HIGH RESOLUTION SPECTROSCOPY OF ${}_{\Lambda}^{12}\text{B}$ HYPERNUCLEI BY THE $(e,e'K^+)$ REACTION

A Dissertation

Presented to

the Faculty of the Department of Physics

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

By

Murad G. Sarsour

May 2002

HIGH RESOLUTION SPECTROSCOPY OF ${}_{\Lambda}^{12}\text{B}$ HYPERNUCLEI BY THE $(e,e'\text{K}^+)$ REACTION

Murad G. Sarsour

APPROVED :

Dr. Ed V. Hungerford, Chairman

Dr. Donald Kouri

Dr. Kwong Lau

Dr. Bill W. Mayes II

Dr. Carlos Ordonez

Dr. Lawrence Pinsky

Dr. Lowell Wood

Dean, College of Natural Sciences
and Mathematics

Acknowledgments

I would like to start by thanking Allah the most gracious, the most merciful. I would like to thank my parents, Ghaleb and Hilweh Sarsour, and my brothers and sisters who supported and encouraged me since the very first day in school. I am blessed to have such a loving and caring family. This dissertation is a result of your love and prayers. I dedicate this work to you, and I hope that I have lived up to your expectations.

I deeply appreciate the help and guidance of my adviser Dr. Ed V. Hungerford who taught me by example. He patiently helped me understand all sides of this study, theoretical and experimental, through many hours of discussions. His door was always open for help. I am very fortunate to be his student.

I thank my graduate committee: Dr. Donald Kouri, Dr. Kwong Lau, Dr. Bill W. Mayes II, Dr. Carlos Ordonez, Dr. Larry Pinsky, and Dr. Lowell Wood for their time and encouragement. Dr. Mayes is more than a committee member; he is a friend.

Nuclear physics experiments require the hard work and dedication of many people, and this work is no exception. While I can not list everyone, I would like to thank our medium energy group at the University of Houston especially Dr. Anton Empl and Dr. John Wilson. Thank you, Anton, for your kindness and help, and John, for your support during my qualifier exams and for being my friend when I needed one. It would have been difficult without the companionship of Stephen Tsui and Narbe Kalantarian – thank you both. I would like also to thank Kerry Lee, for being a good

friend and for his help especially with `mn_fit`.

Likewise, no physics department runs well without a hard working staff. I would like to thank you all. A special thanks goes to a very dear and special friend Naomi Haynes. Thank you for always being there when things got tough despite my bad moods; you are really a special person.

The success of my thesis topic is a result of the hard dedicated work of many people at JLab, especially in Hall C and E89-009 collaboration. I would like to thank them all and especially Dr. Liguang Tang for his guidance and support during my stay at JLab. Also thanks to Dr. Riad Swafta, Dr. Abdallah Ahmadouch, Dr. Riad Suleiman, Dr. Henry Juengst, and Dr. Jinghua Liu. I am also thankful for the companionship and help of great friends: Lulin Yuan, Dr. Xiaofeng Zhu, and Miyoshi Toshinobo. Lulin played a vital role in the analysis of the experiment; thank you again for the help and efforts that you have put in for me.

I would like to thank my special friend, my sister, Fatima Amir, whom with I shared my joys and frustrations of graduate studies. Also, my thanks extends to my friend Dirar Hamouz who made me feel like I was at home again.

HIGH RESOLUTION SPECTROSCOPY OF ${}_{\Lambda}^{12}\text{B}$ HYPERNUCLEI BY THE $(e,e'K^+)$ REACTION

An Abstract of a Dissertation

Presented to
the Faculty of the Department of Physics
University of Houston

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

By
Murad G. Sarsour

May 2002

ABSTRACT

Jefferson Laboratory experiment E89-009 used the reaction $(e,e'K^+)$ to produce ${}_{\Lambda}^{12}\text{B}$ hypernuclei from a carbon target. The scattered electrons were tagged at 0° to take advantage of the increased virtual photon flux at forward angles, and the electro-produced kaons were also detected at small angles, $\sim 3^\circ$, to minimize the momentum transfer. To do this, a splitter magnet was used to bend the scattered electrons into an Enge split-pole spectrometer and the kaons into a short orbit spectrometer. In addition to increasing the production rate, tagging the scattered electrons at 0° minimizes the optical aberrations on the focal plane of the Enge split-pole spectrometer.

In this experiment, the spectroscopy of the ${}_{\Lambda}^{12}\text{B}$ hypernuclei was studied and excellent energy resolution was achieved, ~ 918 keV. The differential cross section of the ground state doublet was also calculated.

Contents

1	Introduction and Physics Motivation	1
1.1	Introduction	1
1.2	Strangeness	7
1.2.1	Hyperons	8
1.2.2	Hypernucleus	9
1.2.3	Hypernucleus Production	13
1.2.4	$(e,e'K^+)$ reaction	15
1.3	History	20
1.3.1	Some Theoretical Work	20
1.3.2	Experimental History	21
1.4	E89-009	25
1.4.1	Zero Degree Electron Tagging	25
1.4.2	Formalism	27
1.4.3	Observables	39

2	Experimental Apparatus and Setup	42
2.1	Overview	42
2.2	The Accelerator and Hall C	44
2.2.1	Accelerator	44
2.2.2	Hall C Arc	45
2.3	Target	51
2.4	The Hypernuclear Spectrometer System	52
2.4.1	Electron Spectrometer	52
2.4.2	Kaon Spectrometer	53
2.5	Detector Package	61
2.5.1	ESPS Detector Package	61
2.5.2	SOS Detector Package	65
2.6	Triggers	77
2.6.1	Trigger	77
2.6.2	Trigger Supervisor	78
2.7	Data Acquisition	79
3	Data Analysis	81
3.1	Analysis Software	81
3.1.1	Main Event Loop	84
3.1.2	Event Reconstruction	85
3.1.3	Tracking	86

3.2	Calibration	88
3.2.1	SOS Hodoscope	88
3.2.2	Drift Chamber	89
3.2.3	Lead Glass Calorimeter	90
3.2.4	Gas Cerenkov	91
3.2.5	Lucite Detector	92
3.2.6	Aerogel Detector	93
3.2.7	ESPS Hodoscope	93
3.2.8	SSD Calibration	94
3.2.9	ESPS Momentum Calibration	95
3.3	Rates and Trigger	106
3.4	Particle Identification	109
3.4.1	Time Of Flight Cut	109
3.4.2	Tracking Cuts	112
3.4.3	Cerenkov Cuts	112
3.4.4	Lead Glass Calorimeter Cut	115
3.4.5	SSD and Enge Hodoscope Cuts	117
3.4.6	Coincidence Cuts	118
3.5	Total Charge	121
3.6	Corrections to the Yield	121
3.6.1	Tracking Efficiency	121

3.6.2	ESPS Hodoscope Efficiency	123
3.6.3	SSD Efficiency	125
3.6.4	Geometrical Efficiency	127
3.6.5	Electronic and Computer Dead time	129
3.6.6	Survival Ratio of K^+	130
3.6.7	Absorption	131
3.6.8	Cut Efficiencies	133
3.7	Acceptance	140
3.7.1	ESPS Acceptance	141
3.7.2	SOS Acceptance	142
3.8	Systematic Errors	147
4	Results and Discussion	150
4.1	Results from the CH_2 Target	150
4.2	Results from the ^{12}C Target	154
4.2.1	The Λ Peak	155
4.2.2	The Quasi-Free Region	156
4.2.3	The Λ Bound State Region	156
4.3	Experimental Resolution	164
4.4	Differential Cross Section	170
4.4.1	Results	172
4.4.2	Discussion	173

5 Summary and Conclusion	176
---------------------------------	------------

Bibliography	180
---------------------	------------

List of Tables

1.1	Leptons and their properties.	2
1.2	Quarks and their properties.	3
1.3	Λ decay modes and fractions	8
1.4	Comparison of the theoretical prediction of the spin-orbit interaction . . .	13
1.5	Comparison of Λ Hyperon production reactions.	14
1.6	Thresholds for kaon photoproduction from a nucleon where the energy of the outgoing kaon is 1.2 GeV at an angle of 10°	33
2.1	E89-009 Targets	51
2.2	Electron spectrometer parameters.	53
2.3	Summary of the SOS parameters.	56
2.4	SSD specifications.	63
2.5	The SOS hodoscope dimensions.	70
2.6	SOS flux by particle type and trigger rate.	77
2.7	SOS flux by particle type and trigger rate. A small part of the production data was acquired with (3/4) hodoscope trigger.	78

3.1	Estimated singles rate for each target from a trigger study.	106
3.2	Estimated singles rate (trigger rate) for each target from a trigger study. .	107
3.3	The total charge in E89009.	121
3.4	The electronic and computer lifetimes for different rates and different targets.	130
3.5	K^+ decay modes with their branching ratios.	131
3.6	Coincidence time efficiency.	136
3.7	PID cuts and their efficiencies.	139
3.8	The dimensions of the detectors that were used in the RAYTRACE data card.	144
3.9	The systematic errors of the detector efficiencies.	148
3.10	Summary of the systematic errors.	149
4.1	Energies and squares of LS OBDME for s_Λ and p_Λ states in $^{12}_\Lambda\text{B}$	159
4.2	Energies and relative strength for s_Λ and p_Λ states in $^{12}_\Lambda\text{B}$	162
4.3	The contributions of the experimental components to the missing mass res- olution.	164
4.4	The individual corrections to the yield.	172
4.5	Cross sections and their parameters.	173
5.1	The observed states in the $^{12}_\Lambda\text{B}$ missing mass spectrum and the location of these states.	177

List of Figures

1.1	Isospin vs strangeness chart for baryons of spin parity $J^\pi = \frac{1}{2}^+$	9
1.2	Doublet splitting by the spin-dependent interaction.	11
1.3	Two-pion exchange and one kaon exchange in the ΛN interaction.	12
1.4	One pion exchange due to $\Lambda\Sigma^0$ coupling.	12
1.5	A neutron is converted to a Λ hyperon by exchanging the strange quark. .	14
1.6	A neutron is converted to a Λ hyperon by associated production in the (π^+, K^+) reaction.	15
1.7	A proton is converted to a Λ hyperon by associated production in the ($e, e' K^+$) reaction.	16
1.8	The momentum transfer as a function of the photon to kaon angle for varying photon energies. The E_γ is in MeV unit.	18
1.9	A comparison of three hypernuclear production reactions on a ^{12}C target. .	19
1.10	The calculated excitation function for the $^{12}\text{C}(\gamma, K^+)_{\Lambda}^{12}\text{B}$ reaction at $p_\gamma =$ 1.2 GeV/c and $\theta_L = 10^\circ$. The solid (dashed) line indicates the positive (negative) parity state.	20

1.11	The calculated angular distributions for the $^{12}\text{C}(\gamma, \text{K}^+)_{\Lambda}^{12}\text{B}$ reaction at $p_{\gamma} =$ 1.1 GeV/c.	21
1.12	$^{12}_{\Lambda}\text{C}$ spectrum measured by the $^{12}\text{C}(\pi^+, \text{K}^+)$ reaction.	22
1.13	$^{12}_{\Lambda}\text{B}$ spectrum produced by the reaction $^{12}\text{C}(\text{K}_{\text{stopped}}^-, \pi^0)_{\Lambda}^{12}\text{B}$	23
1.14	γ ray spectrum for the bound-state region of $^9_{\Lambda}\text{Be}$	24
1.15	The virtual photon flux factor versus scattering angle	26
1.16	The scattering geometry and its kinematics variables.	27
1.17	The four external momenta for the reaction, (e, e', K^+)	28
1.18	(a) s-channel, (b) u-channel, (c) t-channel.	29
1.19	The total cross section for the process, $\gamma p \rightarrow K\Lambda$, as a function of the photon energy in GeV.	32
1.20	Feynman diagrams for the Bremsstrahlung scattering processes.	33
1.21	The bremsstrahlung distribution versus the scattering angle.	35
1.22	Cartoon diagram of the pair production process.	36
1.23	Multiple scattering angular distribution.	38
1.24	Cartoon diagram of kaon electroproduction.	40
2.1	Top view of the E89-009 experimental setup.	43
2.2	Layout of the CEBAF Accelerator	44
2.3	Top view of the hall C arc with the monitoring instruments	46
2.4	Schematic of the Hall C Harp system	47
2.5	A CEBAF Accelerator Cavity	48

2.6	Angular distribution of the virtual Photons.	54
2.7	Side view of the SOS spectrometer.	55
2.8	From right to left, the sieve slit, the small collimator, and the large collimator.	57
2.9	The <i>RAYTRACE</i> simulation of the events distribution on the focal plane.	58
2.10	The gray plot shows the events distribution on the focal plane of the data while the red one, on the top, is calculated by <i>RAYTRACE</i>	59
2.11	X and Y are reconstructed at the face of the sieve slit.	60
2.12	The ESPS Detector Package.	61
2.13	Side view of the SSD strip.	62
2.14	Top view of the SSD chip.	64
2.15	A block diagram of the SSD readout system.	64
2.16	Top view of the SOS detector package with approximate locations in cm.	66
2.17	Top view of the SOS drift chamber.	68
2.18	A view of the SOS drift chamber shows the orientation of the six wire planes.	69
2.19	The SOS DC drift cell.	70
2.20	The electronics diagram of the SOS hodoscopes.	71
2.21	The electronics diagram of the SOS Gas Cerenkov.	72
2.22	A schematic of the SOS aerogel detector.	73
2.23	The electronics diagram of the SOS Aerogel detector.	73
2.24	The electronics diagram of the SOS Lucite detector.	74
2.25	The electronics diagram of the SOS shower counter.	76

2.26	SOS single arm trigger electronics.	79
2.27	Coda software chart.	80
3.1	A flowchart of modified Hall C ENGINE.	82
3.2	Software flow chart for the SOS event construction.	85
3.3	Discriminator operation in cases of a large and a small input signal.	89
3.4	Top: The drift time. Bottom: The drift distance	91
3.5	Average number of the photoelectrons as a function of β	92
3.6	The hodoscope time distribution versus the ADC.	94
3.7	The constructed momentum (MeV/c) versus SSD channel number.	97
3.8	The focal plane of the ESPS simulated by RAYTRACE.	98
3.9	The hit patterns of the second overlapped channels.	100
3.10	The overlapped channels between every two SSD planes for run# 33106.	101
3.11	Top: the focal plane at 1864 MeV beam energy. Bottom: the focal plane at 1721 MeV beam energy.	103
3.12	The overlapped channels between every two SSD planes at beam energy, 1721 MeV. The solid line shows the overlap pattern between the extracted parameters overlap, while the points with error bars show the overlap pattern constructed from the data.	104

3.13	The overlapped channels between every two SSD planes at beam energy, 1864 MeV. The solid line shows the overlap pattern between the extracted parameters overlap, while the points with error bars show the overlap pattern constructed from the data.	105
3.14	Coincidence time for the 1721 MeV data.	108
3.15	β_{tof} distribution for the particles detected in the SOS.	110
3.16	The distribution of the difference between β_{tof} and β_K	111
3.17	The distribution of the number of photoelectrons detected by the aerogel detector versus the velocity ($\beta = v/c$).	113
3.18	The velocity ($\beta = v/c$) distribution versus the number of photoelectrons deposited in the lucite detector.	114
3.19	The velocity ($\beta = v/c$) distribution versus the number of photoelectrons deposited in the calorimeter.	116
3.20	The scintillator channels versus SSD channels.	117
3.21	The SSD and scintillator time difference.	118
3.22	The RF time spectrum.	119
3.23	The coincidence time spectrum.	120
3.24	The efficiency for the individual planes in both chambers for run#32583. . .	123
3.25	The SOS tracking efficiency as a function of time.	124
3.26	A part of the ESPS focal plane where there is an overlap between two hodoscope scintillators and the SSD.	125

3.27	The ESPS hodoscope efficiency as a function of time.	126
3.28	The SSD efficiency as a function of time.	127
3.29	The scintillator hit versus the SSD hits.	128
3.30	The distribution of missed channels as a function of plane number.	129
3.31	Survival ratio of the kaon versus its momentum.	132
3.32	β spectrum after applying PID cuts.	133
3.33	The number of kaons versus the cut on the number of photoelectrons.	134
3.34	The real peak in the coincidence time spectrum.	135
3.35	The ratio of surviving kaons versus the applied cut.	137
3.36	The ratio of surviving kaons versus the applied cut.	138
3.37	The percentage of the particles that pass through the ESPS as a function of the momentum at $P_e = 1721 \text{ MeV}/c$	142
3.38	The percentage of the particles that pass through the ESPS as a function of the momentum at $P_e = 1864 \text{ MeV}/c$	143
3.39	The SOS solid angle distribution versus the momentum for an incident mo- mentum of $P_e = 1721 \text{ MeV}/c$	145
3.40	The SOS solid angle distribution versus the momentum for an incident mo- mentum of $P_e = 1864 \text{ MeV}/c$	146
4.1	The missing mass spectrum obtained from a CH_2 target at a beam energy of 1864 MeV	151

4.2	The missing mass spectrum obtained from a CH_2 target at a beam energy of 1721 MeV.	152
4.3	A Gaussian fit to the missing mass spectrum obtained from the CH_2 target at a beam energy of 1864 MeV.	153
4.4	The summed missing mass spectrum for both 1864 MeV and 1721 MeV. . .	154
4.5	The summed missing mass spectrum for both 1864 MeV and 1721 MeV. . .	155
4.6	The Fitted missing mass spectrum.	157
4.7	The fitted missing mass spectrum by the parameters listed in Table 4.1. . .	160
4.8	The fitted missing mass spectrum by the parameters listed in Table 4.1 with some corrections.	161
4.9	The fitted missing mass spectrum by the parameters listed in Table 4.2. . .	163
4.10	The reconstructed beam energy using the $(e, e' e^+ e^-)$ process.	166
4.11	The reconstructed beam energy.	167
4.12	The fit parameters of the fitted missing mass spectrum shown in Figure 4.5.	169
4.13	The integrated virtual photon flux for $E_e = 1864$ MeV, and $E_e = 1721$ MeV.	171
4.14	The experimental and predicted differential cross section versus the scattering angle.	175

Chapter 1

Introduction and Physics Motivation

1.1 Introduction

Scientists have always been fascinated by the structure of matter and the laws that govern its behavior. With increased resolution and higher energy, new phenomena have emerged. We now believe that all matter is made of elementary particles. Excluding the gravitational interaction, these particles and their interactions are described by *the Standard Model of Fundamental Particles and Interactions*. The Standard Model is an organization of the elementary particles and their interactions based on the knowledge gathered from the data that were collected at particle physics laboratories such as CERN[1], Fermi Lab[2], SLAC[3], etc.

The elementary particles of the standard model are : quarks, leptons, and gauge bosons.

Fermions are half integral spin particles that obey Fermi-Dirac statistics ¹. Elementary fermions are two types: leptons (a word that came from the Greek word *leptos* which means light) and quarks (a name taken from a James Joyce novel).

- Leptons

There are three charged leptons (e , μ , τ), given in Table 1.1[4]. To each charged

Lepton	Mass	Electric charge (e)	Life time
e^-	$m_e \approx 0.51 \text{ MeV}$	-1	$4.3 \times 10^{23} \text{ yrs}$
μ^-	$m_\mu \approx 105.6 \text{ MeV}$	-1	$\tau_\mu = 2.197 \times 10^{-6} \text{ s}$
τ^-	$m_\tau \approx 1777 \text{ MeV}$	-1	$\tau_\tau = (290.0 \pm 1.2) \times 10^{-15} \text{ s}$

Table 1.1: Leptons and their properties.

lepton (electron, muon, tau) is associated a neutral lepton or neutrino (ν_e for the electron, ν_μ for the muon, ν_τ for the tau). According to the standard model, the neutrino has zero charge, zero mass, and spin 1/2. The (massless) neutrino spin is always oriented in the direction opposite to its velocity (it is said to be of left helicity). The anti-neutrino is always of right helicity (spin in the same direction as the velocity)[5]. Many important questions about neutrinos are still not experimentally resolved. In 1998, a team of physicists presented evidence that neutrinos possess mass and change their identities in time[6].

Leptons preserve electric charge and lepton number (L_e , L_μ , and L_τ) in all interactions². There are also six anti-leptons with opposite quantum numbers.

¹They obey Fermi-Dirac statistics in which the wave function of two identical particles is anti-symmetric under particle exchange

²A lepton can change only to another of the same type.

- Quarks

Quarks come in six types (flavors) and carry partial charges ($2e/3, -1e/3$), as listed in Table 1.2[7].

Quark flavors	Electric charge (e)	Mass range
Up (u)	$2/3$	1.5 to 5 MeV
Down (d)	$-1/3$	3 to 9 MeV
Charmed (c)	$2/3$	1.1 to 1.4 GeV
Strange (s)	$-1/3$	60 to 170 MeV
Top (t)	$2/3$	173.8 ± 5.2 GeV
Bottom (b)	$-1/3$	4.1 to 4.4 GeV

Table 1.2: Quarks and their properties.

Fermions interact through fields, and are the source and the sink for the field quanta. The particles (quanta) associated with the fields are called bosons. Bosons are integral spin particles that obey Bose-Einstein statistics³. There are four types of interaction fields: gravitational, electromagnetic, weak, and strong interactions.

The gravitational interaction acts between all particles. Its exchange particle is thought to be the graviton (g). The graviton is an elementary particle of spin 2 (a boson) and zero rest mass, that is believed to be responsible for the propagation of the gravitational interaction, although it has not yet been detected.

The electromagnetic interaction acts between all electrically charged particles. The quanta of the electromagnetic interaction are massless photons of spin 1.

³The wave function describing two identical bosons is symmetric under particle exchange

The weak interaction is mediated by the heavy $W^\pm$ and Z^0 bosons having spin 1 and acting on quarks, leptons ($\beta - decay$), and the field mediators themselves.

The strong interaction is mediated by massless bosons called gluons having spin 1 and acting on the quarks and themselves.

Leptons interact through the electromagnetic, weak, and gravitational interactions, while quarks interact through all the known interactions. Quarks are always confined by the strong interaction into compound systems forming hadrons. Hadrons can be divided into two categories, mesons and baryons. Mesons have an integral spin and consist, in the most naive picture, of a quark and anti-quark pair ($q\bar{q}$). Mesons obey the unusual conservation rules in their production, which generally are based on additional quantum numbers like strangeness, charm, bottomness (or beauty), and topness (or truth). Baryons have half-integer spins and consist of three quarks (qqq). There are baryons, such as strange baryons or hyperons, that display similar properties to those of the mesons. For more details see the reference [8].

Symmetry

There are a number of symmetries that restrict, and thus guide, the interaction processes. Selection rules and conservation laws are a result of the symmetries of the Lagrangian, which restrict its form.

Symmetries are grouped into the following[9]:

- Continuous space-time symmetry: Consisting of translations, rotations, and

accelerations.

