**SPECTROSCOPIC INVESTIGATION OF p-SHELL Λ HYPERNUCLEI
BY THE $(e, e'K^+)$ REACTION**

A Dissertation

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ABSTRACT

SPECTROSCOPIC INVESTIGATION OF p-SHELL Λ HYPERNUCLEI BY THE
($e, e'K^+$) REACTION. (August 2014)

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Hypernuclear spectroscopy is a powerful tool to investigate ΛN interaction. Compared with other Λ hypernuclei productions, electroproduction via the ($e, e'K^+$) reaction has the advantage of exciting states deeply inside of the hypernucleus and achieving sub-MeV energy resolution.

The E05-115 experiment, which was successfully performed in 2009, is the third generation hypernuclear experiment in JLab Hall C. A new splitter magnet and electron spectrometer were installed, and beam energy of 2.344 GeV was selected in this experiment. These new features gave better field uniformity, optics quality and made the “tilt method” more effective in improving yield-to-background ratio.

The magnetic optics of the spectrometers were carefully studied with GEANT simulation, and corrections were applied to compensate for the fringe field cross talk between the compact spectrometer magnets. The non-linear least χ^2 method was used to further calibrate the spectrometer with the events from Λ , Σ^0 and ${}^{12}_{\Lambda}\text{B}$, and uniform magnetic optics as well as precise kinematics were achieved.

Several p-shell Λ hypernuclear spectra, including ${}^{12}_{\Lambda}\text{B}$, ${}^{10}_{\Lambda}\text{Be}$ and ${}^7_{\Lambda}\text{He}$, were obtained with high energy resolution and good accuracy. For ${}^{12}_{\Lambda}\text{B}$, eight peaks were recognized with the resolution of ~ 540 keV (FWHM), and the ground state binding energy was obtained as $11.529 \pm 0.012(\text{stat.}) \pm 0.110(\text{syst.})$ MeV. For ${}^{10}_{\Lambda}\text{Be}$, twelve peaks were recognized with the resolution of ~ 520 keV (FWHM), and the binding energy of the ground state was determined as $8.710 \pm 0.059(\text{stat.}) \pm 0.114(\text{syst.})$ MeV. For ${}^7_{\Lambda}\text{He}$,

three peaks were recognized with the resolution of ~ 730 keV, and the ground state binding energy was obtained as $5.510 \pm 0.050(\text{stat.}) \pm 0.120(\text{syst.})$ MeV.

Compared with the published data of ${}_{\Lambda}^{12}\text{B}$ from the JLab Hall A experiment, four extra peaks were fitted and interpreted thanks to the highest ever energy resolution and sufficient statistics. The determined binding energy of ${}_{\Lambda}^{10}\text{Be}$ provides new information on charge symmetry breaking effect in the ΛN interaction. Compared with the results of ${}_{\Lambda}^7\text{He}$ from the E01-011 experiment, the ground state position is consistent with 4 times more statistics, and two extra peaks corresponding to excited states were recognized.

Dedicated to my parents.

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SECTION 1

INTRODUCTION

1.1 Introduction to Λ Hypernuclei

Hyperons

Hyperons are baryons that contain at least one strange quark in a qqq structure in the $SU(3)_f$ quark model classification [1]. Some of the basic properties of hyperons are presented in Table 1.1. The hyperons with spin-parity $J^P = \frac{1}{2}^+$ occupy the same $SU(3)$ octet representation as the neutron and proton seen in Figure 1.1.

Figure 1.1. Baryon octet of the spin-parity $\frac{1}{2}^+$ particles.

Hypernucleus

A hypernucleus is a particle-stable baryonic many-body system consisting of conventional nucleons (proton[s] and neutron[s]) and one or more hyperon(s) [3, 4]. The hypernucleus is designated by the symbol $^A_Z Y$, where Z is the symbol of the chemical element, A is the total number of baryons, and Y is the symbol of the bound hyperon. A hypernucleus containing Λ hyperon is called Λ hypernucleus ($^A_\Lambda Z$). The Λ hyper-

Table 1.1. Basic properties of hypersons [2].

Name	Mass[Mev/ c^2]	Quark	I(J^P)	Lifetime[sec]
Λ	1115.683	uds	$0(\frac{1}{2}^+)$	2.63×10^{-10}
Σ^-	1197.45	dds	$1(\frac{1}{2}^+)$	1.48×10^{-10}
Σ^0	1192.46	uds	$1(\frac{1}{2}^+)$	7.4×10^{-20}
Σ^+	1189.37	uus	$1(\frac{1}{2}^+)$	0.80×10^{-10}
Ξ^0	1314.83	uss	$\frac{1}{2}(\frac{1}{2}^+)$	2.90×10^{-10}
Ξ^-	1321.31	dss	$\frac{1}{2}(\frac{1}{2}^+)$	1.64×10^{-10}
Ω^-	1672.45	sss	$0(\frac{3}{2}^+)$	0.82×10^{-10}

nuclei with baryon numbers $A = 3, 4$ and 5 are known as the s-shell Λ hypernuclei, while those with baryon numbers in the range $6 \leq A \leq 17$ are generally referred to as the p-shell Λ hypernuclei.

