2}. \quad (1.6)$$

Excited states with lifetimes of around 10^{-23} s, are seen with widths of around 100 MeV. Resonances, however, are typically spaced much closer together than this, leading to significant overlap of neighbouring peaks. This overlapping structure makes a reliable extraction of the spectrum more challenging than in the case of atomic or nuclear physics, when states can generally be well separated.

1.4 Meson Spectroscopy

The study of non-perturbative QCD is not of course limited to the nucleon studies discussed above. Similar basic processes, in terms of hadronic structure and mass generation mechanisms can also occur in mesons.

Central to the aim of the upgraded JLab facility is to obtain a complete map of the spectrum of meson states in the range 1-3 GeV . This would provide a unique fingerprint to constrain our understanding of the confinement of mesons⁷.

States in the low mass region of the meson spectrum are relatively well experimentally characterised [15]. However, the spectrum of higher mass states is established with much poorer confidence and accuracy. As well as mesons states expected from simple constituent quark models, others are predicted outwith the allowed quantum numbers for a simple $q\bar{q}$ system. These take the form of more exotic states like tetraquarks ($q\bar{q}q\bar{q}$), hybrids (qqg) and glueballs (gg) [16] [17] [18] [19]. The latter two occur due to excited gluonic degrees of freedom within the meson system, allowing for the quantum numbers of the gluonic field itself to contribute to the mesonic state. Early theoretical approaches used a flux-tube model [20] [21] for these gluonic components but major recent developments in theory have allowed predictions directly from QCD.

The lowest of the exotic states are predicted around 2 GeV , from LQCD calculations [22] [23]. The lightest of these predicted states include 1^{-+} , 0^{+-} and 2^{+-} in terms of J^{PC} . The hybrid and glueball mass range is thought to be around 1.4-3.0 GeV ; accessible with the 12 GeV beam energy which will be available at *JLab12*.

In photoproduction, the production rate of hybrid mesons is thought to be comparable to normal meson production rates and CLAS12 aims to exploit this fact.

There is some weak and disputed evidence for a few of the predicted states [24] [25] but new measurements and analyses are required to establish their existence and properties. Also for a full confirmation of any of these states they must, of course, be seen in more than one decay mode.

⁷Other goals of the upgraded JLab include, better establishing the internal dynamics of the nucleon, **G**eneralised **P**arton **D**istributions (GPDs) and eventually achieving a 3D image of the nucleon, by mapping out the momentum and spatial location of its constituents [11] [13] [14].

1.5 Theoretical Approaches to Hadron Spectroscopy

There exist many theoretical approaches to model hadrons and predict their excited states. These methods either start from the underlying QCD Lagrangian or attempt to incorporate various properties of QCD such as colour confinement and asymptotic freedom in phenomenological degrees of freedom [26].

1.5.0.1 Constituent Quark Models

These phenomenological models treat the nucleon as a bound state of constituent quarks, each of which are assigned one third of the nucleon mass [27]. These constituent quarks are then bound with a quark-quark interaction which is based on the one gluon exchange potential from QCD. The constituent quarks can be thought of as a *bare* valence quark, as seen in QCD, which has been *dressed* in a cloud of low-momenta virtual gluons, resulting in an effective mass $m_q = \frac{1}{3}m_N$.

These models have some success in predicting the spectra of experimentally observed excited states. These models tend to predict many more states than those currently observed. It is not currently established if this reflects a deficiency in the theory or insensitivity in current experimental measurements. It should be remarked however that a similar quantity of excited states have been predicted from recent LQCD calculations, Section 1.5.1.

Figure 1.7 indicates states predicted by the constituent quark model and highlights their experimental standing. In this plot the heavy uniform-width bars show the predicted masses of states with well established counterparts from PWA, light bars those of states which are weakly established or missing. The length of the thin white bar gives the prediction for each states γN decay amplitude, thin grey bar for its πN decay amplitude, and thin black bar for its $K\Sigma$ decay amplitude.

Figure 1.7: Mass predictions, γN , πN , and $K\Sigma$ decay amplitude predictions for nucleon resonances up to 2200 MeV [28].

1.5.0.2 The Di-quark Model

This model considers the nucleon as a pair of quarks which are strongly correlated and a third valence quark, reducing the number of degrees of freedom in the system [29]. A simple illustration of this is given in Figure 1.8. The reduced number of degrees of freedom results in fewer excited states than the qqq constituent quark models.

Figure 1.8: Representation of the di-quark model inside the nucleon [30].

This model has also had some success in predicting low energy resonances [31], but results from LQCD [32] [33] seem to suggest that di-quarks do not form inside the nucleon. The existence or non-existence of di-quarks is still an unresolved question in the field.

1.5.0.3 Bag Models

Bag models attempt to explicitly model the colour confinement of quarks within the hadron [34]. The model begins with some finite spherical potential, set at a fixed radius, labelled the *bag*. Quarks are placed inside this potential, in which they are seen as massless. The boundary conditions of the bag are set-up such that the quarks are confined by a bag and out-with this volume they have infinite mass. Perturbative QCD can then be used within these boundary conditions.

Variants on this model have also been developed, such as the MIT Bag Model [18], the Cloudy Bag Model [35] and the SLAC Bag Model [36].

Bag models have had some success in predicting the masses of particles, shown in Figure 1.9.

Figure 1.9: Light baryon and meson masses, predicted by the bag model. The actual masses are given by dotted lines, while all other masses are predicted. The masses of N , Δ , Ω and ω were used to determine the parameters [26].

1.5.1 Lattice QCD

Lattice QCD is formulated upon a grid, named the *lattice*, in space-time. Fields are used to represent quarks which are located at points on the lattice; between these lattice points gluon fields are used to link quark fields, this is simply illustrated in Figure 1.10. Within this framework, QCD predictions can be extracted taking the limit, in which the lattice spacing is reduced to zero. The complexity of numerical calculations increases dramatically as the lattice spacing is reduced.

Figure 1.10: Simple interpretation of QCD calculated on a lattice [37].

A central challenge of hadronic physics is to establish whether LQCD can fully explain phenomena at these large distances and low momenta, where realistic analytical predictions from QCD are intractable. The lattice approach offers the possibility to obtain predictions based on QCD using computational methods without explicitly solving the QCD Lagrangian.

Interestingly LQCD predicts many bound quark states beyond the simple nucleon and meson that are yet to be observed experimentally and gives an indication of the expected masses. This includes hybrid mesons, in which the usual two quark degrees of freedom are supplemented with other dynamics [38].

In hybrid mesons the gluonic field which is created in the confinement process of the two quarks can become a degree of freedom in itself. The additional parity and angular momentum quantum numbers are predicted to give rise to exotics, which have combinations of spin, parity and C-parity which cannot be reached from only two degrees of freedom. The search for these objects is a key physics goal of the Forward Tagger [39], discussed in Chapter 10.

In recent years LQCD has progressed such that prediction of the excitation spectrum of the nucleon can be made, this method has had much success predicting the lowest mass hadrons to experimental values to within 1% [40]. Currently computational limits mean that these calculations cannot be carried out at realistically light quark masses in the nucleon, although there is rapid

progress towards this. Current state-of-the-art calculations are carried out at quark masses equivalent to a pion mass of $\sim 400 \text{ MeV}$ ($\sim 260 \text{ MeV}$ above the PDG value). The calculations are extrapolated to realistic quark masses using phenomenological (although QCD-guided) extrapolations.

The spectra of predicted meson states is shown in Figure 1.11. States corresponding to the established mesons are predicted, along with many unobserved or poorly established states. Lattice QCD also predicts a whole family of hybrid mesons which are unobserved. Clearly QCD may be a much richer environment than currently established.

Figure 1.11: The spectra of isoscalar mesons calculated by the JLab LQCD group ($m_\pi \sim 396 \text{ MeV}$) [41].

Predictions for the baryon spectra are shown in Figure 1.12. Many more excited states than currently established are predicted by the models, mirroring the excess of states predicted by the qqq constituent quark model. Also hybrid baryon states are predicted, excited nucleon states which have large gluonic components in their wavefunction. Unfortunately such states do not have exotic quantum numbers but are predicted in a mass range where there is a paucity of qqq states. Future experiments will search for these exotic objects.

Figure 1.12: The spectra of baryons calculated by the JLab LQCD group ($m_\pi \sim 396 \text{ MeV}$), in units of the calculated Ω mass [42].

The results support the idea that there may be many excited nucleon states that remain to be established experimentally. It is crucial to establish whether this is due to a lack of sensitivity in the measurements or whether this is telling us about something lacking in the underlying theory to describe non-perturbative QCD.

1.5.2 Classification of Experimentally Determined Hadronic Excitation Spectra

In identifying resonant states experimentally it is imperative to determine quantum numbers, particle mass, branching ratios and widths to challenge the theoretical models. The **P**article **D**ata **G**roup (PDG) collects data for experimentally observed states; using a star system to indicate the confidence level of each determination, based on the consistency of sightings in different analyses and the significance of the signals obtained. The different ratings are defined below:

- **** Existence is certain, and properties are at least fairly well explored
- *** Existence is very likely but further confirmation of decay modes is required
- ** Evidence of existence is only fair

- * Evidence of existence is poor

Until around a decade ago, most data on resonances came from the study of πN scattering experiments. Recently, photoproduction is being used as a powerful experimental tool and has established five new resonances in recent years [43]. This new sensitivity has arisen from the quality of the photoproduction data and differences in the relative coupling of the missing resonances to the πN and γN channels. The cross sections of meson photoproduction from the proton are shown in Figure 1.13, separated according to the different strong decay channels. It has been predicted that some missing resonances may couple strongly to “strange” photoproduction channels [28]; meaning that the channels $K\Lambda$ and $K\Sigma$ are of specific interest.

Figure 1.13: Photoproduction cross section of γp (*log scale*), including the magnitude of channels contributing to the total cross section [44].

1.6 Summary

Given the non-perturbative behavior of QCD at low energies, states must be investigated through approximate solutions of QCD such as QCD-inspired models

and QCD-based calculations. Within the QCD-inspired models, constituent quark models solve, an *approximate* QCD Lagrangian based on effective degrees of freedom, where the valence quarks are replaced by effective quarks which interact through potentials that mimic QCD's asymptotic freedom and quark confinement. Conversely, LQCD attempts to solve the *exact* QCD Lagrangian with a minimum set of approximations by discretising space-time.

The experimental challenge is to establish the excitation spectrum as unambiguously as possible in order to test whether QCD is a complete theory for describing non-perturbatively bound QCD objects such as nucleons and mesons. This is an ongoing goal and the work described in this thesis is an important part of the ongoing world programme to achieve this.

Chapter 2

Kaon Photoproduction

Experiments involving photoproduction are now commonly used in order to study the excitation spectrum of the nucleon. In this chapter, the extraction of polarisation observables for the $K^+\Sigma^-$ reaction via photoproduction will be discussed. Interest will be directed primarily towards the polarisation observable $\mathbb{E}$, as this is the work of this thesis. Theoretical models will also be considered as there are currently no other experimental data to compare to the results presented.

2.1 Final State

The $\gamma n \rightarrow K^+\Sigma^-$ reaction can be considered as a two stage process:

1. An initial photon-nucleon interaction in the target
2. A decay from the Σ^- baryon

The Σ^- baryon has a very short decay time, of order 10^{-10} s, meaning that it is not possible to directly detect it and so must be reconstructed from its daughter particles. This decay is shown at the quark-level in Figure 2.1.

Figure 2.1: Feynman diagram showing the decay of the Σ^- baryon at the quark level.

At the particle-level, the reaction can be shown as in Figure 2.2, where the final state particles which can be detected are K^+ , π^- and n .

Figure 2.2: Diagram of the reaction $\gamma n \rightarrow K^+ \Sigma^-$.

2.1.1 The Kaon

The kaon has been briefly introduced, in Section 1.2, to demonstrate the construction of particle multiplets.

The kaon family is comprised of *up*, *down* and *strange* quarks, along with their respective antiparticles. The family typically has decay times of the order 10^{-8} s (decay distance of order meters) and so can be directly detected before they decay into other hadrons or leptons. The masses and quark content of these mesons are shown below:

$$\begin{aligned}
 K^+(494) &= u\bar{s}, \\
 K^0(498) &= d\bar{s}, \\
 \bar{K}^0(498) &= \bar{d}s, \\
 K^-(494) &= \bar{u}s.
 \end{aligned}
 \tag{2.1}$$

These are said to be *strange* mesons, as they contain a strange quark and as such have a non-zero *strangeness* quantum number ($S = \pm 1$). Production of strange particles from strong interactions are defined as *associated production*. Although strange particles are produced in associated production, equal amounts of both s and $\bar{s}$ are produced, therefore conserving strangeness overall. If we consider the channel of interest in this thesis:

$$\begin{aligned}
 \gamma \quad n &\rightarrow K^+ \quad \Sigma^- \\
 - \quad udd &\rightarrow u\bar{s} \quad dds \\
 S = \quad 0 &\rightarrow -1 \quad +1
 \end{aligned}
 \tag{2.2}$$

Here we see that although two strange particles are created, the overall strangeness is conserved by $s\bar{s}$ production.

2.1.2 The Σ Baryon

The Σ baryon is a system of three quarks; two *up* and/or *down* along with a third of a higher generation. We wish to consider the case where this third quark is

strange¹. The strange Σ isotriplet masses and quark content are shown below:

$$\begin{aligned}\Sigma^+(1189) &= uus, \\ \Sigma^0(1193) &= uds, \\ \Sigma^-(1198) &= dds,\end{aligned}\tag{2.3}$$

where we are interested in the Σ^- (as a final state particle) and Σ^0 (as a background). The decay times of the Σ family are wide-ranging: Σ^- has a decay of the order 10^{-10} s whereas the Σ^0 has a much faster decay, of the order 10^{-20} s.

The baryon of interest, Σ^- , decays via a strangeness-violating weak reaction with an almost complete **B**ranching **R**atio (BR):

$$\Sigma^- \rightarrow \pi^- n \quad (BR \sim 99.85\%).\tag{2.4}$$

The Σ^0 , decays via an electromagnetic reaction to Λ (uds):

$$\begin{aligned}\Sigma^0 &\rightarrow \Lambda \gamma \quad (BR \sim 100\%), \\ \Lambda &\rightarrow p \pi^- \quad (BR \sim 63.9\%), \\ &\rightarrow n \pi^0 \quad (BR \sim 35.8\%).\end{aligned}\tag{2.5}$$

The Λ then decays in a weak process to $p \pi^-$. The Σ^0 is a background production process in our data sample and will be explicitly discussed in Section 8.7.

2.2 Baryon Photoproduction Kinematics

Figure 2.3 illustrates a kaon photoproduction reaction from a nucleon in both the lab and centre-of-mass frame. This shows the incident photon, E_γ , interacting with a target nucleon, m_{tgt} . This produces a meson, $m_{\pi,\eta,K}$ and a recoil baryon, m_R .

¹Other cases use *charm* (Σ_c^{++} , Σ_c^+ , Σ_c^0), *bottom* (Σ_b^+ , Σ_b^0 , Σ_b^-) or in principle *top* (Σ_t^{++} , Σ_t^+ , Σ_t^0 which are unseen) quarks.

Figure 2.3: Centre-of-mass kinematics of baryon photoproduction in the lab frame (left) and CoM frame (right).

This interaction can be described by three mechanisms; these are labelled s -, t - and u -channel for convenience. These mechanisms are illustrated in Figure 2.4, where we label the photon four-momentum k , the nucleon four-momentum p , the meson four-momentum q and the baryon four-momentum p' .

Figure 2.4: s - (a) t - (b) and u -channel (c) diagram descriptions of kaon photoproduction.

The s -channel corresponds to the incident particles joining into some intermediate state which then decays. The s -channel mechanism is the predominant method in which resonances and unstable particles can be produced and

discovered. The t -channel corresponds to one of the incident particles emitting a particle, which is then absorbed by the other. The u -channel corresponds to a similar process to the t -channel but with the roles of the two final state particles reversed. These production channels are generally shown in terms of the four-momenta squared, as *Mandelstam variables*²:

$$\begin{aligned} s &= (k + p)^2 = (q + p')^2, \\ t &= (p - p')^2 = (k - q)^2, \\ u &= (p - q)^2 = (k - p')^2. \end{aligned} \tag{2.6}$$

These expressions can also be summed to give the sum of the particle masses:

$$s + t + u = \sum_i m_i^2 = m_p^2 + m_k^2 + m_{p'}^2 + m_q^2. \tag{2.7}$$

If we consider the relativistic limit, the momentum is so large that the particles rest mass can be ignored³. The expressions in Equations 2.6 can be expanded and simplified:

$$\begin{aligned} s &= p_k^2 + p_p^2 + 2p_k p_p \approx 2p_k p_p \approx 4Q^2, \\ t &\approx 2Q^2(1 - \cos \theta_{C.M}), \\ u &\approx 2Q^2(1 + \cos \theta_{C.M}), \end{aligned} \tag{2.8}$$

where Q is the centre-of-mass momentum of all four particles and $\theta_{C.M}$ is the scattering angle of the kaon in the centre-of-mass frame.

2.3 Reaction Amplitudes

The cross section of a reaction, σ , is a representation of the probability for the process to occur. The differential cross section, $\frac{d\sigma}{d\Omega}$, parametrises this production within a given solid angle. The cross section can be recovered from the differential cross section by integrating over the full solid angle (4π sr):

²Using only two of these expressions leads to a complete description of the reaction.

³As $E^2 = \underline{p} \cdot \underline{p} + m_o^2 \rightarrow E^2 \approx \underline{p} \cdot \underline{p}$ for large momenta (in natural units).

$$\sigma = \oint \frac{d\sigma}{d\Omega} d\Omega. \quad (2.9)$$

The differential cross section of a photoproduction reaction can be written in terms of s and t , from Equation 2.8, in an amplitude, $\mathcal{A}$, which is a function of the outgoing momentum and the scattering angle:

$$\frac{d\sigma}{d\Omega} = \mathcal{A}(s, \cos \theta) \mathcal{A}(s, \cos \theta) \sim |\mathcal{A}(s, \cos \theta)|^2. \quad (2.10)$$

Any function of θ can be written in terms of associated Legendre polynomials, $\Phi_l(\cos \theta)$. The scattering amplitude can be written in terms of the Mandelstam variable s and these polynomials:

$$\mathcal{A}(s, \cos \theta) = \frac{4}{\sqrt{s}} \sum_{l=0}^{\infty} (2l+1) a_l(k) \Phi_l(\cos \theta), \quad (2.11)$$

where l is the relative orbital angular momentum between the target and the scattered particle, and $a_l(k)$ is defined as the l^{th} partial wave amplitude [45]. The scattering amplitudes can be decomposed into several of these partial wave amplitudes, each denoting scattering in a particular angular momentum.

The photoproduction process can be described mathematically using the scattering matrix, $\mathcal{S}$. The matrix represents the probability of the transition from the initial to final state. The method relates the initial and final states, in a way which allows computation of probabilities related to the scattering process. The initial photon and nucleon state is defined with an eigenstate $|i\rangle$; while the final meson and baryon state is defined with the eigenstate $|f\rangle$, related by the scattering matrix, $\mathcal{S}$:

$$\langle i | \mathcal{S} | f \rangle. \quad (2.12)$$

The scattering matrix can be described in terms of the particle four-momenta, k , p , q and p' , and the transition matrix, T_{fi} :

$$\mathcal{S}_{fi} = \delta_{fi} - i(2\pi)^4 \delta^4(k + p - q - p') T_{fi}. \quad (2.13)$$

The first term here represents the possibility of no scattering, while the second is the scattering term. The transition matrix is a type of stochastic matrix, where

the entries represent the probability of transitions between states.

2.4 Polarisation Observables

In order to fully understand the photoproduction process and extract unambiguous information on intermediate nucleon resonance contributions, it is important to make measurements in addition to the unpolarised differential cross section. These additional observables are extracted by measuring the dependencies of the differential cross section to the known polarisation of the particles involved in the reaction. Specifically for the case of strangeness photoproduction these consist of:

1. Incident photon,
2. Target nucleon,
3. Recoiling hyperon.

Scattering amplitudes in kaon photoproduction are constructed using **C**hew **G**oldberger **L**ow **N**ambu (CGLN) amplitudes [46]. Four of these complex amplitudes are necessary to describe the degrees of freedom of the incident photon and nucleon system. Taking bilinear combinations of these amplitudes allow for 16 independent polarisation observables to be constructed [47], shown in Table 2.1.

The single-polarisation observables arise when only the polarisation of one of the beam, target or recoil is measured in the reaction. Double-polarisation observables are split into three groups: Beam-Target, Beam-Recoil and Target-Recoil. Within these three groups multiple measurements must be made to identify all possible observables. For example, for the Beam-Target observables measurements must be made using all combinations of linearly *and* circularly polarised beam incident on a transversely *and* longitudinally polarised target.

Since these observables are derived from four complex amplitudes, they are not independent. This means that all observables for a photoproduction process can be known by only measuring a sub-set of these 16. Relations between these observables are shown as follows [48]:

Observable	Experiment	Type
σ_0	- / - / -	Unpolarised
Σ	P_{lin} / - / -	Beam
$\mathbb{T}$	- / P_y / -	Target
$\mathbb{P}$	- / - / P'_y	Recoil
$\mathbb{G}$	P_{lin} / P_z / -	Beam-Target
$\mathbb{H}$	P_{lin} / P_x / -	
$\mathbb{E}$	P_{circ} / P_z / -	
$\mathbb{F}$	P_{circ} / P_x / -	
$\mathbb{O}_x$	P_{lin} / - / $P_{x'}$	Beam-Recoil
$\mathbb{O}_z$	P_{lin} / - / $P_{z'}$	
$\mathbb{C}_x$	P_{circ} / - / $P_{x'}$	
$\mathbb{C}_z$	P_{circ} / - / $P_{z'}$	
$\mathbb{T}_x$	- / P_x / $P_{x'}$	Target-Recoil
$\mathbb{T}_z$	- / P_x / $P_{z'}$	
$\mathbb{L}_x$	- / P_z / $P_{x'}$	
$\mathbb{L}_z$	- / P_z / $P_{z'}$	

Table 2.1: Polarisation observables associated with kaon photoproduction, where P_x, P_y, P_z are the components of target polarisation along the x, y, z directions respectively (similarly for the recoiling hyperon $P_{x'}, P_{y'}, P_{z'}$), P_{lin} and P_{circ} are the degrees of linear and circular beam polarisation respectively, and ϕ is the meson azimuthal angle with respect to the scattering plane. Note that the Σ polarisation observable is a different entity to the Σ baryon.

$$\begin{aligned}
 \mathbb{E}^2 + \mathbb{F}^2 + \mathbb{G}^2 + \mathbb{H}^2 &= 1 + \mathbb{P}^2 - \Sigma^2 - \mathbb{T}^2, \\
 \mathbb{F}\mathbb{G} - \mathbb{E}\mathbb{H} &= \mathbb{P} - \Sigma\mathbb{T}, \\
 \mathbb{T}_{x'}^2 + \mathbb{T}_{z'}^2 + \mathbb{L}_{x'}^2 + \mathbb{L}_{z'}^2 &= 1 + \Sigma^2 - \mathbb{P}^2 - \mathbb{T}^2, \\
 \mathbb{T}_{x'}\mathbb{L}_{z'} - \mathbb{T}_{z'}\mathbb{L}_{x'} &= \Sigma - \mathbb{P}\mathbb{T}, \\
 \mathbb{C}_{x'}^2 + \mathbb{C}_{z'}^2 + \mathbb{O}_{x'}^2 + \mathbb{O}_{z'}^2 &= 1 + \mathbb{T}^2 - \mathbb{P}^2 - \Sigma^2, \\
 \mathbb{C}_{z'}\mathbb{O}_{x'} - \mathbb{C}_{x'}\mathbb{O}_{z'} &= \mathbb{T} - \mathbb{P}\Sigma.
 \end{aligned} \tag{2.14}$$

Beyond determining a single polarisation observable, a goal of these meson photoproduction experiments is to perform a full set of measurements on a channel in order to unambiguously constrain the amplitude. Many of these experiments are non-trivial so it is beneficial that all 16 polarisation observables need-not be measured in order to fully define the amplitude.

Measurement of the single-polarisation observables (Σ , $\mathbb{T}$, $\mathbb{P}$) must be made [47], as well as taking a selected number of double-polarisation observables. The exact number and nature of these double-polarisation observables was debated and disagreed upon. This was finally settled by Chiang and Tabakin [49], who showed that four appropriately chosen double-polarisation observables along with the cross section and single-polarisation observables are enough to fully determine the amplitude unambiguously.

2.5 Isolating a Polarisation Observable

The differential cross section is classified into three expressions dependent on the type of double-polarisation experiment being conducted. Considering an experiment with polarised photons incident on a polarised target:

$$\begin{aligned}
 \frac{d\sigma}{d\Omega} &= \left(\frac{d\sigma}{d\Omega} \right)_0 [1 - P_{lin}\Sigma \cos(2\phi) \\
 &\quad + P_x(-P_{lin}\mathbb{H} \sin(2\phi) + P_{circ}\mathbb{F}) \\
 &\quad + P_y(\mathbb{T} - P_{lin}\mathbb{P} \cos(2\phi)) \\
 &\quad + P_z(P_{lin}\mathbb{G} \sin(2\phi) - P_{circ}\mathbb{E})].
 \end{aligned} \tag{2.15}$$

Considering an experiment with Beam-Recoil measurements:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = & \left(\frac{d\sigma}{d\Omega} \right)_0 [1 - P_{lin}\Sigma \cos(2\phi) \\ & + P_{x'}(-P_{lin}\mathbb{O}_{x'} \sin(2\phi) - P_{circ}\mathbb{C}_{x'}) \\ & + P_{y'}(\mathbb{P} - P_{lin}\mathbb{T} \cos(2\phi)) \\ & + P_{z'}(-P_{lin}\mathbb{O}_{z'} \sin(2\phi) - P_{circ}\mathbb{C}_{z'})]. \end{aligned} \quad (2.16)$$

Finally, considering an experiment with Target-Recoil measurements:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = & \left(\frac{d\sigma}{d\Omega} \right)_0 [1 + P_y\mathbb{T} + P_{y'}\mathbb{P} \\ & + P_{x'}(P_x\mathbb{T}_{x'} - P_z\mathbb{L}_{x'}) \\ & + P_{y'}P_y\Sigma \\ & + P_{z'}(P_x\mathbb{T}_{z'} + P_z\mathbb{L}_{z'})]. \end{aligned} \quad (2.17)$$

In this thesis, the observable of interest is the Beam-Target observable $\mathbb{E}$. From Table 2.1, in order to study the observable $\mathbb{E}$, a circularly polarised photon beam and a longitudinally polarised target must be used. Other components of the target polarisation are therefore zero, $P_x = P_y = 0$, while there is no contribution from a linearly polarised photon beam, $P_{lin} = 0$. We simplify our expression for the Beam-Target differential cross section, Equation 2.15, using these conditions:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_0 [1 - P_z P_{circ} \mathbb{E}]. \quad (2.18)$$

2.6 Theoretical Models for Meson Photoproduction

Information on the nucleon resonance spectrum is extracted by fitting a model to experimental data and fitting parameters in the model to extract the masses,

widths and quantum numbers of the contributing resonances [50]. As this fitting separates the contributions from different angular momenta (partial waves) it is often referred to as a **P**artial **W**ave **A**nalysis (PWA) [38].

These models consider the processes as being comprised of a resonant and background component. These components are parametrised and extracted from the experimental data through fitting. As with many models, the more experimental data which is available, the more constraints can be placed upon the reaction channel to provide more accurate and less ambiguous results.

If we consider a generic reaction where we have a photon-nucleon interaction, a , with some intermediate resonance state, c , which finally ends in a meson-nucleon system, b , the Hamiltonian can be written as:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{V}, \quad (2.19)$$

where the first term is the free Hamiltonian, $\mathcal{H}_0$, and the second is the interaction term, $\mathcal{V}$. As is a common feature of reaction models, this interaction term is split into a resonant component, $\mathcal{V}_R$, and a background component, $\mathcal{V}_B$:

$$\mathcal{V} = \mathcal{V}_R(E) + \mathcal{V}_B, \quad (2.20)$$

where the resonant component is a function of the total energy, E .