- Discrete symmetries: Consisting of parity, time reversal, charge conjugation, and G parity.
- Permutation symmetries: Consisting of Fermi-Dirac and Bose-Einstein statistics.
- Gauge transformations.

These symmetries can be expressed mathematically using group theory. Thus, $U(1)$ symmetry represents the conservation laws for electric charge and lepton number, $SU(2)$ symmetry represents the Isospin group, and $SU(3)$ symmetry leads to flavor and color symmetry.

The Lagrangians that represent the interactions are invariant under translations, rotations, Lorentz transformations, and the total combination of charge conjugation-parity-time reversal (CPT) transformations.

Classification of the particle states is provided by global symmetries, while local symmetries define the fundamental interactions. The electromagnetic, weak, and strong interaction can be obtained from the symmetry groups $U_Y(1)$, $SU_L(2)$, and $SU_C(3)$. The group $U_Y(1)$, a local Abelian (commutative) symmetry group, corresponds to weak hypercharge symmetry. On the other hand, the groups $SU_L(2)$ ⁴ and $SU_C(3)$, non-Abelian (non-commutative) symmetry groups, correspond to the weak

⁴ $SU_L(2)$ group involves only left-handed particles.

isospin and strong color symmetries, respectively. It is also possible to unify weak and electromagnetic interactions in a single gauge force by extending the gauge group to $SU_L(2) \times U_Y(1)$. Thus the complete gauge groups of the standard model can be represented by the following : $U_Y(1) \times SU_L(2) \times SU_C(3)$ [8].

1.2 Strangeness

In early cosmic ray studies, strongly produced particles were observed that decayed weakly. The way they were produced and decayed led to the term strangeness. These particles were produced in pairs, so that a K meson was always associated with a Λ or Σ . An explanation of this production was offered by M. Gell-Mann and A. Pais[9]. A new quantum number called the strangeness (S) was introduced, which had to be conserved in the strong interaction, but was violated in weak decays. Strangeness is a property of subatomic particles and applies only to hadrons. A strange quark, s, has non-zero strangeness -1, and so the strangeness of a particle is the sum of the strangeness of its strange (antistrange) quarks.

Strangeness is conserved in all processes mediated by the strong and electromagnetic interactions, but may change in an event governed by the weak interaction[10]. Strangeness violation in weak decay is restricted to be +1 or -1, and strangeness has no known associated force.

The strangeness quantum number of a hadron can be related to its electric charge and baryon number through the Gell-Mann-Nishijima relation[11],

$$Q = I_3 + (B + S)/2 \tag{1.1}$$

where the hypercharge (Y) is defined as the sum of the baryon number and strangeness, $Y = B + S$. Since both B and S are conserved in the strong and electromagnetic interactions, hypercharge is also conserved.

Λ DECAY MODES	Fraction (Γ_j/Γ)
$p\pi^-$	$(63.9 \pm 0.5)\%$
$n\pi^0$	$(38.5 \pm 0.5)\%$
$n\gamma$	$(1.75 \pm 0.15) \times 10^{-3}$
$p\pi^-\gamma$	$[h](8.4 \pm 1.4) \times 10^{-4}$
$pe^-\bar{\nu}_e$	$(8.32 \pm 0.14) \times 10^{-4}$
$p\mu^-\bar{\nu}_\mu$	$(1.57 \pm 0.35) \times 10^{-4}$

Table 1.3: Λ decay modes and fractions

1.2.1 Hyperons

Hyperons (Λ , Σ , Ξ , and Ω) are baryons that contain one or more strange (s) quarks. The Σ , Ξ , and Ω particles decay via the strong interaction into Λ s. Since a Λ is the lightest hyperon, and the strong interaction is strangeness conserving, the Λ only decays via the strangeness-nonconserving weak interaction[12]. The Λ is a neutral hyperon that consists of three quarks: up, down, and strange (ups). It has a spin-parity $J^\pi=\frac{1}{2}^+$ and isospin, $I=0$. The mass of the Λ is, $M_\Lambda = 1115.683 \pm 0.006$ MeV, and its mean lifetime is, $\tau_\Lambda = (2.632 \pm 0.020) \times 10^{-10}$ sec. The Λ hyperon decays through the modes listed in Table 1.3[7].

Hyperons, with the addition of the proton and neutron, form a baryon octet of spin-parity $J^\pi=\frac{1}{2}^+$, as shown in Figure 1.1, except Ω which belongs to the baryon decuplet of spin-parity $J^\pi=\frac{3}{2}^+$.

Figure 1.1: Isospin vs strangeness chart for baryons of spin parity $J^\pi = \frac{1}{2}^+$.

1.2.2 Hypernucleus

The hypernucleus is a nucleus composed of nucleons (protons and neutrons) and one or more hyperons bound to its core. Since all hyperons decay via the strong interaction except the Λ hyperon which decays weakly, only the Λ lives relatively long enough to form a particle-stable system. The Λ is weakly coupled to the nuclear core, and the shell model[10] can be used to describe this system. In this model the Λ resides in the $1s$ shell in the hypernuclear ground state. Excited states are obtained by promoting a Λ to higher orbits or coupling a Λ in the ground state to an excited nuclear core. The shell model is a precise and predictive tool used to describe nuclear spectra. It is used in this work to describe the hypernuclear spectra, excitation

functions in various reactions, and subsequent decays of hypernuclear states. Based on the experimental knowledge of some light hypernuclei, scattering data of hyperons from nucleons, and flavor SU(3) symmetry, an effective ΛN interaction for the shell model can be constructed[13].

Generally, the two-body ΛN interaction can be expressed in terms of five radial integrals[14]

$$V_{\Lambda N}(r) = V + \Delta + s_{\Lambda} + s_N + T \quad (1.2)$$

where:

- $V = V_o(r)$ is the central part.
- $\Delta = V_{\Delta}(r)s_N.s_{\Lambda}$ is the spin-spin coupling between the Λ and N.
- $s_{\Lambda} = V_{\Lambda}(r)s_{\Lambda}.l_{N\Lambda}$ is the Λ spin-orbit coupling term, where $l_{N\Lambda}$ is the relative orbital angular momentum.
- $s_N = V_N(r)s_N.l_{N\Lambda}$ is the N spin-orbit coupling term.
- $T = V_T(r)S_{12}$ is the tensor coupling term, where $S_{12} = 3(\vec{\sigma}_N.\hat{r})(\vec{\sigma}_{\Lambda}.\hat{r}) - \vec{\sigma}_N.\vec{\sigma}_{\Lambda}$ with $\vec{r} = |\vec{r}_N - \vec{r}_{\Lambda}|$.

When a Λ , as an example, couples to a nuclear state of spin (J) and isospin (T), a doublet of states $J = J^{A-1} \pm 1/2$ is formed. The doublet splitting is determined by the terms: Δ , s_{Λ} , and T ; while s_N contributes to the spacing between the dou-

plets, as shown in Figure 1.2. The parameters (Δ , s_Λ , T , and s_N) are determined experimentally from the structure information of Λ hypernuclei.

Figure 1.2: Doublet splitting by the spin-dependent interaction.

The ΛN interaction is much weaker than the NN interaction. Unlike the NN interaction, an isovector boson (π) exchange is not allowed in the ΛN interaction because the Λ has an isospin $I=0$ and cannot exchange, for example, a π ($I=1$) with a nucleon ($I=\frac{1}{2}$), because this violates isospin conservation. Thus, to first order the ΛN interaction is mediated by two-pion exchange or kaon exchange, Figure 1.3.

The central ΛN interaction has no strong spin-spin and tensor contribution to its long range component, but it has a hard core comparable to that in the NN interaction.

It was suggested by Daltiz and Hippel[12] that pion exchange is permitted in the long-range ΛN interaction due to the mutual mixing between the Σ and Λ . In

Figure 1.3: Two-pion exchange and one kaon exchange in the ΛN interaction.

other words, the Σ and Λ do not represent pure eigenstates of isospin, Figure 1.4. Pion exchange creates charge-symmetry breaking (CSB) depending on whether the pion is absorbed by a proton or neutron, because the amplitude has a different sign in these cases. The best example to study CSB is the mirror Λ hypernuclei, ${}^4_{\Lambda}\text{H}$

Figure 1.4: One pion exchange due to $\Lambda\Sigma^0$ coupling.

and ${}^4_{\Lambda}\text{He}$, because of the significant $\Lambda N - \Sigma N$ coupling. The masses of Σ^+ and Σ^- differ by ~ 8 MeV, and so a significant difference occurs between the two couplings: $\Lambda p - \Sigma^+ n$ and $\Lambda n - \Sigma^- p$. The CSB is observed in the difference of the measured Λ -separation energies. A large difference in the B_{Λ} for the ground states is noticed,

Model	V_{SO}^N	V_{SO}^Λ
Additive quark model	1	0.
Mean field theory	1	0.04
Nonrelativistic quark cluster model	1	0.21
One-boson-exchange model	1	0.19-0.26

Table 1.4: Comparison of the theoretical prediction of the spin-orbit interaction

$\Delta B_\Lambda(^4\text{H}-^4_\Lambda\text{He}) \cong 0.34 \pm 0.07$ MeV. The ΔB_Λ in this hypernuclear system reflects true charge symmetry breaking in the ΛN interaction[15]. Generally, several experiments are still required to completely define the ΛN interaction, such as the $3/2^+ \rightarrow 1/2^+$ doublet transition in $^7_\Lambda\text{Li}$ which is sensitive to Δ , and the $1^- \rightarrow 1^-$ transition in $^{17}_\Lambda\text{O}$ which is sensitive to the tensor term T [16].

In contrast to the nucleon spin-orbit splitting, Λ spin-orbit splitting is assumed to be very small[17]. This small value can be explained by the quark model, in which u and d quarks in the Λ couple to zero spin so they do not contribute to the spin-orbit force. However, a larger value for Λ spin-orbit splitting is predicted by other models like the one-boson-exchange model. Table 1.4 shows a comparison between these models[18].

1.2.3 Hypernucleus Production

A variety of reactions can be used to produce hypernuclei, and some are listed in Table 1.5[17]. Each of these reactions has its own characteristics, which selectively populate Λ hypernuclear states. They can be divided into two categories: strangeness

$\Delta Z = 0$ <i>neutron</i> $\rightarrow \Lambda$	$\Delta Z = -1$ <i>proton</i> $\rightarrow \Lambda$
(π^+, K^+)	(π^-, K^0)
in-flight (K^-, π^-) stopped (K^-, π^-)	in-flight (K^-, π^0) stopped (K^-, π^0)
$(e, e'K^0)$ (γ, K^0)	$(e, e'K^+)$ (γ, K^+)

Table 1.5: Comparison of Λ Hyperon production reactions.

exchange and associated production[16].

- Strangeness Exchange. In this reaction the nucleon is converted to a hyperon by strangeness exchange such as (K^-, π^-) , as shown in Figure 1.5.

Figure 1.5: A neutron is converted to a Λ hyperon by exchanging the strange quark.

- Associated Production. In this reaction such as (π^+, K^+) , (γ, K^+) , and $(e, e'K^+)$, an $s\bar{s}$ pair is produced, as shown in Figure 1.6.

Due its relevance to this work, the $(e, e'K^+)$ reaction will be discussed in detail in the following section.

Figure 1.6: A neutron is converted to a Λ hyperon by associated production in the (π^+, K^+) reaction.

1.2.4 $(e, e'K^+)$ reaction

Most hypernuclear information has been obtained from (K^-, π^-) and (π^+, K^+) reactions. Both (K^-, π^-) and (π^+, K^+) involve the elementary transition $n \rightarrow \Lambda$ and excite only natural parity states. The (K^-, π^-) excites low spin states at forward angles due to the small momentum transfer⁵ while the (π^+, K^+) excites high spin states due to high momentum transfer[19]. In contrast to the previous two reactions, the reaction $(e, e'K^+)$ involves the elementary transition $p \rightarrow \Lambda$ and can excite both natural and unnatural parity (spin-flip) hypernuclear states with comparable strength[20]. Similar to the (π^+, K^+) reaction, $(e, e'K^+)$ excites high-spin, bound hypernuclear states. Contrary to the other two hadronic interactions which use a secondary beam, a primary beam with extremely good beam emittance is used in the $(e, e'K^+)$ reaction which can provide much better energy resolution. Also, electron beams are very “clean” and well controlled. In the reaction (K^-, π^-) , both the K^-

⁵Low or zero momentum transfer to the residual nucleus because the mass of the incoming K^- is much larger than the mass of the produced π^- .

and π^- particles are strongly absorbed (the $\bar{u}$ -quark in both K^- ($\bar{u}s$) and π^- ($\bar{u}d$) can easily annihilate with a valence quark “u” in the nucleon (udd or uud) to form a three quark resonance) in the nuclear medium which complicates the reaction mechanism. Also, the initial state particle π^+ , in the reaction (π^+, K^+), is strongly absorbed (the $\bar{d}$ -quark in π^+ ($u\bar{d}$) can also easily annihilate with a valence quark “d” in the nucleon to form three quark resonance) in the nucleus. On the other hand, both e^- and K^+ interact weakly (the u quark in the K^+ can only annihilate with a sea quark) in the nucleus, which leads to only a small distortion in the process ($e, e'K^+$), making the theoretical analysis less complicated and more reliable. Due to the weak interaction of the e^- and K^+ in the nucleus, the possibility of deeply bound hypernuclear states increases. The disadvantage of the ($e, e'K^+$) reaction is that it has a smaller cross section.

In the (K^-, π^-) reaction, which is exothermic, it is possible to reach zero momentum transfer, whereas this is not the case in the ($e, e'K^+$) reaction. The reaction

Figure 1.7: A proton is converted to a Λ hyperon by associated production in the ($e, e'K^+$) reaction.

(e,e'K⁺), shown in Figure 1.7, includes the elementary process,

$$\gamma p \rightarrow K^+ \Lambda, \quad (1.3)$$

where the photon is produced virtually by the (e,e') reaction. The photon is virtual in the sense that its 3-momentum, $\vec{q}$, and energy, w , are independent and are absorbed by the same nucleus. This implies that the virtual photon is absorbed in several wavelengths.

The (e,e'K⁺) reaction gives minimum momentum transfer to the hypernucleus when the angle between the virtual photon and the K⁺ is zero. A plot of the kaon angle with respect to the momentum transfer for various photon energies is shown in Figure 1.8[21], where the typical momentum for the outgoing kaon is 1.2 GeV/c. Thus, the minimum momentum transfer can be obtained at forward angles.

A comparison of the spectra excited by these different production mechanisms is shown in Figure 1.9. Figure 1.9 shows that the spectrum of ${}^{12}_{\Lambda}\text{B}$, produced by the reaction ${}^{12}\text{C}(e,e'K^+){}^{12}_{\Lambda}\text{B}$, has much more spectroscopic information than the reactions ${}^{12}\text{C}(K^-, \pi^-){}^{12}_{\Lambda}\text{C}$ and ${}^{12}\text{C}(\pi^+, K^+){}^{12}_{\Lambda}\text{C}$. A difference in the cross sections to the various states is noted. Still the cross section for the ${}^{12}\text{C}(K^-, \pi^-){}^{12}_{\Lambda}\text{C}$ reaction is larger than the other two reactions by at least a factor of ten.

With the previously stated advantages of the (e,e'K⁺) reaction, new physics can be explored. These include the following.

- A study of high resolution hypernuclear spectroscopy.

Figure 1.8: The momentum transfer as a function of the photon to kaon angle for varying photon energies. The E_γ is in MeV unit.

- Energy positions of the high spin states of Λ -spin doublets can be determined to further determine the effective ΛN interaction[22].
- The transition form factors (Response functions) in a wide momentum range may be measured providing valuable structural hypernuclear information[23].
- The mesonic ($\Lambda \longrightarrow \pi + N$) and nonmesonic ($\Lambda + N \longrightarrow N + N$) weak decay modes in hypernuclei, using the strong polarization of the hypernuclear states by electroproduction can be studied.
- Σ -hypernuclei production can be studied.

Figure 1.9: A comparison of three hypernuclear production reactions on a ^{12}C target.

1.3 History

1.3.1 Some Theoretical Work

Many theoretical investigations have been published on electromagnetic production. Bernstein *et al*[24] discussed the electroproduction of kaons, and calculated the cross section for the photo-production of hypernuclei from ^{12}C and ^4He nuclei. The cross

Figure 1.10: The calculated excitation function for the $^{12}\text{C}(\gamma, K^+)_{\Lambda}^{12}\text{B}$ reaction at $p_{\gamma} = 1.2$ GeV/c and $\theta_L = 10^\circ$. The solid (dashed) line indicates the positive (negative) parity state.

section for the formation of hypernuclei from a ^{12}C target was also calculated by Cotanch and Hiaso[25] using single virtual photon exchange and the density matrix formalism. T. Motoba *et al*[26] calculated the ^{12}C excitation function for the $^{12}\text{C}(\gamma, K^+)_{\Lambda}^{12}\text{B}$ reaction at $p_{\gamma} = 1.2$ GeV/c and $\theta_L = 10^\circ$. The results are shown in Figure 1.10. The calculated angular distributions for the $^{12}\text{C}(\gamma, K^+)_{\Lambda}^{12}\text{B}$ reaction at $p_{\gamma} = 1.1$ GeV/c are displayed in Figure 1.11.

Figure 1.11: The calculated angular distributions for the $^{12}\text{C}(\gamma, K^+)^{12}_{\Lambda}\text{B}$ reaction at $p_{\gamma} = 1.1$ GeV/c.

1.3.2 Experimental History

The earliest hypernuclear studies involved K^- absorption at rest in bubble chambers. More systematic studies started with the availability of higher intensity separated kaon beams. The majority of these hypernuclear studies were carried out through the strangeness exchange, (K^-, π^-) , and the associated, (π^+, K^+) , reactions at CERN, BNL, and KEK. The CERN experiments started in the 1970's and the BNL experiments in early 1980's. The KEK experiments followed a few years later.

In 1972 the existence of a particle-unstable state in the $p_{3/2}$ shell was confirmed[27] and led to the first hypernuclear spectroscopy experiments at CERN in 1973[28]. In an experiment at the BNL Alternating Gradient Synchrotron (AGS), γ -ray transitions in both $^7_{\Lambda}\text{Li}$ and $^9_{\Lambda}\text{Be}$ were established for the first time in hypernuclei produced by the (K^-, π^-) reaction[29]. In 1984 at BNL, the (π^+, K^+) reaction succeeded in exciting

non-substitutional, stretched states of ${}^{12}_{\Lambda}\text{C}$ [30].

This work stimulated scientists at BNL to extend the (π^+, K^+) studies up to the mass systems $A \simeq 9 - 89$, ${}^{89}\text{Y}$, to determine the binding energies of the single particle states of a Λ in a nucleus[31, 32].

In 1987 scientists at KEK, were able to use a 650 MeV/c Kaon beam to study the $(K^-_{\text{stopped}}, \pi^-)$ reaction. The KEK experiments also extended the (π^+, K^+) studies in E336 which provided high-quality excitation spectra with 1.9-2.5 MeV (FWHM) resolution and high statistics for ${}^7_{\Lambda}\text{Li}$, ${}^9_{\Lambda}\text{Be}$, ${}^{12}_{\Lambda}\text{C}$, ${}^{13}_{\Lambda}\text{C}$, and ${}^{16}_{\Lambda}\text{O}$ [33].

E336 was followed by E369. The E369 experiment measured the spectra of ${}^{89}_{\Lambda}\text{Y}$ and ${}^{51}_{\Lambda}\text{V}$, as well as ${}^{12}_{\Lambda}\text{C}$ with high statistics and improved resolutions of 1.4-1.7 MeV/c (FWHM). The energy resolution of 1.45 MeV (FWHM) for ${}^{12}_{\Lambda}\text{C}$ is shown in Figure 1.12[34].

Figure 1.12: ${}^{12}_{\Lambda}\text{C}$ spectrum measured by the ${}^{12}\text{C}(\pi^+, K^+)$ reaction.

Another experiment at KEK studied the (π^+, K^+) reaction, E419. This experiment used a germanium (Ge) detector, Hyperball, for studying γ spectroscopy. From these γ ray energies and their yields, several ${}^7_\Lambda\text{Li}$ levels were determined with high precision[35].

In a 1997 experiment, E907 at BNL AGS, carried out a study of the reaction ${}^{12}\text{C}(K^-_{\text{stopped}}, \pi^0){}^12_\Lambda\text{B}$, where a K^- was stopped in a ${}^{12}\text{C}$ target. This is a strangeness and charge exchange reaction, and the Λ particle was produced from a proton instead of neutron. This reaction produces, in the case of a zero isospin nucleus, mirror hypernuclei to the (K^-, π^-) reaction. Figure 1.13 shows the ${}^12_\Lambda\text{B}$ spectrum[36].

Figure 1.13: ${}^12_\Lambda\text{B}$ spectrum produced by the reaction ${}^{12}\text{C}(K^-_{\text{stopped}}, \pi^0){}^12_\Lambda\text{B}$.

The Hyperball detector, E930, aimed to determine all the ΛN interaction terms using γ spectroscopy in 2000-2001. It ran in 1998 and 2001. Some of the preliminary results are shown in Figure 1.14[37].

Figure 1.14: γ ray spectrum for the bound-state region of ${}^9_{\Lambda}\text{Be}$

Experiment E89-009 ran at TJNAF in the spring of 2000, using the $(e,e'\text{K}^+)$ reaction. The data analysis and results of this experiment will be presented in this work.

Experiment E931 at BNL studies non-mesonic decays and their branching ratios, especially the decay of the light hypernucleus ${}^4_{\Lambda}\text{H}$, to determine if the $\Delta I = \frac{1}{2}$ rule holds.

1.4 E89-009

Experiment E89-009 used the beam quality of the Thomas Jefferson National Accelerator Facility (TJNAF)⁶, as well as the advantages of the electromagnetic interaction ($e,e'K^+$) to provide information about strange nuclear systems. The goal of this experiment was to investigate hypernuclear states of ${}^{12}_{\Lambda}\text{B}$ using the reaction ($e,e'K^+$), and to use the outcome of this spectroscopy to study the effective ΛN interaction.

E89-009 has unique features which include: a high resolution of 600-1000 keV (FWHM), spectra from the ($e,e'K^+$) reaction which has never been obtained before, the excitation of unnatural parity states, and zero-degree electron tagging. The Hypernuclear Spectrometer System, HNSS, was used in E89-009[22]. Due to a conflict of beam requirements for the different TJNAF Halls, two beam energies were used in E89-009. These were 1864 and 1721 MeV.

1.4.1 Zero Degree Electron Tagging

As mentioned earlier, the minimum momentum transfer in the reaction ($e,e'K^+$) is attained when the kaon and the virtual photon angles are zero. In addition, the virtual photon flux factor grows very steeply at forward angles, as shown in Figure 1.15. It falls to less than one-tenth of its maximum value in ~ 5 mrad. Thus, at forward angles the scattered electrons are naturally confined to small angles. Consequently, aberrations in the optical system will be very small. Therefore, only a small magnet

⁶The beam quality and other TJNAF features will be discussed in chapter two.

Figure 1.15: The virtual photon flux factor versus scattering angle

is needed to detect almost all scattered electrons and to obtain good momentum resolution. An Enge Split-Pole magnet was chosen for this purpose.

Among the features of zero degree electron tagging is that the $0^\circ(e,e')$ yield is sufficient to use low beam luminosity, leading to a good resolution. However, at forward angles the bremsstrahlung rate also peaks very strongly. This creates a high bremsstrahlung background in the spectrometer which limits the luminosity by decreasing the true to accidental ratio[38]. This requires a balance between the

virtual photon flux and the bremsstrahlung rate. The E89-009 geometry was chosen to maximize resolution with an acceptable signal/noise ratio⁷.

1.4.2 Formalism

In the electroproduction process the electron interacts with a proton through the reaction,

$$e(p_e) + p(p_p) \rightarrow e'(p_{e'}) + K^+(p_K) + \Lambda(p_\Lambda) \quad (1.4)$$

The values in the parentheses are the 4-momenta. The diagram of this reaction and its kinematics are shown in Figure 1.16. The momentum for the virtual photon is

Figure 1.16: The scattering geometry and its kinematics variables.

$\vec{q} = \vec{p}_e - \vec{p}_{e'}$ and its energy is $w = E_e - E_{e'}$. The four external momenta can be defined as shown in Figure 1.17.

⁷The geometry of E89-009 is discussed in Chapter Two.

Figure 1.17: The four external momenta for the reaction, $(e,e'K^+)$.

From Figure 1.17, the Mandelstam variables can be defined as:

$$s = (q + p_p)^2 = (p_k + p_\Lambda)^2 , \quad (1.5)$$

$$t = (q - p_k)^2 = (p_p - p_\Lambda)^2 , \quad (1.6)$$

$$u = (q - p_\Lambda)^2 = (p_p - p_k)^2 , \quad (1.7)$$

The corresponding Feynman diagrams in these channels, shown in Figure 1.18, consist of Born terms in the s-channel, u-channel, and t-channel. These channels are determined by whether the propagator is a baryon, a strange baryon, or a strange meson.

Formulas for calculating the cross sections have been developed in detail for the electroproduction reaction of kaons by J. Adam *et al*[23]. In general, the triple differential cross section for the elementary electroproduction process can be expressed in terms of the photoproduction differential cross section, $d\sigma / d\Omega_K$, and the virtual

Figure 1.18: (a) s-channel, (b) u-channel, (c) t-channel.

photon flux factor, Γ [21, 23, 39, 40, 41, 42],

$$\frac{\partial^3 \sigma}{\partial E_{e'} \partial \Omega_{e'} \partial \Omega_k} = \Gamma \frac{d\sigma}{d\Omega_K}, \quad (1.8)$$

$$= \Gamma \left[\frac{d\sigma_T}{d\Omega_k} + \varepsilon_L \frac{d\sigma_L}{d\Omega_k} + \varepsilon \frac{d\sigma_P}{d\Omega_k} \cos(2\phi_k) + \sqrt{2\varepsilon_L(1+\varepsilon)} \frac{d\sigma_I}{d\Omega_k} \cos(\phi_k) \right], \quad (1.9)$$

where $\alpha = e^2/4\pi = 1/137.0359895$, $E_{e'}$ and $\partial\Omega_{e'}$ are the energy and the solid angle of the scattered electron, $\partial\Omega_k$ is the kaon solid angle, and the azimuthal angle ϕ_K defines the angle between the scattering and reaction planes. Here Γ is the number of virtual photons that radiate per unit photon energy per unit electron solid angle per incident electron. This factor is evaluated with electron kinematics in the lab frame, and has the form:

$$\Gamma = \left(\frac{\alpha}{2\pi^2 Q^2} \right) \left(\frac{E_\gamma}{1-\varepsilon} \right) \left(\frac{E_{e'}}{E_e} \right), \quad (1.10)$$

where E_e is the incident electron energy, E_γ is the photon energy, and Q is the four-momentum transfer carried by the virtual photon. The factors ε and ε_L are the virtual

photon transverse and longitudinal polarization, respectively, and defined as:

$$\varepsilon = [1 + \frac{2|\vec{q}|^2}{Q^2} \tan^2(\frac{\theta_e}{2})]^{-1} , \quad (1.11)$$

$$\varepsilon_L = \frac{Q^2}{\omega^2} \varepsilon , \quad (1.12)$$

where $\vec{q}$ is the virtual photon three-momentum, θ_e is the electron scattering angle, and $w = E_\gamma - q^2/2m_p$. The terms σ_T , σ_L , σ_P , and σ_I represent the unpolarized transverse, longitudinal, polarized transverse and interference cross sections, respectively.

At forward angles the photon is nearly on shell, so Γ can be calculated on shell as an approximation, and for real photons ($E_\gamma = p_\gamma$), so that only the transverse cross section term is nonvanishing. Thus, it is easier to use the following approximations. To first order, both incident and scattered electron momenta can be expanded as:

$$p_e \approx E_e [1 - \frac{1}{2}(\frac{m_e}{E_e})^2] \quad (1.13)$$

$$p_{e'} \approx E_{e'} [1 - \frac{1}{2}(\frac{m_e}{E_{e'}})^2] \quad (1.14)$$

where e and e' are the incident and scattered electron; and p , E , and m are the three-momentum, energy, and mass, respectively. Now, the square of the three-momentum

for the virtual photon can be written as:

$$q^2 \approx E_e^2 + E_{e'}^2 - 2m^2 - 2E_e E_{e'} \cos \theta_e + \frac{m^2}{E_e E_{e'}} (E_e^2 + E_{e'}^2) \cos \theta_e, \quad (1.15)$$

and the quantity q_μ , which is related to four-momentum as $q_\mu^2 = -Q^2$, can be written as:

$$q_\mu^2 \approx 2m^2 - 4E_e E_{e'} \sin^2(\theta_e/2) - \frac{m^2}{E_e E_{e'}} (E_e^2 + E_{e'}^2) \cos \theta_e, \quad (1.16)$$

Substituting in ε we have,

$$\varepsilon \approx \frac{2p_e^2 p_{e'}^2 \sin^2(\theta_e)}{2p_e^2 p_{e'}^2 \sin^2(\theta_e) + q^2 q_\mu^2} \quad (1.17)$$

Substituting for ε in Γ we have,

$$\Gamma \approx \left(\frac{\alpha}{2\pi^2}\right) \frac{w}{q^2 q_\mu^4} \left(\frac{E_{e'}}{E_e}\right) [2P_e^2 P_{e'}^2 \sin^2(\theta_e/2) + q^2 q_\mu^2] \quad (1.18)$$

The cross section for the $(e, e'K^+)$ reaction rises from threshold at 911 MeV to a broad maximum at 1.5 GeV, as shown in Figure 1.19. The differential cross section at zero degrees is $\sim 0.3 \mu\text{b/sr}$ which is much smaller than for the (π^+, K^+) reaction[21]. In $(e, e'K^+)$, the upper energy of the virtual photon flux must be as low as possible, otherwise a high flux of background kaons can be produced which could add to the accidental rates. Table 1.6[21] shows some threshold values for processes which could occur along with the hypernuclear reaction. Background kaons can be reduced by

Figure 1.19: The total cross section for the process, $\gamma p \rightarrow K\Lambda$, as a function of the photon energy in GeV.

selecting a threshold where the processes with higher momentum than the maximum needed for the hypernuclear reaction can be cut off.

It is worthwhile to mention that there are processes that greatly contribute to the background in this experiment. These processes are bremsstrahlung and pair production. Also, multiple scattering affects to some extent the angular distribution of the virtual photon flux. These three processes will be discussed next.

Bremsstrahlung

When an electron passes through the field of an atom, it emits radiation because it is accelerated. This radiation is called bremsstrahlung and the process is shown in

Reaction	γ threshold (GeV/c)
$\gamma p \rightarrow K \Lambda$	1.55
$\gamma p \rightarrow K \Sigma$	1.67
$\gamma p \rightarrow K^*(892) \Lambda$	1.87
$\gamma p \rightarrow K \Lambda(1405)$	2.00
$\gamma p \rightarrow K^*(892) \Sigma$	2.02
$\gamma p \rightarrow K \Lambda(1520)$	2.20
$\gamma p \rightarrow \phi(1020) P$	2.30

Table 1.6: Thresholds for kaon photoproduction from a nucleon where the energy of the outgoing kaon is 1.2 GeV at an angle of 10° .

Figure 1.20.

Figure 1.20: Feynman diagrams for the Bremsstrahlung scattering processes.

The probability of radiating a real photon can be written as [38],

$$\begin{aligned}
d\sigma = & \frac{Z^2\alpha^3}{2\pi} \frac{p}{p_0} \frac{dw}{w} \frac{dcos\theta_0 dcos\theta d\phi}{q^4} \left[\frac{p^2 \sin^2\theta}{(E - pcos\theta)^2} (4E_0^2 - q^2) + \right. \\
& \frac{p_0^2 \sin^2\theta_0}{(E_0 - p_0 cos\theta_0)^2} (4E^2 - q^2) - \\
& 2(4E_0E - q^2 + 2w^2) \frac{p_0 p \sin\theta \sin\theta_0}{(E - pcos\theta)(E_0 - p_0 cos\theta_0)} + \\
& \left. 2w^2 \frac{p_0^2 \sin^2\theta_0 + p^2 \sin^2\theta}{(E - pcos\theta)(E_0 - p_0 cos\theta_0)} \right], \tag{1.19}
\end{aligned}$$

where E_0 , $\vec{p}_0$, E , and $\vec{p}$ are the energy and momentum of the incident and scattered electrons, respectively. Here w and $\vec{w}$ are the energy and momentum of the real photon, θ and θ_0 are the angles between $\vec{w}$ and $\vec{p}$, $\vec{p}_0$ respectively, and ϕ is the angle between the incident and scattering planes.

The bremsstrahlung flux (dN_e) at zero degrees can be determined by:

$$dN_e = (x/\chi_0)(dE_e/E_\gamma)N_e; \tag{1.20}$$

Here $(x/\chi_0) = 2.3 \times 10^{-4}$ is the thickness of the target in radiation lengths, $dE_e \sim 120 MeV$ is the energy acceptance of the spectrometer, and $E_\gamma \sim 1500 MeV$.

Figure 1.21 shows the bremsstrahlung distribution versus the scattering angle. In this figure, it can be noticed that the bremsstrahlung distribution is spread over a much smaller angular range, it drops a factor of 20 at 0.4 msr as shown in Figure 1.21, compared to the virtual photon flux which drops a factor of 10 at 5 msr as shown in Figure 1.15. The importance of this is that bremsstrahlung can be reduced

Figure 1.21: The bremsstrahlung distribution versus the scattering angle.

significantly, $\sim 90\%$, by blocking 1 or 2 milliradians of the solid angle around the zero point while reducing the virtual photon flux by only $\sim 15\%$.

Pair production

When the virtual photon is emitted by the scattered electron, it may create a positron-electron (e^+e^-) pair through the interaction with the nuclear field in the target as shown in Figure 1.22. The energy spectrum for this process is flat up to the maximum value of 1.8 GeV. At energies greater than a few tens of MeV's the virtual photon will create e^+e^- pairs in the photon direction. Due to the equal probability of production

Figure 1.22: Cartoon diagram of the pair production process.

of the e^+e^- pair per energy bin, the electroproduction of a virtual photon can be approximately used to describe the production of a positron. Thus the energy angular distribution for pair production can be written as[22]:

$$\frac{\partial\sigma}{\partial\Omega_\gamma\partial p_{e^+}} = \int \partial w \left[\frac{\Gamma\sigma_T}{w} \right] \frac{\partial\Omega_e}{\partial\Omega_\gamma} \quad (1.21)$$

where $\partial\Omega_\gamma$ is the solid angle of the virtual photon, p_{e^+} is the momentum of the positron, Γ is the flux of the virtual photons, σ_T is the total cross section for photo-production of pairs, and w is the photon energy.

Substitution and integration yields:

$$\frac{\partial\sigma}{\partial\Omega_\gamma\partial p_{e^+}} = \frac{\alpha\sigma_T}{2\pi^2\theta_{\gamma^2}} \left\{ \frac{E_0}{p_e^2} - \frac{4}{p_{e^+}} + \frac{2}{E_0} \left[1 + \frac{3}{2} \ln\left(\frac{E_0}{p_{e^+}}\right) \right] + \frac{p_{e^+}}{E_0^2} \right\}. \quad (1.22)$$

Substitution for the geometry of this experiment (E89-009) gives:

$$\frac{\partial\sigma}{\partial\Omega_\gamma\partial p_{e^+}} \approx 6\mu b/Sr - MeV/c. \quad (1.23)$$

The positron rate in the SOS for 10^{13} electrons, solid angle of 10 msr, and momentum bite of 120 MeV/c is[36]:

$$N_{e^+} = 3.6 \times 10^4 sec^{-1}.$$

Multiple scattering

Even though a thin target was used in E89-009, multiple scattering is an important process to discuss because the *RMS* angle of the multiple scattering is larger than that for bremsstrahlung. However, it has a limited effect because the *RMS* angle is smaller than that for the virtual photon flux distribution.

In calculating the multiple scattering effect, the Gaussian approximation for the central 98% of the projected angular distribution was used. This distribution has a width[7]:

$$\theta_0 = \frac{13.6 MeV}{\beta c p} z \sqrt{\frac{x}{\chi_o}} [1 + 0.038 \ln(\frac{x}{\chi_o})] \quad (1.24)$$

where p , βc , and z are the momentum, velocity, and charge number of the scattered particle, and x/χ_o is the thickness of the scattering medium in radiation lengths.

In E89-009, multiple scattering happens to both the incident and scattered electrons. The contribution from the scattered electrons is much larger than that of the incident

electrons because the scattered electrons have much lower momentum.

Figure 1.23 shows the angular distribution of the multiple scattering with E89-

Figure 1.23: Multiple scattering angular distribution.

009 kinematics. In the kinematics, $\theta_0 = 0.499$ mr for the $22mg/cm^2$ target, but the scattered electron was considered to pass through half of the target so in this calculation the target width was considered $x \sim 11mg/cm^2$. The momentum of the incident and scattered electron are 1800 and 300 MeV/c, respectively.

1.4.3 Observables

Both Λ and Σ are observed from the CH_2 target through the reaction $p(e,e'K^+)Y$ by measuring the momentum/energy of both the e' and the K^+ that are in coincidence⁸.

The energy levels of the ${}^{12}_{\Lambda}\text{B}$ hypernuclei are also observed by measuring the energy of both e' and K^+ in coincidence. Using energy and momentum conservation, the information from both e' and K^+ can be used to measure the mass of the recoiling hypernucleus.

Since both the $p(e,e'K^+)Y$ and ${}^{12}\text{C}(e,e'K^+){}^{12}_{\Lambda}\text{B}$ reactions have similar kinematics, I discuss the kinematics of the latter reaction, as this is the focus of experiment E89-009.

The reaction ${}^{12}\text{C}(e,e'K^+){}^{12}_{\Lambda}\text{B}$, studied in E89-009, is described as:

$$\gamma + A \rightarrow K^+ + X$$

where A is the target (${}^{12}\text{C}$ or ${}^7\text{Li}$), and X is the final hadronic state which was either a free particle, or a bound nuclear state. A cartoon diagram of the reaction is shown in Figure 1.24.

Applying the conservation of energy and momentum relations, we have:

$$w + m_T = E_{K^+} + E_R \tag{1.25}$$

⁸This measurement was carried out mainly for calibration.

Figure 1.24: Cartoon diagram of kaon electroproduction.

$$\vec{q} = \vec{P}_{K^+} + \vec{P}_R \quad (1.26)$$

where $w = E_e - E_{e'}$ and $\vec{q} = \vec{P}_e - \vec{P}_{e'}$ are the energy and momentum of the virtual photon, respectively. Now, squaring both equations,

$$E_R^2 = E_0^2 + E_{K^+}^2 - 2E_0 E_{K^+} \quad (1.27)$$

$$P_R^2 = q^2 + P_{K^+}^2 - 2P_{qK} \quad (1.28)$$

where $E_0 = w + m_T$ and P_{qK} are defined as:

$$P_{qK} = \vec{q} \cdot \vec{P}_{K^+} = P_e P_{K^+} \cos(\theta_{eK^+}) - P_{e'} P_{K^+} \cos(\theta_{e'K^+}). \quad (1.29)$$

Here θ_{eK^+} is the angle of the scattered kaon with respect to the incident electron and $\theta_{e'K^+}$ is the angle of the scattered electron with respect to the incident electron.

Finally, the missing mass is equal to,

$$m_R = \sqrt{E_R^2 - P_R^2}. \quad (1.30)$$

The experimental apparatus and setup, the analysis and Monte Carlo simulations, and the results and summary are discussed in Chapters 2, 3, 4, and 5, respectively.

Chapter 2

Experimental Apparatus and Setup

2.1 Overview

Experiment E89-009 was carried out from March through May 2000 in Hall C at TJNAF. The experiment used virtual photons obtained from the (e, e') reaction at 0° to produce hypernuclei essentially via the photoproduction reaction, (γ, K^+) ¹. The experimental setup is shown in Figure 2.1.

During experiment E89-009, the Continuous Electron Beam Accelerator Facility (CEBAF) provided an unpolarized, continuous wave (CW) electron beam of one of two energies, 1.721 or 1.864 GeV. Beam current varied between $0.2 - 1.0 \mu\text{A}$, depending on the target, target thickness, and scattering geometry. The electron beam consisted of short (1.67 ps) bursts at an effective frequency of 499 MHz (every 2 ns). The beam emittance was $\sim 2 \times 10^{-9}$ m-rad, with energy spread $\frac{\Delta E}{E} \sim 10^{-4}$.

¹Both process (e, e') and (γ, K^+) are mentioned in chapter one.

Figure 2.1: Top view of the E89-009 experimental setup.

A magnetic dipole was placed so that the reaction particles near zero degrees are bent into either an electron or a hadron spectrometer. The scattered electrons were detected by a small Split-Pole spectrometer, and the hadrons by the standard Hall C Short-Orbit Spectrometer, SOS.

Data were acquired for four nuclear targets: Mylar, CH_2 , ^{12}C , and ^7Li . The experimental setup is described in this chapter.

to the south linac where it gains an additional 400 MeV. At this point, the beam can be sent to the Beam Switch Yard (BSY) where it can be delivered to any of the three experimental halls, or it can be recirculated through the linacs for additional acceleration. The beam can make up to five passes through the accelerator, each pass providing 800 MeV in energy, for a maximum value of 4045 MeV. Since beams of different energies require different magnetic fields to bend the electrons around the arcs, the beams separate in each arc in accordance with their energy. Thus the east arc has five, and the west arc four stacked bending elements, each set to bend a beam of different energy.

2.2.2 Hall C Arc

After the beam reaches the required energy, it is transported to the BSY, and then for this experiment, to the target through the Hall C beam transport system. This system is 41.6 meter long, and consists of 8 dipoles, 12 quadrupoles, 8 sextupoles, 8 pairs of beam correctors, and monitoring devices which measure the beam energy, position, and current. The Hall C arc is shown schematically in Figure 2.3.

Beam Position/Profile Measurements

The beam profile was measured using a wire scanner, called a harp. The harp contains a fork supporting three $22\mu\text{m}$ diameter tungsten wires. Two wires determine the horizontal(X) and the third measures the vertical (Y) beam position, as these wires scan through the beam, as shown in Figure 2.4.

Figure 2.3: Top view of the hall C arc with the monitoring instruments

As each wire crosses the beam, secondary electrons are emitted from the wire and produce a signal that is amplified and sent to an Analog-to-Digital Converter (ADC) module, while the position of the wire itself is measured by an 18-bit absolute shaft encoder. The ADC information and encoder readout are transferred into an ASCII file format for subsequent analysis.

There are several harps located in the beam line of the accelerator in order to monitor the position and shape of the beam. In the Hall C transport system, superharps are used. These are basically constructed in a similar way except that they have been more accurately surveyed for absolute position measurements. There are three superharps along the Hall C transport as shown in Figure 2.3. Readout accuracy of the superharp is $\sim 10\mu\text{m}$, which is adequate for reconstruction of the beam width ($\sim 100\mu\text{m}$). More details about the operation and construction of the superharps can

Figure 2.4: Schematic of the Hall C Harp system

be found in reference[43].

Beam Position Monitors (BPM)

A BPM is a resonant cavity², as shown in Figure 2.5. It is mounted in the beam line such that its axis coincides with the nominal axis of the beam. The shape, size, and material of the resonant cavity are chosen so that the operational frequency of the accelerator is resonant. A BPM has four antennae placed at 45° intervals to collect signals from the beam repetition frequency. These signals are proportional to the distance of the beam from each antenna, and so the relative (X,Y) position of the beam can be determined. Since the (X,Y) position information is relative, superharp position information is needed to calibrate the absolute position of the BPMs.

²In Figure 2.5, the charge, “+”, “-,” resonates at a frequency such that the electron bunches are continuously attracted to the next node.

Figure 2.5: A CEBAF Accelerator Cavity

Beam Current Measurement

There are two different types of beam current measurements, the beam cavity monitor (BCM) and the Unser monitor. A BCM is a cylindrical microwave cavity with a wire antenna that picks up the resonant modes which are excited by the beam when it passes through the cavity[44]. The power of the antenna is proportional to the square of the beam current. A BCM is similar to a BPM except that the BCM picks up the resonant modes that are sensitive to the beam current, and it is relatively insensitive (e.g. TM_{101} mode) to the beam position inside the cavity. The shape and material of the cavity are chosen to adjust the quality factor Q (i.e. $Q = w_o W / P_d$, where w_o is the resonant frequency, W is the stored energy, and P_d is the dissipated power). A BCM measurement is temperature dependent, so the temperature must be constantly monitored. There are three BCMs along the Hall C arc. Since the the BCM doesn't give an absolute reading of the beam current, a Unser monitor was used to calibrate the BCMs.

A Unser monitor is a parametric current transformer, and consists of two toroids that measure the absolute current. A Unser monitor is used to calibrate the BCM, as mentioned earlier, and has a very stable, absolute gain.

Beam Energy Measurements

The magnet settings in the arc, the current values in the arc magnets, and the beam position information were used to measure the energy of the beam in the accelerator.

The energy of the beam in the Hall C transport system is measured by using the system as a magnetic spectrometer. The superharps³ are used to measure the position and direction of the beam at the beginning and end of 34.3° bend in the transport. Once the beam is steered to its nominal central path, its trajectory is then determined. The magnetic field in the dipoles can be determined from the current settings, as the dipoles have been extensively field-mapped as a function of the current. The beam trajectory information and magnetic fields of the dipoles can then be used to measure the beam momentum (P) via:

$$P = \frac{e}{\Theta} \int B dl \quad (2.1)$$

where e is the electron charge, Θ is the bend angle, and B is the magnetic field in the dispersive elements. The uncertainties in the field integral, path length variation, and the large energy acceptance (0.2–0.3 %) of the transport, limit the accuracy of

³Superharps are mentioned earlier

this measurement to $\sim 10^{-3}$ [45].