The probability of the process to occur is governed by a transition matrix, T_{ba} , which can be similarly reduced into components:

$$T_{ba}(E) = T_{ba}^R(E) + T_{ba}^B. \quad (2.21)$$

The resonant component of this transition matrix can be expanded by summing over all possible paths in the process $a \rightarrow c \rightarrow b$, and introducing a propagator of state c , g_c :

$$T_{ba}(E) = \sum_c \mathcal{V}_{ba} g_c(E) T_{bc}(E) + \mathcal{V}_{ba}. \quad (2.22)$$

2.6.1 Isobar Models

Isobar models attempt to use an *effective* Lagrangian to simulate the properties of interactions. They do this by evaluating tree-level Feynman diagrams for the

resonant and non-resonant exchange of mesons and baryons. By considering the possible exchanges which take place in s -, t - and u -channel reactions, excited states can be identified. This tree-level method is useful to simplify the interaction to first order, but neglects to take into account effects such as interactions in the final state or coupled-channel effects.

The isobar model we will consider in this thesis is the KaonMAID model [51]⁴. The model considers low-order diagrams for the interaction, which are then split into resonant and non-resonant terms (Born terms). The s -channel mechanism represents the resonant contributions, while the t - and u -channel mechanisms represent the background contribution.

These isobar models have seen much use in the energy region under 2 GeV due to the smaller importance of higher order diagrams and Born terms at lower energies. The models attempt to produce theoretical predictions of polarisation observables using various combinations of resonances. This allows for comparison between data and prediction in order to infer the presence or absence of a resonance. This is not a trivial procedure as many partial waves can be present and interfere strongly.

2.6.2 Coupled-Channel Analysis

Coupled-Channel (CC) analysis is an attempt to improve the accuracy of the isobar model to include final state particle interactions, as well as intermediate states such as πN ⁵. These processes can be described as production of a non-resonant state which rescatters from the nucleon in order to produce a resonance.

Coupled-channel analysis also hopes to reduce the ambiguity of resonance combinations used to fit data [52]. As it is possible for more than one combination of resonances to fit the data well, this disambiguous nature can be removed by considering multiple observables on multiple final states. This analysis method allows more constraints to be added to the channel which acts as a filter to remove resonances which do not contribute to the final state.

The model we wish to consider in this thesis is the **Bonn-Gatchina** (BoGa)⁶.

⁴Maintained and developed by the Institut für Kernphysik, Universität Mainz, Germany.

⁵Amplitudes of $\gamma N \rightarrow \pi N$ process is thought to play a considerable effect in the overall process $\gamma N \rightarrow \pi N \rightarrow KY$, where Y is a final state hyperon.

⁶Maintained and developed by the Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Germany; and Kurchatov Institute, **P**etersburg **N**uclear **P**hysics **I**nstitute

This is a coupled-channel model which aims to consider multiple decay channels at once, with angular and energy dependencies of different observables are analysed simultaneously [53]. This provides stable fits for partial waves with high spin and provides a smooth behaviour in energy.

Two particle final states, such as πN , ηN , $K\Lambda$, $K\Sigma$, ωN and $K^*\Lambda$ are fitted with the χ^2 method. At fixed energies, the unpolarised cross section of pseudoscalar mesons is characterised by the differential cross section only. For vector mesons however, the unpolarised cross section is characterised by the differential cross section and three spin density matrix elements.

2.7 Summary

Experiments utilising both polarised beams and targets are crucial in gathering data in order to characterise photoproduction scattering amplitudes. Reaction models such as KaonMAID and Bonn-Gatchina can be fitted to experimental data and used to extract properties of nucleon resonances contributing to the reaction.

An outline of the process is shown in Figure 2.5, showing the relations between the experiment, reaction model theory and QCD.

(PNPI), Gatchina, Russia.

Figure 2.5: Process for nucleon structure calculation and experimentation [54].

Chapter 3

Previous Experimental Data

In this chapter, key experimental data from the $K^+\Sigma^-$ channel are discussed. Since there are no previous measurements for the $\mathbb{E}$ double-polarisation observable, these measurements focus on differential cross sections and beam-asymmetries.

3.1 Current Experimental Knowledge

Polarisation observable experiments from strangeness channels from neutron targets are relatively few: this is particularly true for the reaction $\gamma n \rightarrow K^+\Sigma^-$. Experiments were conducted at Cornell in the late 1950s, followed by experiments at LEPS and Jefferson Lab in the mid-2000s.

3.1.1 Kaon Photoproduction at Cornell

The experiment which took place at Cornell in the 1950s aimed to measure the differential cross section of the $\gamma n \rightarrow K^+\Sigma^-$ reaction [55]. This used both liquid hydrogen and liquid deuterium target with kaon momenta of 0.405 and 0.455 GeV , and a bremsstrahlung beam of peak energy 1.170 GeV .

They wished to consider the total K^+ photoproduction cross section from three reaction channels:

k (MeV)	θ_{CM} ($^\circ$)	$\gamma p \rightarrow K^+\Sigma^0$ ($10^{-31}cm^2/sr$)	$\frac{\gamma n \rightarrow K^+\Sigma^-}{\gamma p \rightarrow K^+\Sigma^0}$
1122	82	0.6 ± 0.1	1.6 ± 0.7
1146	75	1.1 ± 0.2	0.8 ± 0.6

Table 3.1: Data points and associated errors obtained from cross section measurements at Cornell [55].

$$\begin{aligned}
 \gamma p &\rightarrow K^+\Lambda, \\
 \gamma p &\rightarrow K^+\Sigma^0, \\
 \gamma n &\rightarrow K^+\Sigma^-.
 \end{aligned} \tag{3.1}$$

The cross sections from the proton had already been measured at Cornell in 1959/60 respectively [56] [57]. From the total kaon yield and the previous measurements at Cornell, it was possible to estimate the cross section for the $K^+\Sigma^-$ reaction. Only two data points were obtained from this analysis, with error bars of order $\sim 50\%$, these are shown in Table 3.1.

3.1.2 Kaon Photoproduction at LEPS

The experiment which took place at the **L**aser **E**lectron **P**hoton beam-line at **S**Pring-8 (LEPS) in the 2000s, aimed to measure differential cross sections and photon-beam asymmetries for the $\gamma n \rightarrow K^+\Sigma^-$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions [58]. This used linearly polarised photons on liquid hydrogen and deuterium targets. The photon beam was of energy 1.5 - 2.4 GeV with a high polarisation (typically $\sim 90\%$ at 2.4 GeV), with kaons measured at $0.6 < \cos \theta_{CM}^{K^+} < 1.0$.

Differential cross sections for $K^+\Sigma^-$ and $K^+\Sigma^0$ in four angular bins were obtained, shown in Figure 3.1. They found the cross sections of both channels were comparable at higher energies. The theoretical models tended to agree well with the $K^+\Sigma^0$ data but overestimate the $K^+\Sigma^-$ data at higher energies.

Figure 3.1: Differential cross sections for $\gamma n \rightarrow K^+\Sigma^-$ (circles) and $\gamma p \rightarrow K^+\Sigma^0$ (squares). Only statistical errors are shown. The solid and dashed curves are the Regge model [59] calculations for the $K^+\Sigma^-$ and $K^+\Sigma^0$, respectively. The dotted curve is the KaonMAID model calculations for the $K^+\Sigma^-$ [58].

Measurements for the photon-beam asymmetry were also taken, Figure 3.2. These indicated the asymmetries of $K^+\Sigma^-$ were typically larger than for the $K^+\Sigma^0$ channel. Another key feature was the increase in asymmetry for $K^+\Sigma^0$ with the centre-of-mass energy, whereas $K^+\Sigma^-$ shows minimal dependence above 2 GeV. The Regge model agrees well with the $K^+\Sigma^-$ channel but overestimates the $K^+\Sigma^0$ channel.

Figure 3.2: Photon-beam asymmetries for $\gamma n \rightarrow K^+\Sigma^-$ (circles) and $\gamma p \rightarrow K^+\Sigma^0$ (squares). The solid and dashed curves are the Regge model calculations for the $K^+\Sigma^-$ and $K^+\Sigma^0$, respectively [58].

3.1.3 Kaon Photoproduction at Jefferson Lab

The ‘ $g10$ ’ experiment which took place at Jefferson Lab in the 2000s, measured the differential cross section of the $\gamma D \rightarrow K^+\Sigma^-(p_s)$ reaction using the Hall-B CLAS detector [60]. The experiment used a bremsstrahlung photon beam with energies 0.8 - 1.6 GeV on a liquid deuterium target, measuring kaons with centre-of-mass angles between 10 - 140°. The data are shown, along with the data from LEPS in Figure 3.3.

Figure 3.3: Differential cross sections of the reaction $\gamma D \rightarrow K^+ \Sigma^-(p_s)$ obtained by CLAS (full circles). The error bars represent the total (statistical plus systematic) uncertainty. LEPS data (empty triangles) and a Regge-3 model prediction (solid curve) are also shown. Notice the logarithmic scale for high energy plots [60].

This was the first high precision measurement of the Σ^- photoproduction from the neutron over a broad range of kaon angle and photon energies. At photon energies of $\sim 1.8 \text{ GeV}$ a predominant peak in the forward direction begins to form as the photon energy increases. This peak is attributed to increased contributions from t -channel mechanisms, whereas at lower energies s -channel mechanisms dominate. At energies above $\sim 2.1 \text{ GeV}$ show possible indications of a backwards peak beginning to form, thought to be coming from the presence of u -channel mechanisms.

Chapter 4

Experimental Apparatus

In this chapter, the main features of the Jefferson Lab facility and the experimental set-up in Hall B are discussed.

4.1 Experimental Overview

The data used in this analysis for this thesis were taken during the $g14$ ($HDice$) run period at the **T**homas **J**efferson **N**ational **A**ccelerator **F**acility (TJNAF - JLab), in Virginia, USA. The dates during which this experiment was carried out were from November 2011 until May 2012. This timeframe corresponds to the experimental proposal “ N^* Resonances in Pseudoscalar-Meson Photo-Production from Polarized Neutrons in $\vec{H}.\vec{D}$ and a Complete Determination of the $\gamma n \rightarrow K^0 \Lambda$ Amplitude” (E06-101) [61]. This experiment used linearly and circularly polarised photon beams on a frozen spin HD target in order to extract polarisation observables.

4.2 Jefferson Lab

JLab consists of four experimental halls: A, B and C have been long-standing constructions used in many iterations of JLab physics research; Hall D is a newly built experimental facility.

Feeding these experimental halls is the **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility (CEBAF). An aerial view of the facility is shown in Figure 4.1. CEBAF allows for a 6 GeV electron beam to be simultaneously delivered to up to three

experimental halls, meaning that each hall may pursue its own experimental program independently of the others.

Figure 4.1: Aerial view of the JLab facility, highlighting the CEBAF accelerator and experimental halls [62].

Prior to May 2012, the facility and its detectors were designed to perform experiments with a maximum beam energy of 6 GeV . The $g14$ experiment was the final incarnation and this date marked the end of what was generally referred to as *JLAB6*. Subsequently an upgrade began across the entire facility to enable the production and receipt of a 12 GeV electron beam - *JLAB12*.

4.3 CEBAF

The CEBAF accelerator consists of two anti-parallel superconducting **LIN**ear **A**ccelerators (LINACs) connected using recirculation arcs to form a “racetrack” accelerator with a total length of 1.4 km . The main components of the CEBAF accelerator are shown in Figure 4.2.

Figure 4.2: Schematic of CEBAF at Jefferson Lab, including the experimental halls [63].

An aggregate of nine arcs are used to recirculate beam-bunches allowing them to be further accelerated with each pass through the LINAC sections, gaining energies of up to 6 GeV . Multiple recirculation arcs are needed in order to accept electrons after each new pass through the LINAC sections. The set of four recirculation arcs in the east also contain an RF separator [64], which allows the beam to be extracted and sent to individual experimental halls.

The electrons injected into the CEBAF accelerator are initially produced using a 780 nm laser incident on a Gallium Arsenide (GaAs) photocathode. After initial acceleration by an anode potential, these electrons are then accelerated to 67 MeV in the injector¹ and separated into 2.0005 ns beam buckets, which are then injected into the CEBAF accelerator. The electrons circle the racetrack up to five times, gaining up to 0.6 GeV in each LINAC. The LINACs use superconducting

¹The injector consists of three pulsed lasers, one which supplies each hall, striking the photocathode at a rate of 499 MHz leads to the characteristic $\sim 2\text{ ns}$ beam bucket structure of CEBAF. The use of three separate lasers also allows each beam to have independent current and polarisations.

Duty Factor	Continuous Wave
Number of Passes	5
Energy Gain per Pass	1.2 <i>GeV</i>
Electron Beam Energy Range	0.6 - 6.0 <i>GeV</i>
Number of Cryomodules	40
Electron Polarisation	85%

Table 4.1: Summary of CEBAF characteristics.

Radio **F**requency (RF) cavities (liquid-helium cooled niobium) to accelerate the electrons to a maximum of ~ 1.2 *GeV* for one full circuit (commonly referred to as a “pass”) and up to ~ 6.0 *GeV* for five full passes. These electrons can then be taken out of the recirculating arc and delivered to the experimental halls using the RF separator. A summary of the characteristics of the CEBAF accelerator are presented in Table 4.1.

A simple schematic of the upgrade of the CEBAF accelerator to allow for delivery of a 12 *GeV* beam is shown in Figure 4.3.

Figure 4.3: Schematic of CEBAF at Jefferson Lab, showing additions for the upgrade to the beam-line, including the placement of the new Hall D [65].

4.4 Experimental Halls

Halls A, B, C and D are each equipped with bespoke detector systems. Hall D, is the fourth experimental hall to be constructed off the beam-line of CEBAF; this was recently completed in the quadrant off the northern LINAC, shown in Figure 4.3.

The physics explored at JLab centres on exploring the nature of the nucleon. Each hall uses its experimental set-up to probe various properties:

- Hall A [66]:
 - Largest experimental hall containing two high-resolution spectrometers.
 - Experiments study: nucleon form factors, strange-quark structure of the proton, and nucleon spin structure.

- Hall B [67]:
 - Smallest experimental hall, containing CLAS; a spectrometer with a nearly full angular range ($\sim 4\pi$) based around a toroidal magnetic field.
 - Experiments study: excited states of the nucleon, 3D imaging of the nucleon's quark structure and nucleon-nucleon correlations in nuclei, exotic and hybrid mesons.
- Hall C [68]:
 - Contains a high momentum spectrometer, using unique set-ups for each experiment.
 - Experiments study; weak interaction of the proton, transitions from hadrons to quarks and strange nuclei.
- Hall D [69]:
 - Contains a hermetic detector based around a solenoid magnet, designed for use with *JLAB12*.
 - Experiments will study: exotic and hybrid mesons.

During 6 GeV operation, Halls A and C received much greater beam currents than that supplied to Hall B; typical beam currents are 100 μA and 10 nA respectively. This factor of 10^4 difference is necessary due to the luminosity restrictions of the Hall B detectors, which were not designed for high-flux measurements. The fact that CEBAF is able to deliver beam currents with such divergent beams simultaneously is a major achievement of the accelerator.

The *g14* experiment was conducted in Hall B, therefore the remainder of the chapter will be dedicated to exploring the Hall B experimental set-up.

4.5 Hall B

Hall B is the smallest experimental hall at Jefferson Lab and within it, the **CEBAF Large Acceptance Spectrometer** (CLAS) is situated. A schematic view of Hall B is shown in Figure 4.4. Although electron beam is delivered to the halls;

for some experiments, such as g14, it is desirable to use polarised photons on a target. This is achieved in Hall B using a some kind of medium (a *radiator*) in order to produce bremsstrahlung photons.

Figure 4.4: Diagram showing the scale of CLAS in Hall B at Jefferson Lab [63].

4.5.1 The Bremsstrahlung Process

The photon beam produced for use with CLAS uses electrons incident upon a radiator, which decelerates the electrons while they interact with the electromagnetic field of nuclei. Due to conservation of energy, the decelerated electrons must emit the energy it has lost, which takes the form of a photon. The bremsstrahlung method allows for the production of photons with energies in the range of 20–95% of the incident electron beam energy [70]. A simple representation of this process is shown in Figure 4.5.

Figure 4.5: Simple illustration of bremsstrahlung radiation [71].

Bremsstrahlung is kinematically possible if only a small amount of momentum is transferred to the radiator nucleus, $\vec{q} \sim 0$. This is actually the typical method of energy loss for electrons in material, and the nucleus recoil energy can usually be neglected.

4.5.2 Bremsstrahlung Photon Tagging

Hall B has the ability to use CEBAF's electron beam to create a photon beam for use with certain targets [70]. In the case of the $g14$ experiment, both linearly and circularly polarised photon beams were required for use on a HD target. Photons were “tagged”, event-by-event, by the tagging spectrometer, which consists of a large dipole magnet and a focal plane hodoscope. The dipole magnet bends the electrons from the beam-line towards the timing and energy counters in the hodoscope. A schematic of the tagging spectrometer is shown in Figure 4.6.

Figure 4.6: Schematic of the coherent bremsstrahlung facility in Hall B [70].

The electron and photon beams emerge from the radiator approximately parallel to the incident electron beam, and are produced with an angular distribution as follows:

$$\theta_c = \frac{1}{\gamma} = \frac{mc^2}{E_{e^-}}, \quad (4.1)$$

where m is the electron rest mass. The electron scattering angle is a function of the photon production angle, energy and the electron energy:

$$\theta_{e^-} = \theta_c \frac{E_\gamma}{E'_{e^-}} = \frac{mc^2 E_\gamma}{E_{e^-} E'_{e^-}}. \quad (4.2)$$

For typical JLab energies, to a first approximation, the photons and electrons are parallel. The photon and electron beams are then separated using the dipole tagger magnet. The electrons are bent downwards while the photons continue down the beam-line to interact with the target.

The tagging hodoscope consists of two separate layers of scintillator arrays. The upper plane of scintillation counters (E-counters) are used to measure the energy of the bent electrons after the bremsstrahlung emission, E'_{e^-} . When combining this measurement with knowledge of the initial electron beam energy, E_{e^-} , a simple calculation of the produced photon energy, E_γ can be made:

$$E_\gamma = E_{e^-} - E'_{e^-}. \quad (4.3)$$

The E-counters allow for energy resolution of up to $0.0013 \times E_{e^-}$.

The lower plane of scintillation counters (T-counters) are used to measure the timing of the photon, with a resolution of ~ 300 ps. This timing measurement allows the electron to be correlated with its bunch and can be used to calculate the photon time at the target. A full description of the tagging hodoscope can be found within [70].

4.5.3 Beam Polarisation

Hall B is able to run using both linearly and circularly polarised photon beams. These running modes require special conditions in the bremsstrahlung process.

4.5.3.1 Linear Polarisation

In Hall B, linearly polarised photons are generated from an unpolarised electron beam using the coherent bremsstrahlung technique [72] [73]. This results in two contributions to the photon spectrum; one from polarised (coherent) and another from unpolarised (incoherent) bremsstrahlung photons².

In Hall B, the electron beam is scattered from a diamond radiator, of thickness $50 \mu\text{m}$, in order to produce a linearly polarised photon beam from coherent bremsstrahlung. Further information on the diamond radiator and linearly polarised beam can be found in [74].

4.5.3.2 Circular Polarisation

To produced circularly polarised photons, it is required that a longitudinally polarised electron beam be used. Foil was used as a radiator in this case, with two main properties considered before a material was chosen:

1. Minimise the number of electron interactions
2. Maximise the probability of interaction

²This is true for both linearly and circularly polarised periods.

This first property leads to the realisation that very thin foils must be used to ensure that statistically one electron produces one photon. The second property, when coupled with the information that the cross section for bremsstrahlung emission is proportional to Z^2 [75]³, leads to the realisation that high- Z materials should be used. The chosen material was a foil of gold ($Z = 79$) with thickness 10^{-4} radiation lengths.

The degree of circular polarisation obtained from this method is dependent on the ratio of the photon energy, E_γ , and the incident electron energy, E_{e^-} , often labelled x for convenience ($x = E_\gamma/E_{e^-}$):

$$P_{circ} = \left(\frac{4x - x^2}{4 - 4x + 3x^2} \right) P_{e^-}, \quad (4.4)$$

where P_{circ} and P_{e^-} are the photon circular and electron helicity polarisations respectively. The distribution of the transfer of polarisation is shown in Figure 4.7.

Figure 4.7: Degree of circular polarisation as a function of the ratio of beam energies, E_γ/E_{e^-} [76].

³ Z denotes the atomic number of the material, which indicates the number of protons in the nucleus.

4.5.4 CLAS Detector

The *CEBAF Large Acceptance Spectrometer* (CLAS) is housed in Hall B of the Jefferson Lab facility. CLAS is a combination of many different types of particle detector, giving almost complete angular coverage ($\sim 4\pi$) [67]. CLAS is built around six superconducting coils, which produce a toroidal magnetic field, giving a field-free region at the centre for use with polarised targets. These coils split CLAS into six azimuthal regions going outward, which are defined as *sectors*. The design is focused keenly on accurate detection of charged particles with good momentum resolution. A diagram of CLAS and its associated sub-detectors is shown in Figure 4.8.

Figure 4.8: The CLAS detector, including drift chambers, Cherenkov counters, electromagnetic calorimeters, and time-of-flight detectors [77].

When a photon beam is used in Hall B, these photons interact with a target at the centre of CLAS, causing a cascade of reaction products. These particles travel outwards from the centre of CLAS passing through the multiple detector layers. Particles firstly travel through the *ST*art counter (ST), giving the start time of

the event. Particles then pass through the *Drift Chambers* (DC) which, using the toroidal field, measures the bending of particles in order to calculate their velocity and therefore momenta. They then pass through the time-of-flight *Scintillation Counters*, giving the particle flight time from the target. The final layers are focussed on forward particle detection; the penultimate being the *Cherenkov Counters* and the final being the *Electromagnetic Calorimeter* ⁴. These final layers are used in electron beam experiments where negative pion and electrons must be separated. Further information on the CC and EC can be found in [78] and [79] respectively.

4.5.4.1 Torus Magnet

The toroidal field, around which CLAS is centred, is used to bend the paths of charged particles in order to calculate particle momenta. The superconducting coils themselves are kidney-shaped and equally spaced (60°) around the beam-line. The magnetic field within CLAS and the typical field strength of a superconducting coil are shown in Figure 4.9. The coils create areas of low acceptance at the boundaries of sectors, reducing the CLAS acceptance to $\sim 70\%$ of the 4π solid angle. Close to the coils, the magnetic field is very unstable and not confined to the azimuthal direction which leads to this low acceptance. At larger distances from the coils, charged particles are confined to a single sector using the azimuthal field.

⁴It should be noted that this analysis does not use these final forward layers.

Figure 4.9: Left: Magnetic field for the CLAS torus magnet around the target region. Right: Magnetic field shape created by the magnets in CLAS [67].

The $g14$ run used two running conditions for the torus magnet. These were:

- $+1920\text{ A}$: where negative particles are bent towards the beam-line.
- -1500 A : where positive particles are bent towards the beam-line.

In principle, higher currents could be used during running although this leads to a reduction in acceptance for oppositely charged particles [80]. Further information about the CLAS torus can be found in [81].

4.5.4.2 Start Counter

The **ST**art Counter (ST) system is used to associate a beam bucket with a particle track, with a timing resolution of $\sim 300\text{ ps}$ [82]. Specifically the start counter is used to indicate the start time for time-of-flight measurements of charged particles produced from photon interactions with the target. The ST is split into six sectors of thin scintillation counters surrounding the target. The paddles of the start counter are shown in a cross section of the assembly in Figure 4.10.

Figure 4.10: Cross section of the CLAS start counter [82].

Before commencing the $g14$ experiment, the light guides of the start counter were increased in length. This was in an effort to move the PMTs further away from the target area as the cryostat which would hold the target generates a sizeable magnetic field (1 T). Further information on the start counter can be found in [82].

4.5.4.3 Drift Chambers

Drift Chambers (DC) are used to calculate particle momenta from the bending of charged tracks [83]. Like most of the CLAS sub-detectors the DC is split into six sectors, these are then sub-divided into three *regions*. These regions, simply referred to as 1, 2, 3, have their own purposes:

- Region 1
 - Closest to target, in an area of minimal magnetic field.
 - Used to determine the start of the charged particle track.
- Region 2

- Central layer, in an area where the magnetic field peaks.
- Best momentum resolution due to the drastic bending of the tracks in this region.
- Region 3
 - Furthest from target, in an area of low magnetic field.
 - Used to determine the end of the charged particle track.

This system provides $\sim 80\%$ coverage, due to the regions which are not covered around the superconducting coils. Figure 4.11 shows the drift chamber regions within CLAS. Further information on the drift chambers can be found in [84].

Figure 4.11: Simple diagram of the CLAS drift chambers, highlighting the DC regions, time-of-flight counters and torus coils [65].

4.5.4.4 Time-of-Flight Scintillators

The *Time-of-Flight* (ToF) counters, also called *Scintillation Counters* (SC), are used to determine the timing for a particle to travel from its initial interaction

vertex in the target to the ToF counters. The counters are situated outside the radius of the drift chambers, enclosing CLAS. Combining their timing information with timing information from the ST allows the particle β to be calculated ($\beta = v/c$). From this, using the ToF and tracking information allows for the particle mass to be estimated [85]. As with other sub-detectors, the scintillator is split into six segmented areas following the sectors of CLAS. The counters within these sectors have varying lengths and widths, shown in Figure 4.12, and have timing resolutions varying from 110 – 200 ps . Further information on the time-of-flight scintillators can be found in [85].

Figure 4.12: Diagram showing one sector of the CLAS time-of-flight scintillator counters [82].

Chapter 5

The HD -ice Target

In this chapter, the properties and manufacturing process of **H**ydrogen-**D**euterium (HD) targets used in the $g14$ run period are described.

5.1 Introduction

The $g14$ run period was named the HD ice experiment due to the *frozen-spin* nature of the target. The target was designed such that it would be able to achieve high polarisation of both “free” protons (H) and neutrons (D) with frozen spins (‘ice’).

The advantage of using HD as a polarised (bound) neutron target is many fold. Firstly, the HD target material requires conditions (with respect to magnetic field and temperature) achievable in CLAS and it can maintain its polarisation for long periods under experimental conditions. Secondly, when compared to other bound neutron targets, such as ammonia and butanol (as in the FROST target at CLAS), there is less background from unpolarised target material. Thirdly, it contains also a highly polarisable proton source.

In principle very high polarisations are achievable for this set-up; as high as 90% H polarisation and up to 60% D polarisation [86] [61]. The drawbacks for such a target are that the handling procedures are complex and, as was experienced during the $g14$ run, the risk of losing target polarisation is significant. Compounding this, while polarisation can quickly be lost, if no targets are waiting to replace a failed target, new targets take months to properly produce.

5.2 HD-ice Target Geometry

The cells used for the *HDice* target have dimensions of $15\text{ mm}\phi \times 50\text{ mm}$; an exploded-view of the target cell is shown in Figure 5.1.

Figure 5.1: Photograph of a deconstructed *HDice* target, showing the cell, copper ring and *Al* wires [61].

The aluminium wires are used to mitigate any heat build up in the solid *HD*, these are inserted into holes in a copper ring. This copper ring is double-threaded such that it allows the cell to be transferred between dewers without violating the magnetic field or temperature conditions. The cell walls are made from *PolyChloroTriFluoroEthylene* (PCTFE - C_2ClF_3), also referred to as *KelF*, which provides a clean cell with no background for *H* and *D* from *Nuclear Magnetic Resonance* (NMR) measurements. A more detailed schematic of a constructed *HD* target is shown in Figure 5.2.

Figure 5.2: *HD* target schematic, indicating the target sizes [87].

The constituent materials in the target are broken down into their relative abundances in Table 5.2.

Material	Abundance (%)
<i>HD</i>	77
<i>Al</i>	16
<i>KelF</i>	7

Table 5.1: Target material abundances by mass.

5.3 *HD-ice Target Physics*

The *HD* target, for use with CLAS, utilised deuterium as a relatively clean source of neutrons and hydrogen as a source of protons. The ease of polarising a state is dependent on the spin-lattice coupling, or rather the molecule’s angular momentum. Molecules with the angular momentum state $L = 0$ are hard to polarise and hence have very long relaxation times; whereas molecules with the angular momentum state $L = 1$ are easy to polarise and hence have very short relaxation times. This long spin-lattice relaxation time is critical to the success of the target, although the production is challenging.

The hydrogen molecule has two identical protons, with two available spins states. *Ortho- H_2* ($J = 1$), where the spins are aligned and *Para- H_2* ($J = 0$), where they are anti-aligned. At low temperatures *O- H_2* decays to the *P- H_2* state and makes up around 75% of H_2 .

States with $J = 0$, such as *Para- H_2* , have long relaxation times and cannot be easily polarised, this means that states with $J = 1$ in H_2 and D_2 are needed to allow the transfer of spin to the $J = 0$ *HD* state. This $J = 0$ state of *HD* is diamagnetic

The spins are aligned with a high magnetic field (15 T) and low temperature (12 mK) with small concentrations of $J = 1$ H_2 and D_2 . A diagram showing the states within H_2 , D_2 and *HD* are shown in Figure 5.3.

Figure 5.3: Decay mechanism within the *HDice* target [61].

The *HD* molecule has a very long spin-relaxation times [88], dependent on impurity levels in the target. Direct polarisation takes very long preparation times, so indirect polarisation is used. A small concentration of *O-H₂* (of order 10^{-4})¹ which will readily polarise and transfer polarisation between the *H* in *H₂* and the *H* in *HD* via spin-coupling. After many *O-H₂* half-lives (~ 3 months) almost all the *H₂* impurity had decayed to the inert *P-H₂* state ($1/e$ decay time $\tau = 6.5$ days), leaving the *H* in *HD* in a frozen-spin state. For *D₂* a similar method is followed using a small concentration of *D₂*. The *P-D₂* state has $J = 1$ and polarises readily like *O-H₂*, and transfers spin to *HD* via spin-exchange. *P-D₂* decays to *O-D₂* ($\tau = 18$ days), so again after a significant number of half-lives the *D* in *HD* will reach a frozen-spin state.

The polarisation of *D* will always be less than that of *H* due to a smaller magnetic moment of *D* ($\mu_D/\mu_H \sim 1/3$). Once polarised, the target has a beam life of a few years due to the long relaxation time, meaning that there is no need to ‘repolarise’ the target during running. Practically, the degree of polarisation is given by the Brillouin function [90]:

$$P_J(x) = \frac{2J+1}{2J} \coth \left(\frac{2J+1}{2J} x \right) - \frac{1}{2J} \coth \left(\frac{1}{2J} x \right), \quad (5.1)$$

$$x = \frac{\mu B}{k_B T},$$

¹Impurities in the *HD* gas are characterised using gas chromatography and Raman spectroscopy [89].

where this is dependent on the nuclear spin J , magnetic moment μ , magnetic field B , Boltzmann constant and the temperature T . For D this is limited to $\sim 15\%$ at 25 mK and 15 T . The characteristic curves for H and D are shown in Figure 5.4.

Figure 5.4: Equilibrium polarisation within the HD target as a function of magnetic field, B , and temperature, T . This shows the polarisation of **hydrogen**, **vector deuterium** and **tensor deuterium** [91].

The D polarisation can be further increased by exploiting the adiabatic fast-passage method [92] in order to transfer polarisation from H to D . The Zeeman levels in solid HD are shown in Figure 5.5. Once the impurities of H_2 and D_2 are decayed, the population of the $m_D = +1$ and $m_H = +\frac{1}{2}$ substates are greater than the $m_D = -1$ and $m_H = -\frac{1}{2}$ substates. Forbidden RF transitions can be driven in order to transfer state population from the initial $\|m_H = +\frac{1}{2}, m_D = -1, 0\rangle$ states to the $\|m_H = -\frac{1}{2}, m_D = 0, +1\rangle$ states. Employing this RF method allows for the D polarisation to increase to up to 30%.

 Figure 5.5: Zeeman levels within solid *HD* [61].

During the $P-H_2$ and $O-D_2$ decays heat is released, which generates a problem as the temperature must be kept low to retain polarisation. Solid *HD* has poor thermal conductivity so cooling must be done by using embedded aluminium wires in the solid *HD*. At low temperatures energy is transported through phonons and experience an impedance mismatch at the *HD/Al* boundary, which limits the *HD* temperature to around 12 *mK*. This method of target allows for much shorter run times to obtain high statistics, around 75 days rather than 1000-2000 days with the previous FROST target at CLAS.

5.4 *HD-ice Target Production Equipment*

Production for these particular targets is a complex and time consuming process. As such, there are many stages and various pieces of equipment involved in the production. Specifically these need to be able to maintain low temperatures and high magnetic fields in order to hold the target polarisation.

The following sections outline these cryogenic containers, a far more detailed description of these can be found in [87] [93].

5.4.1 Production Dewar

The **P**roduction **D**ewar (PD) was used to condense the *HD* gas into a solid form within the target cell. *HD* solidifies at temperatures of ~ 16 *K* but much lower temperatures are required to induce the polarisation required for the target.

Once the HD gas is condensed, the PD is designed such that **N**uclear **M**agnetic **R**esonance (NMR) measurements can be performed. A detailed schematic of the PD is shown in Figure 5.6.

Figure 5.6: Schematic of the production dewar [87].

- Production Dewar Conditions: 1.5 K temperature; 2 T magnetic field.

5.4.2 Transfer Cryostat

The **T**ransfer **C**ryostat (TC) was used for moving the targets between the various dewars and cryostats. The double-threaded copper ring in the base of the target cell, shown in Figure 5.1, allows for the maintenance of temperature and magnetic field conditions during these transfers. One set of threads connects to the TC, while the other links to the dewar for transfer. For example, removing a target

from the PD using the TC: once the TC is screwed into the copper ring at the base of the target, continuing the rotation unscrews the target from the PD. A picture of the TC is shown in Figure 5.7.

Figure 5.7: Photograph of the transfer cryostat [87].

- Transfer Cryostat Conditions: 2 K temperature; 0.1 T magnetic field.

5.4.3 Dilution Refrigerator

The *D*ilution Re*F*rigerator (DF) was used to polarise the solid *HD* target. Due to the length of target production time this was designed to hold up to three targets at once, allowing for several targets to be produced concurrently. A picture of the DF is shown in Figure 5.8.

Figure 5.8: Photograph of the dilution refrigerator [87].

- Dilution Refrigerator Conditions: 10 mK temperature; 15 T magnetic field.

5.4.4 Storage Dewar

The *S*torage *D*ewar (SD) was used for the storage of target cells which were well polarised, having spent several months in the DF. Similarly to the DF, the SD was designed to be able to hold several targets simultaneously. The purpose of this was to maintain the polarisation of targets before use in the experimental hall while freeing up space in the DF so more targets could be placed into production.

- Storage Dewar Conditions: 1 K temperature; 6 T magnetic field.

5.4.5 In-Beam Cryostat

The *I*n-*B*eam *C*ryostat (IBC) was used to hold the target in the beam line under conditions such that the production polarisation was maintained. It was designed for operation in two positions: for loading from the TC (vertically) and running inside CLAS (horizontally); these positions are shown in Figure 5.9.

Figure 5.9: External schematic of the IBC, shown in both the vertical (left) and horizontal positions (right) [87].

A schematic, showing the inside of the IBC is shown in Figure 5.10.

Figure 5.10: Internal schematic of the IBC [87].

- In-Beam Cryostat Conditions: 50 – 300 mK temperature; 1 T longitudinal magnetic field 0.07 T transverse magnetic field.

5.5 Full Target Production Procedure

Industrial standard HD gas has a purity of $\sim 98\%$, with $\sim 1.5\%$ of impurities from H_2 and $\sim 0.5\%$ of impurities from D_2 ².

To begin target production, HD gas is condensed into liquid and then to solid in a 2-4 K production dewar. Target calibration was also done with the aid of NMR measurements to characterise the polarisation. This is then transferred

²This can however be purified further using a procedure developed by James Madison University (JMU) [94], giving impurities as low as 10^{-4} .

to the dilution refrigerator using the transfer cryostat, a simple illustration of a typical transfer is shown in Figure 5.11. The cell is then left to polarise at 15 T and 12 mK for 2-6 months, with potentially two other targets; during this, the HD is able to achieve a frozen spin state.

Figure 5.11: Simple illustration of a target transfer [93].

Transferring targets into CLAS is a long and careful process, as it's important to keep the target cooled and in a magnetic field at all times. The target is removed from the dilution refrigerator (0.01 K /15 T) with the transfer cryostat (2 K /0.1 T). The target is then transferred to the production dewar for a pre-run NMR measurement (2 K /2 T) and once complete transferred to the storage dewar (1 K /3 T). The storage dewar is then mounted onto a shock absorbing frame on a truck and transported to Hall B. The storage dewar is then craned to *level 2* of CLAS and the target transferred to the IBC (0.2-0.7 K & 0.1-0.9 T) on *level 1* and rolled into the centre of CLAS. Once the experimental runs are completed, it is moved to the dewar for a post experiment polarisation measurement. A diagram of this production cycle is shown in Figure 5.12.

Figure 5.12: The life cycle of a *HDice* target for use with CLAS [87].

5.6 Produced Targets

Only three targets were produced for use with production running during *g14*, although others were used for beam tests. The details of these targets are presented in Table 5.2.

Target Cell	Cell Name	$\rho(g/cm^2)$	ρ wrt 21a	Beam Conditions Used
21a	<i>Silver</i>	0.028	1.0	Circularly polarised
19b	<i>Gold</i>	0.020	0.70	Circularly/linearly polarised
22b	<i>Last</i>	0.027	0.96	Linearly polarised

Table 5.2: Summary of the targets produced for the *g14* run period and their characteristics.

Chapter 6

Data Calibration and Optimisation

In this chapter, the data obtained from the $g14$ run period will be discussed. This includes an overview of the data reconstruction, the skimming routine for the $K^+\Sigma^-$ reaction and the corrections which were applied to the data.

6.1 $g14$ Overview

The $g14$ experiment, also known as the $HDice$ experiment, ran for seven months from November 2011 to May 2012. The dataset was subdivided into smaller sets based on conditions such as the target cell used, its polarisation and the polarisation direction. A breakdown of these periods are shown in Table 6.1.

Unfortunately during the run period several incidents occurred which led to accidental reduction of target polarisation. These occurred in both target $21a$ (periods labelled *Silver1/2/3/4/5*) and in target $19b$ (*Gold2*). At the end of *Silver5b* the target lost almost all polarisation; subsequently the $21a$ target was used in order to take data for an empty target. This is a target which contains no polarised material, only unpolarised HD . Note that for empty target data it is necessary to produce runs with both positive and negative torus setting, to account for any differing acceptance effects; these were labelled *emptyA* and *emptyB* for negative and positive torus settings respectively. Due to the unexpected drop in polarisation seen in *Silver5b*, another target had to be installed prematurely, before it was fully polarised and ready for data taking.

Period	Beam Energy (GeV)	e^- Beam pol (%)	Run Range	Date Range	Events (10^6)	Torus Current (A)	Target Pol. (%)
<i>Silver1</i>	2.281	$81.5 \pm 1.4 \pm 3.3$	68021 – 68092	01/12 – 06/12	830	+1920	$+25.6 \pm 0.7 \pm 1.5$
<i>Silver2</i>	2.281	$81.5 \pm 1.4 \pm 3.3$	68094 – 68176	06/12 – 11/12	1170	+1920	$+23.2 \pm 0.7 \pm 1.4$
<i>Silver3</i>	2.281	$76.2 \pm 1.4 \pm 3.1$	68188 – 68230	12/12 – 16/12	250	–1500	$+21.2 \pm 0.8 \pm 1.3$
<i>Silver4</i>	2.281	$88.8 \pm 1.5 \pm 3.6$	68232 – 68305	16/12 – 04/01	820	–1500	$-6.4 \pm 0.4 \pm 0.4$
<i>Silver5</i>	2.258	$88.8 \pm 1.5 \pm 3.6$	68335 – 68769	04/01 – 05/02	5210	–1500	$-5.9 \pm 0.2 \pm 0.4$
<i>Gold2</i>	2.542	$83.4 \pm 1.5 \pm 3.3$	69227 – 69364	10/04 – 18/04	2100	–1500	$+26.8 \pm 1.0 \pm 1.6$
<i>EmptyA</i>	3.356	$88.2 \pm 1.5 \pm 3.6$	68993 – 69037	08/03 – 11/03	660	–1500	0
<i>EmptyBb</i>	3.356	$88.2 \pm 1.5 \pm 3.6$	69038 – 69044	11/03 – 12/03	120	+1920	0

Table 6.1: Summary of the $g14$ run period. This shows each sub-period, including the beam, torus and target characteristics [95].

Target 19*b* was substituted for the 21*a* target, giving a good set of runs with highly polarised *HD*.

6.1.1 Estimating Target Polarisations for Periods Silver 4 and 5

Some discrepancies were raised with initial results obtained from the *Silver4* and 5 periods. This manifested in a drop in the magnitude of the $\mathbb{E}$ observable when compared to other periods. This indicated that the true polarisation values for *Silver4* and 5 were smaller than originally calculated using NMR measurements. Members of the *g14* group¹ studied this issue using the $\gamma n \rightarrow \pi^- p$ reaction, in order to see what the target polarisation would have had to be to produce the same $\mathbb{E}$ asymmetry in $\pi^- p$ as seen in the *Gold2* period, assuming compatible and comparable beam helicities. The study indicated a disparity of the values given for the target polarisation using the NMR and what was seen for the target polarisation of the *Silver4* and 5 periods.

Experimentally, at the start of the *Silver4* period the target was rotated from spin $+Z$, parallel to the beam momentum, to $-Z$ anti-parallel to the beam momentum. During this process it was noted that there were some mechanical failures, although it is not believed that any of these issues should have caused significant polarisation loss and it is not known why there should be any disparity with the NMR measurement.

The result from the NMR was given as $\sim 25\%$ whereas the analysis method gave a target polarisation of only $\sim 6\%$. The true cause of this is unknown and still being considered within the group.

6.2 Organisation of the *g14* Data

Data is collected from detectors into **B**ank **O**bject **S**ystem (BOS) files [96]. These contain the raw data from ADCs and TDCs taken directly from the detectors, which can be thought of as purely binary data. In itself this information offers no insight into properties of the detected particles as they are generally simply a correlation of various hits within sub-detectors. The dataset is then *cooked*,

¹Dao Ho and Peng Peng were responsible for providing this study to the group.

where it is converted into usable variables such as charge, momentum and particle beta. The cooking was done using the CLAS reconstruction and analysis package RECIS and was overseen by the *g14* “chef”, Franz Klein.

After the cooking was completed, each detector went through a detailed calibration procedure. These were to apply individual corrections to the data for each subsystem; ensuring consistency across all runs and indicating potential problems. Responsibility for these calibrations were split across the *g14* group, indicated in Table 6.2.

Calibration	Responsible	Prerequisite
Tagger	Natalie Walford	None
Time-of-Flight	Haiyun Lu	Tagger
Start Counter	Jamie Fleming	Tagger
Drift Chamber	Dao Ho	Time-of-flight & Start Counter
Drift Chamber Alignment	Franz Klein	Drift Chamber
Electromagnetic Calorimeter	Irene Zonta	Time-of-flight & Start Counter

Table 6.2: Calibration responsibilities and prerequisites.

Once calibration is completed the datasets are cooked once again, allowing for the new calibration constants for all subsystems to be used. This iterative calibration-cooking cycle is continued until the calibration of the data is of a high standard² and there are no misalignment artefacts in the data.

The files produced after cooking are in a compact ROOT **D**ata **S**ummary **T**ape (DST) format, which contains banks of the physical variables allowing for the reconstruction of events. It is these DST files which go on to be used in the physics analysis.

The analysis for this thesis was completed using an analysis framework based around the (C++ based) object-orientated ROOT framework from CERN [97]. This framework is named ROOT **B**ank **E**vent **E**xtraction **R**outines (ROOTBEER), which allows the reading of DST files in a form which is independent of CLAS analysis programs and allowing analysis code to be made

²Each sub-detector has its own requirements for a *good* calibration.

into executables [98].

6.2.1 Data Reconstruction

If the complete experimental goals of Jefferson Lab are considered, the sheer number of reaction channels which are of interest is staggering, meaning that often very wide and generic triggers are used to record events³. When one channel is considered for analysis, the volume of other events contained within the data are considerable in scale. It is completely impractical to run an analysis over the entire dataset in terms of computational time alone. It is much more productive to remove the extraneous data to massively reduce the size of the set, this practice is called *skimming*; the channel of interest can then be identified with much less processing time. These skims can be set up for exclusive final states, such as $K^+\Sigma^-$, or much more generic inclusive final states, such as K^+X .

Events are reconstructed from the basic data acquired from detector subsystems. Arrays of measurable quantities for each particle are obtained from the various detectors; these are used to describe the particle properties during the reconstruction, with variables such as charge, mass, momentum and velocity.

6.2.1.1 Particle Charge and Momenta

The charge of a particle can be ascertained from the interaction of the particle with the magnetic field of the drift chambers. The direction of the curvature identifies whether the particle charge is positive or negative; neutral particles will be unaffected by the magnetic field.

A particle can be described using the Lorentz force:

$$\mathbf{F} = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})], \quad (6.1)$$

where $\mathbf{F}$ is the Lorentz force acting on the particle, of charge q moving with velocity $\mathbf{v}$ in the presence of an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$. In the case of the CLAS drift chambers, the electric field is absent so this can be simplified to:

³The trigger at CLAS consists of two levels. Trigger Level 1 processes all prompt (90 ns) signals, with a more robust Level 2 trigger which requires a candidate for a track in the DC.

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}). \quad (6.2)$$

From the Lorentz force, the radial orbit induced by the field on the charged particle can be considered, where $\mathbf{v} \perp \mathbf{B}$. This motion can be described using the centripetal acceleration:

$$a = \frac{v^2}{r}, \quad (6.3)$$

where r is the radius of curvature of the track. The expressions from Equations 6.2 and 6.3 can be equated to give:

$$\begin{aligned} F &= q(v \times B) = m \frac{v^2}{r}, \\ mv &= qrB, \\ p &= qrB. \end{aligned} \quad (6.4)$$

This allows the momentum of a particle to be calculated from the curvature in the drift chambers.

6.2.1.2 Particle Beta

The particle velocities are commonly presented as a fraction of the speed of light, c , denoted by β . This is done independently of the calculation of the particle momentum, Equation 6.4. For the velocity; timing information is used from the timing difference of the hit in the start counter (ST) and the scintillation counter, also called the time-of-flight counter (ToF). The path length is then determined from the reconstructed track in the drift chambers, l :

$$\beta = \frac{l}{c(t_{ST} - t_{ToF})}. \quad (6.5)$$

6.2.2 Start Counter Calibration

The start counter was outlined in Section 4.5.4.2, the timing information must be accurately calibrated, as this information will be used to determine particle timing and in isolating the tagged photon for the event.

The ST is composed of 24 paddles across the 6 sectors of CLAS. These paddles have a non-linear geometry which adds some subtlety to the calculation of the propagation times of photons. The geometry of an ST paddle was shown in Figure 4.10, where the paddle can be considered in two sections; a *leg* and a tapered *nose*.

Before calibration constants can be determined, some simple calculations are performed on the timing information available. The quantities calculated are the estimated event based time on the ST timing, t_{eST} , and on the tagger timing, t_{eT} :

$$\begin{aligned} t_{eST} &= t_{ST} - \frac{l}{\beta c}, \\ t_{eT} &= t_0 + t_\gamma, \end{aligned} \tag{6.6}$$

where l is distance from the event vertex to the paddle hit vertex, t_0 is the zero-time for the event and t_γ is photon time.

The calibration process is iterative and relies on a good quality calibration of the tagger. The final goal of this calibration is to have the timing resolution of each paddle ~ 300 ps and an offset < 3 ps from zero. The results from this calibration and other CLAS sub-detectors must be carefully considered before the calibration stage is concluded.

The calibration of the ST is carried out in three separate phases:

1. Time-walk Corrections
2. Propagation Time
3. Timing Offset

After each stage of the calibration, the calibration constants which are obtained are uploaded to the CLAS database and implemented in the data. The process continues until the fits match the required resolution.

6.2.2.1 Stage 1: Time-walk Correction

The first stage in the calibration was to calculate the energy-deposit dependent time-walk corrections. The ADC pulse height, A , is plotted against the ST and tagger time difference, Δt , so these shapes can be characterised in each paddle. In

order to get clear values for a wide variety of pulse heights, both pion and proton signals are used for this calibration⁴. A projection is taken along the A -axis and fitted with a Gaussian. This can then be used to fit the data with the time-walk function, t_w :

$$t_w = W_0 + \frac{W_1}{A - W_2}, \quad (6.7)$$

where the three constants W_0 , W_1 and W_2 are given by the fit. An example of these plots and accompanying fits are given in Figure 6.1.

Figure 6.1: Examples of timewalk calibration plots as part of a calibration GUI. Showing ST paddle 5 with *all* particles present (top left); paddle 6 with pions present (top right); paddle 7 with protons present (bottom left) and paddle 8 with kaons present (bottom right).

6.2.2.2 Stage 2: Propagation Time

Due to the non-linear geometry of the paddles, the propagation time, t_p is calculated using a non-linear function:

⁴Pions produce small pulse heights, while protons produce much greater pulse heights. Kaons may also be used but they lack the statistics needed.

$$t_p = \frac{z_0}{V_{eff}} + k_0 z_1 + k_1 z_1^2, \quad (6.8)$$

where z_0 is the distance of the hit along the paddle leg from the light guide and z_1 is the distance along the paddle nose from the paddle leg. The variables k_0 , k_1 and V_{eff} , which is defined as the effective velocity, are determined from fitting.

The timing difference of the event vertex is plotted against the distance along the paddle, which is then projected along the d -axis and fitted with a Gaussian to find the peak Δt in each d bin. This is then fitted with the following function:

$$\Delta t = \frac{z_0}{V_{eff}} + k_0 z_1 + k_1 z_1^2 + K_{RF}, \quad (6.9)$$

where K_{RF} is some constant timing offset. An example of one of these plots and its accompanying fit is given in Figure 6.2.

Figure 6.2: Example plot of Δt vs distance along the paddle. This is the distribution for sector 6, paddle 2.

6.2.2.3 Stage 3: Timing Offset

The timing must be corrected for the timing offset, K_{RF} shown in Equation 6.9, using the propagation time Δt which is fitted with a Gaussian. An example of these plots and its accompanying fits are given in Figure 6.3.

Figure 6.3: Example of plots used to correct the timing offset in the calibration GUI. These are shown for paddles 1, 2, 3 and 4, where the average resolution is ~ 300 ps.

6.3 Data Banks and Skimming

The information reconstructed for each event is stored in “banks”, which can be considered as tables of information stored independently for each event. These banks are numerous and organised in various ways, such as by detector or by reconstruction method. Information contained within banks includes physical variables such as position and momentum but also can give the status of detector systems, highlighting if a specific event is correlated with a hit in a certain detector.

6.3.1 Banks

During the process of data reduction, bank s can be kept or removed as required. From the complete list of banks retained from the skim⁵ only a handful were used

⁵The full bank list is as follows: HEAD, TGBI, EPIC, CL01, ECHB, SCRC, STRE, TAGR, HBTR, HDPL, TBER, TDPL, MVRT, VERT, RGLK, PART, HBID, TBID, GPID, HEVT, EVNT, DCPB, TRPB, ECPB, SCPB, STPB, TGPB.

in the final analysis, although others were useful for diagnostic purposes. The main bank used in the analysis was the GPID bank [99].

The GPID bank contains particle information, as well as information from the time-of-flight scintillators, start counter and tagger. Initially during the selection the **P**article **ID**entification (PID) variable of this bank was used as some initial particle selection, though this is not a very robust method. The PID variable was mainly considered for some initial diagnostic tests and was later dropped in favour of a more robust method of selection.

The PID variable is defined as follows; the momentum is determined from the bending of the particles in the DC magnetic field. From this, values of the particle β are trialled using the PDG particle masses. The value of β is measured using time-of-flight information and the difference between these measured values and the trail values are minimised. This best suited identity is then assigned to the particle. This method has associated issues, particularly when particle corrections are not taken into account and particularly struggles to separate pions and kaons at high momenta.

Other banks used in this analysis are outlined below:

- HEAD: Bank containing information about the run; primarily used to obtain the number of the current run.
- MVRT: Bank containing information about the event vertex.
- TBID: Bank containing information about time-based particle ID; using details from the time-of-flight, Cherenkov counter, electromagnetic calorimeter, start counter and large angle calorimeter.
- TAGR: Bank containing information from the photon tagger; primarily used for the selection of the event photon.

6.3.2 $K^+\Sigma^-$ Skim

The skim used in this analysis was an exclusive $K^+\Sigma^-$ skim. The particle identification for charged tracks were taken from the EVNT or PART banks of CLAS, and selecting particle β using momentum p (in GeV): $\beta_{min} < \beta < \beta_{max}$. The full requirements of the $K^+\Sigma^-$ skim were as follows:

- Pions:

$$\begin{aligned}\beta_{min} &= \frac{p}{\sqrt{p^2 + 0.3^2}} - 0.03, \\ \beta_{max} &= \frac{p}{\sqrt{p^2 + 0.05^2}} + 0.03.\end{aligned}\tag{6.10}$$

- Kaons:

$$\begin{aligned}\beta_{min} &= \frac{p}{\sqrt{p^2 + 0.6^2}} - 0.05, \\ \beta_{max} &= \frac{p}{\sqrt{p^2 + 0.4^2}} + 0.05.\end{aligned}\tag{6.11}$$

- Protons:

$$\begin{aligned}\beta_{min} &= \frac{p}{\sqrt{p^2 + 1.1^2}} - 0.06, \\ \beta_{max} &= \frac{p}{\sqrt{p^2 + 0.8^2}} + 0.06.\end{aligned}\tag{6.12}$$

- Z vertex distance for a $\pi^+\pi^-$ pair must be < 2.0 cm.
- No particle identification cut for neutral particles.
- Event particles: $K^+ = 1$, $\pi^- = 1$, $\pi^+ = 0$, $p = 0$, *neutrals* < 3 .

6.3.3 Selection of Experimental Data to be Analysed

Some individual files and runs were removed due to poor quality data or corrupted files. This included runs which were not production quality, either due to the stability of the beam delivered to the Hall or simply that these runs were designed for some diagnostic reason. The removal of this data was primarily carried out during cooking and calibration phases.

6.4 Applied Corrections to Data

Although the data had undergone a cycle of calibration and cooking, other corrections were still required. These are to account for various systematic effects of detectors and the energy loss of particles during detection.

6.4.1 Kinematic Fitting

The goal of using a correction to particle momentum is to improve the resolution of the data; for the $g14$ period this was done using kinematic fitting [76] [100].

A measured quantity, the particle 4-vector, must fulfil certain kinematic constraints, such as the conservation of momentum. Since these measured quantities have some associated uncertainty, the constraints are not perfectly satisfied. The constraint boundaries can then be used to slightly change the measured values, within the parameters of their uncertainties, without breaking conservation.

The goal of kinematic fitting is to have an event-by-event least squares fitting to ensure the measured values fulfil the constraints. The software used for this iterative procedure was developed at **C**arnegie **M**ellon **U**niversity (CMU).

Least squares fitting, utilises the minimisation of the sum of the squares of the data offsets from some fit, commonly referred to as *residuals*. If we consider the sum of the residuals for a set of n points for some function f :

$$R^2 = \sum_i [y_i - f(x_i, a_1, a_2, \dots, a_n)]^2, \quad (6.13)$$

where y_i is the measured value for each of the n events.

The sum of the squares is used so we can exploit the fact that the residuals can be treated as a continuous differentiable quantity. This does mean however that outlying points are given disproportionately large weighting due to the construction of R^2 . The condition to minimise R^2 for some dataset $i = 1, \dots, n$ is:

$$\frac{\partial(R^2)}{\partial a_i} = 0. \quad (6.14)$$

If some measurable quantity is considered, we can write:

$$\vec{\eta} = \vec{y} + \vec{\epsilon}, \quad (6.15)$$

where $\vec{y}$ are the estimator variables as given by a fit and $\vec{\epsilon}$ are the set of deviations needed to shift the observed values of $\vec{\eta}$ to satisfy the constraints. Ideally these shifts in $\vec{\eta}$ should have a Gaussian distribution around zero. The shift distributions are checked at each iteration, which is done by using pull distributions in order to measure the relative difference of the values and their

uncertainties, reminiscent of the residuals. The pulls are defined as:

$$z = \frac{\eta_{it} - y_{it}}{\sigma_{\eta_{it}}^2 - \sigma_{y_{it}}^2}. \quad (6.16)$$

The iterations continue until they converge on an ideal Gaussian distribution, $\mu = 0; \sigma^2 = 1$.