Beam Rastering System

The CEBAF accelerator generates a high power density, high intensity, and small transverse beam size typically $\lesssim 200 \mu\text{m}$ (FWHM). To protect the targets and the dump from damage that might result from this high power density, two rastering systems effectively increase the beam size.

A slow raster was installed a few meters upstream of the target, as shown in Figure 2.3, to protect the beam dump. It was not needed during any of the run conditions of E89-009 because this experiment only used low currents $\lesssim 2 \mu\text{A}$.

The fast raster system was installed 25 m upstream of the target, and was designed to protect the targets⁴. It consisted of two sets of bending magnets, one mounted vertically and one horizontally to disperse the beam in both directions. Currents through the magnets were varied sinusoidally, 17 kHz vertically and 24.2 kHz horizontally, forming a Lissajous pattern of the beam spot on the target. The typical raster size in E89-009 was $\pm 2.2 \text{ mm}$.

⁴In E8-9009, it was only used for the CH₂ target(thickness $\sim 0.1 \text{ mm}$) .

2.3 Target

The target assembly consisted of the target chamber and the target ladder. The target chamber was installed in the gap of the Splitter magnet⁵ and was vacuum-connected to the beam line, split-pole, SOS spectrometer, and the dump line. The ladder was built as a part of the chamber, and its motion was controlled by a stepper motor.

Target	Thickness (mm)	Density (g/cm ³)	Purity
BeO	0.1	2.86	99.5%
CH ₂	0.1	0.88	with Be backings
¹² C	0.1	2.2	99.99%
⁷ Li	0.35	—	92.5% ⁷ Li/ 7.5% ⁶ Li
⁹ Be	0.05	1.85	—
Si	0.025	2.34	99.999%

Table 2.1: E89-009 Targets

Seven targets, listed in table 2.1, were installed in the target ladder. The targets were placed at the effective field boundary on the upstream entry to the splitter magnet. During E89-009, only three targets were used. The CH₂ target was used for calibration and optics tuning. The ¹²C and ⁷Li targets were used to produce ¹²_ΛB and ⁷_ΛHe hypernuclei, respectively.

⁵The Splitter magnet will be mentioned in the next few sections

2.4 The Hypernuclear Spectrometer System

The hypernuclear spectrometer system (HNSS), shown in Figure 2.1, consisted of a splitting magnet for separating the scattered electrons at 0° and scattered kaons at 3° , an electron Spectrometer for measuring the momentum of the scattered electrons, and a kaon spectrometer to detect the electroproduced kaons. The Splitter magnet bent the scattered electrons⁶ by 33° and the kaons by 10.6° . The splitting magnet contained the target ladder in its gap, where it was connected to the beamline, and kept in vacuum.

2.4.1 Electron Spectrometer

The electron spectrometer is a Split-Pole magnet designed by H. Enge[46], the Enge Split-Pole Spectrometer (ESPS), and was used to measure the momentum of the scattered electrons at zero degrees. The characteristics of the electron Spectrometer are listed in Table 2.2[22].

The solid angle acceptance is about 1.6 msr which was enough for the purpose of this experiment (E89-009) because the intensity of the electrons falls rapidly with the scattering angle, as shown in Figure 1.15. An acceptance of 1 msr acquires about 94% of the scattered electrons within the momentum range of interest, see Figure 2.6.

The spectrometer had an excellent momentum resolution of $\delta p/p \sim 3 \times 10^{-4}$ so that only a focal plane detector was needed. The focal plane was located near the

⁶The scattered electrons were bent with such a large angle away from the beam direction because of their low momentum.

Momentum	240–360 MeV/c
Design central momentum	276 MeV/c
Total length	~ 5 m
Solid angle acceptance	1.6 msr
Horizontal	25 mr
Vertical	20 mr
Momentum bite	$\pm 2\%$
Focal plane dimension	
Length	104 cm
Tilt	50°
Horizontal	80 cm
Momentum resolution	$\sim 3 \times 10^{-4}$

Table 2.2: Electron spectrometer parameters.

back face of the Split Pole spectrometer and near this position detector components for timing and particle position measurements were mounted.

2.4.2 Kaon Spectrometer

The kaon spectrometer is a short orbit spectrometer (SOS). The SOS, a conventional (non-superconducting) magnetic spectrometer, was designed with a short optical length ~ 9 m to detect short lived particles (kaons, and low momentum pions). The SOS is composed of one quadrupole (Q) magnet and two dipole magnets, the two dipoles share the same yoke, in a $QD\bar{D}$ arrangement⁷ as shown in Figure 2.7. The quadrupole focuses the particles in the horizontal direction, the first dipole after the quadrupole bends the central ray upward by 33° , and the second dipole bends the central ray back by 15° for a total of 18° upward. The SOS parameters are listed

⁷The SOS design was based on the Medium Resolution Spectrometer (MRS) at LAMPF.

Figure 2.6: Angular distribution of the virtual Photons.

in Table 2.3[47].

The basic optical tune of the SOS spectrometer had first-order point-to-point focusing in both the dispersive and non-dispersive directions. In this tune the particles from the same point in the target with the same momenta and different angles are focused to a single point on the focal plane. The focal plane was defined to be perpendicular to the central ray and located 6 cm in front of the first drift chamber. The true focal plane of the spectrometer was tilted forward by $\sim 70^\circ$ from the detector plane.

For calibration, a collimator system made of machinable Tungsten with 10% CuNi; density = 17 g/cm^3 , as shown in Figure 2.8, was placed in front of the SOS quadrupole and consisted of a sieve slit, large collimator, and small collimator. The sieve slit,

Figure 2.7: Side view of the SOS spectrometer.

~ 3.175 cm thick, had an array of small holes (0.508 cm diameter) and was used to study the optics of the SOS. Two holes were missing to determine the slit orientation. The central hole had a smaller diameter to measure the resolution of the angular reconstruction. The two collimators, ~ 6.35 cm thick, are octagonal apertures designed to limit the solid angle of the SOS.

RAYTRACE[48], a very general ion-optical computer code, was used to calculate the elements of the transport matrix. The transport matrix was used to calculate the focal plane quantities (x_{FP} , x'_{FP} , y_{FP} , and y'_{FP}) in terms of the target quantities (x'_{TAR} , y_{TAR} , y'_{TAR} , and $\delta = (p - p_0)/p_0$, where p_0 is the central momentum of the spectrometer. The focal plane quantities are expressed in terms of:

$$a = \sum_{i,j,k,l} A_{i,j,k,l}^a (x'_{TAR})^i (y_{TAR})^j (y'_{TAR})^k \delta^l, \quad i, j, k, l \in [0, N] ;$$

Maximum central momentum	1.8 GeV/c
Momentum bite $[(p_{max} - p_{min})/p_0]$	40%
Momentum resolution $[\delta p/p]$	$< 0.1\%$
Solid angle (no collimator)	~ 9 msr
Angular acceptance - scattering angle	± 60 mr
Angular acceptance - out of plane	± 40 mr
Min. central scattering angle	14.5°
Scattering angle reconstruction	0.5 mr
Out of plane angle reconstruction	1.0 mr
Useful extended target acceptance	4 cm
Horizontal vertex reconstruction	2-3 mm
Momentum setting flexibility	$0.1 \Rightarrow 1.8 GeV/c$
Angle setting flexibility	$14.5^\circ \Rightarrow \sim 169.4^\circ$

Table 2.3: Summary of the SOS parameters.

where $a \in (x_{FP}, x'_{FP}, y_{FP}, y'_{FP})$, N is the order of the expansion, and $A_{i,j,k,l}^a$ is the forward⁸ transport matrix. The transport matrix was calculated to 6th order. The *RAYTRACE* code was fine tuned instead of tuning the matrix parameters because of the large number of the matrix parameters.

The forward matrix was used through *RAYTRACE* to propagate the tracks produced by the event generator from the target to the focal plane, and the coordinates of the successful events are dispersed to account for multiple scattering and the finite resolution of the detectors. The resulting coordinates are then used to reconstruct the event at the target.

Figure 2.9 shows the focal plane distribution simulated by *RAYTRACE*, while Figure 2.10 shows both the simulated and real data distribution. The reconstruction

⁸The matrix is called forward because it uses the target parameters to calculate the focal plane parameters.

Figure 2.8: From right to left, the sieve slit, the small collimator, and the large collimator.

of the events from the experiment at the target for the sieve slit runs is shown in Figure 2.11. In Figure 2.11, one sees the reconstructed X and Y at the face of the sieve slit.

Figure 2.9: The *RAYTRACE* simulation of the events distribution on the focal plane.

Figure 2.10: The gray plot shows the events distribution on the focal plane of the data while the red one, on the top, is calculated by *RAYTRACE*.

Figure 2.11: X and Y are reconstructed at the face of the sieve slit.

2.5 Detector Package

2.5.1 ESPS Detector Package

The detector package consisted of position and time measuring components; a Silicon Strip Detector (SSD) and a scintillation hodoscope. This system was constructed as a package, as shown in Figure 2.12. The aluminum frame containing the detector

Figure 2.12: The ESPS Detector Package.

package was located behind the vacuum window near the back face of the ESPS. This approximately placed it along the optical focal plane. The entrance and exit windows of the frame were covered by aluminized Mylar acting as a light shield.

SSD

Because the rate of the scattered electrons, $\sim 10^8/\text{sec}$, was high, a silicon strip detector was used to determine the position of the scattered electrons. The scattered electrons had a small vertical distribution so that a one dimension SSD was chosen to measure the position in the horizontal direction. A position measurement of $500\text{ }\mu\text{m}$ provided an energy resolution of $\sim 100\text{ keV}$ (FWHM).

Figure 2.13: Side view of the SSD strip.

When a particle enters the depletion region⁹ of a silicon detector, it creates

⁹The depletion region is a region created in the vicinity of the junction between a p-type and n-type material when they are brought in contact.

electron-hole pairs, and these pairs are then collected by an electric field. The total number of the collected electrons forms a pulse whose amplitude is proportional to the energy deposited by the particle.

The SSD had a P+N-N+ coupling structure, and Figure 2.13, and Table 2.4 shows the specifications[49].

Effective area	72 mm $\times$ 50 mm
Strip pitch	0.5 mm
p+ strip width	0.36 mm
Al electrode width	0.352 mm
Thickness	0.325 ± 0.015 mm
Number of channels	144
poli-Si resistance	10 M Ω
Strip capacitance	≤ 20 pF

Table 2.4: SSD specifications.

A total of 10 SSD segments were used to cover the entire focal plane, and each segment contains 144 channels. A top view of a single SSD segment is shown in Figure 2.14.

The SSD segments were tilted by an angle of 42° with respect to ESPS focal plane direction, so that the incident electrons are approximately perpendicular to the SSD.

Readout of parallel signals from the SSD channels was transferred to multi-hit TDCs (LeCroy 1877). The signals were amplified and discriminated by a multi-channel amplifier-discriminator chip. Each chip has 64 amplifier-discriminator channels, but only 48 channels were used, providing a few spare channels per chip. The signals are then fed to an ECL driver. Figure 2.15 shows the readout system. Because

Figure 2.14: Top view of the SSD chip.

the intrinsic time resolution of the SSD is 30 nsec (FWHM), a scintillation hodoscope was used for timing. The SSD readout was clocked by a 50 MHz clock-frequency to eliminate oscillations.

Figure 2.15: A block diagram of the SSD readout system.

Scintillation Hodoscopes

Due to the poor time resolution of the SSD, scintillation hodoscopes were used (providing a time resolution ~ 250 psec for σ).

The hodoscopes were thin paddles of plastic scintillators wrapped with one layer of aluminized Mylar and two layers of Tedlar.

As the particle passes through the plastic, it suffers interactions, which ionize the atoms, and when the excited states of these atoms decay they emit visible light. The light is passed through a Lucite light guide at the end of the scintillator to a photomultiplier tube (PMT). A small number of electrons is released by the light at the photocathode, which are then multiplied and focused by a series of dynodes and finally collected at the anode.

There was a total of 80 scintillation hodoscopes, and every 8 of them were grouped behind each SSD segment. Each scintillator ($1 \times 6 \times 0.4$ cm³ in volume) was readout through a UVT lucite light guide by a (3469 HAMMATSU) photomultiplier tube. No rate related changes to the time resolution were observed up to a maximum rate of ~ 2.5 MHz. During E89-009, the rate per scintillator was (~ 1.5 MHz).

2.5.2 SOS Detector Package

The SOS detector package consists of two separated wire chambers, four hodoscope planes as a pair in each of the X and the Y direction, a gas Cerenkov detector, an aerogel Cerenkov, a lucite Cerenkov, and a shower counter. All the detectors except

for the shower counter are attached to sliding mounts so that the individual detectors may be removed and serviced without the need to take them out of the detector hut. The shower counter is attached to a rigid mount fixed to the back and ceiling of the shield hut. A schematic of the SOS detector package is shown in Figure 2.16. All of these detector systems are described in detail below[47].

Figure 2.16: Top view of the SOS detector package with approximate locations in cm.

Drift Chambers

The drift chamber is a particle tracking device. When a charged particle traverses the chamber it ionizes the chamber gas, which liberates electrons. An electric field is set up between the anode and cathode wires, to drift the liberated electrons toward the anode. The charged particle also generates a pulse in the scintillation hodoscope.

The hodoscope timing information was used as a trigger to the chamber's TDC. The position of the track is known by determining the wire number and the distance between this wire and the track position. The distance is determined from the drift time. The relationship between the distance and the drift time was determined by accumulating the drift time data and looking at the distribution of the drift times. The distribution is then mapped onto a flat distribution in distance between 0 and 0.5 cm. However, the side of the wire where the track occurs is ambiguous. This is called left/right ambiguity, and it is resolved by having a second plane with wires parallel to, but offset from, the first plane. The final position resolution (σ) per plane for SOS drift chambers was $\sim 200\mu\text{m}$.

The drift chambers are placed directly after the dipole and are located to minimize multiple scattering effects as they measure the position and angle of the particles. The drift chamber is constructed of 16 layers of 1/8" G10 plates sandwiched between two 1/2" Al plates. The G10 plates support alternating planes of cathode foils and wires (the anode and cathode wires), as shown in Figure 2.17.

There are six measurement planes (X, X', V, V', U, U') in each chamber. The X and X' planes measure the position in the dispersive direction, the V and V' planes are rotated 60° clockwise, and U and U' planes are rotated 60° counterclockwise as shown in Figure 2.18.

The drift cell consists of sense wires $30\mu\text{m}$ (in diameter) alternating with field

SOS DC construction:

Figure 2.17: Top view of the SOS drift chamber.

wires $60\mu\text{m}$ diameter, as shown in Figure 2.19.

The wires are made of gold plated tungsten. The field wires and cathode foils are kept at large negative high voltage ($\sim -1900\text{V}$) to isolate the drift cells from each other and minimize the cross talk between the sense wires. The sense wires are kept at ground potential. The chambers are filled with a mixture of Argon (49.5%), Ethane (49.5%), and Isopropyl Alcohol (1%).

Each sense wire is connected to an amplifier/discriminator card, and the discriminated levels are then fed into a FASTBUS multi-hit Time-to-Digital Converter (TDC). A TDC readout occurs after receiving the trigger.

Figure 2.18: A view of the SOS drift chamber shows the orientation of the six wire planes.

Scintillation Hodoscopes

The SOS has two pairs of hodoscope¹⁰ planes, one pair before the gas Cerenkov detector (S1X, S1Y) (total active area of 635x365 mm) and one between the Cerenkov and the Shower counter (S2X, S2Y) (total active area of 1125x365 mm). The number of elements in each plane and their dimensions are listed in Table 2.5. The distance between the front planes and the back planes is ~ 180 cm. The scintillators are read out from both ends by Philips PMTs. The electronics setup is shown in Figure 2.20.

The hodoscopes were used in E89-009 to provide Time of Flight (TOF) for the particles, a trigger for the drift chamber TDC, and as one input to the system trigger.

¹⁰The hodoscope operation principal is mentioned earlier.

SOS DC Drift Cell

Figure 2.19: The SOS DC drift cell.

Plane	Number of paddles	Vertical Size Δx (cm)	Horizontal Size Δy (cm)	Thickness Δz (cm)
S1Y	9	63.5	4.5	1.0
S1X	9	7.5	36.5	1.0
S2Y	9	112.5	4.5	1.0
S2X	16	7.5	36.5	1.0

Table 2.5: The SOS hodoscope dimensions.

Cerenkov Detectors

A charged particle passing through a medium with a velocity larger than the speed of light in that medium will emit Cerenkov radiation at a critical angle, θ_c . The critical angle is given by:

$$\cos(\theta_c) = 1/\beta n;$$

where β is the velocity of the particle, and n is the index of refraction. The threshold velocity for Cerenkov emission depends on n . Therefore, by choosing a suitable n , one can fix the threshold velocity so that it can discriminate between different particles provided these are preselected to have the same momentum. Gas Cerenkov, aerogel

Figure 2.20: The electronics diagram of the SOS hodoscopes.

Cerenkov, and lucite Cerenkov detectors were used in E89-009.

- Gas Cerenkov detector

The gas Cerenkov detector is enclosed in an aluminum box of volume 99x73.7x111 cm³. The entrance and exit windows consist of one layer of 0.254 mm Lexan graphics film and one layer of 0.05 mm Tedlar, having a total thickness of 39 mg/cm. There are four spherical mirrors at the back of the detector, which focus the light onto four (Burle 8854) PMTs. The four PMTs are mounted in Winston cones within the gas. The signals from the PMTs run through a 50-50 splitter. One set of outputs was summed in a (Philips 740) linear fan-in module

and then put through a discriminator to give signals for the trigger as well as outputs for the TDCs and scalers. The second set of the outputs goes through a 350 ns delay to an (LeCroy 1881M) ADC module. The electronics diagram is shown in Figure 2.21.

Figure 2.21: The electronics diagram of the SOS Gas Cerenkov.

The detector is normally filled with 1 atm of Freon 12(CCl_2F_2) which has an index of refraction, n , of 1.00108. This gives a positron detection threshold of 11 MeV, and a pion threshold well above the maximum central momentum setting of the SOS. It was used in E89-009 to separate positrons from hadrons.

- Aerogel Cerenkov detector

The aerogel detector is contained in a 12.5 mm thick aluminum frame that supports the tray in which the aerogel material is packed, and the diffusion box, as shown in Figure 2.22.

The aerogel material $(\text{n}(\text{SiO}_2)+2\text{n}(\text{H}_2\text{O}))_3$ is packed three layers deep. The

Figure 2.22: A schematic of the SOS aerogel detector.

diffusion box is lined with a reflective Millipore paper. On each side of the box there are seven (Burle 8854) PMTs. The ADC signals from each PMT are recorded in the data stream, as shown in Figure 2.23.

Figure 2.23: The electronics diagram of the SOS Aerogel detector.

The aerogel material had a measured index of refraction of 1.034 ± 0.001 which gives a higher threshold for the kaon than the pion. The aerogel detector was used in E89-009 to separate pions from heavier hadrons (like K^+).

- Lucite Cerenkov detector

The lucite detector consisted of eight ($40 \times 13.7 \times 2.5$ cm³ in volume) UVT lucite paddles wrapped with black Teflon foil[50]. The detector was mounted on a metal frame in the SOS detector hut between the gas Cerenkov detector and S2Y hodoscope. Each paddle has one PMT on each end. The signal from each tube is amplified by a factor of 10. One third of this signal goes to the ADC module and the other two thirds are sent to the discriminator. The electronics setup is shown in Figure 2.24.

Figure 2.24: The electronics diagram of the SOS Lucite detector.

For $\beta (= v/c) = 0.91$, the lucite detector produces on average 10 photoelectrons, while for $\beta = 0.88$ it gives 2 photoelectrons. The lucite detector was a very useful tool in E89-009 in order to separate protons ($\beta = 0.88$) from K^+ ($\beta = 0.91$).

Lead-Glass Shower Counter

The shower counter is an electromagnetic calorimeter that detects the energy deposited by a high-energy particle passing through the glass. High energy photons radiate bremsstrahlung, and create e^+e^- pairs. This produces an electromagnetic shower which gives off Cerenkov photons. These Cerenkov photons can be collected and correlated with the total amount of the deposited energy in the glass. Electrons, positrons, and photons will deposit almost all of their energy in the shower counter whereas hadrons (pions, kaons, ...etc) deposit a small fraction of their energy. The shower counter is therefore used to distinguish between hadrons and positrons (photons, electrons ...etc).

The shower counters consisted of 4 stacks of 11 lead-glass blocks of $10 \times 10 \times 70$ cm³ each. Each block is wrapped in one layer of aluminized Mylar and two layers of Tedlar. A Phillips XP3462B PMT is attached at one end of each block to read out the signal. The signal is split into two 50% signals and sent to the trigger and ADC as shown in Figure 2.25.

2.6 Triggers

2.6.1 Trigger

Because of the large background of protons, pions (π^+), and positrons (e^+), discrimination between various particles was needed. The rates of these particles are listed in Table 2.6.

Particle	Trigger Rate (s^{-1})	Singles Rate (s^{-1})
kaons (K^+)	0.4	0.4
pions (π^+)	0.5	180
protons (p^+)	6.0	18
positrons (e^+)	5.0	4×10^4
Total	12	4×10^4

Table 2.6: SOS flux by particle type and trigger rate.

For particle ID, two types of triggers were provided, the on-line trigger and coincidence trigger. The on-line trigger was used for K^+ identification, and to provide ADC and TDC gates for the electron arm. In the on-line trigger, there were two basic hodoscope triggers. One was created when three out of four planes (3/4) fired and the other for (4/4). The latter provided a tighter scintillator cut in the formation of the trigger. All Cerenkov detectors and the shower counter provided particle identification cuts for generating the trigger. The on-line trigger included hodoscope coincidence, an aerogel veto, a gas Cerenkov veto, a lucite coincidence, and a shower counter veto. E89-009 trigger conditions are listed in Table 2.7[51].

The logic diagram of the electronic setup for the trigger is shown in Figure 2.26.

Run type	Particle	Trigger condition
Timing calibration	π^+	$(4/4)(\overline{GC})(\overline{SH})$
Sieve slit	e^+	$(4/4)(\overline{AC})(\overline{LC})$
Λ production	K^+	$(4/4)(\overline{GC})(\overline{AC})(\overline{LC})$
Carbon production	K^+	$(4/4)(\overline{GC})(\overline{AC})(\overline{SH})$

Table 2.7: SOS flux by particle type and trigger rate. A small part of the production data was acquired with (3/4) hodoscope trigger.

The coincidence trigger between the kaon arm and the electron arm was applied off-line. In the coincidence with the electron arm, a wide time window was used to include a sufficient number of random coincidence peaks to extract a precise accidental contribution.

2.6.2 Trigger Supervisor

The trigger supervisor (TS) is an interface between the trigger hardware and the computer data acquisition system. The TS determines how the individual triggers are processed. Any time the run is in progress, a TS GO signal is activated. The TS EN1 signal indicates that the run is in progress and normal data taking is enabled. A TS BUSY signal is active whenever the TS is busy processing an event. During the run, the TS allows pedestal triggers from a pulser. After 1000 pedestal events, the TS enables physics triggers and blocks the pedestal triggers. In addition, the TS provides a busy signal whenever it is processing an event.

The pretrigger that comes from the hardware trigger, and TS control signals are

Figure 2.26: SOS single arm trigger electronics.

fed into a LeCroy 2365 Octal Logic Matrix (8LM) module.

2.7 Data Acquisition

The data acquisition system (DAQ)[52] used for E89-009, was the CEBAF On-line Data Acquisition system (CODA), shown in Figure 2.27. The primary components of the DAQ are the read-out controller (ROC) and event builder and analyzer (EBANA). The ROC handles the read-out of the front-end module memory, and places the event fragments onto the network data system. The EBANA collects and merges the event

Figure 2.27: Coda software chart.

fragments into a complete event, which is written to the magnetic disk.

The run control, a CODA graphical user interface, performs the calibrations of the electronic pedestals at the beginning of every run and reads out slow control diagnostics and scalers. The slow controls are handled by the experimental and physics industrial control system (EPICS)[53].

All data log files were moved from the hard disks of Hall C and saved on the Jlab storage machine, the Silo.

Chapter 3

Data Analysis

This chapter provides a detailed description of the data analysis and software. It includes the various analysis tools and techniques, the calibration procedures, the rates, the particle identification cuts, and the performance of various detector components including efficiencies. The last part of this chapter is dedicated to Monte Carlo simulations and acceptance calculations.

3.1 Analysis Software

The raw data of the experiment E89-009, which consists of the raw CODA and EPICS events¹, were stored in raw data files. The primary analysis software of these files is the modified Hall C analysis software², a modular FORTRAN code, called “REPLAY

¹Mentioned in the previous chapter.

²The old analysis software was written to handle both HMS and SOS spectrometers while in E89-009 only SOS was used along with the new spectrometer, ESPS; thus the analysis software was modified to fit the ESPS.

ENGINE”[54]. This code reads and decodes the raw events, generates tracks, and particle identification information for each event. The flow chart of the Hall C engine is shown in Figure 3.1. Input data are of two types: 1) the raw events, and 2) the

Figure 3.1: A flowchart of modified Hall C ENGINE.

parameters describing the experiment used to analyze the raw events. The output data are in the following format:

- ASCII report files (hardware and software scalers including integrated charge, and a rough estimate of detector efficiencies, etc.);
- A set of histograms in Physics Analysis Workstation (PAW)[55] format, used for

monitoring the detectors and other hardware components, as well as for trouble shooting and testing;

- PAW ntuples which includes event by event information.

This analysis code follows a specific model. In this model the analysis is done sequentially for each spectrometer separately (the only exception is that events in the ESPS spectrometer are chosen based on a trigger from the SOS spectrometer), and then are combined to produce coincidence events.

The input and output of the code are handled using the CEBAF Test Package. The CEBAF Test Package (CTP)[56] is a set of tools developed to receive parameters, cuts, and histogram definitions which are loaded through ASCII files at the beginning of every run. At the end of each event, the CTP test parameters are evaluated, which includes examining and modifying Fortran variables. After this evaluation the histograms are filled, and the software scalers are incremented. Therefore, the CTP can be used as a debugging tool.

The analysis starts by reading in the file “REPLAY.PARM” which sets up the main configuration. Through this file, the input and output flags can be set as well as the path to the various run parameters. After defining all the run parameters, the analysis opens the raw data file and reads the beginning of run information (beam energy, spectrometer angle and momentum, target, etc.). At the beginning of each run, the first 1000 events are analyzed to calculate the pedestal values for all the

ADCs. After this initialization the main event loop begins.

3.1.1 Main Event Loop

In this loop the events are read and analyzed according to their type. There are three types of events to be analyzed.

1. EPICS events

EPICS events include the beam position and energy monitor readings, magnetic settings of the magnets in both spectrometers, etc. These events are stored in ASCII files.

2. Scaler events

The scaler events include the total charge and run time. These events are stored independently from other types of output files.

3. Physics events

Physics events can be divided into three types: SOS, ESPS, and COIN events. An SOS event is generated in the following manner. A raw detector hit is decoded and passed through the SOS reconstruction routine. After being successfully reconstructed, particle identification (PID) information is saved. For each successfully constructed event, a trigger is sent to the ESPS spectrometer, and only the events that fall within a gate that is triggered by the SOS-trigger are chosen.

3.1.2 Event Reconstruction

Figure 3.2: Software flow chart for the SOS event construction.

Figure 3.2 shows a flow chart for event reconstruction in the SOS spectrometer. Reconstruction starts by decoding the ADC and TDC hits of the hodoscope. Timing corrections due to pulse height variations and other offsets are then applied. The decoded information is used to determine the preliminary velocity and start time of each particle. After decoding the hodoscope hits, the Cerenkov, drift chamber, and

calorimeter hits are decoded.

The tracking routine is called after decoding all hit information. The tracking algorithm obtains the position and angles of each track at the focal plane of the SOS spectrometer. After tracking, the time of flight between the front and back planes of the hodoscope (the velocity of the particle corrected for path length) and the energy deposited in the calorimeter for each track are determined. Finally, the track is reconstructed to the target to obtain the momentum, the angle in the dispersive direction, and the position and angle in the non-dispersive direction.

If tracking reconstruction succeeds, all the basic physics quantities for the successful track are calculated, and the scalers and histograms for a single event are filled.

3.1.3 Tracking

The goal of tracking is to determine the equation of the track for an event providing the best fit to the measured drift chamber coordinates. The track is determined by the parameters x , y , x' , and y' at the focal plane position.

Tracking is done in the SOS spectrometer using two drift chambers, each having six planes. Before starting the tracking, each chamber is required to have hits in at least 5 of the 6 planes. The tracking in these chambers starts by identifying all intersections of non-parallel pairs of wires that were hit such that intersections that

fall within a radius of 1.2 cm of one another are used to form space points³. Space points in each chamber are then linked to form a stub, which is essentially a short track. Stubs that are approximately collinear are then linked into tracks. In case of more than one track-situation, the track with the minimum χ^2 is selected. The best track is then projected to the focal plane to give the focal plane parameters (position and slope[57]) x_{fp} , y_{fp} , x'_{fp} , and y'_{fp} at $z = 0$. The focal plane parameters are then used to reconstruct the target parameters using the backward transport matrix M^i (where the forward matrix⁴ was used to calculate the focal plane quantities from the target quantities). As mentioned earlier, all coefficients of the SOS matrix elements were optimized by fitting the optics of the calibration data.

³Tracking here is done by defining space points rather than projections because of the small number of the planes in each chamber and the fact that the first chamber is not parallel to the second one.

⁴The forward matrix is discussed in Chapter 2.

3.2 Calibration

In this section, the calibrations of the various detectors installed in the SOS and ESPS detector huts is described. These calibrations were necessary to ensure good performance of the detectors. They include hardware tests and calibrations that were done before the run, and software calibrations that were done at the beginning of the analysis.

3.2.1 SOS Hodoscope

The high voltage (HV) calibration was done by gain matching the tubes with a gamma ray source (^{60}Co) to an output pulse height of ~ 500 mV.

Time calibrations included the corrections of cable length variations and time (TDC) corrections.

The TDC signal of the hodoscope passes through a fixed threshold discriminator. Thus a larger signal fires the discriminator earlier than a smaller one, even though they arrive at the same time, as shown in Figure 3.3. This difference (time walk) must be corrected, and this was done by using crossed pairs of scintillators. In this calculation, mean times⁵ were used. Applying the pulse height correction to three of the four tubes, the fourth tube can be fit to[58]:

$$\Delta t = C_{ph} * \sqrt{\max(0, (ADC/C_{off} - 1))} + t_0 \quad (3.1)$$

⁵The mean time is the average time of the PMTs at the opposite ends of the scintillator paddle and it was used to eliminate the dependency on the position along the scintillator.

Figure 3.3: Discriminator operation in cases of a large and a small input signal.

where ADC is the raw ADC signal, C_{ph} and C_{off} are the fit parameters, and t_0 is an offset between the crossed scintillators used in the calculations.

3.2.2 Drift Chamber

As mentioned in the previous chapter, the position resolution in the drift chamber is greatly enhanced by determining the time-to-distance map. Thus, a very good calibration of the time-to-distance map is necessary. This calibration is done by collecting the TDC values for all the wires in each plane⁶ which then gives the drift time distribution. Loose cuts are applied to reject random hits (noise). After averaging over all cells, the drift distance is assumed to be uniformly distributed in space. With this assumption, integration over time leads to the drift distance[58],

⁶For this calibration a high statistics run is needed with at least 50k events.

$$d = d_{max} \frac{\int_{t_{min}}^T F(\tau) d\tau}{\int_{t_{min}}^{t_{max}} F(\tau) d\tau} \quad (3.2)$$

where d is the distance between the hit and the sense wire (drift distance), d_{max} is the maximum drift distance (set to be 0.5 cm), t_{max} and t_{min} are the maximum and minimum limits of the time interval to be included in the fit (-25 to 250 ns), and $F(\tau)$ is the drift time distribution. Since hodoscope timing was used as a trigger to the chamber's TDCs, hodoscope calibrations need to be completed first. One time-to-distance map was used for all the data (sdriftmap.param.32783), an example of the drift time and the equivalent drift distance of plane (x1) in chamber 1 are shown in Figure 3.4.

3.2.3 Lead Glass Calorimeter

The calorimeter required gain matching by adjusting the HV on the photomultiplier tubes. This was done using cosmic rays which provided minimum ionizing signals, and was further improved by a software code using positrons⁷.

The ADC channel scale was converted to GeV to measure the deposited energy, but before the conversion, the ADC needed to be corrected for attenuation. Attenuation results because the signal in the calorimeter is read by only one PMT at one end, and this causes a variation in the signal size depending on the hit position in the calorimeter. The correction was done using positrons of the same momentum incident

⁷Here, the positrons are chosen after the tracking is done and the momentum of these positrons is reconstructed from the optics.

Figure 3.4: Top: The drift time. Bottom: The drift distance

on different positions along the lead glass block being corrected⁸. The ADC reading is then plotted against the distance from the PMT, and the distribution is fitted to a second order polynomial including an exponential decay to model attenuation.

3.2.4 Gas Cerenkov

The gains of the PMTs in the gas Cerenkov detector were closely matched ($\sim 10\%$) by adjusting the HV. The gains were also monitored online.

The signals from the gas Cerenkov were normalized by determining the conversion

⁸The position information was obtained from tracking.

factor between the ADC signal and number of detected photoelectrons⁹. The ADC peak was fit to a Gaussian distribution. The conversion factor was then determined by comparing the mean value, $\bar{x}$, to the width, σ .

3.2.5 Lucite Detector

The gains of the lucite PMTs were matched using cosmics by adjusting the HV. To determine the average number of photoelectrons as a function of velocity (β), a lucite prototype was tested at BNL using the AGS secondary K^+ beam. Figure 3.5[50]

Figure 3.5: Average number of the photoelectrons as a function of β .

⁹The number of the photoelectrons should follow Poisson distribution.

shows the average number of photoelectrons as a function of β .

3.2.6 Aerogel Detector

As for the other Cerenkov detectors, the gain was matched, at first by setting the HV so that the output signals have equal pulse height for single photoelectron events. Better gain matching was then done using the ADCs.

Generally, the relation between the pedestal and the single photoelectron peak can be written in the following manner[47]:

$$ADC(calibrated) = [ADC(raw) - pedestal] * gain. \quad (3.3)$$

A calibration of a 100 channels per photoelectron is obtained at the values, pedestal = 500 and gain = 0.3. A detailed calibration procedure for the aerogel detector is mentioned in appendix A of reference [59].

3.2.7 ESPS Hodoscope

Before data acquisition in E89-009, HV gain matching was done using a gamma source (^{60}Co), and more accurate gain matching was done at the beginning of the experiment using the ADC information. Offsets were added to account for differences in cable lengths.

The timing of the logical signal from the discriminator depends on the pulse height, as shown in Figure 3.3. Figure 3.6 shows the time distribution versus the pulse height

Figure 3.6: The hodoscope time distribution versus the ADC.

(ADC). The function $(1/x)$ was chosen to fit this relation. The corrected TDC can be written as:

$$TDC = P_1 + \frac{P_2}{ADC - pedestal}$$

where P_1 and P_2 are the fitting parameters.

3.2.8 SSD Calibration

The SSD was calibrated using a pulser by measuring the hit occupancy per strip as a function of the threshold voltage for several calibration input charges. The 50% occupancy was plotted versus the threshold voltages used in the measurement. Fitting these points with a straight line, the offset threshold was obtained ($V_{off} = 177$ mV). Using this threshold value and gain, ($G = 160$ mV/fC)[49], the input charge (Q_{in})

was calculated using the formula:

$$Q_{in} = \frac{V - V_{off}}{G} \quad (3.4)$$

where V is the measured voltage, and a relation between Q_{in} and V_{off} was established.

Thus, the input charge was calibrated by setting a suitable threshold voltage.

3.2.9 ESPS Momentum Calibration

When scattered electrons entered the ESPS, they were bent horizontally according to their momenta¹⁰, and the position along the focal plane of the ESPS is a function of the momentum of these incident electrons. Ten SSD segments were used to measure the position along the ESPS focal plane in the horizontal direction¹¹. Thus, it was essential to define a relation between the position measured by the SSD segments and the momentum of the incident particles. The SSD segments were tilted by 42° and the scattered electrons incident on the ESPS focal plane at an angle from $\sim 25^\circ$ to $\sim 70^\circ$, which creates an overlap between some neighboring SSD segments as shown in Figure 2.12. This overlap means that the same momentum can have hit positions at two SSD channels at these overlap areas. Thus, the relation between the momentum, the position along an SSD, and the SSD segment must be calibrated together (Even though each segment is described by a separate function, these function are related).

¹⁰The scattered electrons have a very small vertical distribution.

¹¹See Chapter 2.

At the beginning of the analysis, the calibration procedure was not very clear and was developed as the analysis progressed. The steps which were taken are described below.

- The position-to-momentum calibration was started by studying the momentum correlation in the CH_2 data. Using the kinematics of the reaction $p(e, e'K^+)\Lambda$, the momentum of the scattered electron ($P_{e'}$) was constructed (the masses m_p , m_e , m_{K^+} , and m_Λ are all known, and the K^+ momentum is measured by the SOS). The distribution of $P_{e'}$ versus the SSD channels is shown in Figure 3.7. Since the Λ belt¹², shown in Figure 3.7, represents the $P_{e'}$ distribution, the focal plane of each SSD plane (segment) should lie inside this belt. Thus, this belt gives a clue to the position of the focal plane. However, because of the large width of the belt, other methods were still needed to obtain an accurate expression of the focal plane.
- A RAYTRACE simulation was done to get a clearer idea about the focal plane. Figure 3.8 shows the result of this simulation. In this figure the scattered electron momentum ($P_{e'}$) is shown as a function of the SSD channel (the position along the focal plane). Even though the results of this simulation look promising, they are still not very accurate because the RAYTRACE data card¹³ of the combined system (the Splitter and Enge magnets) was not known exactly

¹²This belt is called Λ belt because the Λ mass was used in the construction.

¹³The data card is the file that has the parameters of the spectrometer system which includes dipoles, collimators, etc.

Figure 3.7: The constructed momentum (MeV/c) versus SSD channel number.

and needed to be tuned, introducing human error. However, the advantage of this simulation is that we can get an idea about the shape of the focal plane and the nature of the function that represents it. It is clear (especially at low momentum) that a second order polynomial is needed to represent the focal plane.

- The Λ belt calibration and the RAYTRACE simulation provided an initial estimate of the focal plane calibration. The Λ belt was separated into ten areas

Figure 3.8: The focal plane of the ESPS simulated by RAYTRACE.

equivalent to the SSD planes. In each of these areas random points¹⁴ were selected, and then fitted to a second order polynomial:

$$P_{e'} = offset(pln) + slope(pln) \times x + secodr(pln) \times x^2 \quad (3.5)$$

where $P_{e'}$ is the scattered particle momentum, $x, = (pln - 1) * 144 + ssdch$, is

¹⁴These points should be located inside the belt.

the position along the focal plane, pln is the SSD plane (segment) number (10 planes), $ssdch$ is the channel number (144 channels in each plane), $offset()$ is the zeroth order, $slope()$ is the first order, and $secodr()$ is the second order parameter in the polynomial.

- Since the fitted points, and thus the resulting polynomial have an error of $\sim 3 - 5$ MeV (the belt width), the calibration is not well defined. Thus, the overlap between the SSD planes was used to improve the calibration function. The overlap pattern was extracted from the raw data by choosing the overlap area between the two planes intended for the study. One channel in the first plane¹⁵ is selected and then the hit pattern of the second plane is studied. Figure 3.9 shows the results of some of this overlap analysis fitted by a Gaussian distribution .

After fitting these hit patterns by a Gaussian distribution, the mean value of the fit was considered as the hit position in the second plane and the sigma (σ) is the error of this value as shown in Figure 3.10. In this figure the y-axis represents the first plane and the x-axis the second plane.

- The overlap constraint improved the accuracy of the fitted focal plane functions. Since these functions are second order polynomials, further constraints were necessary to achieve the desired resolution.

Every combination of parameters gives a value for the momentum of the scat-

¹⁵The first plane means that the plane that the particle hits first.

Figure 3.9: The hit patterns of the second overlapped channels.

tered electron ($P_{e'}$). Thus, given $P_{e'}$ and P_{K^+} (from SOS) information, the missing mass of the resulting nuclear system can be constructed. In the CH_2 target, both $p(e,e'K^+)\Lambda$ and $p(e,e'K^+)\Sigma^0$ reactions are possible so that both Λ and Σ^0 appear in the reconstructed missing mass. The masses of both Λ and Σ^0 are well known ($m_{\Sigma^0} = 1192.642 \pm 0.024$ MeV and $m_{\Lambda} = 1115.683 \pm 0.006$ MeV[7]) and thus the mass difference, $\Delta m = 76.959 \pm 0.081$ MeV, can be used to calibrate the mass difference in the constructed missing mass spectrum. This

Figure 3.10: The overlapped channels between every two SSD planes for run# 33106.

calibration was done for each plane by changing the parameters of the fitted function until the mass difference was equal to the calculated one.

- Further fine tuning was done on the parameters using the missing mass spectra of ${}^{12}_{\Lambda}\text{B}$ resulting from the reaction ${}^{12}\text{C}(e,e'\text{K}^+){}^{12}_{\Lambda}\text{B}$ in the ${}^{12}\text{C}$ target. An estimated value of ${}^{12}_{\Lambda}\text{B}$ s-shell states ($\Delta E_{g.s.} = 11359.31 \text{ MeV}$) was subtracted from the missing mass spectra so that, in principal, the ground state lines up at 0 MeV. Fine tuning was done by changing the parameters slightly so that the

s-shell states for all the planes aligned at 0 MeV.

With all these constraints final focal plane calibrations were obtained. There are two different sets of data in the E89-009, different in the sense that they have two beam momenta: 1864 and 1721 MeV/c. However, since the splitter magnet probe was not placed in the uniform field region, an accurate and proper scaling of the magnet field between the two momenta was not possible. Thus, two different sets of the focal plane parameters for both sets of data were calibrated individually. The distribution of the focal plane function versus SSD channel for 1864 and 1721 MeV/c data is shown in Figure 3.11.

As a check on this calibration, Figure 3.12 shows the overlap pattern of the data (the points with the error bar) from *run#33106*, and that of the 1721 MeV calibrated parameters (solid line). Figure 3.13 shows the overlap pattern of the data (the points with the error bar) from *run#32535*, and that of the 1864 MeV calibrated parameters (solid line).

Figure 3.11: Top: the focal plane at 1864 MeV beam energy. Bottom: the focal plane at 1721 MeV beam energy.

Figure 3.12: The overlapped channels between every two SSD planes at beam energy, 1721 MeV. The solid line shows the overlap pattern between the extracted parameters overlap, while the points with error bars show the overlap pattern constructed from the data.

Figure 3.13: The overlapped channels between every two SSD planes at beam energy, 1864 MeV. The solid line shows the overlap pattern between the extracted parameters overlap, while the points with error bars show the overlap pattern constructed from the data.

3.3 Rates and Trigger

The rate of electrons in the ESPS was about 100 MHz for the entire ESPS focal plane.

Table 2.6 lists the proposed singles and trigger rates in the SOS spectrometer[51].

A rough estimate of the singles rates[60] from the scalers is listed in Table 3.1.

Nucleus	e^+ (kHz)	π^+ (kHz)	p (kHz)
${}^6\text{Li}$	11.3	1.6	0.21
${}^7\text{Li}$	11.6	1.6	0.19
${}^{10}\text{B}$	9.1	1.3	0.17
${}^{11}\text{B}$	9.7	1.3	0.13
${}^{12}\text{C}$	10.1	1.4	0.14

Table 3.1: Estimated singles rate for each target from a trigger study.

This study shows that the positron and pion rates were consistent with the pair production cross section in the proposal, while the proton rate was at least an order of magnitude higher than the value listed in Table 2.6.

As a part of this study, the effect of the trigger components was studied, as listed in Table 3.2. In Table 3.2 AC, GC, and LC are the Aerogel, Gas, and Lucite Cerenkov counters, respectively; and SHhi is the Shower counter (Calorimeter) detector. The bar means veto.

The true coincidence rate (R_{true}) was calculated using the formula:

$$R_{true} = \frac{(T + A) - A}{t} \quad (3.6)$$

Target	${}^7\text{Li}$	${}^{10}\text{B}$	${}^{11}\text{B}$	${}^{12}\text{C}$
Trigger Current (μA)	1.3	0.75	0.5	0.22
(4/4)	1081k	1480k	1090k	1073k
(4/4)($\overline{GC}$)	18.6k	27.0k	19.4k	18.7k
(4/4)($\overline{AC}$)	32.1k	49.5k	34.6k	33.3k
(4/4)($\overline{GC}$)($\overline{AC}$)	4.16k	6.3k	4.5k	3.9k
(4/4)($\overline{GC}$)($\overline{AC}$)(LC)	2.42k	3.6k	2.8k	2.4k
(4/4)($\overline{GC}$)($\overline{AC}$)($\overline{SHhi}$)	6.0k	4.6k	-	

Table 3.2: Estimated singles rate (trigger rate) for each target from a trigger study.

where $T+A$ is the number of the counts under the real peak, A is the number of the counts under the accidental peak, A is the average of eight accidental peaks, and t is the total time. In this formula, T can not be obtained individually, see Figure 3.14, because the real peak includes both T and A .