6.4.2 CLAS tracking parameters

Three separate coordinate systems are used in CLAS. These are the tracking system, lab system and sector system. It is important to consider the transition from the tracking system to the lab system within CLAS for use with the correction methods. The track system defines x along the beam line; y through the sector centre and z along the average magnetic field direction. Whilst the lab system defines the x through the centre of sector 1; y is vertically upwards and z is along the direction of the beam line. These systems are shown in Figure 6.4.

Figure 6.4: Diagram outlining the two coordinate systems used in CLAS [63].

The track system can be related to the lab system as follows:

$$\begin{pmatrix} x_{track} \\ y_{track} \\ z_{track} \end{pmatrix} = \begin{pmatrix} z_{lab} \\ \cos(\alpha)x_{lab} + \sin(\alpha)y_{lab} \\ -\sin(\alpha)x_{lab} + \cos(\alpha)y_{lab} \end{pmatrix}, \quad (6.17)$$

where $\alpha = \frac{\pi}{3}(N_{sector} - 1)$.

The momenta of the tracks are considered in terms of the ratio of momentum and charge, $q/|p|$, the dipolar angle relative to the sector plane, λ and the angle in the sector plane relative to the x_{track} axis, ϕ [101]:

$$\begin{pmatrix} p_{x_{lab}} \\ p_{y_{lab}} \\ p_{z_{lab}} \end{pmatrix} = \begin{pmatrix} p(\cos(\lambda) \sin(\phi) \cos(\alpha) - \sin(\lambda) \sin(\alpha)) \\ p(\cos(\lambda) \sin(\phi) \sin(\alpha) + \sin(\lambda) \cos(\alpha)) \\ p \cos(\lambda) \cos(\phi) \end{pmatrix}. \quad (6.18)$$

6.4.3 Energy Loss Correction

CLAS uses the curvature of charged particle tracks in the DC to determine particle momentum. However the code used during the reconstruction does not take into account the energy loss due to material the particle encounters before it reaches the drift chambers. This becomes critically important for photon runs as the start counter is placed surrounding the target, removing yet more energy. This is particularly important for low momentum particles which lose their energy easily. The Eloss software⁶ attempts to correct for these energy losses.

From the event vertex to the drift chambers, the particle must pass through a significant amount of material such as the start counter paddles, beam pipe and target cell material/wall. The software looks at the path of the particle to identify which materials it has passed through. The thicknesses of the various materials are calculated and the software attempts to correct the 4-vector for the energy which would be lost in the material. Although this has been done for many previous experiments at CLAS, the software target was updated specifically for the *HDice* target geometry and material [102].

⁶The Eloss software was written and updated for the *g14* run by Eugene Pasyuk of Jefferson Lab.

6.4.4 Momentum Correction

Several factors lead to the need for momentum corrections after the calibration phase. The CLAS reconstruction momentum is taken from DC information; which means that any errors in the alignment of the DC or inaccuracies in the field map will be propagated into the reconstructed momenta. The reaction $\gamma p \rightarrow p\pi^+\pi^-$ was studied to obtain the corrections. The Eloss correction was applied to the final state particles before the event was kinematically fitted. The correction works in terms of considering three hypotheses; wherein one of the final state particles is considered “missing”:

- $\gamma p \rightarrow (p)_{missing}\pi^+\pi^-$,
- $\gamma p \rightarrow p(\pi^+)_{missing}\pi^-$,
- $\gamma p \rightarrow p\pi^+(\pi^-)_{missing}$.

The corrections applied are:

$$\begin{aligned}\Delta p_x &= p_x^{kfit} - p_x^{meas}, \\ \Delta \lambda_x &= \lambda_x^{kfit} - \lambda_x^{meas}, \\ \Delta \phi_x &= \phi_x^{kfit} - \phi_x^{meas},\end{aligned}\tag{6.19}$$

where p is the magnitude of the momentum vector; λ is the dipolar angle relative to the sectors (x, y) for the track and ϕ is the the angle of the x_{track} relative to the (x, y) plane.

6.4.5 Tagger Correction

An additional correction must be added to the tagger after calibration, as alignment issues lead to photon energies being reconstructed with some offset [101]. This misalignment comes from the weight of the paddles over time moving them from their original alignment, leading to inaccurate values given by certain tagger channels. Note that these corrections will also differ according to the energy of the electron beam and so must be considered for each beam setting. The reaction $\gamma p \rightarrow p\pi^+\pi^-$ was again studied after the Eloss correction was applied. The events were then kinematically fitted, and events with a **C**onfidence **L**evel

(CL) greater than 10% were used to determine the correction. The correction for each beam energy, E_{beam} is:

$$\Delta E_{tag} = \frac{E_{\gamma}^{kfit} - E_{\gamma}^{meas}}{E_{beam}}, \quad (6.20)$$

where E_{γ}^{kfit} is the photon energy value from the kinematic fitting and E_{γ}^{meas} is the photon energy from the tagger system. The correction was then used for the associated beam period and then for each tagger paddle on an event-by-event basis.

6.4.6 Neutron Vertex Correction

If the neutron was able to be reliably detected and the complete final state $K^+\pi^-n$ identified, more corrections would need to be made. This consideration is not required for this work but would become important during any higher statistics experiments.

Neutrons are detected finally in the CLAS EC. Due to the large interaction length for the neutron in the EC, it is difficult to accurately pinpoint the hit coordinates. Any offsets in the interaction vertex within the EC can be considered using a careful study of the channel $\gamma D \rightarrow \pi^+\pi^-pn$. This takes advantage of a common production vertex, therefore giving a reliable neutron vertex in the target.

When considering the $K^+\Sigma^-$ channel rather than $\pi^+\pi^-pn$, there is a subtlety. The neutron that we would consider has a displaced vertex as the decay length of the Σ^- is $\sim 4.43cm$. Though generally when CLAS assigns vertex it chooses the vertex of the fastest particle in the event (e.g. a fast $\pi^\pm$). This is usually a good approximation when the neutron comes from the primary interaction vertex, but something more subtle would have to be considered and studied to have some idea what influence this vertex choice would have in the data.

These neutron corrections were implemented in the previous measurements in CLAS [54] [60].

Chapter 7

$\gamma N \rightarrow K^+ \Sigma^-$ Event Selection

This chapter details the use of the *g14* period dataset to reconstruct and identify the reaction yield of:

$$\gamma n \rightarrow K^+ \Sigma^- \rightarrow K^+ \pi^- n. \quad (7.1)$$

7.1 Outline

The *g14* experiment is one of the first measurements of the photoproduction of mesons from a polarised neutron target and will be instrumental in the world programme to better establish the excitation spectrum of the nucleon. Expected rates are given in [61] as ratios to other decay channels. It is expected that the cross section of $K^+ \Sigma^-$ is one fifth of the cross section of $K^0 \Lambda$. An estimate of $K^0 \Lambda$ was made by JLab of 10^4 events for the experimental period, giving 2000 expected events for $K^+ \Sigma^-$. It has since been thought that this initial ratio of 1 : 5 is a large underestimate, from a relative comparison of other run periods. Previous experiments at JLab have shown that this ratio may be much closer to 1 : 1¹. Since this was clearly uncertain, a rough event study was undertaken before the full analysis was initiated. This study confirmed that enough events were present to warrant a complete analysis.

This channel is particularly challenging for several reasons other than the low relative cross section. Firstly, power of the polarisation observable measurement is correlated with the available target polarisation, which was predicted to be able

¹From private correspondence with Franz Klein.

to have values of 75% for H and 40% for D . In practice typical values of 15-25% were obtained for both H and D . Secondly, CLAS itself was not designed as a neutral particle detector, with a neutron efficiency of only 5-7% [61], so with a final state neutron this becomes problematic. Misidentification is also a concern, specifically the false ID of K^+ as π^+ . Finally, because the target neutron is bound inside deuterium, from this bound state inside the deuteron there will be Fermi motion of the nucleon.

7.2 Event Selection

After the data is skimmed, as outlined in Section 6.3.2, the files were transferred to a storage space at the University of Edinburgh. These individual run files were arranged and merged into periods as outlined in Table 6.1. Once this was complete the event selection procedure could begin. Each stage of selection was carefully monitored in terms of statistics of events removed, in order to ensure sensible reductions.

7.2.1 Coarse Data Reduction

The skimmed CLAS data contains the events of interest, as well as other reaction channels not studied in this thesis. Initial coarse selection cuts were applied to the skimmed data to further reduced the data sample.

The multiplicity of an event is the number of particles successfully identified in the final state. Of course, ideally for this analysis all three final state particles would be identified, $K^+\pi^-n$. However, due to the restrictions of CLAS to identify neutral particles this is not always possible. This means that the two particles, non-exclusive, final state, $K^+\pi^-$, where the neutron has not been detected is the primary consideration. For this case the (undetected) neutron can be reconstructed from the missing mass : $\gamma n \rightarrow K^+\pi^-X$. M_x can be evaluated on an event-by-event basis to select neutron candidates from the reaction yield.

By considering the hit multiplicity in CLAS and selecting events with two and three particle final states we can reduce the data to be processed. Furthermore we can improve the quality of the data selected by requiring that events also have a valid hit in the tagger. The distribution of the selected final states are shown in Figure 7.1:

Figure 7.1: Event multiplicity selection.

- 2 or 3 final state particles *and* a corresponding hit in the tagger.

Events which do not meet this requirement are removed from the analysis.

7.2.2 Detector Hits

Some simple detector requirements can be used to attempt to identify “good” events. That is to say, that events are required to have a certain amount of information associated with it. The requirements are as follows:

- All events require at least one corresponding hit in the focal plane detector.
- All charged particles require a valid event in the drift chamber and the time-of-flight paddles.
- All charged particles require a charge of only one unit.
- All neutral particles require a valid hit in the electromagnetic calorimeter and no hit in the DC.

Events which do not meet these requirements are removed from the analysis.

7.2.3 Particle Mass² Windows

The particle mass is calculated using the momentum from the track curvature and the particle velocity:

$$M_{calc}^2 = \frac{p^2(1 - \beta^2)}{\beta^2}. \quad (7.2)$$

Events of interest in the analysis were kept using a selection on the mass of the particles of interest (K^+ or π^-). A typical mass squared spectra for positive particles in CLAS is shown in 7.2. The particle selection cuts were kept wide for this initial stage, as refinements to the energy and momentum reconstruction of the particles can be carried out at a later stage, as described in Section 6.4.

Figure 7.2: Histogram showing the mass squared distribution of positive particles after skimming (*log scale*). The selection windows are shown in red.

If we consider Figure 7.2, the well defined peaks of the pion (π^+), kaon (K^+) and proton (p) can clearly be seen. For the channel of interest, the final state particles are initially selected using charge in tandem with the chosen M^2 windows. The following M^2 windows were chosen:

- Kaon : $0.1 < M_{K^+}^2 < 0.49 \text{ GeV}^2/c^4$ (PDG $0.244 \text{ GeV}^2/c^4$).
- Pion : $0.0 < M_{\pi^-}^2 < 0.1 \text{ GeV}^2/c^4$ (PDG $0.0196 \text{ GeV}^2/c^4$).

Particles which do not meet these mass requirements are removed from the analysis. Figure 7.3 shows the mass squared distribution for all (positive, negative and uncharged) particles. The distribution shows similar general features to Figure 7.2 but there is a large neutron spike at seen at $\sim 0.875 \text{ GeV}^2/c^4$. The identification of neutrons is discussed in 7.2.4.

Figure 7.3: Histogram showing the mass squared distribution of all particles after skimming (*log scale*).

Once the mass squared windows are applied, these candidates particles are assigned a preliminary particle identification. Further cuts improve the quality of this identification and remove the background which is present.

7.2.4 Neutron Selection

Neutral particles in CLAS are assigned a nominal value ($0.939 \text{ GeV}/c^2$), therefore neutrons and photons must be separated. This separation is achieved using the particle β ; the distribution for neutral particle β is shown in Figure 7.4.

Figure 7.4: β distribution for neutral candidates. The selection cut is shown in red, with neutrons falling on the left and photons on the right.

The photon peak can be clearly seen centred around $\beta = 1$, with neutron populating the lower β regions. In order to decide where the cut should be placed to differentiate neutrons and photons, the peak was fitted and the width, σ , extracted. To eliminate the photons from the sample, a 3σ wide exclusion window was applied to the data. From the extracted σ this corresponded to:

- Neutrons $\beta_n < 0.9$.

Particles which do not meet this requirement in β are removed from the analysis.

7.2.5 Topology

Following the initial particle identification, a cut on the channel topology for the channel of interest was employed. This cut is dependent on the multiplicity of the final state:

- If 2 final state particles; these must have the identities of $K^+\pi^-$.
- if 3 final state particles; these must have the identities of $K^+\pi^-n$.

Events which do not meet these requirements are removed from the analysis.

7.2.6 Momentum vs $\Delta\beta$

Further refinements to the particle ID are carried out by utilising the correlation between the independently measured momentum (from the DC) and the measured time-of-flight (from the SC). The momentum vs β distribution for positive and negative particles is shown in Figure 7.5. The proton and pion bands are clearly seen in red, while the kaons can be made out in between. The other bandings, having a more horizontal locus, can be attributed to misidentified particles. The shadows in the bands (i.e. a mirror band occurring at a different β) are attributed to events where the photon was taken to be from the wrong beam bucket and as the time-of-flight was calculated by using an incorrect start time. The error in the momentum from the track curvature is of the order of $\sim 1\%$, while in β it is up to $\sim 5\%$ as the uncertainty comes from the time-of-flight and path length [67].

Figure 7.5: Momentum vs β distribution for positive and negative particles (*log scale*).

Figure 7.5 shows that at higher momenta the kaon and pion candidates begin to converge, particularly at $> 1.5 \text{ GeV}/c$. At these higher momenta their separation becomes difficult due to the worsening β resolution and the proximity of their loci.

To allow more simple particle ID regions to be identified, it is useful to present

the data as the difference between the calculated and measured β , referred to as $\Delta\beta$.

The calculated β is obtained using the measured momentum and the PDG mass of the particle. By using the PDG mass, we assume that the particle ID is correct and the mass is absolute. $\Delta\beta$ is calculated as follows:

$$\beta_{meas} = \frac{path_{DC}}{ct_{ToF}}, \quad (7.3)$$

$$\beta_{calc} = \sqrt{\frac{p^2}{m_{PDG}^2 + p^2}}, \quad (7.4)$$

$$\Delta\beta = \beta_{meas} - \beta_{calc}. \quad (7.5)$$

$\Delta\beta$ is calculated separately for the kaon and pion candidates, with the distributions plotted against momenta, as shown in Figure 7.6.

Figure 7.6: Momentum vs $\Delta\beta$ distribution (*log scale*) for K^+ candidates (upper) and for π^- candidates (lower).

If we consider the kaon plot, we can see that misidentification of π^+ at this stage of the analysis is a large problem. Also present are events which correspond to photons from adjacent beam buckets, since no timing selections have yet been implemented. We can remove the obvious misidentified pions, the curved band, by using 2D momentum dependent $\Delta\beta$ cuts, this is kept deliberately wide as its only purpose is for misID removal.

For the π^- candidates the selection is already relatively clean and we use a simple 3σ cut in $\Delta\beta$.

After the boundaries of the cuts were decided they were applied to the sample,

the result of which can be seen in Figure 7.7.

Figure 7.7: Momentum vs $\Delta\beta$ distribution (*log scale*) for K^+ candidates (upper) and π^- candidates (lower) after cuts in $2D$.

Particles which do not meet these requirements in $\Delta\beta$ and momenta are removed from the analysis.

7.2.7 Candidate Photons and Tagger ID

Removing “accidental events” is used to clean up the timing spectra before more formal timing cuts are introduced. Key variables used for this are NGRF and

TAGRID from the GPID bank. NGRF stores the number of candidate photons associated with an event, while TARGID stores an indexing to the TAGR bank indicating which candidate photon corresponds to a particle. The requirements introduced were:

- Number of candidate photons in same RF bucket, must be 1 for K^+ and π^- candidates.
- The tagger ID of the event must be the same for both the K^+ and π^- , showing they came from the same photon.

Events which do not meet these requirements are removed from the analysis.

7.2.8 Photon Identification

An important step in selection is to clarify the photon corresponding to an event. In order to do this, it must be shown that the timing from the tagger and ToF are consistent i.e. their difference is in the form of a Gaussian centred around zero. The tagger and the photon flight time are used to calculate the arrival time of the photon at the vertex, t_γ . The ToF and tracking information are used to calculate the vertex time from CLAS, t_v . The difference between these quantities should be minimised in order to identify the photon which most accurately represents the event.

The CLAS time-of-flight vertex time is calculated as:

$$\begin{aligned} t_v &= t_{SC} - t_{est}, \\ t_v &= t_{SC} - \frac{l}{c\beta}, \end{aligned} \tag{7.6}$$

where t_{SC} is the time-of-flight with respect to the global start time, measured by the scintillation counters (SC) and t_{est} is the estimated time-of-flight, obtained by using the length of the particle track from the vertex to the SC, l .

The photon time is calculated from the time of the photon to arrive at the target centre, t_{centre} , and the time for the photon to propagate from the target centre to the interaction vertex, t_{prop} :

$$t_\gamma = t_{centre} + t_{prop}. \tag{7.7}$$

The propagation time can be expanded:

$$t_{prop} = \frac{z_{vert} + d_{targ}}{c}, \quad (7.8)$$

where z is the coordinate of the event vertex on the beam axis and d_{targ} is the offset of the centre of the target on the z -axis². This then gives:

$$t_{\gamma} = t_{centre} + \frac{z_{vert} + z_{targ}}{c}. \quad (7.9)$$

Some offset in the x and y directions will also be present due to the spot size of the beam (of order cm) but it should be noted that these will be comparable to the vertex resolution.

The photon coincidence time can then be calculated using Equation 7.6 and 7.9:

$$\Delta t = t_{\gamma} - t_v. \quad (7.10)$$

This is shown in Figure 7.8 for both kaons and pions. This plot also gives some indication of how well the time-of-flight and tagger were calibrated, as the times should be distributed around zero; in this respect, this plot is a useful diagnostic aid during iterations of calibration.

We see a clear structure oscillating at a characteristic 2 ns ; the structure is a symptom of the beam timing, indicating these are photons from other beam buckets taken in as a random correlation between a particle and the event trigger.

²In the $g14$ run period, the offset for the $HDice$ target was -7.5 cm .

Figure 7.8: K^+ (upper) and π^- (lower) timing difference between the start counter and time-of-flight scintillators.

There is a clear background present in the kaon distribution, which is partially derived from the dependence of the vertex time on the momentum but the underlying background gives a much clearer indication there are many misidentified pions in the sample. From these plots, it is clear the pions would give a cleaner timing selection due to the smaller background. The main consideration in doing this is, if we use this do we still select the same the best photon? A study addressing this was done and this method actually selects the same photon $\sim 99\%$ of the time.

For many events there will be more than one photon registered in the tagger.

It is important to consider which of these is the *best* photon for the event. This is done by minimising the timing difference between the vertex and the photon time. As well as misidentification, the kaons are influenced by pions which come from hyperon decays. This occurs because the hyperon can travel some distance before decaying, giving a displaced vertex for these pions. It is thought that this is the cause for the asymmetric kaon timing spectrum seen.

The best photon for both the kaon and pion candidates are shown in Figure 7.9.

Figure 7.9: K^+ (upper) and π^- (lower) timing difference using the selected *best photon*. The selection cut is shown in red.

Once the best photon is chosen all external beam bucket structure is removed, although in the case of the kaon other candidates from outside the main peak can still be seen. Because of this, the time correlation for the event was taken from the pion alone.

The pion peak was fitted with a Gaussian and σ extracted; a 3σ selection was introduced to eliminate the background within the tails of the distribution. These backgrounds are generally from random hits which are correlated to an event but which do not correspond to the triggered event in CLAS. These events are removed by requiring that only a single photon hit is associated with the central beam bucket.

- $|\Delta t_{\pi-}| < 1.5 \text{ ns.}$

Events which do not meet this timing requirement are removed from the analysis.

7.2.9 Data Corrections

At this stage in the analysis, tagger, momentum and Eloss corrections are applied to the data. These corrections were outlined in Section 6.4.

7.2.10 Corrected $\Delta\beta$ Selection

After the corrections to the data were complete, another $\Delta\beta$ selection could be done. The $\Delta\beta$ distributions after the data corrections are shown in Figure 7.10. These plots use the newly corrected β to construct this $\Delta\beta$.

Figure 7.10: Momentum vs $\Delta\beta$ distribution (*log scale*) for K^+ (upper) and π^- (lower) after data corrections.

For the case of the K^+ , the background of misidentified events has been strongly suppressed. Though pions can be seen in the curving loci coming from above, leave some residual signal in the K^+ selection region at high momenta. This means that even a subtle use of momentum dependent cuts will not sufficiently remove the background. Due to this fact a simple linear cut was used, as a more complex and sophisticated cut would not yield any great benefits. After a Gaussian fit, 3σ cuts were used on the main peaks, allowing the outlying misidentified particles to be removed. Note that in Figure 7.11 there is still background present, particularly at higher momenta, which is considered in

forthcoming sections.

Figure 7.11: Momentum vs $\Delta\beta_{corrected}$ distribution (*log scale*) for K^+ (upper) and π^- (lower) after a further selection cut.

- $|\Delta\beta_{K^+\pi^-}| < 0.036$.

Events which do not meet this requirements on $\Delta\beta$ are removed from the analysis.

7.2.11 Reaction 4-Vectors

Considering the 4-vectors of the particles involved³, we can represent the $K^+\Sigma^-$ reaction as:

$$\underline{\underline{\gamma}} + \underline{\underline{n}} = \underline{\underline{K}}^+ + \underline{\underline{\Sigma}}^-, \quad (7.11)$$

which due to 4-momentum conservation is equivalent to:

$$\underline{\underline{\gamma}} + \underline{\underline{n}} = \underline{\underline{K}}^+ + \underline{\underline{\pi}}^- + \underline{\underline{n}}. \quad (7.12)$$

However since we have difficulty detecting the neutron, the Σ^- must be reconstructed from the missing mass of the kaon, rather than the invariant mass of the π^-n system, leading to:

$$\begin{aligned} \underline{\underline{\Sigma}}^- &= \underline{\underline{\gamma}} + \underline{\underline{n}} - \underline{\underline{K}}^+, \\ MM(K^+) &= \underline{\underline{\gamma}} + \underline{\underline{n}} - \underline{\underline{K}}^+. \end{aligned} \quad (7.13)$$

This allows for the reconstruction of the Σ^- . Similarly, the neutron may be reconstructed using K^+ and π^- :

$$\begin{aligned} \underline{\underline{n}}_{recon} &= \underline{\underline{\gamma}} + \underline{\underline{n}} - \underline{\underline{K}}^+ - \underline{\underline{\pi}}^-, \\ MM(K^+\pi^-) &= \underline{\underline{\gamma}} + \underline{\underline{n}} - \underline{\underline{K}}^+ - \underline{\underline{\pi}}^-. \end{aligned} \quad (7.14)$$

7.2.12 Misidentification of Particles

A common problem with all kaon analyses in CLAS is the ***misID***entification (misID) of pions as kaons. Although initially we established a wide M_K^2 window, there is still contamination from pions - and protons. The backgrounds can be thought of in two categories:

- background correlated with the Σ^- .
- background uncorrelated with the Σ^- .

³Where we use the notation $\underline{\underline{X}}$ to denote the 4-vector of particle X .

Figure 7.12: Correlated background seen in the neutron mass spectrum, reconstructed using the missing mass method.

The mass of the neutron, as reconstructed from the missing mass of $K^+\pi^-$, is shown in Figure 7.12. The correlated background appears as a bump peaking around $1.1 \text{ GeV}/c^2$, mainly coming from the reactions:

- $\gamma D \rightarrow K^{*+}\Sigma^-(p_s)$,
- $\gamma D \rightarrow K^+\Sigma^{*-}(p_s)$,

with K^{*+} and Σ^{*-} decaying into $K^+\pi^0$ and $\Sigma^-\pi^0$ respectively⁴. These therefore contribute to $\gamma D \rightarrow K^+\Sigma^-(p_s)$ with an additional final state π^0 .

The uncorrelated background is a smaller shoulder below $0.8 \text{ GeV}/c^2$ in the missing mass, related to misidentification, prominently from:

- $\gamma D \rightarrow \pi^+\pi^-n(p_s)$,
- $\gamma D \rightarrow \pi^+\pi^-n(p_s)\pi^0$,

where the π^+ is misidentified as our final state K^+ .

The method of using photon timing (Section 7.2.8) and momentum-dependent $\Delta\beta$ cuts (Sections 7.2.6 & 7.2.10) do remove large proportion of these misidentified

⁴It should be noted that the notation of (p_s) indicates the spectator proton within deuterium.

particles. However the sample of events selected is still not clean. Figure 7.13 shows the M^2 window for kaon candidates initially and after the timing/ $\Delta\beta$ selection; from this the reduction in the background is clearly shown. The final distribution however shows several features that indicate contamination, as highlighted in Figure 7.11.

Figure 7.13: Initial K^+ candidates (upper) in comparison to the K^+ candidates after selections performed using $\Delta\beta$ and photon timing (lower).

These background events are dealt with by implementing cuts in the following sections, specifically formulated to identify misidentified particles by looking reaction kinematics, including missing mass distributions and the reconstructed

(undetected) neutron mass.

7.2.12.1 Misidentification of π^+ as K^+

The misID of pions as kaons is the major source of background to be contended with in the $K^+\Sigma^-$ channel. In order to separate out the contribution from pions we can exploit the use of the particle PDG masses. The final state $K^+\pi^-$ can be considered for a single event as follows: What if the selected K^+ is really a misidentified π^+ , such that the final state is really $\pi^+\pi^-$? If we assign the ‘kaon’ to have the PDG mass of a pion we can look at a $2D$ representation, allowing us to separate events where the kaons are correctly identified from events where this is incorrect. In this vein Equation 7.14 becomes:

$$MM(K_{\pi_{PDG}}^+) = \underline{\gamma} + \underline{n} - \underline{K_{\pi_{PDG}}^+}, \quad (7.15)$$

where $K_{\pi_{PDG}}^+$, is a kaon candidate which has been assigned the PDG mass of the pion.

This idea can be simply extended, when the reconstruction of the undetected neutron is considered, from Equation 7.14:

$$MM(K_{\pi_{PDG}}^+ \pi^-) = \underline{\gamma} + \underline{n} - \underline{K_{\pi_{PDG}}^+} - \underline{\pi^-}. \quad (7.16)$$

The 4-vectors outlined in Equations 7.15 and 7.16 can be plotted in $2D$, as in Figure 7.14.

Figure 7.14: Missing mass of $K^+\pi^-$ vs $'K^+\pi^-$, where $'K^+$ has the PDG mass of a π^+ . The selection cut is shown in red.

Here the pion band can be seen corresponding to $\sim 0.9 \text{ GeV}/c^2$ in $MM('K^+\pi^-)$. A horizontal cut may be applied at 1.0 GeV to remove much of its contribution. The remaining background is not as cleanly separated and will need to be removed by another method.

- $MM(K^+\pi_{PDG}^+\pi^-) > 1.0 \text{ GeV}$.

Events which do not meet this requirement are removed from the analysis.

7.2.12.2 Misidentification of K^- as π^-

$$MM(K^+\pi_{K_{PDG}}^-) = \underline{\gamma} + \underline{n} - \underline{K}^+ - \underline{\pi}_{K_{PDG}}^-. \quad (7.17)$$

We can consider kaons which are misidentified as pions in a similar way, as in Equation 7.17, although this contribution is far lower than that shown in Section 7.2.12.1. This is plotted in the same way, shown in Figure 7.15.

Figure 7.15: Missing mass of $K^+\pi^-$ vs $K^+\pi'^-$, where ' π^- ' has the PDG mass of a K^- .

The main central peak corresponds to a reconstructed neutron while the right-hand peak shows a neutron plus an additional π^0 . These come from the decays; $\gamma D \rightarrow K^{+*}\Sigma^-(p_s)$ and $\gamma D \rightarrow K^+\Sigma^{*-}(p_s)$. The events we wish to separate are the uncorrelated background present above the neutron peak, as these are kaons which have been misidentified as pions. The majority of this uncorrelated background was removed using a linear cut, shown in Figure 7.16.

Figure 7.16: Missing mass of $K^+\pi^-$ vs $K^+\pi^-$, after the 2D selection cut has been applied.