The kaon singles rate (R_K) was calculated using the formula:

$$R_K = \frac{1}{\tau R_e} \frac{A}{t} \quad (3.7)$$

where τ is the width of the coincidence window ($\tau = 2$ ns) and R_e is the ESPS singles rate.

The rate was calculated[60] for two samples from 1721 MeV/c data.

- For 1721 MeV at $I=0.22 \mu A$ (C target, runs# 32778-32966)

$$R_{true} = 0.0054/\text{sec.} \quad (\sim 0.015/\text{sec at } 0.6 \mu A)$$

$$R_K = 0.075/\text{sec.} \quad (\sim 0.20/\text{sec at } 0.6 \mu A)$$

- For 1721 MeV at $I=0.60 \mu A$ (C target, runs# 33090-33341)

Figure 3.14: Coincidence time for the 1721 MeV data.

$$R_{true} = 0.011/\text{sec.}$$

$$R_K = 0.22/\text{sec.}$$

Thus, the kaon singles rate is proportional to the beam current, but the coincidence rate goes as the square of the beam current. This causes the signal-to-noise ratio to decrease for higher currents ($0.6 \mu A$). Moreover, the kaon singles rate is much higher than the true coincidence rate, which reduces the signal-to-noise ratio (~ 0.8 for $I=0.22 \mu A$).

3.4 Particle Identification

The primary task of the data analysis is to identify the coincidence particles, e' and K^+ . In the ESPS, the electron rates were very high compared to the other particles, and so no particle identification was needed. On the other hand, in the SOS the kaon rate was much smaller than other detected particles, as listed in Table 2.6. Trigger vetos reduce the rates of these background particles, but do not eliminate them. Thus, particle identification (PID) was needed to select kaons. The PID in the SOS included the time of flight calculation, tracking cuts, a set of detector cuts (AC, GC, LC, and SC cuts), and the coincidence time cut.

3.4.1 Time Of Flight Cut

Time Of Flight (TOF) is the time it takes the particle to travel the distance between the front (S1) and back (S2) hodoscope planes. TOF is used to calculate the velocity (β_{tof}) of the particles that are detected by the SOS spectrometer. In the analysis routine, β_{tof} is calculated twice for each event. First, β_{tof} is calculated using the hodoscope timing information to get the first guess of β_{tof} . After going through tracking corrections where the best tracks are chosen and tracking dependent variables are calculated¹⁶, β_{tof} is calculated again taking into account track length. Figure 3.15 shows the β_{tof} spectrum for the particles detected in the SOS¹⁷.

¹⁶The tracking information is used to avoid spurious hodoscope hits

¹⁷The β_{tof} resolution in the SOS is about $\delta\beta = 0.018$ (for $\beta = 1$) because the resolution of the SOS hodoscopes is about $\sim 100ps/plane$.

Figure 3.15: β_{tof} distribution for the particles detected in the SOS.

One of the TOF cuts that was applied during the analysis was a combination of β_{tof} from this distribution and β_K . The β_K was obtained from the measured momentum of the particles that are detected by the SOS and the kaon mass using the relation $\beta_K = p/\sqrt{p^2 + m_K^2}$. The cut was applied on the difference between β_{tof} and β_K , as shown in Figure 3.16;

$$\Delta\beta = \beta_{tof} - \beta_K$$

$$|\Delta\beta - 0.0035| \leq 0.0385$$

Figure 3.16: The distribution of the difference between β_{tof} and β_K .

In Figure 3.16, the region of interest is indicated by the two arrows.

The other TOF cut was the difference between β_{tof} and β_p , where β_p was obtained using the measured momentum and the proton mass. The cut was :

$$\beta_{tof} - \beta_p > 0.085$$

In Figures 3.15 and 3.16, we can see that the kaons are still not well separated from pions and positrons. Thus, other cuts were needed to distinguish kaons.

3.4.2 Tracking Cuts

For each successfully constructed (reconstructed) track, four quantities were calculated (two coordinates x and y , and the angles of the constructed track at the coordinates x' and y' ; the z-coordinate is parallel to the central ray). These quantities can be calculated at any given point along the focal plane. However, they were calculated at the nominal focal plane¹⁸ (x_{fp} , y_{fp} , x'_{fp} , y'_{fp}) and at the target (y_{tar} , x'_{tar} , y'_{tar} , where x_{tar} is a constant and assumed to be zero). The focal plane quantities are constructed during tracking and they were used to reconstruct the target quantities, and δ (δ is the percentage deviation of the detected momentum p from the central momentum, p_{cen}).

In order to reject any events outside the SOS acceptance, a set of cuts was applied on the these quantities. The cuts were:

$$\begin{aligned} |x'_{tar}| &< 0.05; \\ |y'_{tar}| &< 0.1; \\ |\delta| &< 15.0. \end{aligned}$$

3.4.3 Cerenkov Cuts

- Aerogel Cerenkov

The aerogel detector was used for π^+/K^+ discrimination. Figure 3.17 shows the

¹⁸The nominal focal plane is a conventional focal plane, normal to the z-axis, and positioned at the intersection between the central ray and the real focal plane. This was chosen because the real focal plane was a relatively complicated surface.

distribution of the number of photoelectrons detected by the aerogel versus the velocity (β_{tof}).

Figure 3.17: The distribution of the number of photoelectrons detected by the aerogel detector versus the velocity ($\beta = v/c$).

The aerogel Cerenkov (AC) was put into the trigger as a veto to reduce the high background of π^+ ; but since the trigger veto was applied loosely, a tighter AC cut was applied during the analysis to achieve a better π^+ rejection. The following AC cut was applied in the off-line analysis:

$$saer_npe < 1.6$$

This means that the only accepted events are the ones that deposited less than two photoelectrons in the aerogel detector. This cut rejects almost all pions while keeping most kaons, as shown in Figure 3.17.

- Lucite Cerenkov

The lucite detector is mainly used for (some) p/K⁺ discrimination. Figure 3.18 shows the β_{tof} distribution versus the number of photoelectrons deposited in the lucite detector.

Figure 3.18: The velocity ($\beta = v/c$) distribution versus the number of photoelectrons deposited in the lucite detector.

Since, as we can see in Figure 3.15, the protons are well separated by the TOF (β_{tof}) cut, the lucite cut was not very important in the data analysis. The main contribution of the lucite Cerenkov (LC) detector came in the trigger where it reduced the high rate of protons. The applied cut in the analysis was:

$$sluc_npe > 0.68$$

With this cut a large number of protons can be neglected without significantly affecting the number of kaons, as shown in Figure 3.18.

- Gas Cerenkov

Gas Cerenkov (GC) was used as a veto in the trigger. It was not particularly effective in the analysis, and it was designed to differentiate between the pions and positrons. In order to keep kaons, a loose cut was applied. The GC cut was:

$$scer_npe < 13.0$$

3.4.4 Lead Glass Calorimeter Cut

The shower counter was very effective in discriminating e^+ from the π^+ and K^+ . As shown in Figure 3.19, the positrons are very well separated from the other particles. This detector was used in the trigger as a veto to reject the positrons and also it

Figure 3.19: The velocity ($\beta = v/c$) distribution versus the number of photoelectrons deposited in the calorimeter.

was a very powerful tool in data reduction. As shown in Figure 3.15, positrons left in the data are even less than protons, a very effective reduction when compared to the original rates, see Table 2.6. Even with such efficiency, the trigger cut and data reduction cut were not very tight to make sure that no kaons were lost in the process. Later in the analysis, a shower counter cut was applied to reject the remaining positrons. The cut was the following:

$$\frac{dE}{E} < 0.75$$

3.4.5 SSD and Enge Hodoscope Cuts

Two cuts were applied to events in the electron arm, 1) the position and 2) time coincidence. The position coincidence cut came from the fact that the ESPS hodoscope was located behind the SSD and used for timing. Thus, the relevant events pass through both the SSD and hodoscope. Figure 3.20 shows the correlation between the

Figure 3.20: The scintillator channels versus SSD channels.

hodoscope and SSD channels. In this Figure, it can be seen that there are dark areas which represent events that pass through both the SSD and the hodoscope and the random hits which occur in between. As an example, the two arrows in Figure 3.20 show the SSD channel cut which is equivalent to scintillator#60.

The other cut was the time coincidence between the SSD and hodoscope. With a fixed distance between the SSD and hodoscope, the time between these two components can be used as a tool to reduce accidental hits. Figure 3.21 shows the time

Figure 3.21: The SSD and scintillator time difference.

difference spectrum, where the arrows point to the cut that was used during the analysis ($|t_{SSD} - t_{Hodo}| \leq 35.0$ ns which is equivalent to $\pm 3.5\sigma$).

3.4.6 Coincidence Cuts

The events of interest in E89-009 were the coincidences of the SOS events (kaons) and ESPS events (electrons) which are used to study the hypernuclear system. However,

it is possible to have coincidences that were formed by random chance (accidental coincidences); especially with the very high rates in the ESPS. There are also real coincidences that come from other hadrons in the SOS such as protons and pions. As mentioned in the previous chapter, the CEBAF accelerator provided a narrow current pulse (~ 1.67 ps) every 2 ns, and an RF time signal is sent to the DAQ every 8 bursts (16 ns) as shown in Figure 3.22. Thus, if we were to detect the hadrons in

Figure 3.22: The RF time spectrum.

coincidence with the scattered electrons, one expects to reproduce the microstructure of the beam provided that the coincidence time resolution was sufficient. Figure 3.23 shows the corrected time coincidence spectrum with the real (kaons) peak at 0 ns.

A 2 ns cut was applied around the real peak (± 1 ns). To get a good statistical

Figure 3.23: The coincidence time spectrum.

estimate of the random events, the average of eight peaks (-9.: -1. ns & 3.: 11. ns) was taken. The peak from 1 to 3 ns was excluded from the background calculations because of pion and kaon contamination. The average was then subtracted from the real peak to obtain the number of true coincidences.

3.5 Total Charge

The total charge measurement for each run was obtained by the BCM. The scaler rates of the BCMs along the beam line are sent to the DAQ every two seconds during the run. The average value of these rates is converted to average current (the BCM calibration is discussed in chapter 2), and then the average current values are saved in an ASCII file called stats#.txt. Table 3.3 shows the total charge for each target at beam energies of 1721 and 1864 MeV. The total charge was calculated for the runs that were used in the missing mass calculation.

Beam Energy (GeV)	Target	Total Charge (mC)	Error (mC)
1864	CH ₂	315.96	0.56
	¹² C	158.19	0.40
1721	CH ₂	153.71	0.39
	¹² C	100.20	0.32

Table 3.3: The total charge in E89009.

3.6 Corrections to the Yield

3.6.1 Tracking Efficiency

Tracking efficiency is the ratio of the number of events for which the track is found to the number of 'good' events that are expected to have a track. Each chamber was handled separately. The tracking efficiency for each chamber was extracted from

the efficiencies of the planes in the chamber. The efficiency of a plane is the ratio of the number of events that are detected by the plane to the number of good events (triggers). The good events are the ones that are detected by the other five planes in the chamber. For each event to be detected, it is required to have at least one hit in each plane and a maximum of 15 hits in the whole chamber. Time of flight information, determined before tracking by using the hodoscopes, was also used such that β ($=v/c$) is required to be greater than zero. Finally, the event must form a space point where a χ^2 fit test is applied and only the events with χ^2 less than 10 are accepted.

The efficiency was calculated for all the triggered events that passed the PID cuts and fall within the fiducial region of the hodoscopes. Using run#32583, the efficiency of all 12 planes (both chambers) is shown in Figure 3.24.

After calculating the tracking efficiency of all the planes in both chambers. The tracking efficiency of each chamber is calculated by permutation using five out of six planes, and then the total efficiency is obtained by multiplying the efficiencies of both chambers. Figure 3.25 shows the SOS tracking efficiency as a function of time¹⁹). On average, the tracking efficiency is equal to, 0.9877 ± 0.0081 .

¹⁹This run period is the 1864 MeV data and CH₂ target.

Figure 3.24: The efficiency for the individual planes in both chambers for run#32583.

3.6.2 ESPS Hodoscope Efficiency

The hodoscope efficiency was calculated using the overlap between the scintillators themselves and between the scintillators and SSD channels. This means that the efficiency was only calculated for the overlapped components of the scintillators and the SSD. These overlapped components are scattered along the focal plane, which means that calculating the efficiency for these components is equivalent to taking samples along the focal plane. Thus, averaging the results for all these components is an accurate description of the whole focal plane because the rate is not the same along the focal plane. As shown in Figure 3.26, the triggers in this calculation are

Figure 3.25: The SOS tracking efficiency as a function of time.

considered to be the events that cross scint#1 and the overlapped SSD channels. The coincidence time (Δt_{tr}) between scint#1 and the SSD was used to determine the true and false triggers. The true triggers are the ones that fall within the gate, $-35.0 \text{ ns} \leq \Delta t_{tr} \leq 35.0 \text{ ns}$ and the false triggers (accidentals) are the ones that fall in the following ranges, $-70.0 \text{ ns} \leq \Delta t_{tr} < -35.0 \text{ ns}$ & $35.0 \text{ ns} < \Delta t_{tr} \leq 70.0 \text{ ns}$. In a similar manner, the coincidence time (Δt) between scint#2 and the SSD segment is used to determine the true hits (detected events) from the false ones. The true hits (T) are the ones that fall within the gate, $-35.0 \text{ ns} \leq \Delta t \leq 35.0 \text{ ns}$ and the false hits in the range $-70.0 \text{ ns} \leq \Delta t < -35.0 \text{ ns}$ & $35.0 \text{ ns} < \Delta t \leq 70.0 \text{ ns}$. Figure 3.27 shows the

Figure 3.26: A part of the ESPS focal plane where there is an overlap between two hodoscope scintillators and the SSD.

ESPS hodoscope efficiency as a function of time. In this figure there is a slight rise in the efficiency ($\sim 0.5\%$) and that is due to changes in the rate and not due to a time factor. On average, the ESPS hodoscope efficiency is, 0.9766 ± 0.0070 .

3.6.3 SSD Efficiency

The overlapped components along the focal plane were also used to calculate the SSD efficiency. The coincidence time between the overlapped scintillators behind the SSD planes was used to determine the true and false triggers. The time difference between every two overlapped scintillators was chosen to be within ± 5.0 ns for the true triggers while the accidentals occur in the range from -10.0 to -5.0 ns and from 5.0 to 10.0 ns. The coincidence time between the SSD and the hodoscope was used to determine the true and false hits that were detected by the SSD. The true-hits cut was ± 35.0 ns which is equivalent to $\pm 3.5\sigma$ when fitting the timing spectrum by a

Figure 3.27: The ESPS hodoscope efficiency as a function of time.

Gaussian distribution. The false hits were in the range from -70.0 to -35.0 ns and from 35.0 to 70.0 ns. Because the scintillators did not cover 100 % of the focal plane due to geometrical inefficiency, a cut on the SSD channels that is equivalent to the scintillators was needed.

The SSD efficiency (ϵ) was calculated according to the following relation:

$$\epsilon = \left(\frac{T - F}{T_{tr} - F_{tr}} \right) \quad (3.8)$$

where T is the number of the hits that happened in the true timing gate, F is the

number of the hits that happened in the false timing gate, T_{tr} is the number of trigger hits that happened in the true coincidence gate, and F_{tr} is the number of trigger hits that happened in the false coincidence gate.

Figure 3.28: The SSD efficiency as a function of time.

Figure 3.28 shows the SSD efficiency as a function of time. On average, the SSD efficiency is equal to 0.9581 ± 0.0047 .

3.6.4 Geometrical Efficiency

As mentioned in Chapter 2, the hodoscope planes (8 pieces in each) were tilted by a 42° angle, and the scattered particles fall on the focal plane with an angle between

$\sim 25^\circ$ and $\sim 70^\circ$. Thus, some spots along the focal plane were not covered by these scintillators which caused a loss of some good events. Figure 3.29 shows the overlap

Figure 3.29: The scintillator hit versus the SSD hits.

between the scintillator hits and the SSD hits. It also shows the missed spots and thus the inefficiency. The geometrical inefficiency is obtained using the hit pattern of the SSD channels for each hodoscope plane²⁰.

Therefore, the geometrical inefficiency can be considered as the ratio of the missed SSD channels to the total number of SSD channels. A SSD channel is considered missed if it has less than 70% of the average number of counts per channel on the

²⁰The SSD channels cover all the focal plane.

whole plane. Figure 30 shows the distribution of the missed SSD channels as a

Figure 3.30: The distribution of missed channels as a function of plane number.

function of plane number. The geometrical efficiency was equal to, 0.9097 ± 0.0161 .

3.6.5 Electronic and Computer Dead time

To have a better estimate of the experimental yield, the results need to be corrected for both electronic and computer dead times. The electronic dead time is the time when the electronic hardware is busy processing earlier triggers and thus the triggers that arrive during this time are lost.

The computer dead time is the time when the data acquisition computers are busy processing events, which blocks new events and thus some of these events are lost.

The lifetimes for both the electronics and computer are listed in Table 3.4,

Target		Electronic Lifetime	Computer Lifetime
1864	CH ₂	99.50 $\pm$ 5.12	92.24 $\pm$ 2.79
	¹² C	93.35 $\pm$ 4.63	80.83 $\pm$ 4.38
1721	CH ₂	98.34 $\pm$ 5.03	90.08 $\pm$ 3.15
	¹² C	99.31 $\pm$ 5.10	91.85 $\pm$ 2.85

Table 3.4: The electronic and computer lifetimes for different rates and different targets.

3.6.6 Survival Ratio of K⁺

The K⁺ is an unstable meson with a mean lifetime $\tau = (1.2386 \pm 0.0024) \times 10^{-8}$ s. Thus, some kaons that were created by the process (e,e'K⁺), decay before being detected, and when calculating the yield, this factor must be included. The survival probability $P(x)$ of the kaon is given by[10]:

$$P(x) = e^{-mx\Gamma/|\vec{p}|}$$

where x is the distance traveled by the kaon, m is the rest mass of the kaon, Γ ($= 1/\tau$) is the inverse of the mean lifetime, and $\vec{p}$ is the momentum of the kaon.

All of the above variables are well known except for x . In determining x , the decay modes of the kaon must be considered because some of the decay products can trigger the detectors. Looking at the decay modes listed in Table 3.5[7] only the positive pions and the muons have a substantial effect. Previous work[50] shows that

Decay Modes	Branching Ratio (%)
$\mu^+ \nu_\mu$	63.51 ± 0.18
$\pi^+ \pi^0$	21.16 ± 0.14
$\pi^+ \pi^+ \pi^-$	5.59 ± 0.05
$\pi^0 e^+ \nu_e$	4.82 ± 0.06
$\pi^0 \mu^+ \nu_\mu$	3.18 ± 0.08
$\pi^+ \pi^0 \pi^0$	1.73 ± 0.04

Table 3.5: K^+ decay modes with their branching ratios.

a correction for the decays in this energy range is on the order of 3%. In E89-009, the correction is even less than 3% because the aerogel detector, which is capable of distinguishing these decay products from the kaons, as shown in Figure 3.17, was used in the trigger. Thus, no simulations were done to determine the effect of the decays and the distance traveled (x) was taken to be at the aerogel detector, ~ 9.80 m. Figure 3.31 shows the results of this calculation.

3.6.7 Absorption

The kaons travel through various vacuum windows and portions of the detectors in the SOS and its detector package where some of these kaons get absorbed through elastic or inelastic scattering. The absorption in the SOS, from the aluminum chamber window at the SOS entrance to the aerogel Cerenkov, was calculated in reference [50], $\sim 5\%$.

Figure 3.31: Survival ratio of the kaon versus its momentum.

3.6.8 Cut Efficiencies

As stated earlier, the main task of the data analysis was the PID which was done by applying cuts on the detector components of the spectrometers. Because the same method was used to extract the efficiency for all the cuts that were applied on the SOS components, the method will be mentioned in general, and then the results will be shown for the individual components. The calculation started by fitting the β spectrum by a Gaussian distribution after applying all the detector cuts, as shown in Figure 3.32, and then calculating the number of counts under the fitting function which represents the number of the surviving kaons. As an example of this

Figure 3.32: β spectrum after applying PID cuts.

Figure 3.33: The number of kaons versus the cut on the number of photoelectrons.

method, Figure 3.33 shows the number of counts versus the cut on the number of photoelectrons in the aerogel Cerenkov detector.

After performing the same procedure for the rest of the cuts, the distribution of the number of counts versus the cut was fit by a suitable function. The maximum value of the fitting function was considered to be 100 % efficiency, and the value of the function at the particular cut divided by the maximum value of the function is the cut efficiency. Figures 3.35 and 3.36 show the results of this study.

As mentioned in Section 3.4.6, the peak from 1 to 3 ns in the coincidence time spectrum, shown in Figure 3.23, was excluded from the background calculations be-

cause of the pion and kaon contamination. The kaons contamination was due to the time resolution and a time offset for some of the hodoscopes. Thus, these kaons need to be accounted for when calculating the efficiency of the coincidence time cut. Figure

Figure 3.34: The real peak in the coincidence time spectrum.

3.34 shows the real coincidence time peak with a tail extending in the time period from 1 to 3 ns, which represents the leaked kaons. This peak, from -1 to 3 ns, is constructed from the coincidence time spectrum. Thus, the efficiency is simply the ratio of the number of events in the period 1 to -1 ns to the number of events in the period -1 to 3 ns.

Table 3.6 lists the coincidence time cut efficiencies from the parts of the data that

Energy (MeV)/Target	Efficiency (%)	Error (%)
1864 / ^{12}C	89.89	1.26
1721 / ^{12}C	90.80	1.69
1864 / CH_2	93.53	1.23
1721 / CH_2	90.95	1.89

Table 3.6: Coincidence time efficiency.

were involved in the cross section calculations.

For the ESPS spectrometer, there were only two cuts, the coincidence time cut and the cut on the overlapped scintillators with the SSD channels. The overlapped SSD channels represent the overlap between the SSD and hodoscope channels as well as the overlap between the hodoscope channels. The result of the overlap cut study is shown in Figure 3.36. The SSD and hodoscope coincidence time spectrum was fitted by a Gaussian distribution and the cut was chosen to be $\pm 3.5\sigma$. Therefore, the efficiency of the coincidence time cut is $\sim 99.99\%$. Table 3.7 lists the efficiencies of these cuts²¹.

²¹ δ cut was not applied when calculating the missing mass spectrum, and so it was not included in the cross section calculations.

Figure 3.35: The ratio of surviving kaons versus the applied cut.

Figure 3.36: The ratio of surviving kaons versus the applied cut.