7.2.12.3 Misidentification of p as K^+

The final, and smallest, contribution from misidentified particles is from protons being falsely identified as kaons. Again, the missing mass can be considered as:

$$MM(K_{pPDG}^+ \pi^-) = \underline{\underline{\gamma}} + \underline{\underline{n}} - \underline{\underline{K}}_{pPDG}^+ - \underline{\underline{\pi}}^-. \quad (7.18)$$

Figure 7.17: Missing mass of $K^+\pi^-$ vs ' K^+ ' π^- , where ' K^+ ' has the PDG mass of a p .

This 4-vector is plotted as before and similarly we remove the left peak.

Figure 7.18: Missing mass of $K^+\pi^-$ vs ' K^+ ' π^- , after the 2D selection cut has been applied.

7.2.13 $\Sigma\Lambda$ Separation

In $1D$, we can consider the spectrum of the reconstructed Σ^- , as in Figure 7.19. This explicitly shows the missing mass from the selected kaon. Although there is a clear peak of the Σ^- , there are still peaks present from Λ and $\Sigma^*(1385)$ channels.

Figure 7.19: Missing mass spectrum of the K^+ , clearly showing the Λ , Σ^- and $\Sigma(1385)$.

These background channels decay as follows:

- Λ

$$\begin{aligned} p\pi^- &\propto 63.9\%, \\ n\pi^0 &\propto 35.8\%. \end{aligned} \tag{7.19}$$

- $\Sigma(1385)$

$$\begin{aligned} \Lambda\pi &\propto 87.0\%, \\ \Sigma\pi &\propto 11.7\%, \\ \Lambda\gamma &\propto 1.25\%. \end{aligned} \tag{7.20}$$

This distribution can be considered far more clearly when plotted in $2D$ with $MM(K^+\pi^-)$, as shown in Figure 7.21.

Figure 7.20: 2D plot of the reconstructed Σ^- [$MM(K^+)$] vs. the reconstructed neutron [$MM(K^+\pi^-)$].

In this plot, the Σ^- (*PDG* 1198 *MeV*) can be seen; in addition the Λ (*PDG* 1116 *MeV*) is also present at lower mass, although clear separation can only be seen in 2D. Considering the 2D distribution also clearly shows a contribution from Σ^0 (*PDG* 1193 *MeV*), where there is an additional π^0 in the final state. The Σ^0 decays as follows:

- Σ^0

$$\Lambda\gamma \propto 100\%. \quad (7.21)$$

The Σ^- can then be isolated using a linear cut in 2D, to remove contributions from Λ and Σ^0 . The distribution after this cut is shown in Figure 7.21.

Figure 7.21: 2D plot of the reconstructed Σ^- vs the reconstructed neutron after introducing a linear 2D selection cut. Both the Λ and Σ^0 peaks are removed, leaving only Σ^- .

7.2.14 Neutron Reconstruction

In order to reconstruct the Σ^- , only the final state kaon is required, however this method comes with a large amount of associated background, mostly in the form of misidentification. To overcome this it is key to also detect the final state pion, in order to reconstruct the neutron from the non-exclusive reaction. Using the missing mass technique, we are able to reconstruct the neutron from the kaon and the pion produced from the Σ^- decay.

The missing mass distribution from Equation 7.14 can be seen in Figure 7.22. The neutron peak (PDG 940 MeV) is clear, although a higher mass background can be seen.

Figure 7.22: Reconstructed neutron using the missing mass technique $[MM(K^+\pi^-)]$ after misID selections have been applied.

The nature of this background is clearer when presented in $2D$ versus momentum of the K^+ , Figure 7.23. The neutron peak was fitted with a Gaussian, in $1D$, and σ extracted. A study was undertaken to show affect of varying σ around this peak⁵.

⁵After the study was concluded a selection cut of 2σ was chosen.

Figure 7.23: Reconstructed neutron using the missing mass technique vs Momentum. The selection cut is shown in red.

- $MM(K^+\pi^-) < 1.0 \text{ GeV}/c^2$.

Events which do not meet this requirement are removed from the analysis.

7.2.15 Quasi-free Selection for the Complete Final State

Considering the reaction $\gamma D \rightarrow K^+\Sigma^-(p_s)$ is a different proposal than $\gamma n \rightarrow K^+\Sigma^-$. There are two contributions to this channel, one where the proton is a spectator to the reaction and one where it has an interaction with the produced particles. The former is the quasi-free reaction, where the proton momentum distribution is mainly dominated by the Fermi motion; the latter represents rescattering in which the proton is hit by a kaon or a sigma and gains momentum.

If the final state neutron can be detected, the proton in the deuterium nucleus can be reconstructed. The hope is then that quasi-free regions in this proton can be identified such that the proton is truly a spectator, p_s . For this the spectator proton will recoil with the Fermi momentum of the initial state. In our case, the inability to detect the final state neutron without compromising the available statistical data sample, means that this is not applicable to the main data set but as a formality this procedure will be briefly discussed. The 4-vector equation can be constructed:

$$\underline{\underline{\gamma}} + \underline{\underline{D}} = \underline{\underline{p}}_s + \underline{\underline{K}}^+ + \underline{\underline{\pi}}^- + \underline{\underline{n}}. \quad (7.22)$$

Provided the final state neutron can be detected, the undetected proton can then be reconstructed using the missing 4-momentum method:

$$\underline{\underline{p}}_{\text{missing}} = \underline{\underline{\gamma}} + \underline{\underline{D}} - \underline{\underline{K}}^+ - \underline{\underline{\pi}}^- - \underline{\underline{n}}. \quad (7.23)$$

The distributions of the reconstructed spectator proton mass and momentum are shown in Figures 7.24 and 7.25 respectively.

Figure 7.24: Missing mass of the spectator proton, p_s , from the missing mass technique.

Figure 7.25: Missing momentum of the spectator proton, p_s . The selection cut is shown in red.

The form the missing momentum the quasi-free events can be isolated. The Fermi motion inside the deuteron nucleus results in final state interactions having a greater contribution at high momenta. There should therefore be a restriction placed upon the momentum of the (reconstructed) spectator proton.

- Momentum $p_s < 0.2 \text{ GeV}/c$.

For the cases where the neutron is detected, events which do not meet this requirement are removed from the analysis.

7.2.16 $K^+\Sigma^-$ Threshold Energy

When considering the $K^+\Sigma^-$ channel, in order to create the final state particles there is a minimum photon energy required. This can be calculated and the minimum threshold energy for the incident photon applied. A typical distribution of the photon energies is given in Figure 7.26.

Figure 7.26: A typical spectrum of photon energy when using circularly polarised beam. The selection cut is shown in red.

The energy-momentum relation is used to relate the total energy E , rest mass m_0 and momentum p :

$$E^2 = (pc)^2 + (m_0c^2)^2, \quad (7.24)$$

where c is the speed of light. This can be reduced, using natural units to:

$$E^2 = p^2 + m_0^2. \quad (7.25)$$

It can then be extended into a many-body equation:

$$\left(\sum_n^{n=1,2,\dots} E_n \right)^2 = \left(\sum_n^{n=1,2,\dots} p_n \right)^2 + (m_0)^2. \quad (7.26)$$

Specifically, considering the final state of $K^+\Sigma^-$, this becomes:

$$(E_\gamma + m_n)^2 = (p_\gamma + p_n)^2 + (m_{K^+} + m_{\Sigma^-})^2. \quad (7.27)$$

We assume that the neutron is at rest in this case for simplicity (although in reality it will have some intrinsic Fermi momentum). This leads to:

$$E_\gamma^2 + 2E_\gamma m_n + m_n^2 = p_\gamma^2 + (m_{K^+} + m_{\Sigma^-})^2, \quad (7.28)$$

$$E_\gamma = \frac{(m_{K^+} + m_{\Sigma^-})^2 - m_n^2}{2m_n}.$$

Substituting the *PDG* particle masses, we find the minimum energy required to produce this final state.

- Threshold energy for photons: $E_\gamma > 1.055 \text{ GeV}$.

Events which do not meet this requirement are removed from the analysis.

7.2.17 Event z -vertex

Events must be consistent with a vertex originating from the polarised target material rather than any of the surrounding unpolarised material, thus a selection in the z -vertex must be added. In the case of our reaction channel only the final state kaon originates from the target, whereas the pion has a displaced vertex, as this is a decay product of the Σ^- which will have a decay distance of $c\tau \sim 4.43 \text{ cm}$. Although this may still decay within the target area, there is a considerable proportion of Σ^- decays which will take place outside of the target. Therefore it would be unwise to exclude all pion event from out-with the target, as these may well be consistent with good $K^+\Sigma^-$ events.

The events from the *HD* were selected by simply looking at the z -vertex and initiating a cut from -10.5 to -5.5 cm , this excludes events originating from the target cell windows. The distribution of kaons in the z -vertex is shown in Figure 7.27.

Figure 7.27: K^+ z -vertex from the centre of CLAS. The selection cut is shown in red.

- $(-10.5) < Z_{vert}^{K^+} < (-5.5) \text{ cm}.$

Events which do not meet this requirement are removed from the analysis.

7.2.17.1 Cell Contributions

It is important to note that although a cut in the z -vertex has been performed, there are still unpolarised events within the sample present from the empty target. In order to maintain the low temperatures required in the cell, the design required aluminium cooling wires to be placed inside and the cell walls to be made of KelF. These materials contain only unpolarised protons and neutrons and so events which consider these as the target proton or neutron will have no analysing power.

Runs with an empty target (containing no polarised material) were conducted in order to assess the contribution from the cell. Note that these runs were conducted for each torus setting ($+1920 \text{ A}$ and -1500 A). The z -vertex distribution from the empty target can be compared to the production target. The peaks outside the polarised target area were normalised by considering the integrals of the region -2 to $+30 \text{ cm}$. The empty target data was then scaled to reflect the true contribution in the data, as shown in Figure 7.28. An explicit discussion of the method to account for this target background is given in Section 8.4.

Figure 7.28: K^+ z vertex from the centre of CLAS, compared with scaled empty target data.

7.2.18 Fiducial Cuts

The segmented design of the CLAS detector, using six superconducting coils of the torus magnet leads to low acceptance regions around the sector boundaries, these can be seen in Figure 7.29. These regions are primarily used for placement of cabling and electronics for CLAS sub-detectors, monitoring and are considered as dead regions of the detector. These acceptances are non-uniform and difficult to model accurately as the magnetic field changes quickly and is inaccurately mapped.

Figure 7.29: K^+ polar vs azimuthal angles (*log scale*).

Events which are detected around these areas tend to have much larger uncertainties and cannot be thought of as reliable, so a standard cut is implemented to remove the regions close to the coils. This selection introduces a 5° band on the azimuthal angle around each coil, the effect of this cut is shown in Figure 7.30.

Figure 7.30: K^+ polar vs azimuthal angles, after the removal of the fiducial regions around the CLAS sectors (*log scale*).

The areas removed around the coils are as detailed in Table 7.2.18.

Coil	Angular Range Removed ($^{\circ}$)
1	25 – 35
2	85 – 95
3	145 – 155
4	205 – 215
5	265 – 275
6	325 – 335

Table 7.1: Removed azimuthal regions.

7.2.19 Final Reconstructed Σ^- Selection

The particles to be used in the construction of the $\mathbb{E}$ double-polarisation observable are finally chosen with a selection cut on the mass of the reconstructed Σ^- . A typical distribution of the events are shown in Figure 7.31.

Figure 7.31: Events which have been selected, reconstructed as Σ^- , using the $MM(K^+)$. The selection cut is shown in red.

This is simply fitted with a Gaussian and a 3σ cut applied, giving the final selection of particles used in the construction of the asymmetry.

- $1.10 < M_{\Sigma^-} < 1.30 \text{ GeV}/c^2$.

Events which do not meet this requirement are removed from the analysis.

7.2.20 Three particle final state

The desired final state to identify is the full $K^+\pi^-n$, rather than the incomplete $K^+\pi^-$. The detection efficiency of neutrals in CLAS is low and combining this with the relatively low cross section of the channel, this leaves too few events for a useful analysis.

The Σ^- can be reconstructed given a three particle final using both the missing-mass of the kaon, Figure 7.32, and the invariant mass of the π^-n system, Figure 7.33.

Figure 7.32: Events which has been selected, reconstructed as Σ^- , where the final state neutron has been identified.

Figure 7.33: Reconstructed Σ^- , using the invariant mass method $[M(n\pi^-)]$.

Comparing these plots to the final selection in the two particle final state, we find a difference in statistics of a factor ~ 20 . This would be a preferable final state to analyse, in terms of minimising background and taking advantage of the ability to use the invariant mass, as has been done in measurements of the cross section [60], however the statistics available for this work does not make this viable.

7.2.21 Summary

A summary of the applied selection cuts and corrections in this chapter are outlined below.

Cut	Constraint
Particle Multiplicity	2 or 3 final state particles
Tagger Condition	Events must have a valid hit in the tagger
DC Condition	For charged particles require an event in the DC
SC Condition	For charged particles require an event in the ToF
EC Condition	For neutral particle require an event in the EC
Charge Removal	For charged particles, require only one unit of charge
Kaon M^2	$0.1 < M_{K^+}^2 < 0.49 \text{ GeV}^2/c^4$
Pion M^2	$0.0 < M_{\pi^-}^2 < 0.1 \text{ GeV}^2/c^4$
Neutron β	$\beta_n < 0.9$
Topology	Final state $K^+\pi^-$ or $K^+\pi^-n$
Kaon $\Delta\beta$	Momentum dependant, see 7.2.6
Pion $\Delta\beta$	$ \Delta\beta_{\pi^-} < 0.051$
Candidate Photons	$NGRF_{K^+} = NGRF_{\pi^-} = 1$
Event best photon	$TAGRID_{K^+} = TAGRID_{\pi^-}$
Best photon selection	$ \Delta t_{\pi^-} < 1.5 \text{ ns}$
Post correction $\Delta\beta$	$ \Delta\beta_{K^+/\pi^-} < 0.036$
Misidentification π^+	Remove π^+ selected as K^+
Misidentification K^-	Remove K^- selected as π^-
Misidentification p	Remove p selected as K^+
Σ^-/Λ Separation	see 7.2.13
Reconstructed neutron	$MM(K^+\pi^-) < 1.0 \text{ GeV}/c^2$
Threshold energy	$E_\gamma > 1.055 \text{ GeV}$
Z-vertex	$-10.5 < z_{K^+} < -5.5 \text{ cm}$
Fiducial	$\pm 5^\circ$ around sector boundaries
Sigma mass	$1.10 < M_{\Sigma^-} < 1.30 \text{ GeV}/c^2$

Table 7.2: Table summarising the particle identification cuts of the $K^+\Sigma^-$ channel.

Chapter 8

Extraction of Polarisation Observables

This chapter outlines the extraction of the double-polarisation observable $\mathbb{E}$ for the reaction $\gamma n \rightarrow K^+ \Sigma^-$ from the $g14$ experimental data.

8.1 Introduction

The polarised cross section, $\frac{d\sigma}{d\Omega}$, is related to the unpolarised cross section, $(\frac{d\sigma}{d\Omega})_0$, by:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - P_\gamma P_\oplus \mathbb{E}), \quad (8.1)$$

where P_γ is the polarisation of incident photon and $P_\oplus$ is the polarisation of the target. The observable $\mathbb{E}$ can be extracted from the beam-asymmetry [103], $\mathcal{A}$, which is defined as:

$$\mathcal{A} = \frac{N_{\frac{1}{2}}(\rightarrow\leftarrow) - N_{\frac{3}{2}}(\leftarrow\leftarrow)}{N_{\frac{1}{2}}(\rightarrow\Rightarrow) + N_{\frac{3}{2}}(\leftarrow\Rightarrow)}, \quad (8.2)$$

where N represents the appropriate number of events for the corresponding target ($\rightarrow$) and beam ($\Rightarrow$) polarisation vectors. The beam-asymmetry is then used in conjunction with the target and photon polarisations to give an expression for the double-polarisation observable $\mathbb{E}$:

$$\mathbb{E} = \frac{1}{P_\gamma P_\oplus} \mathcal{A}. \quad (8.3)$$

8.2 Angle and Energy Bin Choice

The extraction of the $\mathbb{E}$ observable from the $\gamma n \rightarrow K^+ \Sigma^-$ reaction is considered as a function of E_γ (lab frame) and $\cos\theta_{K^+}^{CM}$ (centre-of-mass frame).

Figure 8.1: Diagram showing the kinematics for the $\gamma n \rightarrow K^+ \Sigma^-$ in the centre-of mass frame [54].

The binning of each of these must be carefully chosen. There are were two possibilities considered:

- Bin according to some standard spacing of bin centres.
- Bin according to equal bin statistics.

In the first case, some bins can suffer from very low statistics and therefore be of little use in terms of analysing power. In the second case, bins are often asymmetric and may be problematic when integrating over large intervals. Therefore it can be seen that there is a balance to consider between these two binning methods.

8.2.1 E_γ Binning

The binning in E_γ , was chosen to be 200 MeV. This was chosen after considering the total statistics available to the channel. Although more bins are preferable, this would mean that the errors within each E_γ bin would be considerably larger. Fortunately, the $\mathbb{E}$ observable does not evolve quickly in terms of photon energy and at the scale of 200 MeV there is limited movement. The asymmetry predictions are considered explicitly in Section 8.9. The full photon energy spectrum is shown in Figure 8.2.

Figure 8.2: Energy spectrum of photons, after all event selections have taken place. The binning is shown in red.

The photon energy bins chosen are shown in Table 8.1, along with the respective statistics of each bin.

8.2.2 $\cos\theta_{K^+}^{CM}$ Binning

The binning in $\cos\theta_{K^+}^{CM}$ was selected using symmetric bins over the complete angular range of $\theta_{K^+}^{CM}$ ($\cos\theta_{K^+}^{CM} = [-1, 1]$). Again, due to statistics a relatively small number of angular bins were selected. Five angular bins per photon energy were used to extract the measurement of $\mathbb{E}$. The distribution of $\cos\theta_{K^+}^{CM}$ over all energies is shown in Figure 8.3.

E_γ Bin	Energies (GeV)	Percentage of Events (approx. %)
1	1.1-1.3	12.7
2	1.3-1.5	27.2
3	1.5-1.7	25.4
4	1.7-1.9	15.3
5	1.9-2.1	10.2
6	2.1-2.3	9.2

Table 8.1: Energy bins (200 MeV width) used for the polarisation observable measurement.

Figure 8.3: Centre-of-mass angular distribution for K^+ . The binning is shown in red.

From this distribution, it is clear that it is the central bins which contain most of the events, and although this is roughly symmetric, it is skewed towards the backward angles. An equal bin width was chosen in order to maintain the good statistics in the central bins. The bins were chosen to be of width 0.4 in $\cos \theta_{K^+}^{CM}$; these are shown explicitly in Table 8.2.

$\cos \theta_{K^+}^{CM} \theta$ Bin	Values	Percentage of Events (approx. %)
1	(-1.0)-(-0.6)	7.3
2	(-0.6)-(-0.2)	19.7
3	(-0.2)-0.2	36.0
4	0.2-0.6	31.1
5	0.6-0.8	5.9

Table 8.2: Angular bins (0.4 width) used for the polarisation observable measurement.

8.3 Asymmetry of Empty (Unpolarised) Targets

A first test of the integrity of the data and analysis method is to extract the asymmetry from the unpolarised (or empty) target. This of course should be consistent with zero as the target cell itself is made of only non-polarised protons and neutrons. The analysis also allows these events to be removed or accounted for when calculating the value of $\mathbb{E}$, as these target support structures will still contribute to the yield with the polarised material in place.

The plots given in Figures 8.4 - 8.7 show the $\mathbb{E}$ observable across all energy bins along with a linear fit for the *emptyA* period, the results of which are provided in Table 8.3. Similar results are shown for the *emptyB* period in Figures 8.8 - 8.11, with the results shown in Table 8.4. It should be noted that empty bins correspond to points which are considerably non-zero, with large associated error bars; as such, these are not included in the plot area.

Figure 8.4: $\mathbb{E}$ double-polarisation observable for empty target period A: *all energies* (1.1-2.3 GeV).

Figure 8.5: $\mathbb{E}$ double-polarisation observable for empty target period A: 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 8.6: $\mathbb{E}$ double-polarisation observable for empty target period A: 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 8.7: $\mathbb{E}$ double-polarisation observable for empty target period A: 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

Empty Target A		
E_γ Bin (GeV)	Fit value	Fit Error
All Energies	-0.04	0.06
1.1-1.3	0.10	0.26
1.3-1.5	-0.04	0.14
1.5-1.7	0.10	0.14
1.7-1.9	-0.18	0.16
1.9-2.1	-0.01	0.16
2.1-2.5	-0.01	0.18

Table 8.3: Summary of linear fitting to $\mathbb{E}$ double-polarisation observable for the empty target A.

Figure 8.8: $\mathbb{E}$ double-polarisation observable for empty target period B: *all energies* (1.1-1.3 GeV).

Figure 8.9: $\mathbb{E}$ double-polarisation observable for empty target period B: 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 8.10: $\mathbb{E}$ double-polarisation observable for empty target period B: 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 8.11: $\mathbb{E}$ double-polarisation observable for empty target period B: 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

From these results, we can see that the target value of $\mathbb{E}$ is consistent with zero for both targets at all energies as there is no statistically significant deviation from zero. Therefore it can be said that an empty target cell does not contribute to the asymmetry.

Empty Target B		
E_γ Bin (GeV)	Fit value	Fit Error
All Energies	-0.06	0.15
1.1-1.3	-0.27	0.49
1.3-1.5	0.01	0.37
1.5-1.7	-0.29	0.35
1.7-1.9	0.51	0.48
1.9-2.1	0.27	0.44
2.1-2.5	-0.46	0.49

Table 8.4: Summary of linear fitting to $\mathbb{E}$ double-polarisation observable for the empty target B.

8.4 Removing the Empty Target

The cell walls of the HD target will remain present in the events selected. It is important to remove this contribution as these protons and neutrons are not polarised. Including these non-polarised events would lead to a dilution in the asymmetry and the value of the polarisation observable $\mathbb{E}$. To account for this effect, two paths can be taken. Firstly, the removal of the empty target data using a simple subtraction or secondly by diluting the asymmetry in order to account for the unpolarised material. Both methods are considered in this thesis and compared for consistency.

8.4.1 Empty Target Subtraction

The first method attempts to subtract the yield from the unpolarised empty target cell material before calculating the $\mathbb{E}$ observable. To achieve this, a suitable normalisation of the empty target data should be made to accurately assess its contribution to the polarised target run period.

The method adopted was to normalise the yield from the empty and polarised run periods for beam-line components downstream of the target cell. These should give the same contribution to the yield from both run periods if the normalisation is correct. A typical target distribution is shown in Figure 8.12; the spikes seen

at $z > 0$ cm are peaks which characterise the physical structure of the cell.

Figure 8.12: K^+ z vertex from the centre of CLAS, compared with scaled empty target data.

The yield of events, Y_{total} , from running with the polarised HD target can be expressed as having contributions from the polarised HD , Y_{HD} , and the non-polarised target cell, Y_{empty} :

$$Y_{total} = Y_{HD} + Y_{empty}. \quad (8.4)$$

This can then be separated into the aligned and anti-aligned helicity conditions, where the beam (magnitude 1) and target (magnitude 1/2) polarisation vectors are parallel and anti-parallel respectively:

$$\begin{aligned} Y_{HD}^{\frac{3}{2}} &= Y_{total}^{\frac{3}{2}} - \frac{\epsilon}{2} Y_{empty}, \\ Y_{HD}^{\frac{1}{2}} &= Y_{total}^{\frac{1}{2}} - \frac{\epsilon}{2} Y_{empty}, \end{aligned} \quad (8.5)$$

where we also introduce a normalisation factor, ϵ . The factor 2 is introduced to ensure a zero contribution to the asymmetry from the empty data.

The z component of the interaction vertex for empty target and full target runs are plotted, Figure 8.12. The histograms are scaled in order to account for differences in beam and run time¹.

It is clear that the yields from the downstream components in the beam-line are in good agreement between the the production data and the scaled empty target data. Target scaling is done in each E_γ bin rather than across the whole energy range, in an attempt to account for variations seen across the energy range. The scaled empty target events are then subtracted from the production data. This is the used in association with the average photon beam polarisation of the energy bin, giving the total scaling factor. Typical scalings for each energy bin are presented in Table 8.5.

E_γ Bin (GeV)	Empty Target Scaling
1.1-2.3	6.5
1.1-1.3	9.5
1.3-1.5	8.1
1.5-1.7	7.1
1.7-1.9	6.2
1.9-2.1	5.6
2.1-2.3	5.2

Table 8.5: Summary of the empty target scaling factor with respect to the selected photon energy bins, $1/(\bar{P}_\gamma P_T)$.

8.4.2 Empty Target Dilution Factor

The second approach to dealing with the empty target contribution is to leave the yield in the data sample used to calculate the asymmetry - but to calculate the resulting dilution of the extracted value due to the unpolarised contribution.

We can consider the yield of events, as in Equation 8.1, for the signal (S) and empty target (E) respectively:

¹Note that there exists a special case for the *Gold2* target, as there are less aluminium wires in the cell. As such, there is an additional factor of 0.7 introduced in the scaling.

$$Y_S^\pm = A_S^\pm(1 \mp \mathbb{E}P_\gamma P_\oplus), \quad (8.6)$$

$$Y_E^\pm = A_E^\pm(1 \mp \mathbb{E}P_\gamma P_\oplus), \quad (8.7)$$

where $\pm$ indicates the beam helicity and $A^\pm$ represents some acceptance present. As it has been shown in Section 8.3, the value of the $\mathbb{E}$ observable is consistent with zero for the empty target. Hence the second term within Equation 8.7 is in fact zero.

If the total yield of events for a process is considered, where there is some weighting of the true signal and empty target, Equations 8.6 and 8.7 can be combined as follows:

$$\begin{aligned} Y_T^\pm &= Y_S^\pm + Y_E^\pm, \\ &= A_S^\pm + A_E^\pm \mp A_S^\pm \mathbb{E}P_\gamma P_\oplus, \end{aligned} \quad (8.8)$$

$$Y_T^\pm = A_T^\pm \mp A_S^\pm \mathbb{E}P_\gamma P_\oplus, \quad (8.9)$$

where $A_S^\pm$ and $A_E^\pm$ have been enveloped into some total acceptance $A_T^\pm$. Using this, the total asymmetry of yields can be constructed, similarly to Equation 8.2:

$$\mathcal{A} = \frac{Y_T^- - Y_T^+}{Y_T^- + Y_T^+}, \quad (8.10)$$

$$= \frac{(A_T^- + A_S^- \mathbb{E}P_\gamma P_T) - (A_T^+ - A_S^+ \mathbb{E}P_\gamma P_T)}{(A_T^- + A_S^- \mathbb{E}P_\gamma P_T) + (A_T^+ - A_S^+ \mathbb{E}P_\gamma P_T)}.$$

We assume that the acceptance effects for both $\pm$ cases are equivalent, which then allows us to simplify to:

$$\mathcal{A} = \frac{A_S \mathbb{E}P_\gamma P_\oplus}{A_T}. \quad (8.11)$$

It is important to note that A_S is not known as the signal cannot be sufficiently separated from the total and empty data. $\mathbb{E}$ can then be written:

$$\begin{aligned}
 \mathbb{E} &= \frac{A_T}{A_S} \frac{1}{P_\gamma P_\oplus} \mathcal{A}, \\
 &= \frac{A_T}{A_T - A_E} \frac{1}{P_\gamma P_\oplus} \mathcal{A}, \\
 &= \frac{1}{\frac{A_T - A_E}{A_T}} \frac{1}{P_\gamma P_\oplus} \mathcal{A}, \\
 &= \frac{1}{1 - \frac{A_E}{A_T}} \frac{1}{P_\gamma P_\oplus} \mathcal{A}, \\
 \mathbb{E} &= \frac{1}{1 - \frac{\epsilon N_E}{N_T}} \frac{1}{P_\gamma P_\oplus} \mathcal{A},
 \end{aligned}
 \tag{8.12}$$

$$\tag{8.13}$$

where $N_{E/T}$ are the number of events in the empty target and total data respectively, while ϵ is the scaling factor of the empty target in regions outside the target material.

The additional factor present in Equation 8.13 represents the dilution factor and uses the calculated scaling of the empty target to account for the contribution of the target cell to the polarisation observable $\mathbb{E}$.