Applied Cut	Efficiency (%)	Error (%)
$Aerogel < 1.6 \text{ p.e.}$	99.14	1.96
$ \beta - \beta_K < 0.042$	89.23	1.72
$\beta - \beta_p > 0.085$	99.36	1.97
Gas Čerenkov $< 13. \text{ p.e.}$	99.99	1.98
$ fptime < 40. \text{ ns}$	99.40	1.97
Lucite $> 0.68 \text{ p.e.}$	99.79	1.98
Calorimeter < 0.75	97.61	1.93
$ ssxptar < 0.05 \text{ mm}$	98.08	1.94
$ ssyptar < 0.10 \text{ mm}$	99.77	1.98
$ \text{SSD coincidence time} < \sim 35. \text{ ns}$	99.99	0.03
Total	83.26	4.93

Table 3.7: PID cuts and their efficiencies.

3.7 Acceptance

The spectrometer acceptance is the probability that an event coming from the point (x, y, z) with the parameters (x', y', δ) will be detected by the detector package of that particular spectrometer. Therefore, the acceptance is a function of these space and momentum parameters, $A = A_6(x, y, z, x', y', \delta)$.

As the angle and momentum deviate from the central kinematics, a fraction of the events will be lost due to some limitations in the spectrometer (SOS and ESPS spectrometers). These limitations include: the collimators, the magnet gaps, and the size of the detector elements. Therefore, when calculating the cross section, an accurate estimate of the ratio of the particles that pass through the spectrometer (the acceptance) is necessary.

Instead of calculating the acceptance function that varies over the space and momentum parameters, the effective solid angle is calculated using Monte Carlo simulations. The solid angle for this experiment can be defined as:

$$\Delta\Omega = (\Delta\Omega_{initial}) \frac{N_{final}}{N_{initial}} \quad (3.9)$$

where $\Delta\Omega_{initial}$ is the input solid angle, $N_{initial}$ is the number of particles that enters the spectrometer, and N_{final} is the number of the particles that pass through the spectrometer. Monte Carlo simulations were done first for the ESPS spectrometer, and then the result was used to guide the simulations for the SOS spectrometer. The

Monte Carlo code used for this purpose is based on RAYTRACE.

3.7.1 ESPS Acceptance

As mentioned in Chapter 1, the scattered electrons that produce virtual photons are the only electrons that are relevant to this work, and so the only ones needed to be included in the acceptance study. Thus, the simulation began by randomly generating the momentum for the in-going electron under the virtual flux factor, see Figure 1.15. The momentum deviation, δ , was generated within the range from -26.0 % to 26.0 % (the central momentum depended on the momentum of the incident electrons, $P_{central}(1864\text{MeV}) = 306.066\text{MeV}/c$ and $P_{central}(1721\text{MeV}) = 276.3728\text{MeV}/c$) which was larger than that of the spectrometer, and the solid angle was also randomly generated with a full azimuthal angle and a polar angle 0.-0.6 radians.

The generated events were then sent through the ESPS spectrometer. These events were transported through the magnets to the detector plane by a set of matrix elements which were derived from RAYTRACE. Since there was only one detector (SSD & hodoscope for position and timing measurements, respectively) for the ESPS, a simple Fortran code was used to transport the events to the detector, and thus calculate the number of events that passed through the spectrometer to the detector. Figures 3.36 and 3.37 show the percentage of the particles that pass through the spectrometer as a function of the momentum for 1721 and 1864 MeV, respectively.

In both of these figures there is a momentum period where the percentage of the

Figure 3.37: The percentage of the particles that pass through the ESPS as a function of the momentum at $P_e = 1721$ MeV/c.

particles that pass through the spectrometer is zero, and this is because this part of data was neglected in the missing mass reconstruction. It was neglected because it needed further analysis due to some problems that are not currently understood.

3.7.2 SOS Acceptance

The experiment E89-009, involved a coincidence between the scattered electrons and the electroproduced kaons, see chapter one, which concludes the correlation between ESPS and SOS spectrometer acceptances. Consequently, only the kaons that are produced by the accepted scattered electrons in the ESPS spectrometer are relevant to this acceptance study. Using the kinematics of the reaction $^{12}\text{C}(e,e'\text{K}^+)_{\Lambda}^{12}\text{B}$, the

Figure 3.38: The percentage of the particles that pass through the ESPS as a function of the momentum at $P_e = 1864$ MeV/c.

momentum acceptance distribution of the K^+ was extracted from the momentum acceptance distribution of the scattered electrons shown in Figures 3.36 and 3.37. The K^+ momentum was then randomly generated under the obtained distribution. Such a method was used to ensure the correlation between the ESPS and SOS acceptances. The solid angle was also generated randomly with a full azimuthal angle and a polar angle 0.-0.1 radians.

As for the ESPS spectrometer, a set of matrix elements derived from RAYTRACE were used to transport the event through the magnets to the detector hut. It was easier to consider the detectors as a set of collimators and they were entered as such in the RAYTRACE data card. Table 3.7 lists the detectors that were entered in

Detector	x_0 (cm)	y_0 (cm)	x_{max} (cm)	y_{max} (cm)
DC1	4.541	0.595	33.435	20.0
DC2	0.353	0.382	33.400	20.0
S1Y	0.	0.	36.8	18.423
S1Y	-1.0	0.	31.75	23.5
LC	-1.5	0.	41.5	20.
S2Y	0.	0.	57.15	18.423
S2X	0.	0.	50.	34.0

Table 3.8: The dimensions of the detectors that were used in the RAYTRACE data card.

the RAYTRACE data card and their dimensions, where x_0 and y_0 are the x and y coordinates of the collimator center, respectively. The dimensions, x_{max} and y_{max} are the half-axes in the x and y direction, respectively. The results of the simulations are shown in Figures 3.38 and 3.39.

On average, the solid angle of the spectrometer system at beam energy of 1864 MeV is equal to, 5.085 ± 0.078 msr; and at beam energy of 1721 MeV is equal to, 5.056 ± 0.068 msr.

Figure 3.39: The SOS solid angle distribution versus the momentum for an incident momentum of $P_e = 1721 \text{ MeV}/c$.

Figure 3.40: The SOS solid angle distribution versus the momentum for an incident momentum of $P_e = 1864 \text{ MeV}/c$.

3.8 Systematic Errors

Systematic errors arise due to limited knowledge of the experimental equipment, inaccuracy of calibration procedures, and inefficiency of the calculations and algorithms used for the analysis.

The uncertainty associated with the beam energy measurement is 0.3%, as mentioned in Chapter 2. The integrated charge used for the yield normalization has an absolute uncertainty of 5% based on the beam current calibrations[61].

In order to evaluate the systematic error associated with the acceptance, the Monte Carlo cuts were varied to investigate the effect on the result. These cuts include the polar angle (i.e. 0.0-1.0 radians) and the K^+ momentum which is limited by the momentum distribution obtained from the ESPS acceptance calculation²². The cuts were varied by $\pm 20\%$ around the nominal values. The error associated with the acceptance is found to be $\sim 1.9\%$, which is then taken as the systematic error for this parameter.

The systematic errors of the detector efficiencies are calculated by comparing the efficiency (e.g. tracking efficiency) of different runs with similar run conditions. The half-difference between the maximum and the minimum variations of the efficiency values (see chapter 3) is considered to be the total systematic error. Table 3.9 lists the results of these calculations. Likewise, the systematic error of the cut efficiencies

²²There are other factors contribute to the systematic error such as the position of the magnets, the size of the collimators, the detector cuts, etc. But the contributions of these factors are negligible compared to the input solid angle and the momentum.

Detector Eff.	Random Error (%)
Tracking	0.6
ESPS hodoscope	0.4
SSD	0.6
Geometrical	1.0
Total	1.4

Table 3.9: The systematic errors of the detector efficiencies.

is the half-difference between the maximum and minimum variations around the fit function for each cut. The total systematic error, added in quadrature, is 1.6%.

The systematic error of the target thickness, $\sim 10\%$, was obtained from the specifications given by the company[62] that provided the target.

To estimate the systematic errors in the lifetime calculations (i.e. computer and electronic lifetimes), the lifetime was plotted as a function of the rate and then fitted by a first order polynomial. The variations of the lifetime values from the fit function were used to obtain the errors. These errors were 1.4% for the electronic lifetime and 0.9% for the computer lifetime.

A central value of the momentum bite was used in the decay factor calculations which introduces a systematic error in the results. Thus, the half-difference between the decay factor values at the maximum and minimum momenta, respectively, divided by the decay factor value at the central momentum is considered the systematic error. The systematic errors at 1721 and 1864 MeV beam energies are 4.5% and 4.1% respectively. Therefore, The total systematic error of the decay factor is 6.1%.

The systematic errors of the experiment E89-009 are summarized in Table 3.10

Source of the Error	Systematic Error (%)
Beam Energy	0.3
Integrated Charge	5.0
Acceptance	1.9
Detector Efficiencies	1.4
Cut Efficiencies	1.6
Target Thickness	10.0
Lifetimes	1.7
Decay Factor	6.1
Total	13.2

Table 3.10: Summary of the systematic errors.

Chapter 4

Results and Discussion

This chapter presents the results of the E89-009 experiment. It includes the calculated missing mass spectra for both C and CH₂ targets at 1721 and 1864 MeV. The differential cross sections and a comparison of these results with theoretical predictions, are also presented.

4.1 Results from the CH₂ Target

The elementary process $H(e,e'K^+)\Lambda/\Sigma^0$ using a CH₂ target was used for momentum calibrations, as mentioned in Chapter 3. since the cross section for this reaction is well known, it was hoped that it would provide a scale for the cross section of the hypernuclear process, but because the beam adversely effected the target this was not possible as will be discussed later. Figures 4.1 and 4.2 show the missing mass spectrum obtained from 1864 MeV and 1721 MeV data, respectively. The horizontal

Figure 4.1: The missing mass spectrum obtained from a CH_2 target at a beam energy of 1864 MeV.

axis indicates the mass difference of the reconstructed missing mass and the mass of a Λ (1115.683 ± 0.006 MeV). There are two peaks in each of these figures corresponding to Λ production by the $p(e,e'K^+)\Lambda$ reaction and Σ^0 production by the $p(e,e'K^+)\Sigma^0$ reaction. The shaded area indicates the accidental background which is caused by accidental coincidences ($\sim 95\%$), and π^+ contamination. It was constructed from eight accidental coincidence peaks to improve the statistics. The difference between the signal and background is mainly due to the unresolved quasi-free production processes of the Λ and Σ^0 production from the $p(e,e'K^+)\Lambda/\Sigma^0$ reaction on protons in the C nucleus, and the Σ^- production from the $n(e,e'K^+)\Sigma^-$ reaction on neutrons in the C nucleus. After being fitted by a Gaussian distribution, as shown in Figure 4.3, the

Figure 4.2: The missing mass spectrum obtained from a CH_2 target at a beam energy of 1721 MeV.

width of the Λ peak is, ~ 2.36 MeV (FWHM). This width is dominated by kinematic energy spread from reactions on H nucleus caused by the angular acceptance. The missing mass spectra provides an estimate of the yields, and these yields are used in the cross section estimates.

Figure 4.3: A Gaussian fit to the missing mass spectrum obtained from the CH_2 target at a beam energy of 1864 MeV.

4.2 Results from the ^{12}C Target

Figure 4.4: The summed missing mass spectrum for both 1864 MeV and 1721 MeV.

Figures 4.4 and 4.5 show the sum of the missing mass spectra taken with 1721 and 1864 MeV beam energies and the accidental background at 0.6 MeV/bin and 0.35 MeV/bin, respectively. The horizontal axis indicates the mass difference of the reconstructed missing mass and that of a $^{12}_{\Lambda}\text{B}$ nucleus, 11359.31 MeV. The spectrum shows the $^{12}_{\Lambda}\text{B}$ hypernuclear structure produced by the reaction $(e,e'K^+)$ from a ^{12}C nucleus in both the C and CH_2 targets¹. The background (the shaded area) was

¹All E89-009 data was used in this spectrum including CH_2 target data.

Figure 4.5: The summed missing mass spectrum for both 1864 MeV and 1721 MeV.

constructed from eight accidental coincidence peaks to improve the statistics. Most of the background was due to accidentals ($\sim 95\%$) with a small π^+ contamination. In addition to the background, there are three distinctive features in this spectrum; 1) the Λ peak, 2) the quasi-free region, and 3) the Λ bound state region.

4.2.1 The Λ Peak

The Λ peak represents Λ particles that were produced from protons in the hydrogen (H) nucleus in the CH_2 target. The peak is spread over the range $\sim 34 - 40$ MeV, as indicated in Figure 4.4. The reason for this spread is that the missing mass spectrum

is calculated using ^{12}C kinematics so that the corrections for recoil versus angle are mis-applied to the data[36]. Using two body kinematic calculations this spread and position of the peak were confirmed.

4.2.2 The Quasi-Free Region

The quasi-free region indicates the production of unbounded hyperons. Since there are no bound states of these hyperons in this region a continuum of energies is obtained which begins at the quasi-free threshold, ~ 11.37 MeV. The shape of the quasi-free region can be approximated by treating the nucleus as a non-interacting Fermi-gas of baryons.

4.2.3 The Λ Bound State Region

The Λ bound state region is the region in which a Λ particle is inserted in a bound nuclear state. In the $^{12}_{\Lambda}\text{B}$ hypernucleus Λ particles in both the s and p shells are bound. In this region, there are two prominent peaks and some intermediate structure. However, due to the low statistics the intermediate structure is not well defined. The structure in the Λ bound state region can be interpreted as proton-hole Λ -particle coupling. In order to understand this region, the missing mass spectrum, shown in Figure 4.4, was fitted by a series of Gaussian distributions. As an initial condition the widths of these Gaussians were set to be 450 keV, and the widths of the first four Gaussians were constrained to be equal throughout the fitting process. The positions

of these Gaussians were chosen according to theoretical expectations of the spectrum strength. The region was fitted by six Gaussian distributions where the mean value of the fit is considered as the location of the peak. A Gaussian fit is not exact because the peaks have a tail, but due to the low statistics the Gaussian fit is adequate. The background was assumed to be a straight line. Assuming that the nucleus can be treated as a non-interacting Fermi-gas of baryons, a positive-going Fermi function was used to fit the quasi-free region. The result of this fit is shown in Figure 4.6².

Figure 4.6: The Fitted missing mass spectrum.

The first peak (#1) is the doublet 1_1^- and 2_1^- of the configuration $_{\Lambda} s_{1/2} p_{3/2}^{-1}$. The

²The peaks #1 and #5 are dominant and real; but the position and strength of the peaks #2, #3, and #4 are not very clear and depend on judgment. However, in the area where these peaks are located, there is a real structure, as shown in Figure 4.4.

splitting of these two states is predicted to be very small (≤ 165 keV) so it is difficult to resolve them, especially with our expected resolution. However, when investigating the spectrum at 0.35 MeV/bin, as shown in Figure 4.5, we can see that the split could be larger than 0.165 MeV. The 2_1^- state is expected to dominate the spin-flip, $\Delta S = 1$, case (as in the $(e,e'K^+)$ reaction) while the state 1_1^- dominates in the no spin-flip, $\Delta S = 0$, case (as in the (π^+, K^+) reaction)[63].

The states in the region above the ground state doublet (#2, #3, and #4) are known as the core-excited states, in which the Λ is in the s-shell and couples to excited states of the ^{11}B core. This region was fitted by three Gaussian distributions. According to this fit the positions of these peaks are 3.11 ± 0.26 MeV, 5.22 ± 0.36 MeV, and 7.02 ± 0.18 . The factor 0.375 MeV is subtracted from these values because the whole spectrum is shifted by 0.375 MeV due to the binning effect.

The other prominent peaks (#5 and #6) represent p-shell states which include a series of positive parity states of the configurations $_{\Lambda}p_{1/2}p_{3/2}^{-1}$ and $_{\Lambda}p_{3/2}p_{3/2}^{-1}$, as shown in Figure 4.6. However, it was theoretically predicted[63] that the state 3_1^+ is the most strongly populated in $\Delta S = 1$ case while the 2_2^+ is populated with a similar strength in both cases ($\Delta S = 0$ and $\Delta S = 1$). The position of peak #5 is 10.87 ± 0.10 MeV and peak #6 is 12.50 ± 0.36 MeV, after subtracting the factor 0.375 MeV. The structure above peak #6 is difficult to study due to the continuum of states and low statistics. The χ^2 for this fit is 43.1 for 42 d.o.f..

There are few theoretical calculations for the $^{12}_{\Lambda}\text{B}$ system. In the next two sections

I will discuss two of these, namely: the calculations done by D. J. Millener[63] and Motoba, et al[26].

Millener's Calculations

J_n^π	E_x (MeV)	$\Delta S = 0$	$\Delta S = 1$
1_1^-	0.000	0.5201	0.1953
2_1^-	0.165		0.6903
1_2^-	2.728	0.0886	0.2889
0_1^-	2.752		0.3765
2_2^-	4.553		0.0060
2_3^-	5.829		0.1104
1_3^-	5.894	0.0545	0.0356
2_1^+	10.330	0.0877	0.0454
1_1^+	10.358		0.1182
2_2^+	10.786	0.4161	0.2909
3_1^+	10.873		0.7080
0_1^+	10.953	0.6200	
1_2^+	11.389		0.0000
2_3^+	12.639	0.0909	0.1863
1_3^+	12.726		0.2825
1_4^+	13.007		0.0000

Table 4.1: Energies and squares of LS OBDME for s_Λ and p_Λ states in $^{12}_\Lambda\text{B}$.

Table 1 lists the theoretical calculations[63] for s_Λ and p_Λ states in $^{12}_\Lambda\text{B}$. These calculations are used to fit the missing mass spectrum in Figure 4.5. Some of the predicted states (2_2^- , 1_3^- , 2_1^+ , 1_2^+ , and 1_4^+) have negligible strength ($\leq 5\%$ of 3_1^+ state) compared to states like 3_1^+ , so that they will be neglected. The spectrum was fitted by the states 1_1^- , 2_2^- , 1_2^- , 0_1^- , 2_3^- , 1_1^+ , 2_2^+ , 3_1^+ , 2_3^+ , and 1_3^+ by applying a Gaussian distribution for each state with the relative strengths and positions, and constraining

them to the same width. The result of the fit is shown in Figure 4.7. In general

Figure 4.7: The fitted missing mass spectrum by the parameters listed in Table 4.1.

there is an agreement between the theoretical calculations by D. J. Millener and the spectrum obtained from E89-009. However, there is a clear disagreement in the expected strength of some of the states (especially the states 2_2^- , 1_2^- , 0_1^- , 2_3^-) and a disagreement in the position of some (0_1^- , 2_3^-). Another issue is the splitting of the ground state doublet, which is predicted to be less than 165 keV, but in both Figures 4.5 and 4.7 the fit requires it to be more than 165 keV. As an attempt to establish this, I increased the strength of the 2_2^- state, decreased the strength of 1_2^- and 0_1^- states, and increased the ground doublet splitting and fitted the spectrum. The results of

the fit is shown in Figure 4.8. As a result, I obtained a much better fit for the data

Figure 4.8: The fitted missing mass spectrum by the parameters listed in Table 4.1 with some corrections.

because χ^2 decreased from 63.4 to 52.1 for 59 d.o.f., and σ decreased by $\sim 20\%$. This confirms that the ground doublet splitting might be larger than 165 keV and the 2_1^- state populated stronger than the 3_1^+ state.

Motoba's Calculations

The positions and strengths of the s_Λ and p_Λ states in the $^{12}_\Lambda\text{B}$ system are obtained from Figure 1.10. The obtained information for s_Λ and p_Λ states are listed in Table 4.2.

J_n^π	E_x (MeV)	Relative Strength
1_1^-	0.000	0.22
2_1^-	0.165	1.00
1_2^-	1.689	0.21
2_3^-	4.868	0.14
3_1^+	10.03	0.77
2_1^+	10.53	0.31
1_1^+	11.03	0.16
2_2^+	11.72	0.12

Table 4.2: Energies and relative strength for s_Λ and p_Λ states in ${}^{12}_\Lambda\text{B}$.

In this table, the relative strength is obtained by measuring the amplitude of each state and dividing it by the measured amplitude of the 2_1^- state. Following the same procedure in the previous section, the information in Table 4.2 was used to fit the missing mass spectrum. The results of the fit are shown in Figure 4.9.

The χ^2 for this fit is 73.6 for 59 d.o.f. which concludes that this is not a good fit of the data. The predicted positions of the hypernuclear states do not agree with the data especially in the core-excited region. However, the shifts in the spectrum positions could be because Motoba did his work for the charge symmetric hypernucleus, ${}^{12}_\Lambda\text{C}$.

Therefore, it is safe to say that neither of these two calculations have a good description of the core excited region, but the positions predicted by Millener have much better agreement with data. On the other hand, Motoba has a better cross section calculation.

Figure 4.9: The fitted missing mass spectrum by the parameters listed in Table 4.2.

The hypernucleus, ${}_{\Lambda}^{12}\text{B}$, is a mirror³ to the hypernucleus, ${}_{\Lambda}^{12}\text{C}$, having a Coulomb energy difference ΔE_c of the order of 1.5 MeV[64]. The difference between the energy levels of these two nuclei, to the first order, is the Coulomb energy difference. Since this difference is relatively small, the ${}_{\Lambda}^{12}\text{B}$ energy levels are expected to follow those in ${}_{\Lambda}^{12}\text{C}$ when comparing to existing experimental data. The population strength depends on the production reaction. The latest spectrum for the ${}_{\Lambda}^{12}\text{C}$ system produced by the (π^+, K^+) reaction in KEK-SKS is shown in Figure 1.12. With ~ 1.45 MeV resolution,

³The mirror nuclei are the nuclei that have the number of protons and neutrons mirrored; the number of protons is equal to the number of neutrons, and vice versa.

the ground state, three core excited states, and p-shell states were observed.

4.3 Experimental Resolution

The resolution of the HNSS setup was expected to be between 600 - 1000 keV. The total resolution is calculated from the experimental contributions according to the relation⁴;

$$\sigma_{total}^2 = \sigma_{beam}^2 + \sigma_{target}^2 + \sigma_{SOS}^2 + \sigma_{ESPS}^2 + \sigma_{angle}^2 \quad (4.1)$$

The expected contributions of these components to the total resolution are listed in Table 4.3.

Component	Resolution (keV)
Beam	160
Target	20
Scattering Angle	200
Splitter and SOS magnets	550
Splitter and Split-pole magnets	120

Table 4.3: The contributions of the experimental components to the missing mass resolution.

As seen in Table 4.3, the resolution is dominated by the SOS spectrometer because of its large momentum bite and low dispersion. Generally, the SOS was not designed

⁴This is just a rough estimation because the experimental contributions are not totally independent.

for high resolution experiments, but because of its short path length, which reduces the decay factor of the K^+ , it was chosen for this experiment. The SOS contribution is well known and studied in previous experiments while the Splitter/Split-pole system was used for the first time in E89-009. Thus, they have not been studied like the other components. The contribution of the Splitter and Split-pole system comes mainly from the momentum calibrations mentioned in Chapter 3.