8.5 Extracting Observables for Kaon Photoproduction

The three parameters to consider in the extraction of the $\mathbb{E}$ observable are the beam-asymmetry ($\mathcal{A}$), the polarisation of the photon (P_γ) and the polarisation of the target ($P_\oplus$).

The beam-asymmetry is calculated as shown in Equation 8.2, while the target polarisation was calculated using NMR measurements during the run and are shown in Table 6.1. The photon polarisation however, is calculated on an event by event basis.

The circularly polarised photons are produced using a longitudinally polarised

electron beam, incident on a bremsstrahlung radiator. The degree of polarisation depends on the ratio of energies $x = E_\gamma/E_{e^-}$. This ratio allows for calculation of the polarisation of the incident photon [75]:

$$P_\gamma = P_{e^-} \frac{4x - x^2}{4 - 4x + 3x^2}. \quad (8.14)$$

The degree of photon polarisation is considered separately in each energy bin as there is a photon energy dependence that must be accounted for. So the mean value of photon polarisation is taken for each bin. The evolution of photon polarisation with photon energy is shown in Figure 8.13, while the photon polarisation for each energy bin is considered in Table 8.6.

Figure 8.13: Photon energy (E_γ) vs photon polarisation.

8.6 Investigation of Systematics in Extraction of the Asymmetry

This section presents results from investigations into potential systematics in the extraction of the asymmetry, $\mathcal{A}$, arising from detector acceptance effects. The extracted value for the asymmetry should not show any dependence on the azimuthal angle of the reaction products. This lack of dependence on ϕ was checked using the final state kaon in the analysis presented below.

E_γ Bin (GeV)	Average Photon Polarisation (approx. %)
1.1-1.3	60
1.3-1.5	68
1.5-1.7	76
1.7-1.9	82
1.9-2.1	86
2.1-2.3	87
1.1-2.3	76

Table 8.6: Summary of how photon beam polarisation relates to the selected photon energy bins.

The initial step is to plot the polarisation observable $\mathbb{E}$ versus ϕ of the kaon, Figures 8.14 - 8.17. This allows the value of $\mathcal{A}_\phi$ to be compared to the double-polarisation observable $\mathbb{E}$ ². This comes from rearranging Equation 8.3 into:

$$\mathcal{A}_\phi = P_\gamma P_\oplus \mathbb{E}. \quad (8.15)$$

²Note that the region $\phi = 0 - 30^\circ$ have been shifted to $360 - 390^\circ$ so that no sectors are split while plotting.

Figure 8.14: $\mathbb{E}$ double-polarisation observable in terms of the azimuthal angle ϕ : *all energies* (1.1-2.3 GeV).

Figure 8.15: $\mathbb{E}$ double-polarisation observable in terms of the azimuthal angle ϕ : 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 8.16: $\mathbb{E}$ double-polarisation observable in terms of the azimuthal angle ϕ : 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 8.17: $\mathbb{E}$ double-polarisation observable in terms of the azimuthal angle ϕ : 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

A fit was made with a zero degree polynomial, the results of which are shown in Table 8.7, giving an average value for $\mathcal{A}_\phi$ in each energy bin. The average value for $\mathbb{E}$ was calculated from this and could be compared to the values of the asymmetry $\mathcal{A}$, calculated for $\cos \theta_{K^+}^{CM}$.

These results indicate that the calculated value of $\mathbb{E}$ in terms of ϕ is consistent with the average value seen in terms of $\cos \theta_{K^+}^{CM}$. This is shown in all E_γ bins and integrated over all kaon angles. A study was also performed in order to see how the way in which the ϕ acceptance is modelled influences the results of the

$E_\gamma \text{ Bin}$ (GeV)	$\mathcal{A}_\phi$ fit	Calculated $\mathbb{E}$	Fitted $\mathbb{E} (\cos \theta_{K^+}^{CM})$	Fit Error
1.1-2.3	0.054	0.30	0.29	0.01
1.1-1.3	0.020	0.11	0.13	0.19
1.3-1.5	0.048	0.26	0.29	0.10
1.5-1.7	0.089	0.48	0.48	0.10
1.7-1.9	0.038	0.21	0.18	0.12
1.9-2.1	0.042	0.23	0.19	0.14
2.1-2.3	0.059	0.33	0.26	0.14

Table 8.7: Summary of the $\mathbb{E}$ double-polarisation observable, as calculated in terms of ϕ . This can be compared with the average value of the $\mathbb{E}$ observable plotted with $\cos \theta_{K^+}^{CM}$.

observable $\mathbb{E}$.

8.6.1 Effect of ϕ Acceptance

Further studies of any potential ϕ dependent systematics were explored using simulated pseudo-data. Events were generated using an event generator with a fixed value for $\mathbb{E}$. These data were then passed through the data analysis code used for the real data. Different conditions were placed on this pseudo-data sample to explore possible systematic effect. These were assessed by comparison of the extracted value of $\mathbb{E}$ from the data. Three scenarios were considered for this study:

- Uniform acceptance in ϕ .
- Removing fiducial regions in CLAS, which limit the ϕ acceptance of the final state particles.
- Realistic cosine function (mimicking some realistic CLAS acceptance)³.

Each time the generator was run, plots were made of $\mathbb{E}$ vs ϕ for each scenario. These plots were then fitted with a zero degree polynomial and compared to the

³This function was obtained from Nicholas Zachariou.

‘true’ value of $\mathbb{E}$ given to the generator. As well as investigating the acceptance effects described above in extracting $\mathbb{E}$, two different methods were explored:

1. Using the histograms for the asymmetry method.
2. Using bins for the asymmetry method then performing a *pol0* fit of the observable in ϕ .

An example of the results obtained from one run is given in Figure 8.18 with fitted values given in Table 8.8, where the value of $\mathbb{E}$ is shown for all three acceptance scenarios. It should be noted that this only indicated one trial, so there will be some natural deviation from the *true* value of $\mathbb{E}$.

Figure 8.18: An event generator is used to compare the results of three acceptances to a given *true* value of the double-polarisation observable $\mathbb{E}$ (0.7). This shows the results for one trial.

Acceptance	Fit Value	Fit Error
Constant	0.695	0.011
Fiducial Regions	0.680	0.014
Realistic CLAS Acceptance	0.670	0.018

Table 8.8: Summary of produced values of $\mathbb{E}$ for the three acceptances. The *true* value of $\mathbb{E}$ given to the generator was 0.7.

Many trials are carried out in order to account for any statistical deviation and in aid of obtaining a more accurate estimate of the observable $\mathbb{E}$. The *true* value, was fixed for the study, so that any deviations coming from the ϕ acceptance or extraction method could be easily identified.

A detailed run was performed where 5000 trials, in each of which 25K events were produced. The results from these trials are plotted to give a Gaussian distribution which is then fitted. Results from these trials are presented in Figures 8.19 and 8.20, using the ratio and fit methods respectively.

Figure 8.19: Collated results for 5000 generated trials, with the value of the E observable calculated using the ratio method.

Figure 8.20: Collated results for 5000 generated trials, with the value of the $\mathbb{E}$ observable calculated using the fitting method.

As expected from these, we see that there is a clear distribution forming around the *true* value of 0.7. This is shown for both methods of calculating the polarisation observable, note that these methods are only comparable because we have chosen for $\mathbb{E}$ to be a constant, rather than having a dependence in energy or ϕ . Although these plots seem to confirm that the introduction of some acceptance does not change the value of $\mathbb{E}$ obtained, a more thorough comparison can be made to check the hypothesis. The results of fitting these two methods are presented in Tables 8.9 and 8.10.

Acceptance	Fit Mean	Fit σ
Constant	0.7	0.011
Fiducial Regions	0.7	0.014
Realistic CLAS Acceptance	0.7	0.018

Table 8.9: Summary of produced values of $\mathbb{E}$ for the three acceptances over 5000 trials. The value of $\mathbb{E}$ was calculated using the ratio method.

Acceptance	Fit Mean	Fit σ
Constant	0.7	0.011
Fiducial Regions	0.7	0.014
Realistic CLAS Acceptance	0.7	0.18

Table 8.10: Summary of produced values of $\mathbb{E}$ for the three acceptances over 5000 trials. The value of $\mathbb{E}$ was calculated using the fitting method.

These show that for both methods and all acceptances that the obtained values for $\mathbb{E}$ are consistent with the initial value given to the generator within 1σ . This illustrates that there is no effect of the ϕ acceptance on the construction of the $\mathbb{E}$ observable.

8.7 Background Estimation from the $K^+\Sigma^0$ Channel

The main backgrounds present in the $K^+\Sigma^-$ channel arise from the decays of Λ and Σ^0 . As was presented, in Section 7.2.13, the contribution from $K^+\Lambda$ can be efficiently removed using the data selection cuts. The $K^+\Sigma^0$ channel has a similar kinematics to the channel of interest and its full suppression is not possible. An accurate estimate of the contribution from $K^+\Sigma^0$ to the $K^+\Sigma^-$ yield can be made using the experimental data.

The background contribution coming from the proton in this channel can be estimated by considering the inclusive K^+X skim. This allows for proton events to be included in the selection rather than being removed during the initial skim. This is useful because if we remember that CLAS does not have 100% detector acceptance, some of these events will be incorrectly selected because the proton, which would usually be used to veto the event, was not detected. This can occur when the proton hits the torus coils for example.

It is possible to include a final state proton in the particle selection, where these events can be considered, while allowing all other selection requirements to remain intact. This means that we can evaluate the contribution of events containing an undetected proton by comparing events with detected protons and evaluating the detection efficiency of protons in CLAS.

Using the K^+X skim, the standard analysis code can be run alongside a code which includes the proton. This leaves us with two different final states:

- $K^+\pi^-n$
- $K^+\pi^-p$

where if there is a third particle detected it must be a neutron or a proton respectively. These final states can be compared which indicates the ratio of Σ^0 events which are rejected using the exclusive $K^+\Sigma^-$ skim. Considering all energies and angles, the comparison between the events in these final states are shown in Table 8.11.

The total amount of Σ^0 which can contaminate the final sample, of course, depends on the proton detection efficiency of CLAS. For the $g14$ run period this

Events Present $K^+\pi^-n$	Events Present $K^+\pi^-p$	Proton Final State Percentage (%)
10193	1662	16.3

Table 8.11: Summary of the number of final state events when excluding and including a final state proton.

Energy Bin GeV	Proton Contamination (%)	Error (%)
1.1-1.3 GeV	12.5	2.1
1.3-1.5 GeV	12.7	1.5
1.5-1.7 GeV	11.7	1.3
1.7-1.9 GeV	17.9	2.4
1.9-2.1 GeV	14.1	1.9
2.1-2.3 GeV	14.8	2.4

Table 8.12: Outline of how the proton contribution evolves with the photon energy, E_γ .

was calculated to be $\sim 60\%$ ⁴, meaning that $\sim 40\%$ of the proton events were not detected and removed but remain in the sample.

The percentage contamination of over all energies and angles can be calculated to be 10.5(3)%.

8.7.1 Energy Dependence of $K^+\Sigma^0$

The percentage of proton events mixing with the $K^+\Sigma^-$ channel can be considered in terms of the photon energy. The contributions in each 200 MeV energy bin are outlined in Table 8.12.

There is some variation in the contribution with energy, particularly in the fourth energy bin, detailed further in Section 8.7.2. Otherwise these results indicate that the contribution is relatively stable with respect to photon energy, which is expected as the cross section for the $K^+\Sigma^0$ channel mirrors that of the

⁴From private conversations with Franz Klein; periods *silver1* and *silver2* had a proton efficiency of $\sim 70\%$, whereas all other periods were $\sim 60\%$. We use the worst case scenario for the calculations here.

Angular Bin ($\cos \theta_{K^+}^{CM}$)	Contamination (%)	Error (%)
1.1-1.3 GeV		
$(-1.0)-(-0.6)$	25.6	7.8
$(-0.6)-(-0.2)$	10.6	2.0
$(-0.2)-0.2$	6.1	1.4
0.2-0.6	7.5	2.1
0.6-1.0	N/A	N/A
1.3-1.5 GeV		
$(-1.0)-(-0.6)$	16.9	4.0
$(-0.6)-(-0.2)$	14.8	2.0
$(-0.2)-0.2$	9.8	1.2
0.2-0.6	5.5	1.0
0.6-1.0	16.7	5.9
1.5-1.7 GeV		
$(-1.0)-(-0.6)$	22.8	5.2
$(-0.6)-(-0.2)$	13.5	2.3
$(-0.2)-0.2$	6.9	1.0
0.2-0.6	8.5	1.3
0.6-1.0	6.9	2.4

Table 8.13: Outline of how the proton contribution evolves with the cosine of the K^+ centre-of-mass angle, $\cos \theta_{K^+}^{CM}$, from 1.1- 1.7 GeV .

$K^+\Sigma^-$ channel well.

8.7.2 Angular Dependence of $K^+\Sigma^0$

Similarly the contribution can be expanded in terms of the kaon production angle, shown in Tables 8.13 and 8.14.

A key feature seen here is the strong contribution at very backward angles, as much as a factor 2 or in some cases greater, than at central and forward angles. Considering the issue seen in the photon energy bin 1.7-1.9 GeV ; we see that in the first angular bin the contamination is $\sim 40\%$. This is a significantly larger value than other bins.

Angular Bin ($\cos \theta_{K^+}^{CM}$)	Contamination (%)	Error (%)
1.7-1.9 GeV		
$(-1.0)-(-0.6)$	39.3	10.3
$(-0.6)-(-0.2)$	16.7	3.5
$(-0.2)-0.2$	14.2	2.1
0.2-0.6	9.6	1.7
0.6-1.0	9.8	3.3
1.9-2.1 GeV		
$(-1.0)-(-0.6)$	23.8	7.2
$(-0.6)-(-0.2)$	14.6	4.3
$(-0.2)-0.2$	16.0	2.8
0.2-0.6	8.0	1.8
0.6-1.0	8.0	3.2
2.1-2.3 GeV		
$(-1.0)-(-0.6)$	16.7	5.4
$(-0.6)-(-0.2)$	25.0	8.5
$(-0.2)-0.2$	14.9	3.8
0.2-0.6	5.7	1.7
0.6-1.0	11.8	5.2

Table 8.14: Outline of how the proton contribution evolves with the cosine of the K^+ centre-of-mass angle, $\cos \theta_{K^+}^{CM}$, from 1.7- 2.3 GeV .

An estimation of the background is included in the systematic error estimate for the final results.

8.8 Combining Period Results

The *Gold2* and *Silver* periods were combined into one complete dataset in order to improve the statistics for calculating the beam-asymmetry and therefore the errors of the observable $\mathbb{E}$. It is important to ensure that these periods are appropriately weighted when they are combined as each will have differing statistics. This can be thought of as weighting the value of the polarisation observable in accordance with the error on the value; i.e. imprecise values with large errors are thought of as less reliable while more accurate values with smaller errors are weighted more heavily.

A weighted mean was used when periods were combined to ensure that contributions from each target period are appropriately accounted for. For a set of data, $[x_1, x_2, \dots, x_n]$, the weighted arithmetic mean is written as:

$$\bar{x} = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i}, \quad (8.16)$$

where w_i is the variable which is being used to weight the data⁵.

8.9 Current Theoretical Model Prediction

The two models used as a comparison in this thesis were KaonMAID, and Bonn-Gatchina. Although the MAID prediction has not been updated since its calculation in 2000, it is one of the few models to actually include the $K^+\Sigma^-$ reaction.

The plots of the polarisation observable $\mathbb{E}$, use two theoretical predictions for each model. These are added because bins are relatively wide (200 MeV) due to the low statistics available. The predictions shown are the bin end points with

⁵In our case, the number of events in the target period is used to represent the analysing power of each period.

the upper shown in red and lower in blue. This clearly highlights the evolution of the $\mathbb{E}$ observable prediction across the width of the energy bin.

8.9.1 KaonMAID

Predictions from the KaonMAID model [104] evolving with photon energy are shown in Figures 8.21 and 8.22.

Figure 8.21: Predictions from KaonMAID for $\mathbb{E}$ in the reaction $\gamma n \rightarrow K^+ \Sigma^-$. These are plotted every 100 MeV: 1050, 1150, 1250, 1350, 1450, 1550.

Figure 8.22: Predictions from KaonMAID for $\mathbb{E}$ in the reaction $\gamma n \rightarrow K^+ \Sigma^-$. These are plotted every 100 MeV : 1650, 1750, 1850, 1950, 2050, 2100.

One obvious comment on these predictions as a whole are that they seldom become negative. We see that at low energies the prediction is largely featureless with peaks near the central angles. As energy increases, the minimum begins to shift towards backward angles and a maximum begins to emerge at central angles. As the energy limit of the KaonMAID model is reached the backward minimum has become more pronounced and a minimum at very forward angles has developed. The KaonMAID model is currently only applicable below 2.1 GeV .

8.9.2 Bonn-Gatchina

Predictions from the Bonn-Gatchina model evolving with photon energy are shown in Figures 8.23 and 8.24. These predictions were requested from the Bonn-Gatchina group specifically for this analysis and include the most recent data on

resonances⁶.

Figure 8.23: Predictions from Bonn-Gatchina for $\mathbb{E}$ in the reaction $\gamma n \rightarrow K^+ \Sigma^-$. These are plotted every 100 MeV: 1050, 1150, 1250, 1350, 1450, 1550, 1650.

⁶Predictions received from Andrey Sarantsev of the Universität Bonn in May 2016, during the writing of this thesis.

Figure 8.24: Predictions from Bonn-Gatchina for $\mathbb{E}$ in the reaction $\gamma n \rightarrow K^+ \Sigma^-$. These are plotted every 100 MeV : 1750, 1850, 1950, 2050, 2150, 2250, 2350.

Similar to KaonMAID at low energies, Bonn-Gatchina shows a minimum at central angles, although this is much wider in the BoGa case. As the photon energy reaches ~ 1350 MeV the prediction begins to see an additional minimum at very backward angles as well as making the central minimum thinner. At photon energies of ~ 1750 MeV the central minimum begins to shift towards backward angles while a central maximum begins to evolve, with a corresponding minima at very forward angles.

It is clear that the KaonMAID and Bonn-Gatchina models are not currently in agreement for the $\mathbb{E}$ observable in $\gamma n \rightarrow K^+ \Sigma^-$.

Chapter 9

Results and Discussion of the Double-polarisation Observable $\mathbb{E}$

This chapter will present the results of the analysis, describing the results of the polarisation observable $\mathbb{E}$ for the $\gamma n \rightarrow K^+ \Sigma^-$ reaction. $\mathbb{E}$ will be compared to predictions from the KaonMAID model and the Bonn-Gatchina model, as these are the only theoretical models currently available for this channel.

9.1 Beam-Target Observable $\mathbb{E}$

The results for the $\mathbb{E}$ observable are shown, binned in 200 MeV energy bins (E_γ) as a function of the kaon centre-of-mass angle ($\cos \theta_{K^+}^{CM}$) with bins of width 0.4. A comparison is made between the empty target subtraction and dilution methods.

9.1.1 Empty Target Dilution Method

The motivation behind this method were outlined in Section 8.4.2, with the results for the $\mathbb{E}$ double-polarisation observable for the target dilution method shown in Figures 9.1 - 9.4:

Figure 9.1: Results for the $\mathbb{E}$ double-polarisation observable using the target dilution method: 1.1-2.3 GeV .

Figure 9.2: Results for the $\mathbb{E}$ double-polarisation observable using the target dilution method; 1.1-1.3 *GeV* (upper), 1.3-1.5 *GeV* (lower).

Figure 9.3: Results for the $\mathbb{E}$ double-polarisation observable using the target dilution method; 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 9.4: Results for the $\mathbb{E}$ double-polarisation observable using the target dilution method; 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

9.1.2 Empty Target Subtraction Method

The motivation behind this method were outlined in Section 8.4, with the results for the $\mathbb{E}$ double-polarisation observable for the target subtraction method shown in Figures 9.5 - 9.8:

Figure 9.5: Results for the $\mathbb{E}$ double-polarisation observable using the target subtraction method: 1.1-2.3 GeV .

Figure 9.6: Results for the $\mathbb{E}$ double-polarisation observable using the target subtraction method; 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 9.7: Results for the $\mathbb{E}$ double-polarisation observable using the target subtraction method; 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 9.8: Results for the $\mathbb{E}$ double-polarisation observable using the target subtraction method; 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

9.1.3 Comparison of Empty Target Methods

It is important that the two empty target methods are shown to be consistent. To that end the differences in the value of $\mathbb{E}$ for the dilution and subtraction methods are shown in Figures 9.9 - 9.12. These are fitted with a 0^{th} order polynomial, the fit values of which are presented in Table 9.1.

Figure 9.9: Difference in $\mathbb{E}$ for both target methods: all energies 1.1 -2.3 GeV .

Figure 9.10: Difference in $\mathbb{E}$ for both target methods; 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 9.11: Difference in $\mathbb{E}$ for both target methods; 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 9.12: Difference in $\mathbb{E}$ for both target methods; 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

The two target methods are consistent, as should be expected. This indicated that the HD target used in this experiment is indeed a relatively clean target where the empty target subtraction method is valid.

Energy Bin GeV	Fit Value	Error
All Energies	0.05	0.07
1.1-1.3	0.13	0.29
1.3-1.5	0.05	0.16
1.5-1.7	0.12	0.15
1.7-1.9	0.04	0.18
1.9-2.1	0.05	0.19
2.1-2.3	0.02	0.22

Table 9.1: Summary of the differences in the target methods, using a 0^{th} degree polynomial fit.

9.2 $\mathbb{E}$ Observable Results Compared with Model Predictions

The results obtained for the $\mathbb{E}$ observable must be compared to the available theoretical models in order to be able to draw any conclusions from the analysis. As discussed in Section 2.6, the available models for this thesis are KaonMAID and Bonn-Gatchina and in the absence of available data with which to compare the results, model predictions are used¹.

9.2.1 KaonMAID

KaonMAID predictions for the $\mathbb{E}$ observable are compared with the $K^+\Sigma^-$ data in Figures 9.13 - 9.15. These KaonMAID predictions are shown for the extreme bin end points, corresponding to each bin of the experimental data². This gives an indication of the variation in the model predictions over the bin.

¹Only statistical errors are presented in this thesis.

²It should be noted that KaonMAID begins to break down at energies of greater than 2.1 GeV , therefore there is no prediction for the upper end point energy of the final bin. The end point energies are indicated by **blue** for the lower edge and **red** for the upper edge.

Figure 9.13: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from KaonMAID; 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 9.14: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from KaonMAID; 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 9.15: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from KaonMAID; 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

The experimental data for $\mathbb{E}$ generally shows a positive asymmetry for most of the measured photon energy range. The data near threshold has somewhat poorer statistical accuracy due to the smaller cross section. At the higher photon energies, the backward kaon angle data indicates a small or possibly negative asymmetry.

Apart from the lowest E_γ bins, only a small variation in $\mathbb{E}$ is predicted across experimental bins, evidenced by the similarity of the prediction lines on each figure. The KaonMAID model gives a reasonable description of the experimental data within statistical uncertainties up to photon energies around 1.7 GeV . Above this energy the model gives poorer agreement, predicting a larger (and positive) asymmetry at forward kaon angles than indicated in the data. Despite these discrepancies at forward angles, very backward angles see reasonable agreement at these energies.

9.2.2 Bonn-Gatchina

Bonn-Gatchina predictions for the $\mathbb{E}$ observable are compared with the $K^+\Sigma^-$ data, in Figures 9.16 - 9.18. Once again the predictions are included for the bin end point energies.

1.1 - 1.3 GeV

1.3 - 1.5 GeV

Figure 9.16: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from Bonn-Gatchina; 1.1-1.3 GeV (upper), 1.3-1.5 GeV (lower).

Figure 9.17: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from Bonn-Gatchina; 1.5-1.7 GeV (upper), 1.7-1.9 GeV (lower).

Figure 9.18: Results for the $\mathbb{E}$ double-polarisation observable including the bin end point predictions from Bonn-Gatchina; 1.9-2.1 GeV (upper), 2.1-2.3 GeV (lower).

Contribution to polarisation systematic	σ_{sys}
Photon Beam Polarisation	3.4%
Target Polarisation	6.0%
Total	6.89%

Table 9.2: Systematic uncertainties associated with polarisation measurements during the *g14* run period.

The Bonn-Gatchina predictions do not show very significant variation across the experimental bins, with predictions from the bin edges indicating similar trends and magnitude. The Bonn-Gatchina model predicts more negative asymmetries than KaonMAID for photon energies below 1.7 GeV . This behaviour is not well reflected in the data, as we see a clear difference in sign between the model and data at central kaon angles. At higher photon energies the smaller predicted asymmetries show better general agreement with the data within uncertainties. The Bonn-Gatchina model is constrained by a much larger database including recent meson photoproduction data, so this poorer agreement is interesting.

9.3 Systematic Uncertainties

Two kinds of systematic uncertainties were considered. Firstly, those associated with event selection and observable extraction. Secondly, those systematic uncertainties associated with the presence of the $K^+\Sigma^0$ background channel were assessed on a bin-by-bin basis.

The systematic error associated with the empty target subtraction was taken to be negligible compared to the statistical error, from the agreement between different analysis methods, shown in Section 9.1.3. Systematics in the measured photon flux are assumed to cancel in the asymmetry and to be of similar magnitude for both helicities. There was no significant variation in the asymmetry found when varying the particle selection cuts, these were found to be consistent within uncertainties.

Systematic uncertainties of the photon and target polarisations were calculated by the *g14* run group [105]. These are shown in Table 9.2.

These polarisation uncertainties are combined in quadrature in order to give a systematic in the polarisation factor of the $\mathbb{E}$ observable:

$$\frac{1}{P_\gamma P_\oplus}. \quad (9.1)$$

The main systematic uncertainty arises from the contamination of $K^+\Sigma^-$ by the $K^+\Sigma^0$ reaction. This has been considered by studying the effect of the Σ^0 events on the $\mathbb{E}$ observable. In calculating the systematic, we estimated the effect of the background yield if taking the full range of the $\mathbb{E}$ asymmetry $(\pm 1)^3$. The event contamination presented in Tables 8.12 - 8.14 was used in the estimate. The resulting systematic in $\mathbb{E}$ is given in Tables 9.3 and 9.4 as a function of E_γ and $\cos\theta_{K^+}^{CM}$.

9.4 Summary

The first measurement of the $\mathbb{E}$ observable for $\gamma n \rightarrow K^+\Sigma^-$ has been extracted.

The results were compared with the latest available reaction models for the process. These give divergent predictions for this observable for certain regions of photon energy and kaon angle. The KaonMAID tends to give better agreement in the lower photon energy ranges while Bonn-Gatchina gives better agreement for the higher photon energies measured.

The new experimental data will provide valuable constraints on these models and the properties of nucleon resonances contributing at these photon energies. Definitive physics conclusions will await the new data being incorporated into the database for these models and systematic studies of the effect on resonance properties.

³This is the most pessimistic estimation. The systematic would be smaller if the experimental value for the $K^+\Sigma^0$ asymmetry was included bin-by-bin.

Angular Bin ($\cos \theta_{K^+}^{CM}$)	Value of $\mathbb{E}$ Observable	Shift in $\mathbb{E}$ Observable	
All Energies		(+)	(-)
$(-1.0)-(-0.6)$	0.34	0.15	0.30
$(-0.6)-(-0.2)$	0.33	0.09	0.19
$(-0.2)-0.2$	0.28	0.07	0.13
0.2-0.6	0.27	0.05	0.09
0.6-1.0	0.15	0.08	0.10
1.1-1.3 GeV			
$(-1.0)-(-0.6)$	0.20	0.30	0.20
$(-0.6)-(-0.2)$	0.60	0.04	0.16
$(-0.2)-0.2$	0.09	0.05	0.07
0.2-0.6	0.78	0.02	0.12
0.6-1.0	0.84	0.84	0.84
1.3-1.5 GeV			
$(-1.0)-(-0.6)$	1.18	0.35	0.03
$(-0.6)-(-0.2)$	0.16	0.16	0.11
$(-0.2)-0.2$	0.38	0.06	0.12
0.2-0.6	0.38	0.07	0.15
0.6-1.0	0.14	0.18	0.13

Table 9.3: Systematic uncertainties in $\mathbb{E}$ in terms of E_γ and $\cos \theta_{K^+}^{CM}$. Showing shifts assuming the value of $\mathbb{E}$ for the $K^+\Sigma^0$ channel to be ± 1 .

Angular Bin ($\cos \theta_{K^+}^{CM}$)	Value of $\mathbb{E}$ Observable	Shift in $\mathbb{E}$ Observable	
1.5-1.7 <i>GeV</i>		(+)	(-)
$(-1.0)-(-0.6)$	0.09	0.24	0.20
$(-0.6)-(-0.2)$	0.83	0.02	0.24
$(-0.2)-0.2$	0.49	0.03	0.09
0.2-0.6	0.48	0.04	0.12
0.6-1.0	0.16	0.05	0.07
1.7-1.9 <i>GeV</i>			
$(-1.0)-(-0.6)$	0.87	0.05	0.7
$(-0.6)-(-0.2)$	0.05	0.17	0.15
$(-0.2)-0.2$	0.05	0.13	0.15
0.2-0.6	0.44	0.13	0.05
0.6-1.0	0.11	0.08	0.10
1.9-2.1 <i>GeV</i>			
$(-1.0)-(-0.6)$	0.72	0.06	0.40
$(-0.6)-(-0.2)$	0.65	0.05	0.23
$(-0.2)-0.2$	0.02	0.15	0.15
0.2-0.6	0.01	0.08	0.08
0.6-1.0	0.19	0.06	0.095
2.1-2.3 <i>GeV</i>			
$(-1.0)-(-0.6)$	0.03	0.16	0.16
$(-0.6)-(-0.2)$	0.75	0.06	0.43
$(-0.2)-0.2$	0.10	0.15	0.12
0.2-0.6	0.04	0.04	0.05
0.6-1.0	0.01	0.11	0.10

Table 9.4: Systematic uncertainties in $\mathbb{E}$ in terms of E_γ and $\cos \theta_{K^+}^{CM}$. Showing shifts assuming the value of $\mathbb{E}$ for the $K^+\Sigma^0$ channel to be ± 1 .

Chapter 10

JLab Upgrade and CLAS12

Experimental running of Jefferson Lab ceased after the $g14$ experiment in 2012. The accelerator then began an upgrade in order to deliver an electron beam of 12 GeV and JLab's associated Halls began upgrades in order to perform experiments with such a beam; providing increased kinematic coverage, resolution and particle identification.

A significant fraction of my thesis work concerned the development of new detector apparatus for use with the upgraded JLab facility, CLAS12. In this chapter the new facility is outlined and the detector principle and construction detailed.

10.1 Electroproduction at low Q^2

A key goal of CLAS12 is to search for exotic mesons; this will be done using scattered electrons at small angles to provide tagged quasi-real virtual photons¹ ($Q^2 < 0.1 \text{ GeV}/c^2$). These virtual photons have an intrinsic and sizeable linear polarisation, which can be determined on an event-by-event basis by measuring the scattered electron energy/momentum and the scattering plane. This technique has some advantages with respect to coherent bremsstrahlung where only the average beam polarisation can be determined.

The use of a photon beam when searching for these exotic states is likely to be advantageous and more likely to produce exotic states than a pion beam, as

¹Since the 4-momentum transfer (Q^2) is very small (0.01-0.3 GeV^2), the virtual photon is considered quasi-real.

the use of a *spin* -1 probe may favour production of $q\bar{q}$ states where the quark spins are aligned which is more likely to provide a meson with exotic quantum numbers [106]. Phenomenological studies also suggest that the cross section of these exotic states would be comparable to non-exotic mesons [107] [108].

The use of low Q^2 allows a more controlled use of photon flux, so thin targets can be used. This method is expected to have a luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ with a tagged photon rate of 10^7 s^{-1} [67]. This technique has been used to produce very high energy photon beams at CERN [109] [110] and DESY [111].

The use of unpolarised electrons, allows for a virtual photon to be produce with polarisation:

$$\epsilon = \left(1 + 2 \frac{(Q^2 + \nu^2)}{Q^2} \tan^2(\theta_{e'}/2) \right)^{-1}, \quad (10.1)$$

where ν is the photon energy and $\theta_{e'}$ is the scattering angle of the electron [112]. The longitudinal polarisation is given by;

$$\epsilon_L = \frac{Q^2}{\nu^2} \epsilon. \quad (10.2)$$

At very small values of Q^2 , the virtual photons are seen as quasi-real since $\epsilon_L \approx 0$. From measurements made of the scattered electron, properties of the quasi-real photon can be reconstructed. Three key quantities are required for the correct determination of polarisation; firstly, the azimuthal angle $\phi_{e'}$, in order to determine the polarisation plane. Secondly, the energy of the scattered electron for the calculation of linear polarisation:

$$\begin{aligned} \nu &= E_{beam} - E_{e'}, \\ P_\gamma &= 1 + \frac{\nu^2}{2E_{beam}E_{e'}}. \end{aligned} \quad (10.3)$$

Finally, the polar angle, $\theta_{e'}$, to determine the momentum transfer:

$$Q^2 = 4E_{beam}E_{e'} \sin^2(\theta_{e'}/2). \quad (10.4)$$

10.2 CLAS12 Detector

The Hall B detector, CLAS [67], has been undergoing a full detector upgrade into CLAS12 [113]. An initial projection of what this would look like is presented in Figure 10.1.

Figure 10.1: GEMC visualisation of the CLAS12 detector in Hall B [114].

The detector will consist of two sections [113]: a **F**orward **D**etector (FD) and a **C**entral **D**etector (CD).

10.2.1 CLAS12 Components

The FD is based on a toroidal magnet and retains the six sector symmetry of CLAS, to detect forward scattered particles. Due to the large energy increase once CEBAF is upgraded to 12 *GeV*, many more particles will be peaked in the forward direction, meaning new forward detectors were developed. The FD aims to maintain characteristics similar to CLAS but with the benefit of improved timing and energy resolution, leading to improved particle identification.

The CD is based on a solenoid magnet with full cylindrical symmetry for the detection of large angle recoiling hadrons.

10.2.1.1 Forward Detector

Detectors are added in the forward direction to allow efficient detection of particles, these include [114]:

- *F*orward *V*ertex *T*racker (FVT).
- *H*igh *T*hreshold *C*herenkov *C*ounter (HTCC).
- *F*orward *D*rift *C*hambers (FDC).
- *R*ing *I*maging *C*Herenkov (RICH).
- *F*orward *T*ime-*O*f-*F*light (FTOF).
- *P*re-shower *C*alorimeter (PCal).
- *F*orward *E*lectromagnetic *C*alorimeter (FEC).
- *F*orward *T*agger (FT).

These additions to existing CLAS components aim to improve particle detection as well as timing and energy resolution. Several components of the existing CLAS technology are retained, such as the low threshold Cherenkov counters, electromagnetic calorimeters and time-of-flight scintillators. High threshold Cherenkov counters are added to complement the low threshold Cherenkov in order to improve electron/pion separation. The existing time-of-flight and electromagnetic calorimeter must undergo improvements in order to effectively resolve higher momentum forward-going particles. The time-of-flight is made into three planes of scintillator counters with sub-*ns* timing. A pre-shower calorimeter is also inserted in front of the EC to allow for high energy photon detection and photon/pion separation.

A cross section of CLAS12, highlighting the detector systems is shown in Figure 10.2.

Figure 10.2: Cross sectional view of the CLAS12 FD [114].

10.2.1.2 Central Detector

Some detectors in the central region have also undergone an upgrade for operations with JLab12, these include [114]:

- *C*entral *T*ime-*O*f-*F*light (CTOF).
- *B*arrel *S*ilicon *T*racker (BST).
- *S*ilicon *V*ertex *T*racker (SVT).
- *M*icro*M*esh gas detectors (MM).
- *C*entral *N*eutron *D*etector (CND).

The superconducting solenoid magnet, which the CD is based around, provides magnetic shielding for surrounding detectors from charged particle backgrounds. It is also able to provide a uniform 5 *T* magnetic field for use with polarised target experiments. A cross section of the CLAS12 CD is shown in Figure 10.3.

Figure 10.3: Cross sectional view of the CLAS12 CD [114].

10.3 The Forward Tagger

The increase in the electron beam energy, with the upgrade of the CEBAF accelerator, means that the current JLab tagger system must be redesigned. The current tagger magnets would be unable to bend an electron beam with double the energy in the space currently available. This means that one of the space available or the magnet strength must be increased, both of which would incur great cost. To circumvent these problems a different concept to produce tagged almost-real photons was developed. This involves tagging electrons scattered at very forward angles, in kinematics where the exchanged virtual photon is *quasi-real*.

The new apparatus to detect electrons in this region is called the **F**orward **T**agger (FT). The Nuclear Physics group at the University of Edinburgh has a leading role in this project and were responsible for the design and construction of basic equipment for the FT, namely the forward tagging “Hodoscope”.

GEant4 **M**onte **C**arlo (GEMC) was used to produce an assembly of the FT, two pictures showing this are shown in Figure 10.4.

Figure 10.4: Full view (upper) and cross sectional view (lower) of the FT as implemented in the CLAS12 GEANT4 simulation code. The FT is supported by the tungsten beam pipe (green) and surrounded by thermal insulation (white). The FT-Hodo (blue) and FT-Trck (red-gold) are placed in front of the FT-Cal (cream). A tungsten cone (orange) is located in the upstream region to shield the detector from electromagnetic background [114].

Key requirements of the FT are that it must be able to operate in a high magnetic field with high electromagnetic background²; be able to reconstruct

²The main source of this electromagnetic background is Møller scattering; for which simulations suggest that the rate could be around 10 MHz over the entire detector for a luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$.

electrons with enough accuracy to discriminate between final states; determine the plane of linear polarisation of the photons; sustain high rate; be radiation hard and be contained within a fairly limited space.

To detect the initial photon and cleanly separate the events from the large photon background, the FT is required to detect at very forward angles ($< 5^\circ$). The detection of scattered electrons between $2.5\text{-}4.5^\circ$ and an energy of $0.5\text{-}4.5\text{ GeV}$ is required to give access to the regions where hybrid mesons are predicted.

The FT is a conglomeration of three sub-detectors:

1. A *Tracker* to determine the scattering angle and plane.
2. A *Hodoscope* to separate electrons and photons.
3. A *Calorimeter* to determine the electron energy.

A full outline of the requirements of the FT, is shown below in Table 10.1, and a detailed description of the FT and its sub-detectors can be found in [114].

Variable	Range
$E_{e'}$	$0.5\text{-}4.5\text{ GeV}$
$\theta_{e'}$	$2.5\text{-}4.5^\circ$
$\phi_{e'}$	$0\text{-}360^\circ$
E_γ	$6.5\text{-}10.5\text{ GeV}$
P_γ	$70\text{-}10\%$
Q^2	$0.01\text{-}0.3\text{ GeV}^2$
W	$3.6\text{-}4.5\text{ GeV}$

Table 10.1: Summary of the Forward Tagger kinematic range.

10.3.1 The EM Calorimeter (FT-Cal)

The FT-Cal is designed to accurately measure the energy of scattered electrons. The design is an array comprised of lead-tungstate ($PbWO_4$) crystals. Each crystal is of dimensions $15 \times 15 \times 200\text{ mm}^3$; the complete ensemble contains 332 such crystals. The arrangement of the crystals allows the FT-Cal to cover the

angular range of $2.0\text{-}5.5^\circ$ and contain electromagnetic showers from electrons in the detection range of $2.5\text{-}4.5^\circ$.

The energy resolution of the detected electrons is a key quantity to accurately determine the photon energy. Due to the high rate expected during operation all components of the FT should have a fast recovery time ($\sim 10\text{ ns}$) to avoid pile-up and a sub- ns timing resolution to allow good coincidence timing.

A simple depiction of the FT-Cal is shown in Figure 10.5, demonstrating the arrangement of the crystals.

Figure 10.5: Simple representation of the forward tagger calorimeter (FT-Cal), showing the arrangement of the crystals [114].

A full discussion of the FT-Cal is given in the FT Technical Design Report [114].

10.3.2 The Hodoscope (FT-Hodo)

The hodoscope's purpose is to separate electron and photon events incident on the calorimeter by identifying electrons from a hit in the hodoscope which is correlated in time and position with the FT-Cal. To achieve this the detector must be highly efficient for **M**inimum **I**onising **P**articles (MIPs) ($\sim 99\%$ achievable); have minimal false coincidences (where a photon event has an uncorrelated hit in the hodoscope); sub- ns timing for MIPs and high segmentation for spatial resolution.

The full design of the hodoscope is considered in more detail in Section 10.4. A simple depiction of the FT-Hodo, in place ahead of the FT-Cal, is shown in Figure 10.6.

Figure 10.6: Simple representation of the forward tagger hodoscope (FT-Hodo), which is located upstream from the FT-Cal [114].

10.3.3 The Tracker (FT-Trck)

The FT-Trck is designed to reconstruct the (x, y) coordinates of electron tracks between the $2.5\text{--}4.5^\circ$ operating angles. This involves using two MicroMegas detectors to create the vector of the path and measure the azimuthal and polar angles of the scattered electrons.

Micromegas detectors are gaseous detectors for MIPs, allowing for measurement of position and timing. Particles travelling through the micromegas ionise the contained gas. Each Micromegas detector is double-layered in order to reduced background, maximising the tracking resolution whilst in a spatially restricted area. A simple depiction of the FT-Trck, in place ahead of the FT-Hodo and FT-Cal, is shown in Figure 10.7.

Figure 10.7: Simple representation of the forward tagger tracker (FT-Trck), which is located upstream from the FT-Hodo and FT-Cal [114].

A full discussion of the FT-Trck is given in the FT Technical Design Report [114].

10.4 FT-Hodo Overview

The hodoscope is a segmented array of plastic scintillator tiles, embedded with **WaveLength Shifting** (WLS) fibres (Kuraray Y11) and read out by **Si**licon **PhotoM**ultipliers (SiPMs) via optical fibres.

The plastic scintillator used (*EJ-204*) provides fast timing and good radiation resistance for use in high rate environments. Due to the high radiation flux and large magnetic field in the vicinity of the hodoscope, it is required that the scintillation light is taken to a far more controlled environment for detection.

A unique principle of this is also that the emission spectra, Figure 10.8, matches well the absorption spectra of the WLS, Figure 10.9.

Figure 10.8: Emission spectrum of *EJ* – 204 scintillator [115].

Figure 10.9: Absorption spectra of Kuraray Y – 11 WLS fibre [116].

WLS fibres are used to shift the frequency of the scintillation light and transport it out of the area of high magnetic field. The WLS fibres absorb the UV light produced in the plastic scintillator and emit at a longer wavelength, which matches with the optimal quantum efficiency of a typical SiPM (green). Kuraray Y11 was chosen because of its established radiation hardness and good timing properties. The fibre has been used successfully in other detectors such as the hodoscope used with the inner calorimeter of CLAS [117].

One issue in using WLS fibre is that it has a relatively small attenuation length ($\sim 3.5\text{ m}$). The geometry of CLAS12 and the position of the hodoscope means that a large optical path is necessary in order to reach the photon detectors ($> 5\text{ m}$). If WLS fibre was used for the entire path length, the photons would have already undergone approximately two attenuation lengths, hence only $\sim 13.5\%$ of the original photons remain. Therefore the WLS fibre is fusion spliced at 5-10 *cm* from the scintillator tile onto clear optical fibre (Kuraray Clear-PSM), which have a much greater attenuation length ($> 10\text{ m}$). Splicing fibres does create a boundary however, though this generally induces a photon loss of $< 2\%$. The use of clear optical fibre allows the captured light to be transported with a light of $\sim 40\%$ over the 5-6 *m* distance to the SiPMs.

Figure 10.10: Photograph of a SiPM.

The hodoscope uses Hamamatsu S13360-3075PE SiPMs, Figure 10.10, which due to their $3 \times 3\text{ mm}^2$ active area can easily be used with up to four optical fibres. The detection efficiency spectrum of these SiPMs, Figure 10.11, matches the emission spectrum of the WLS fibre well, allowing for good overall efficiency.

Figure 10.11: Detection efficiency spectrum of the SiPMs [118].

10.5 FT-Hodo Design

The spatial resolution of the hodoscope should be a good match for that of the FT-Cal. To comply with this the hodoscope used pixels of $15 \times 15\text{ mm}$ ($P15s$), which covers a single crystal in the FT-Cal and pixels of $30 \times 30\text{ mm}$ ($P30s$) which cover four crystals of the FT-Cal. These sizes were chosen to compromise between minimising the number of tile boundaries and maximising the number of photons which can be collected by the WLS fibre. The arrangement of these detector elements which make up a layer of the hodoscope is shown in Figure 10.12.

Figure 10.12: Simple representation of hodoscope pixel elements. Red tiles indicate *P30* elements, while blue tiles indicate *P15* elements.

The hodoscope was designed as a 2 layer detector, with each containing 44 *P15s* and 72 *P30s* giving a total of 116 elements per layer. The two layers are of different thickness; a thin layer of 7 mm and a thick layer of 15 mm. The thin layer is placed in front, in order to reduce photon conversion in the hodoscope; whilst the thick layer is placed behind, in order to maximise the number of photoelectrons detected at the SiPM to give accurate timing.

To increase the number of scintillation photons collected from each tile, multiple WLS fibres were used per element; 2 for each *P15* and 4 for each *P30*. The original design called for these fibres to be embedded in trenches in the surface of the scintillator tiles. Due to difficulties in fibre routing - both in terms of multiplicity of fibres and the need to bend the fibres to avoid crazing with others from neighbouring tiles - it was found an improvement in the design was necessary. An improved design was employed using drilled holes in the body of the scintillator which remedied both of these previous issues³.

There are two types of holes which were used with the tiles of the hodoscope:

1. Entry at the corner of the tile, $\mathcal{C}$ (74 tiles per layer).

³Although it should be noted that the production associated with this method is far more complex and labour intensive. Schematics of the final tiles can be seen in Appendix A.

2. Entry at the edge of the tile, $\mathcal{E}$ (42 tiles per layer).

The placement of these *Corner* and *Edge* tiles are shown in Figure 10.13.

Figure 10.13: Simple representation of hodoscope elements, showing the required orientation of tiles.

The design ensures that pixels can touch with minimal dead space while optically isolating the detector elements. Isolation is maintained using thin layers of reflective paint (*BC620*) on all sides of the pixels. This has a similar reflectivity ($\sim 95\%$) to reflective wrappings such as Mylar.

The optically isolated elements were glued into the positions on a 1 mm thick carbon fibre support. Two of these support sheets are cut to the geometry of the hodoscope and each layer is built separately. This separable 2 layer system allows the hodoscope to be separated for construction, maintenance and provides flexibility for possible use in future experiments. The carbon fibre support is shown in Figure 10.14.

Figure 10.14: CAD drawing of a carbon fibre support for one hodoscope layer.

The fibre bundles are arranged and held at the bottom of the hodoscope within a 3D printed section called the *DeltaWing*, Figure 10.15. The bundle are stacked within the wing and held in position using an array of lacing chord.

Figure 10.15: CAD drawing for the deltawing, designed to collect fibre bundles at the base of the hodoscope before routing through CLAS.

As well as the optical fibres to transport the scintillation light from the hodoscope elements, space was also allocated for optical fibres for LED flasher. This was developed by the University of Glasgow, in order to track the recovery time of the hodoscope from radiation exposure.

Figure 10.16: CAD drawing for the Fishtail connectors, designed to connect up to 8 channels to the electronics boards.

The interface with the FT-Hodo electronics is a 3D printed connector, named the *FishTail*, Figure 10.16. This piece holds up to 8 bundles of fibres and guides them into 8 separate SiPM channels. The fibres exit the connector through 8 matrices of 4 holes each, with dimensions matched to the size of the SiPM. The fibres are glued into the holes, after which the protruding fibres are polished down until they are flush with the outer surface. This provides a high quality and reliable light connection to each SiPM.

10.6 Hodoscope Simulations

Two GEANT4 based simulations were developed at the University of Edinburgh to model the hodoscope elements and the operation of the detector⁴. The first simulation models a single tiles and tracks the optical photons to the SiPM. This allows for the tile thickness and number of fibres to be altered and the effect on the number of detected photoelectrons to be monitored. The second simulation uses a full reconstruction of the FT-Hodo and FT-Cal to investigate their coupled performance. The former simulation will be discussed here, with further details

⁴The hodoscope simulations were written and performed by Derek Glazier in 2011.

available for these simulations available in [114].

The validity of the simulation was checked for by comparing consistency to the CLAS Inner Calorimeter hodoscope. The set-up from this detector yielded 18 photoelectrons per MIP, which was in agreement with the most likely value of the simulated set-up, shown in Figure 10.17.

Figure 10.17: Number of photons detected for tile geometry similar to the previous CLAS Inner Calorimeter, which measured 18 photons per MIP [114].

The simulation used the GEANT4 framework, with energy deposits handled using the standard physics classes available. The optical light produced was modelled with the parameters of the construction materials used (light output, reflectivity, etc.) The simulation was then used to explore possible tile and fibre designs for the hodoscope.

A common feature of all the simulations carried out are that they are trialled with multiple fibre-options per tile, typically 1 fibre, 2 fibres and 4 fibres.

10.6.1 Tile Thickness Simulations

The number of photons detected were considered while varying number of fibres, as well as timing resolution. Figure 10.18 shows the number of photons detected for *P15* and *P30* elements. This details the photons while the tile thickness is increased and the number of fibres per tile is also varied.

Figure 10.18: The number of photons detected for different configurations of tile. Left: $P15$. Right: $P30$ [114].

The simulation illustrates important effects in tile thickness and fibre number. Comparing $P15$ and $P30$ elements we see that the increase in size alters the detected photons by more than a factor of 2. While doubling the number of fibres gives less than a factor of 2 increase in the number of detected photons. Simulation results for the tiles used in the final construction are shown in Table 10.3, where $P15s$ are read out by two fibres and $P30s$ are read out by four fibres.

Tile Size	Tile Thickness(mm)	Approx. Number of Photons
$P15$	7	70
	15	150
$P30$	7	55
	15	120

Table 10.2: Summary of approximate numbers of photons expected for tiles similar to those used in the final hodoscope construction.

10.6.2 Timing Resolution

The results for the timing resolution simulation are given in Figure 10.19.

Figure 10.19: Timing resolution for different configurations of tile. Left: *P15*. Right: *P30* [114].

The key point to notice here is that to improve the timing resolution it is important to maximise the number of detected photons. The simulation indicates that sub nanosecond timing resolution is attainable for the kinds of configurations that were used. Simulation results for the tile timing resolution used in the final construction are shown in Table 10.3.

Tile Size	Tile Thickness (mm)	Approx. Timing Resolution (ns)
<i>P15</i>	7	0.40
	15	0.30
<i>P30</i>	7	0.50
	15	0.35

Table 10.3: Summary of approximate timing resolution expected for tiles similar to those used in the final hodoscope construction.

10.6.3 Fibre Bending

Fibre bending was the last effect which was considered in order to study light loss due to routing in CLAS and within the hodoscope enclosure itself. Figure

10.20 was generated in order to show the amount of light lost from the fibre as a function of the bending radius.

Figure 10.20: Effect of bending a fibre. Shown is the fraction of photons transmitted to the detector as a function of the bend radius of the fibre [114].

10.6.4 Radiation Dose

Simulations for the radiation exposure of the hodoscope and calorimeter were carried out by INFN Genoa. These were important, in order to assess the exposed dose and to ensure this wouldn't lead to significant degradation of the hodoscope's efficiency during running.

The simulations showed that the rate on the innermost pixels was equal to 3.8 rad/h without the Møller shield in place. A plot from the INFN simulation is shown in Figure 10.21.

Figure 10.21: Radiation dose on the FT calorimeter crystals in $rad/hour$ at $10^{35} cm^{-2}s^{-1}$ luminosity. The maximum values of about $5 rad/h$ are observed for the innermost crystals [114].

Since $3.8 rad/h$ is the highest rate, we assumed this to be the rate over the entire hodoscope, rather than just the innermost pixels. This gives a yearly rate of $33 krad$. It is known that the irradiation of scintillator causes the properties of the material to change; which leads to a reduction in light yield and a degradation in energy resolution. Similar effects are seen in wavelength shifting fibre where transparency, attenuation length and brightness are reduced.

There are many studies outlining the effects of radiation damage on scintillators and wavelength shifting fibre. For example, [119] suggests that doses of 10-100 $krad$ may overcome difficulties of damage and only once the exposure reaches $\sim 1 Mrad$ is damage a concern, becoming irreversibly damaged at 10 $Mrad$. Many other sources, [120] [121] [122], suggest that damage is only a concern at the $Mrad$ level and even that lower rates ($0.64 krad/h$) can recover while being irradiated. It should be noted that the doses in these studies are given over a period of hours and total dose is of the $Mrad$ level, whereas over a year our total dose is of the 10 $krad$ level. From this, we conclude that at the dose rate expected at CLAS12, the hodoscope is sufficiently radiation hard.

10.6.5 Initial Tests

Although many lab tests were carried out throughout the research and development of the hodoscope project, these were mainly done by using sources or taking cosmic data, leading to low energy spectra and low rates respectively. The ability to use real beam is key in order to improve not just the mechanical design of the detector but also to evaluate the electronics under more realistic conditions. Three key staging tests were done in order to help finalise the hodoscope design. These began with a prototype test at Jefferson Lab, concluding with two separate tests at the **D**ouble **A**nnular Φ **F**actory for **N**ice **E**xperiments (DAFNE or DAΦNE) **B**eam **T**est **F**acility (BTF). All of these major tests were completed in tandem with prototypes of the FT-Cal.

10.6.5.1 First Test: JLab

The initial set-up used only a single tile prototype, of dimensions $15 \times 15 \times 10$ mm³⁵. The tile used a groove rather than holes to read out 2 WLS fibres to a SiPM. The set-up with the calorimeter prototype, in Hall B at JLab, is shown in Figure 10.22.

⁵Note the thickness lies between that of the final thin layer and thick layer thicknesses of 7 mm and 15 mm respectively.

Figure 10.22: Set-up for the first JLab test.

This test was primarily a proof-of-principle for the hodoscope and calorimeter. For the hodoscope it was a chance to use beam conditions to test the readout of WLS (albeit over a relatively short distance ~ 20 cm) to a SiPM. The test tile was placed over a central calorimeter crystal in order to be able to achieve a good coincidence between tile and crystal.

The energy from the hodoscope tile and the calorimeter crystal can be plotted in 2D; Figure 10.23 shows the energy of the calorimeter crystal behind the tile against the tile energy. It is clear that a region of coincidences can be seen.

Figure 10.23: A sample result from the first test at JLab. Shown is the central calorimeter energy vs the hodoscope energy (presented in terms of ADC channel). The small left-hand cluster represents a pedestal, while the large right-hand cluster represents a coincidence measurement between the hodoscope and calorimeter element.

The initial readout set-up provided positive results but also gave many areas of development for the project. These included the optical isolation of the tile; improving the optical connection from fibre to SiPM and considering how this would work for multiple channels.

10.6.5.2 Second Test: BTF at DAΦNE

DAΦNE is an e^-e^+ collider at the INFN Frascati National Laboratory, Figure 10.24. The LINAC is used to accelerate electrons and positrons to $W = 1.02$ GeV in order to create ϕ mesons, which decay into kaons. The BTF [123] is a beam transfer line which allows users to use the DAΦNE facility as a source of electrons and positrons for multiplicity or single-electron running modes.

Figure 10.24: Ariel schematic of the DAΦNE complex [123].

The purpose of this second test was to test multiple hodoscope channels in conjunction with multiple calorimeter channels. A total of 8 tiles were prepared for this test; 4 $P15$ elements and 4 $P30$ which were then split equally between thin (7 mm) and thick (15 mm) tiles. Similarly to the initial test at JLab, the tiles were mounted in front of the calorimeter tile. To facilitate ease of readout the tiles on the left were provided with longer WLS fibre (~ 1 m) than the right side (~ 0.2 m)⁶. This set-up is shown in a simple schematic, Figure 10.25.

⁶Note that the fibres are glued with UV curing glue and still reading out in channels rather than holes. Wrapping uses aluminiumised Mylar rather than reflective paint.

Figure 10.25: Drawing of the set-up of the first test at the BTF at DAΦNE.

This set-up was using initial designs for the electronics, as well as connectors, wrapping, fibre embedding and preparation techniques. The holder designed for this test to couple a channel to a SiPM is shown in Figure 10.26; a board of connectors coupled to a single prototype SiPM and amplifier board is shown in Figure 10.27.

Figure 10.26: Photograph of tiles (left) and a fibre holder (right) used at the first BTF test. It can be seen that the tile design used WLS fibre embedded in channels rather than holes at this early stage.