The pair production process ($e, e'e^+e^-$) was used to observe the resolution of E89-009. In this process an e^+e^- pair was created by the virtual photon. The events, which represent the ($e, e'e^+e^-$) process, were selected by detecting both the scattered and the pair electrons (e' and e^-) using the ESPS spectrometer within a 2 ns coincidence time window triggered by the positron (e^+) in the SOS spectrometer. Since it is not possible to distinguish between the e' and e^- , the analysis was done in terms of the shared energy of both electrons. Figure 4.10 shows the correlation between the momentum of the positron (p_{e^+}), in the SOS spectrometer, and the shared momentum of e' and e^- detected by the ESPS spectrometer. The horizontal axis of this figure is the sum of the SSD channel number for both the e' and e^- , where the sum of the SSD channel number represents the sum of their momenta. The correlation line, which is indicated by a box in Figure 4.10, represents the process ($e, e'e^+e^-$) where $E_e = E_{e'} + E_{e^+} + E_{e^-}$. Figure 4.11 shows the projection of the momentum correlation onto a one-dimensional plot. The peak in this figure indicates the reconstructed beam

Figure 4.10: The reconstructed beam energy using the $(e, e' e^+ e^-)$ process.

energy. It can be seen that the resolution is ~ 900 keV (FWHM).

In the pair production process, a coincidence between two particles (e' , e^-) in the ESPS spectrometer with one particle (e^+) in the SOS spectrometer was required, while in hypernuclei production only two particles (e' and K^+) in coincidence were needed. Therefore, the pair production resolution, ~ 900 keV (FWHM), is considered an upper limit to the experimental resolution. The experimental resolution can be roughly deduced from the pair production resolution by subtracting the contribution from the additional electron detected in ESPS. The pair production resolution can

Figure 4.11: The reconstructed beam energy.

be written as:

$$\sigma_{(e,e'e^-e^+)}^2 = \sigma_{beam}^2 + \sigma_{target}^2 + \sigma_{SOS}^2 + 2 * \sigma_{ESPS}^2 + \sigma_{angle}^2 \quad (4.2)$$

$$= \sigma_{(e,e'K^+)}^2 + \sigma_{ESPS}^2 \quad (4.3)$$

In Equation 4.2, the ESPS contribution (σ_{ESPS}^2) is multiplied by 2 to account for both e' and e^- . Using Equation 4.3 and the values of both $\sigma_{(e,e'e^-e^+)}^2$ and σ_{ESPS}^2 , listed in Table 4.3, the experimental resolution is ~ 890 keV (FWHM).

Generally, the energy resolution is extracted from the fitted spectrum in Figure 4.6. Figure 4.12 shows the fitted spectrum and its fit parameters. As seen in Figure 4.12, the resolution of the ground state doublet peak is, $\sigma = 0.399 \pm 0.052$, which is equivalent to $\sim 918 \pm 120$ keV (FWHM). This value is within the statistical error from the calculated value using the pair production process. As mentioned in the previous section the splitting of the ground state doublet may be larger than 165 MeV which means the experimental resolution is better than the width of the ground state doublet. The obtained energy resolution is more than a factor of 1.5 better than the best energy resolution achieved prior to E89-009, 1.45 MeV (FWHM)[34].

MINUIT χ^2 Fit to Plot 3500

File: all.hbook 12-MAR-2002 10:26
Plot Area Total/Fit 6138.0 / 6138.0 Fit Status 3
Func Area Total/Fit 6094.9 / 6094.9 E.D.M. 7.534E-07

$\chi^2 = 43.1$ for 59 - 17 d.o.f., C.L. = 42.6 Ψ

Errors		Parabolic		Minos	
Function 1: Gaussian (sigma)					
AREA	130.24	A 22.43	- 0.000	+ 0.000	
MEAN	0.37484	A 8.3313E-02	- 0.000	+ 0.000	
SIGMA	0.39899	A 5.1785E-02	- 0.000	+ 0.000	g. s. doublet
Function 2: Gaussian (sigma)					
AREA	34.504	A 17.11	- 0.000	+ 0.000	
MEAN	3.1121	A 0.2584	- 0.000	+ 0.000	
ΦSIGMA	0.39899	A 0.000	- 0.000	+ 0.000	
Function 3: Gaussian (sigma)					
AREA	17.563	A 15.80	- 0.000	+ 0.000	
MEAN	5.2174	A 0.3578	- 0.000	+ 0.000	
ΦSIGMA	0.39899	A 0.000	- 0.000	+ 0.000	
Function 4: Gaussian (sigma)					
AREA	43.857	A 18.14	- 0.000	+ 0.000	
MEAN	7.0213	A 0.1815	- 0.000	+ 0.000	
ΦSIGMA	0.39899	A 0.000	- 0.000	+ 0.000	
Function 5: Gaussian (sigma)					
AREA	107.35	A 23.01	- 0.000	+ 0.000	
MEAN	11.241	A 0.1031	- 0.000	+ 0.000	
ΦSIGMA	0.39899	A 0.000	- 0.000	+ 0.000	
Function 6: Gaussian (sigma)					
AREA	20.758	A 18.32	- 0.000	+ 0.000	
MEAN	12.873	A 0.3628	- 0.000	+ 0.000	
ΦSIGMA	0.39899	A 0.000	- 0.000	+ 0.000	
Function 7: Polynomial of Order 0					
NORM	130.50	A 4.688	- 0.000	+ 0.000	
Function 8: Fermi (positive going)					
NORM	72.454	A 10.26	- 0.000	+ 0.000	
X0	15.036	A 1.251	- 0.000	+ 0.000	
SLOPE	2.7850	A 1.451	- 0.000	+ 0.000

Figure 4.12: The fit parameters of the fitted missing mass spectrum shown in Figure 4.5.

4.4 Differential Cross Section

The differential cross section ($d\sigma/d\Omega$) is the probability per unit solid angle that an incident particle is scattered into the solid angle $d\Omega$ [10].

The yield (N_x , where in this experiment x is Λ or $^{12}_\Lambda\text{B}$) for a virtual photon in the energy range is used to determine the differential cross section for the electroproduction process. The differential cross section in the lab frame is given by;

$$\frac{d\sigma}{d\Omega_{lab}} = \frac{1}{N_T} \frac{N_x}{N_\gamma} \frac{1}{\Delta\Omega} \frac{1}{\varepsilon} \quad (4.4)$$

where N_T is the number of target nuclei per unit square, N_γ is the integrated virtual photon flux, $\Delta\Omega$ is the effective solid angle of the spectrometer system, and ε is the correction factor that accounts for efficiencies, decay, absorption, etc.

The solid angle of the spectrometer system ($\Delta\Omega$), shown in Figures 3.38 and 3.39, is the average of the solid angles for all accepted momentum values. The number of target nuclei (N_T) is given by $\rho x N_A / A$, where ρ is the mass density of the target, N_A is Avogadro's number, x is the target thickness, and A is the atomic mass of the target.

To calculate the integrated virtual photon flux, the virtual photon flux factor defined by Equation 1.18, is integrated over the polar angle range accepted by the ESPS spectrometer, ~ 20 mrad, as shown in Figure 4.13. This figure shows the integration over the Enge polar angle at $E_e = 1864$ MeV and $E_e = 1721$ MeV. Then, the result is integrated over the accepted virtual photon energy range, $E_\gamma \sim 1514$

Figure 4.13: The integrated virtual photon flux for $E_e = 1864$ MeV, and $E_e = 1721$ MeV.

to 1624 MeV at $E_e = 1864$ MeV and $E_\gamma \sim 1378$ to 1495 MeV at $E_e = 1721$ MeV.

The integration resulted in $N_\gamma = 4.156 \times 10^{-4}/e^-$ at $E_e = 1864$ MeV and $N_\gamma = 4.77 \times 10^{-4}/e^-$ at $E_e = 1721$ MeV. Using the total charge values listed in Table 3.3, N_γ can be expressed in terms of the charge.

The overall efficiency, ε , is calculated from the individual efficiencies that are calculated in chapter 3, which are the detector and cut efficiencies, the decay factor, the absorption, and the electronic and computer dead times. Since ε depends on the

run conditions, the values of ε at these conditions will be mentioned later. Table 4.4 lists the corrections to the yield.

Energy (MeV) Target	1864 CH ₂	1864 ¹² C	1721 CH ₂	1721 ¹² C
Cuts Eff. (%)	77.9 $\pm$ 4.7	74.8 $\pm$ 4.6	75.7 $\pm$ 4.8	75.6 $\pm$ 4.7
Detector Eff. (%)	84.1 $\pm$ 1.8	84.1 $\pm$ 1.8	84.1 $\pm$ 1.8	84.1 $\pm$ 1.8
Comp. Lifetime (%)	92.2 $\pm$ 2.8	80.8 $\pm$ 4.4	90.1 $\pm$ 3.2	91.8 $\pm$ 2.8
Elec. Lifetime (%)	99.5 $\pm$ 1.3	93.4 $\pm$ 1.2	98.3 $\pm$ 1.3	99.3 $\pm$ 1.3
Survival Ratio (%) (Absorb.&Decay)	33.2 $\pm$ 1.0	33.2 $\pm$ 1.0	29.4 $\pm$ 1.0	29.4 $\pm$ 1.0
Total (%)	20.0 $\pm$ 1.6	15.8 $\pm$ 1.4	16.6 $\pm$ 1.4	17.1 $\pm$ 1.4

Table 4.4: The individual corrections to the yield.

The yield (N_x) is the integrated number of counts in the ground state doublet when fitting the missing mass spectrum. Since the missing mass spectrum for 1721 MeV data was reconstructed without plane 3 events, see chapter 3, N_x was corrected by 14%⁵.

4.4.1 Results

In E89-009, two main targets were used⁶, CH₂ and ¹²C, and two beam energies, 1864 and 1721 MeV. Thus, there are four different sets of data with different run conditions. Since each set was run under different conditions (beam current, run time, etc.), the previous parameters (N_T , N_x , N_γ , $\Delta\Omega$, and ε) need to be calculated for each set and

⁵This factor, 14%, represents the contribution of plane 3 of all 7 planes active at the SSD focal plane.

⁶It was shown after testing a similar sample of the CH_x target that it was CH_{1.82}[36].

compared for consistency. The values of these parameters and the cross section for each set of data are listed in Table 4.5.

Energy (MeV) Target	1864 CH _{1.82} Λ	1721 CH _{1.82} Λ	1864 ¹² C ¹² Λ B g.s.	1721 ¹² C ¹² Λ B g.s.
N_x	391.05 ± 29.65	164.76 ± 32.66	41.26 ± 13.68	35.16 ± 8.69
$N_\gamma (\times 10^{14})$	8.20 ± 0.01	4.58 ± 0.01	4.10 ± 0.01	2.98 ± 0.01
$N_T (\times 10^{-4}/\text{b})$	6.98	6.98	11.04	11.04
$\Delta\Omega$ (msr)	5.07 ± 0.05	5.07 ± 0.05	5.07 ± 0.05	5.07 ± 0.05
ε	0.200 ± 0.016	0.158 ± 0.014	0.166 ± 0.014	0.171 ± 0.014
$\frac{d\sigma}{d\Omega_{lab}}$ (nb/sr)	674 ± 74	643 ± 138	108 ± 37	123 ± 32

Table 4.5: Cross sections and their parameters.

4.4.2 Discussion

Λ Differential Cross Section

The Λ differential cross section for 1721 MeV data is lower than for the 1864 MeV data, see Table 4.5, but the difference is still within the statistical error. The cross section for the 1864 MeV data is considered more accurate and thus the discussion is limited to the 1864 MeV data results. However, the results from the 1864 MeV CH₂ data, 674 ± 74 nb/sr, is still a factor of three less than that obtained from the measured photoproduction reaction $p(\gamma, K^+)\Lambda$, $\sim 2.0 \mu\text{b/sr}$ [26]. A visual inspection

of the CH₂ target revealed that it was burned[65] explaining the low value for the cross section. Therefore, the data of the CH₂ target is not reliable to calculate the Λ differential cross section.

$^{12}_{\Lambda}\text{B}$ Differential Cross Section

The average differential cross section for the $^{12}_{\Lambda}\text{B}$ ground state doublet for both 1864 and 1721 MeV, see Table 4.5, is 116 ± 24 nb/sr. As mentioned in Chapter 3, this value has a systematic error, 13.2%. Thus, the average differential cross section is 116 ± 28 nb/sr. This value can be compared to the predicted angular distributions of the major excited states by the $^{12}\text{C}(\gamma, \text{K}^+)^{12}_{\Lambda}\text{B}$ reaction shown in Figure 1.11.

Figure 4.14 shows the sum of predicted 1_1^- and 2_1^- states connected by a smooth line and the measured value with the statistical error. In this figure, the predicted angular distributions are calculated at $E_\gamma = 1.1$ MeV[26] while E89-009 was carried out at $E_\gamma \sim 1.5$ MeV, but since the values at both energies are comparable, as shown in Figure 1.19, this comparison is acceptable. Thus, the value 116 ± 28 nb/sr is consistent with the theoretical predications. However, Motoba[66] estimates ~ 145 nb/sr for the $^{12}_{\Lambda}\text{B}$ differential cross section in an update of his previous calculation⁷.

⁷In this calculation, Motoba used the NSC97f ΛN interaction.

Figure 4.14: The experimental and predicted differential cross section versus the scattering angle.

Chapter 5

Summary and Conclusion

Experiment E89-009 was successfully completed in three months of data taking at the Thomas Jefferson National Accelerator Facility (JLab). The data were collected using four targets, Mylar, CH₂, ¹²C, and ⁷Li, but only two targets (CH₂ and ¹²C) were studied in this work. The data from these two targets were collected at two beam energies, 1864 and 1721 MeV.

During this experiment, the electroproduction of the ¹²_ΛB hypernucleus was studied at the approximate Q^2 value of zero. Both the scattered electron and kaon were detected in coincidence in the ESPS and SOS spectrometers, respectively, and the missing mass spectrum of the hypernucleus ¹²_ΛB was produced. The missing mass of Λ for hydrogen in the target was also observed. The cross section of each of these processes was calculated.

This experiment featured the following.

- E89-009 was the first experiment to tag virtual photons at zero degrees providing a higher yield with acceptable rates.
- At forward angles the Bremsstrahlung electron rate also peaks very strongly. For some part of the data the Bremsstrahlung electrons were blocked by an absorber.
- The production rates of the positron and pion were consistent with calculations made prior to the experiment, while the proton rate was at least an order of magnitude higher than calculated.
- A missing mass spectrum of $^{12}_{\Lambda}\text{B}$ was obtained for the first time by the reaction $(e,e'\text{K}^+)$. In this spectrum two narrow structures were observed in the bound state region as well as evidence of other structure in the core-excited region. The locations of these structures are listed in Table 5.1. Generally, these results are

Structure	Equivalent States	Location (MeV)
Ground state doublet	1_1^- & 2_1^-	0.00 ± 0.08
Core excited states	1_2^- & 0_1^-	2.74 ± 0.26
	2_2^-	4.84 ± 0.36
	2_2^- & 2_3^-	6.65 ± 0.18
p-shell excited states	2_2^+ & 3_1^+	10.87 ± 0.10
	2_3^+ & 1_3^+	12.50 ± 0.36

Table 5.1: The observed states in the $^{12}_{\Lambda}\text{B}$ missing mass spectrum and the location of these states.

consistent with Millener's calculations. The 2_1^- state is populated stronger than

predicted and also there are disagreements in the core-excited region, although statistics are poor. While these results show more disagreement in terms of positions, the relative strengths of the stronger excitations agree very well with Motoba's calculations.

- The splitting of the ground state doublet may be larger than predicted, ≤ 165 keV, by Millener, but control of the lineshape is not sufficient to make a conclusive statement.
- The ${}^{12}_{\Lambda}\text{B}$ spectrum includes the excitation of the natural and unnatural parity (spin-flip) states, where the states such as 2_1^- and 3_1^+ were observed for the first time.
- A high resolution of $\sim 918 \pm 120$ keV (FWHM) was achieved, which is a factor of 1.5 better than any previous hypernuclear spectroscopy study.
- Under E89-009 run conditions, the CH_2 target can not be used to provide a scale for the cross section of the hypernuclear process, and was only useful for momentum calibration. This is because beam heating destroyed the CH_2 target.
- The differential cross section of the ${}^{12}_{\Lambda}\text{B}$ ground state doublet, 116 ± 28 nb/sr, was experimentally obtained for the first time, and it is consistent with theoretical calculations.
- The hypernucleus ${}^{12}_{\Lambda}\text{B}$ is a mirror pair of the previously studied nucleus ${}^{12}_{\Lambda}\text{C}$ which potentially allows the study of charge breaking symmetry in this hyper-

nuclear system.

Bibliography

- [1] <http://www.cern.ch>, CERN webpage.
- [2] <http://www.fnal.gov>, FNAL webpage.
- [3] <http://www.slac.stanford.edu>, SLAC webpage.
- [4] Fayyazuddin and Riazuddin, *A Modern Introduction to Particle Physics*, 2nd edition, World Scientific, 2000.
- [5] Phys. Rev. 105, 1413 (1957).
- [6] Y. Fukuda *et al.*, Phys. Rev. Lett., 1562 (1998).
- [7] Particle Data Group, Particle physics booklet, 1998.
- [8] A. Das and T. Ferbel, *Introduction to Nuclear and Particle Physics*. John Wiley & Sons, 1994.
- [9] T. D. Lee, *Symmetries, Asymmetries, and the World of Particles*, 1987.
- [10] K. S. Krane, *Introductory Nuclear Physics*, John Wiley and Sons, 1988.

- [11] F. E. Close, *An Introduction to Quarks and Partons*, 1979.
- [12] B. Povh, Annual Reviews of Nuclear and Particle Science 28, 1 (1978).
- [13] H. Bando, T. Motoba and J. Zofka, International Journal of Modern Physics A5, 4021 (1990).
- [14] D. J. Millener *et al*, Phys. Rev. C31, 499 (1985).
- [15] B. F. Gibson and D. R. Lehman, Phys. Rev. C23, 404 (1981).
- [16] R. E. Chrien and C. B. Dover, Ann. Rev. Nucl. Part. Sci. 39, 113 (1989).
- [17] M. May *et al.*, Phys. Rev. Lett. 47, 1106 (1981).
- [18] O. Hashimoto *et al*, *Spectroscopic study of Λ hypernuclei beyond the $p -$ shell region through the $(e, e'K^+)$ reaction*, Proposal to JLAB PAC-12.
- [19] J. Cohen, Phys. Rev. C32, 543 (1985).
- [20] T. Saito *et al.*, *High - Resolution Electroproduction of Light Hypernuclear*, CEBAF PROPOSAL, 1993.
- [21] E. Hungerford, Progress of Theoretical Physics Supplement 117, (1994).
- [22] E. Hungerford *et al*, E89-009 CEBAF proposal, 1989.
- [23] J. Adam *et al*, Czech. J. Phys. 42, 1167 (1992).
- [24] A. M. Bernstein *et al*, Nucl. Phys. A358, 109c (1981).

- [25] S. R. Cotanch and S. S. Hsiao, Nucl. Phys. A450, 419c (1986).
- [26] T. Motoba, M. Sotona and K. Itonaga, Progress of Theoretical Physics Supplement 117, 123 (1994).
- [27] M. *Jurić*, Nuclear Physics B47, 36 (1972).
- [28] M. A. Faessler *et al*, Physics Lett. 46B, 468 (1973).
- [29] M. May *et al*, Phys. Rev. Lett. 51, 2085 (1983).
- [30] C. Milner *et al*, Phys. Rev. Lett. 54, 1237 (1985).
- [31] R. E. Chrien, Nuclear physics A478, 705c (1988).
- [32] P. H. Pile *et al*, Phys. Rev. Lett. 66, 2585 (1991).
- [33] O. Hashimoto *et al*, Nuclear Physics A639, 93c (1998).
- [34] T. Nagae, Nuclear Physics A670, 269c (2000).
- [35] H. Tamura *et al*, Phys. Rev. Lett. 84, 5963 (2000).
- [36] E. Hungerford, Private Communication.
- [37] H. Tamura *et al*, Proceedings of Jlab sponsored Workshop on *Hypernuclear Physics with Electromagnetic Probes*, 1999.
- [38] E. Hungerford and G. Xu, Electron Distribution in Bremsstrahlung and Virtual photon Production, unpublished.

- [39] C. Bennhold, Nuclear Physics A547, 79c (1992).
- [40] M. Sotona, S. Frullani, Prog. of Theor. Phys. Supp. No. 117, 151 (1994).
- [41] C. E. Hyde-Wright *et al*, *Electron Scattering at 0° : A Photon Tagging Technique*.
- [42] C. B. Dover and D. J. Millener, BNL-44651, 1990.
- [43] R. Abbott, B. Bowling, and E. Woodworth, HARP User's Manual, CEBAF Tech Note TN92-050, 1992.
- [44] G. Niculescu, Resonant Cavities used as Beam Current Monitors, TJNF Document(unpublished), 1995.
- [45] P. Gueye, M. Tiefenback, and C. Yan, Hall C Beam Energy Measurement(unpublished), 1996.
- [46] H. Enge, Nucl. Inst. and Meth. 49, 181 (1967).
- [47] W. J. Cummings, SOS Handbook, CEBAF Internal Document(unpublished), 1996.
- [48] S. Kowalski and H. A. Enge, RAYTRACE, 1986.
- [49] Enge Collaboration Group, *A Silicon Strip Detector Used as a High Rate Focal Plane Sensor for Electrons in a Magnetic Spectrometer* (unpublished), 2001.

- [50] W. L. Hinton, Ph.D. Dissertation, Hampton University, 2001.
- [51] E. Hungerford *et al*, Report on the Status of E89-009 to the Readiness-Review Committee, 1998.
- [52] CEBAF On-line Data Acquisition User's Manual (CODA), TJNAF Internal Document(unpublished), 1993.
- [53] Experimental & Physics Industrial Control System (EPICS), Los Alamos National Laboratories, 1984.
- [54] D. F. Geesaman and S. Wood, *Hall C Analysis Software Vade Mecum*, Jlab Hall C Internal Report (unpublished), 1994.
- [55] C. Group, PAW Users Guide, Program Library Q121, CERN.
- [56] S. T. Wood, The CEBAF Test Package: A Symbolic and Dynamic Test, Histogram, and Parameter Package for On- and Off-line Particle Physics Data Analysis, 1995.
- [57] D. V. Westrum, Ph.D. Dissertation, University of Colorado, 1998.
- [58] J. R. Arrington, Ph.D. Dissertation, California Institute of Technology, 1998.
- [59] R. M. Mohring, Ph.D. Dissertation, University of Maryland, 1999.
- [60] Y. Fujii, HNSS meeting, 2000.
- [61] D. Mack, private communication.

- [62] www.goodfellow.com
- [63] D. J. Millener, private communication.
- [64] M. W. Ahmed, Ph.D. Dissertation, University of Houston, 1999.
- [65] L. Tang, private communication.
- [66] T. Motoba, *Mesons and Light Nuclei*: 8th Conference, 2001.