Figure 10.27: Photograph of 8 hodoscope fibre holders secured to a board of SiPMs.

Results from this test were promising, although it was clear that consistency and reproducibility of the optical connections were an issue. An example of results from these tests are shown in Figure 10.28. The experience with operating the boards and detector modules in a realistic environment led to further improvements in the design.

Figure 10.28: Sample results from the first BTF test for thin tiles (top four frames) and thick tiles (bottom four frames). Beam settings of single-electron and 2-electron beam bunches are clearly seen.

During the test, it was noticed that some tiles were experiencing poor optical connection in terms of reliability and reproducibility; although steps were taken to limit this many were still suboptimal. The source was found to be a combination of poorly performing optical connections and the connectors not performing as well as anticipated. There was also some contribution from noise in the electronics while it was in the beam environment, although this was hard to quantify.

The number of photoelectrons which are seen per MIP are lower than what was expected from simulation. The best performing elements were those in the

lower panels of Figure 10.28, where a clear MIP peak at around 18 photoelectrons was observed.

Following this test, new preparation and gluing methods were developed after detailed analysis. New ideas for the SiPM connection were designed in order to obtain more reliable placement of the fibres onto the face of the active SiPM and improve the optical connection. Also different optical polishing techniques were employed to improve the connection quality and make the connection reproducible.

10.6.5.3 Third Test: BTF at DAΦNE

The new designs were implemented for this final major test. The set-up was similar to that seen in the first DAΦNE test and is shown explicitly in Figure 10.29.

Figure 10.29: Photograph of the set-up for the second BTF test. Although new tiles were constructed, the set-up used for data taking remained the same.

A sample result from this test, Figure 10.30, shows a distinct improvement from those seen at the first test at DAΦNE. The pedestal and single photoelectron peaks are clearly seen at low energies and the detected single electron from the DAΦNE beam is well separated. This photoelectron peak was calculated to have a mean value of around 80 photoelectrons per MIP which is consistent with

the design criteria for detection of the hodoscope. This also showed reasonable agreement with the *GEANT4* simulations.

Figure 10.30: Sample result from the second BTF test for a single *P30* tile. The peak for the single-electron beam mode is shown clearly above the pedestal.

Chapter 11

Hodoscope Construction

In this chapter, the construction procedure of the hodoscope is presented. This spans the preparation of individual elements, assembly and packing for shipment to Jefferson Lab. Once at JLab, the hodoscope was tested in tandem with the calorimeter and a sample of the initial results obtained are also presented here.

11.1 Hodoscope Construction

The hodoscope was constructed in a laboratory of the James Clerk Maxwell Building at the University of Edinburgh. The lab was repurposed for the project, which included constructing a tent to cover the hodoscope materials and specialist low UV lighting, shown in Figure 11.1. These steps were taken in an attempt to minimise dust in the construction area and to ensure the scintillator tiles were not damaged by exposure to excessive UV light. A “growcube”¹ was also purchased in order to have access to a reliably light-tight environment for testing single detector elements. These tests were primarily to fine tune the operation of the electronics which would be used in the final set-up, as well as being used as a quality control area for randomly sampled detector elements as they were completed.

¹“Growcubes” are usually used to aid in growing plants indoors, although their ability to be a light-tight environment highlights our interest.

Figure 11.1: Tent and low UV set-up used during the construction of the hodoscope.

Although the hodoscope was finally constructed into one complete detector, during the initial stages of the construction the hodoscope was treated purely in terms of two single layer detectors. Each half was built upon a piece of carbon fibre support material, which could then be placed together. A cross section of the carbon fibre supports from a prototype design is shown in Figure 11.2.

Figure 11.2: Cross section of the carbon fibre support material for the final stage of the hodoscope.

Once the support columns are removed from each layer, the central piece of carbon fibre is split into the two supports. Once separated, these are used to mount the thin and thick layers of the hodoscope separately.

11.1.1 Preparation of Scintillator

The scintillator tiles were made by Eljen Technology (via Southern Scientific Ltd) after a long consultation for the hodoscope project. The scintillator was manufactured into uniform $P15$ and $P30$ elements for both the thin and thick layer of the hodoscope, with dimensional accuracy of the order of 0.5 mm . These were then machined by Carville Plastics, drilling holes diagonally into the tiles to allow for placement of the fibres; a sample tile post-machining is shown in Figure 11.3.

Figure 11.3: Photograph of a drilled *P15* tile for the thick layer.

Holes were able to be machined with a radial accuracy of 0.2 mm . The dimensional placement of the holes was not a primary concern, as the important quantity to be considered is the ratio of the scintillation material to the fibre area, which will not be effected by location.

11.1.1.1 Tile Cleaning

Once the tiles were delivered, it was paramount that they be kept away from sources of UV light, as such they were kept only in our low UV lab. The tiles were individually checked for any imperfections before they were catalogued and readied for construction.

It was imperative the gloves were worn at all times while handling the scintillator, the reasons were twofold; firstly oils from the skin will damage the scintillator and secondly the outer coating on the scintillator is toxic. The tiles were prepared by first cleaning with *I*so*P*ropyl *A*lcohol (IPA) using fine cloths with particle size of micron order. They were then be polished in order to remove any small imperfections from the surface and maximise transparency. This was done with plastic polishing liquids in order to first polish, then improve clarity.

11.1.1.2 Tile Painting

In order to maximise the number of scintillation photons which are captured in the WLS fibre, each tile should be optically isolated. It was decided that

the isolation would be achieved by using reflective paint (specifically *BC-622A* Reflector Paint [124]). This was selected after considering factors such as total reflectivity, application thickness, work hours required and ability to quality control.

The reflector was applied using fine round, rigger and angle paint brushes². The minimum requirement for paint thickness per side was defined as 0.15 mm ; this and a detailed visual inspection of each tile were the criteria for passing the first stage of QC. An example of a prepared tile is shown in Figure 11.4.

Figure 11.4: Tile shown post-painting. Dummy fibres and aluminium foil were used to protect the drilled channels.

It should also be made clear that the addition of paint adds ‘size’ to the tile. The additional thickness introduced leads to outer tiles of the hodoscope being displaced by the order of several *mm*s. The assigned 0.15 mm thickness is a compromise between a highly reflective surface and a minimised movement of the outer tiles. The concern of this is twofold: firstly, any tiles which exceed the outer radius of the hodoscope area must be cut and secondly, additional tile thickness increases dead regions within the detector,

Once the tiles were painted the first round of QC is performed. This is a visual inspection where any areas which are obviously too thin or streaked must be repainted, the goal of this is to obtain as close to a smooth homogeneous finish as possible. It was necessary to have a thickness larger than 0.15 mm and then to

²This was done in shifts by several members of the department, some of whom were actively involved in the hodoscope project and others who were not. While the painting was done by many people, the *Quality Control* (QC) and additional tile corrections were only undertaken by myself.

apply sandpaper to the tiles to reach their final size, as we also wish to minimise the variation across each surface.

Figure 11.5: Illustration showing the additional thickness created by the thickness of a paint layer and introduced by the surface variation in neighbouring edges.

After the initial QC, the second stage begins. This involves minimising the surface variation in order to keep the boundary between each tile flush and minimise the dead space between each element, illustrated in Figure 11.5. For the tile base, the minimisation is in an effort to keep the tile placement as flat as possible to provide a flush surface when applied to the carbon fibre support. For the top side, the variation is not an issue as this does not impede the tile placement or the optical fibres as they exit the element.

An average surface variation of 0.1 mm was achieved using a two step process. The first polish used 1200 grit wet and dry sanding paper to remove any large uneven areas. These areas generally form close to the edges and corners where during the painting the brush has rounded the edge of the tile. This was then followed by lapping film with a pitch of $3\text{ }\mu\text{m}$.

Each tile was then measured using a dead-flat surface and a vernier height gauge to measure the average surface variation. Tiles were then catalogued numerically by their final length and width such that position in the scintillator array could be chosen. The choice of placement was not trivial and so was carefully considered.

11.1.2 Tile Placement

The layout of the hodoscope has been described in terms of 8 sectors, split into *odd* sectors containing 9 elements and *even* sectors which contain 20 elements, shown in Figure 11.6.

Figure 11.6: Simple representation, breaking the hodoscope down into sectors and elements within them.

Due to the tight restrictions on available space within the hodoscope for optical fibres the *flow* of fibres within the hodoscope is incredibly important. This was carefully considered and the solution devised was to have sets of tiles where the fibres enter at the **C**orner and where the fibres enter at the **E**dge, as described in Section 10.5. A schematic of the hole direction and the resulting orientation of each tile is shown in Figure 11.7.

Figure 11.7: Simple representation of hodoscope elements, showing the required orientation of tiles.

Although there is a strict layout for the tile-types in the hodoscope, the placement of individual tiles was undefined.

Each tile size ($P15/P30$) and type (C/E) had their dimensions measured after QC, and the dimensions were placed into arrays based on tile size and type.

11.1.2.1 Inner Radius

The inner radius of $P15s$ is where the process must begin, as this is the main limiting factor of the size and symmetry of the hodoscope, Figure 11.8. Certain combinations of tiles must be used and in certain orientations, this leads to a set of tile conditions which must be followed for each edge on the inner radius.

Figure 11.8: Illustration showing the tile orientation at the centre of the hodoscope. Since tiles are no longer square both sides of the tile are considered independently.

Firstly consider the top edge:

- Corner tile, Corner tile, Edge tile, Edge tile, Edge tile, Edge tile, Corner tile, Corner tile ... *or*
- $CCEEEEC$.

Including the orientation needed for each tile (where 1 and 2 have been introduced to represent length and width respectively), the length of the top edge becomes:

- $C2 + C2 + E2 + E2 + E2 + E2 + C1 + C1$.

This can be emulated similarly for all inner edges:

- Top: $C2 + C2 + E2 + E2 + E2 + E2 + C1 + C1$,
- Left: $E2 + E2 + E2 + E2 + C2 + C2 + C2 + C2$,
- Right: $E2 + E2 + E2 + E2 + C1 + C1 + C1 + C1$,
- Bottom: $C1 + C1 + E1 + E1 + E1 + E1 + C2 + C2$.

Although we consider each side as a separate entities, the minimisation process is not as trivial as minimising these lengths. Without any consideration of the

correlation of edges, it is easy to end up with asymmetries and a skewed inner radius. To overcome this, some further considerations must be made. Along with the intra-edge properties defined above we also must consider the inter-edge properties. These include the constructed inner circumference to parametrise the inner radius, ζ . The relative differences in the intra-edge lengths and the sum of these values allow for parametrisation of the edge symmetry, ξ . The final minimisation function, χ , becomes some weighting of these two variables:

$$\chi_{inner} = A\zeta + B\xi, \quad (11.1)$$

where $A, B \in \mathbb{Q}[0, 1]$ and $A + B \stackrel{!}{=} 1$. This allows the importance of minimisation and symmetry to be carefully balanced and experimented with to find an ideal configuration.

The minimisation process randomly selects tiles of the appropriate type and orientation, where each can only be selected once. The function χ is then minimised according to the weighted values of ζ and ξ . Many trials of this were run with various weightings in order to find a favoured minimisation. The key to an effective minimisation is a lower number of iterations but many trials with a different random seed; this method ensures that false local minima do not strongly influence the result.

11.1.2.2 Even Sectors

The next key stage is minimising the even sectors, the orientations are shown in Figure 11.9. These four sectors were considered in terms of rows within each sector. We can sub-divide each sector into three constituent rows and label tiles as for the inner radius:

Figure 11.9: Illustration showing the orientation of tiles in the even sectors of the hodoscope. These are considered as three rows.

- Sector 2:
 $(C2 + C2 + C1 + C1) \times 1,$
 $(C2 + E2 + E2 + C1) \times 2.$
- Sector 4:
 $(C1 + C1 + C1 + C1) \times 2,$
 $(E2 + E2 + C1 + C1) \times 1.$
- Sector 6:
 $(E1 + E1 + E1 + E1) \times 2,$
 $(C1 + E1 + E1 + C2) \times 1.$
- Sector 8:
 $(C2 + C2 + C2 + C2) \times 2,$
 $(C2 + C2 + E2 + E2) \times 1.$

Again the minimisation is not trivial. We consider intra-sector properties, such as the average row size, row deviation from the average and the sum of the deviations; giving some indication of the squareness of the sector, μ . Inter-sector properties are also considered, such as the sector deviations from the average size; giving some indication of the sector symmetry, ν . A new χ function can be defined:

$$\chi_{outer} = A\mu + B\nu, \quad (11.2)$$

where $A, B \in \mathbb{Q}[0, 1]$ and $A + B \stackrel{!}{=} 1$. This χ is again minimised for weighted values of μ and ν , for many iterations until a suitable minimisation is found.

Intra-sector properties are considered such as the average width; the deviation from the average in a column; the deviation between columns and the sum of deviations and relative deviations. This gives two considerations: the squareness of the rows, δ and the symmetry of the rows, λ . Inter-sector properties such as the deviation from sector averages and sum of these are considered, giving an insight into the sector symmetry, ψ . We again construct a minimisation function:

$$\chi_{corner} = A\delta + B\lambda + C\psi, \quad (11.3)$$

where $A, B, C \in \mathbb{Q}[0, 1]$ and $A + B + C \stackrel{!}{=} 1$. This is then minimised with weightings of A , B and C , in order to find a suitable arrangement.

11.1.2.4 Optimal Tile Arrangement

Each stage of minimisation must be fully completed before continuing onto the next. This is because once a tile is selected, it must be removed from the array of available tiles. A fully minimised arrangement in the lab is shown in Figure 11.11.

Figure 11.11: Fully minimised layout for the thick layer of the hodoscope. Element types are denoted by colour: *P30C*, *P30E*, *P15C* and *P15E*.

11.1.3 Tile Cutting and Gluing

Once each element was given a finalised position, the tiles were put into their final configuration on the carbon fibre backing. From this it was simple to identify outer tiles which would cutting in order to stay within the radial limitations. A close-up of some of these tiles are shown in Figure 11.12, where it can be seen where certain tiles cross the radial boundary.

Figure 11.12: A close-up view of the edge where tiles cross the outer radius, as outline by the to-scale schematic placed underneath.

The tiles were machined by the mechanical workshop of the physics department at the University of Edinburgh. Once these were machined, the process of cleaning, polishing, painting and quality control were conducted again as outlined in Section 11.1.1.

The order of the tile mounting was also important, as if any small offset was introduced near the centre this would propagate outwards causing offsets and asymmetries towards the outer edges of the hodoscope. The $P30$ s within even sectors are the key pieces to begin with.

Figure 11.13: Photograph showing the 3D printed (black) and machined (silver) jigs used for even sector tile placement.

A 3D printed plastic jig was designed in order to secure into the central hodoscope collar, this would allow for accurate placement of the inner circumference of $P15$ s in terms of position and rotation. A machined metal jig was also produced, and fitted onto this such that the even sector $P30$ s could be inserted and aligned with the inner boundary. These jigs are pictured in Figure 11.13.

The $P30$ s from the odd sectors were the next to be added, as these naturally sit against the even sectors such that they self-align. The $P15$ s in the inner radius and outer edges are inserted finally to complete the scintillator array.

The gluing of the tiles to the carbon fibre board was then undertaken using an Araldite two part epoxy adhesive. These elements were left overnight, covered with a layer of foam with a small weight placed on top to provide a full cure while minimising the risk of tile movement.

Once the gluing process was completed, a full survey of the final tile positions was taken so that the position of each element could be accurately known and included in the monitoring code of the hodoscope.

11.1.4 Spliced WLS-Optical Fibres

The process of splicing the WLS to clear fibre was undertaken at the Fermi National Accelerator Laboratory (Fermilab, IL, USA). The process uses an electric arc to melt two fibres together, providing a reliable joint with low optical loss and high mechanical strength. The fibres consisted of $\sim 6\text{ m}$ long clear optical fibres which had been spliced to approximately 10 cm lengths of WLS fibre. A picture of spliced fibres being placed into a tile is shown in Figure 11.14.

Figure 11.14: Photograph of a sample tile with spliced fibres inserted. The WLS splice is clearly seen on the right-hand side.

These were then collected into groups of four fibres, which were then sheathed together, into what we refer to as “bundles”. These bundles were collected into groups of 20 and placed in bags for transportation to Edinburgh. Figure 11.15 shows a length of bundles in the lab after unpacking.

Figure 11.15: Lengths of spliced fibre in the lab.

11.1.4.1 Preparation of Optical Fibres

Each bundle of optical fibre had to be prepared before they could be glued into the hodoscope elements. This involved similar preparations to that of the tiles, as outlined in Section 11.1.1.

The fibre ends were polished using sand paper from coarse grain down to 3 μm lapping paper. These were then thoroughly cleaned using IPA, before being painted with reflective paint in order to maximise the number of photons collected in the fibres.

Each bundle labelled numerically at both ends, so that each bundle could be mapped to the corresponding hodoscope elements. It is important to remember that each bundle consists of four optical fibres. Due to spatial limitations, there are not sufficient space for each element to have a dedicated bundle. Therefore two *P15* elements were forced to share a bundle. Once the fibre ends were prepared the gluing process could begin.

11.1.4.2 Optical Fibre Gluing

The optical adhesive chosen for gluing the fibres into the drilled channels of the tiles was Epotek 301-2 [125], a two part epoxy with very good optical properties and resistance to radiation damage. Once mixed it was placed in a vacuum

chamber to removed any air bubbles which were added during the epoxy mixing. Each batch of glue had a sample taken and placed between two microscope slides; this was an attempt to have some kind of quantitative QC over the glue used so future problems could be highlighted, such as premature yellowing. A hypodermic needle was used to syringe the glue into the bottom of the drilled channels after they were cleaned with air. Fibres were then cleaned with IPA before being inserted into the holes, being careful to ensure enough glue had been used to fill the cavity. Once this completed, the excess glue was removed and the epoxy left to cure over night.

11.1.4.3 Fibre Routing

Each element was then catalogued along with the associated fibre bundle and batch number. Once a layer of the hodoscope's fibres were fully cured, they had to be appropriately routed. This was an important step, because due to spatial restrictions there was a limit on the height available to each layer of the hodoscope, including fibres. Great care was taken, ensuring that each fibre's path minimised crossing with others and took the simplest available route to the deltawing. The main concern was that when the carbon fibre cover was placed on there would be too much force placed on the fibres, which could lead to crazing, cracking and breaking. A completed thin hodoscope layer is shown in Figure 11.16.

Figure 11.16: The final fibre layout of the thin side of the hodoscope.

The deltawing is shown attached to the base of the hodoscope in Figure 11.17. This area is a key pinch-points in the hodoscope design, as all fibres must pass through this narrow region. There is very limited space to route the 752 fibres through and required extensive planning in order to organise the fibre bundles.

Figure 11.17: Photograph 3D printed deltawing, in place at the base of the hodoscope.

The deltawing is the 3D printed section at the base of the hodoscope tile assembly. This was designed to meet various strict spatial constraints, allowing for two additional fibre bundles to be placed inside: which would later be used to accommodate the LED flasher, Section 11.1.5. Key bundles were systematically identified and placed according to arrangements that would cause minimum stress on the internal fibres. Others were then inserted into the arrangement. The results of this arrangement is shown in Figure 11.18. The positions were catalogued according to bundle number and hodoscope element, so if the deltawing needed to be opened and reconstructed, optimal positions for the bundles were already known. Vertical columns inside the deltawing were secured with lacing chord before a carbon fibre cover was secured with nylon screws.

Figure 11.18: Photograph of the deltawing with fibre bundles arranged and preliminarily secured.

Once the deltawing arrangement was finalised the hodoscope could be closed. The carbon fibre cover for the hodoscope and deltawing were secured with nylon screws into struts placed around the hodoscope edge. An outer enclosure was also made, Figure 11.19, in order to provide a good seal with the lids on both layers. These were also secured with nylon screws, this time into the side of the support struts.

Figure 11.19: Photograph of the edge enclosure of the hodoscope.

Once sealed, the hodoscope was flipped such that the unglued side was exposed. The same procedures for fibre preparation and gluing were followed.

11.1.5 LED Flasher

The aim of installing an LED flasher was to monitor the radiation damage and recovery of the hodoscope's tiles and fibres. Specifically, this would allow measurements of the detector response to be made pre-run and post-run so that any changes could be monitored.

The flasher uses an LED attached to optical fibres, connected to several diffusers within the hodoscope. The flasher uses these optical diffusers to release light onto a section of optical fibres, as shown in Figure 11.20. These were placed into the quadrants of each hodoscope layer and secured to the carbon fibre lid. The placement allows for the study of four areas of each layer. This will allow for the measurements of the change in response of the optical fibres independently, rather than having some convolution of the tile/fibre system. Furthermore, this also allows for separation of the tiles/fibres so that the response of the tiles can be inferred.

Figure 11.20: Photograph of one element of the LED flasher before the hodoscope was sealed for transportation.

The LED Flasher was designed and tested by the Nuclear Physics Department at the University of Glasgow. The main testing the flasher will be undertaken at JLab, as the hodoscope had to be constructed fully before any multi-channel tests could be undertaken.

11.1.6 Electronic Connectors

The connectors to the electronic boards were 3D printed in three parts, referred to collectively as Fishtails:

- Front Panel: which aligns the fibre bundles to the SiPMs.
- Base: interlocking into the front panel.
- Lid: when secured with screws, holds the fishtail together.

Each fishtail is able to align a maximum of 8 channels from the hodoscope to the SiPMs in the electronic rack. 15 of these fishtails were printed for each hodoscope layer. From the arrangement specified inside the deltawing, the order that bundles would be placed into fishtails was mimicked in order to minimise tangling and crossing of the bundles.

Due to the differing path lengths of the fibres within the hodoscope, ends of the bundles were not uniform. These were cut to similar lengths and placed into the front panel of the connector and glued using Araldite, as shown in Figure 11.21.

Figure 11.21: Photograph of fishtail connectors after fibres have been glued. Left: shown only in the front panel. Right: shown in a constructed fishtail.

The additional fibre was then cut back to $\sim 2\text{ mm}$ from the connector face and polished until flush. As before the polishing initially used large grain sand paper, progressing towards fine lapping film. Each channel in each fishtail was then labelled so that it could be easily traced to its original element within the hodoscope.

A picture of two completed fishtails is shown in Figure 11.22.

Figure 11.22: Photograph of fishtail connectors attached to a SiPM board (left) and placed into the SiPM rack (right).

11.1.7 Sealing and Shipping

The hodoscope was sealed using nylon screws as shown in Figure 11.23. All joins of the carbon fibre, enclosure and deltawing were sealed with silicon putty and black tape to create a light-tight seal and provide support for transportation.

Figure 11.23: Photograph of the fully sealed hodoscope after construction.

A crate was custom designed via consultation with Seabourne Group to transport the hodoscope to Jefferson Lab. This was designed to protect all elements of the hodoscope from excess movement that could lead to damage of the fibres or detector. This was designed to use high density foam to absorb any impacts during shipping, and a tailored design for the exact measurements of the hodoscope. The CAD and final packing of the design are shown in Figure 11.24.

Figure 11.24: Upper: CAD illustration of the hodoscope packing design. Lower: Photograph of the hodoscope packed in the lab before shipping.

The hodoscope was shipped from the University of Edinburgh at the beginning of 2016 and arrived at Jefferson Lab in mid-January 2016.

11.2 Complete Test at Jefferson Lab

The key aims of the initial tests at upon arrival at Jefferson Lab, were as follows:

- Ensure no damage was sustained during transportation.
- Unpack and set up the hodoscope for running with all (most) channels.

- Take data in coincidence with the calorimeter.

After the hodoscope was unpacked, the initial checks performed on the detector were mainly cosmetic. After this, the main concerns were broken fibres within the sheathing, and fractures within the hodoscope enclosure or fishtail connectors. These would be most easily identified by taking data over the entire face of the hodoscope and identifying any problematic channels. To fully identify problems, data had to be taken over the entire face of the hodoscope.

The hodoscope was placed on top of the calorimeter, constructed by INFN Genoa, via a tungsten pipe for alignment, Figure 11.25. This also shows the layout of the hodoscope's fibre bundles leading to the covered SiPM boards.

Figure 11.25: Upper: Photograph of the test set-up at Jefferson Lab. The SiPM rack is located in the black box on the left-hand side of the picture, while the hodoscope can be seen on the right. Lower: A close-up photograph of the hodoscope and calorimeter with a scintillator paddle placed on top to act as an external trigger.

11.2.1 Preliminary Results

The preliminary results from tests at Jefferson Lab are very encouraging. Although there were some initial problems with the electronics for some channels, the hodoscope is now running with all channels. A sample event for one tile is

shown, in Figure 11.26, within the hodoscope monitoring software.

Figure 11.26: Hodoscope GUI, showing one event. Shown are the ADC and timing signals.

The datasets were filled with cosmic data, using the calorimeter for coincidence, as well as an external scintillating paddle trigger. The purpose of these tests were to establish how many photoelectrons per MIP are being recorded for each element. Results of a sample run are shown in Figure 11.27.

Figure 11.27: Hodoscope GUI. This shows the results of an entire run, highlighting each hodoscope sector and the number of photoelectrons detected in each element shown for the **thick** and **thin** layers.

This shows the average number of photoelectrons per MIP in each element of the hodoscope. We see that the mean number of photoelectrons seen in an element in the thin layer is ~ 20 , while in the thick layer we see ~ 50 . These values can be considered as the lower bound of operation as further improvements must be made to the software and hardware.

Improvements can be made to the fitting methods within the software, but more importantly the voltages at which the SiPMs operate at influence the gain quite substantially. The operating voltage of the SiPMs must be individually tuned in order to suit each channel, so that the number of photoelectrons can be maximised and the noise can be minimised. These improvements will be implemented over the coming months, and further tests carried out at JLab before installation in Hall B.

Chapter 12

Conclusions

A measurement of the double-polarisation observable $\mathbb{E}$ has been presented for the $K^+\Sigma^-$ channel from the $g14$ (*HDice*) run period at CLAS. These results were presented in the photon energy (E_γ) range 1.1-2.5 GeV and the complete range of the cosine of the kaon centre-of-mass angle ($\cos\theta_{K^+}^{CM}$). The modest statistics of the data allowed for a bin width of 200 MeV in E_γ and 0.4 in $\cos\theta_{K^+}^{CM}$. This measurement represents the first measurement of the $\mathbb{E}$ double-polarisation observable for the $K^+\Sigma^-$ channel.

The data were compared with the current solutions of two theoretical models, KaonMAID and Bonn-Gatchina. These gave divergent predictions for the observable and the new data gave better agreement with KaonMAID at low E_γ ($< 1.7 GeV$), and better agreement with Bonn-Gatchina at higher E_γ . The new data will be an important new constraint on these models. More definitive physics conclusions regarding nucleon resonance properties will await the new data being incorporated into the theoretical predictions. This will occur after the data is published.

Future analysis of the channel would benefit from the capability of achieving a sufficiently large data sample in which the final state neutron is also detected. This would allow cleaner event identification (removing the largest systematic error in the current analysis) and also allow more restrictions on the spectator proton momentum to reduce potential contributions from final state interactions. However the current data is an important first step.

Also presented in this thesis was the design and construction of a new forward tagging hodoscope for use during the CLAS12 era of Jefferson Lab.

The hodoscope is a segmented scintillating detector array, for the separation of photons and electrons within a new tagging system at JLab. The initial design, alongside simulations were presented here, as well as the process of construction.

The hodoscope will be installed alongside the forward tagger calorimeter and tracker during 2016, with the aim of initial data-taking during 2017. There is still a great deal of work to be undertaken for the hodoscope in terms of software development and calibration procedure (which is ongoing). The new apparatus will be key in future experiments searching for exotic hybrid mesons, hybrid baryons and a range of other programmes in hadron spectroscopy.

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Appendix A

Hodoscope Tile Schematics

P30-7-C

Top view

Side view

P30-7-E

Top view

Side view

Note: Drill lines indicated in **red**. Diagrams not to scale. The holes do not come through the bottom of the scintillator.

P30-15-C

Top view

Side view

P30-15-E

Top view

Side view

Note: Drill lines indicated in **red**. Diagrams not to scale. The holes do not come through the bottom of the scintillator.

P15-7-C

Top view

Side view

P15-7-E

Top view

Side view

Note: Drill lines indicated in **red**. Diagrams not to scale. The holes do not come through the bottom of the scintillator.

P15-15-C

Top view

Side view

P15-15-E

Top view

Side view

Note: Drill lines indicated in red. Diagrams not to scale. The holes do not come through the bottom of the scintillator.