Relevance of Λ hypernuclei

Hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions, together with nucleon-nucleon (NN) interactions, lead to a unified description of the baryonic interaction within the flavor SU(3) basis [5]. The new degree of freedom “strangeness” in a hypernucleus can be a probe to study both the structure and properties of baryons in the nuclear medium and the structure of nuclei as baryonic many-body systems [6, 7, 8]. There are many data for conventional NN interactions; however, there is a scarcity of data for YN interactions.

Λ hypernuclei provide a laboratory to explore the Λ N interaction [9], since the Λ , being the lightest hyperon, has a lifetime of ~ 260 ps, which is long enough for it to become bound to a nuclear medium. A Λ hypernucleus having a typical lifetime around 200 ps [10], is stable compared to the strong interaction decays with lifetimes on the order of $\sim 10^{-23}$ s.

A bound Λ in the nuclear medium is not blocked by the Pauli exclusive principle, since it has the flavor quantum number $S = -1$. It can penetrate into the nuclear interior and form various bound hypernuclear states. This provides a way to investigate

the new nuclear structures or unknown properties of the baryonic interaction which cannot be seen from the investigation of ordinary nuclei. The Λ also acts as an “impurity” in a nucleus. It can cause some changes in the nuclear structure, such as size and shape, cluster structure, change of collective motion, etc[11, 12, 13, 14]. In addition, the charge symmetry breaking in the strong interactions can be studied by the comparison of mirror hypernuclei [15].

Spectroscopic investigation of Λ hypernuclei provides a unique and currently the only practical tool to study the ΛN interaction, since direct ΛN scattering experiments are technically difficult. The Λ decays only weakly and has a relatively long lifetime; therefore, Λ hypernuclei feature narrow states commonly described by the coupling of low-lying core states to a Λ in low-level shell states with widths ranging from a few keV to 100 keV. This makes spectroscopic studies possible.

1.2 Production of Λ Hypernuclei

Λ Hypernuclear Production Mechanisms

Λ hypernuclei can be produced by two mechanisms: strangeness exchange and associated production, shown as the quark flow diagrams in Figure 1.2.

The strangeness exchange via (K^-, π^-) and (π^+, K^+) reactions convert a neutron in the target nucleus AZ into a Λ , which can be expressed as

$$\begin{aligned} K^- + n &\rightarrow \pi^- + \Lambda, \\ \pi^+ + n &\rightarrow K^+ + \Lambda. \end{aligned} \tag{1.2.1}$$

Then the Λ is coupled to the nuclear core to form a Λ hypernucleus ${}^{\Lambda}_AZ$.

Figure 1.2. Quark flow schematic diagrams of Λ hypernuclear production [16].

The associated production via (π^+, K^+) or (γ, K^+) (or $(e, e'K^+)$) reactions convert a proton in a nucleus AZ to Λ , which can be expressed as

$$\begin{aligned} \gamma + p &\rightarrow \Lambda + K^+, \\ K^- + p &\rightarrow \Lambda + \pi^0. \end{aligned} \tag{1.2.2}$$

Then the Λ is coupled to the nuclear core to form a hypernucleus ${}^{\Lambda}_\Lambda(Z-1)$.

Distorted wave impulse approximation

The production reaction can be described by the distorted wave impulse approximation (DWIA) [17]. The target is viewed as a collection of single-particle levels. The nucleons occupy the corresponding energy levels according to their quantum numbers and Pauli exclusion principle, filling the shells up to the Fermi level. A hyperon interacts with one of the nucleons and the other nucleons are considered as a set of spectator particles, contributing to an overall potential. For the electroproduction of hypernuclei, the matrix element of hadron current in DWIA approximation is given

by [18]:

$$T_{\text{if}}^{\mu} = \langle \Psi_{\text{H}} | \sum_{n=1}^Z \chi_{\gamma} \chi_{\text{K}}^{*} J^{\mu}(n) | \Psi_{\text{A}} \rangle, \quad (1.2.3)$$

where, the sum runs over the Z target protons, and Ψ_{H} (Ψ_{A}) is the many-particle translationally invariant wave function of the target nucleus (hypernucleus), χ_{γ} is the photon wave function, and χ_{K}^{*} is the kaon distorted wave function.

Kinematics and cross section

The cross section and the recoil momentum are the two major factors that need to be considered in hypernuclear experiments. The kinematics for several elementary reaction processes at 0° and 10° are shown in Figure 1.3.

Figure 1.3. The recoil momentum of a hyperon in various elementary reactions at 0° and 10° as a function of the incident particle momentum [19].

As indicated in the figure, the recoil momentum of the Λ hyperon in the $n(\text{K}^-, \pi^-)\Lambda$ reaction is low and essentially zero (magic momentum). There is a large probability for this hyperon to interact with or be bound to the spectator nucleons. On the other hand, the hyperons produced by reactions such as (π^+, K^+) or (γ, K^+) carrying high momentum have a high probability to escape the nucleus, and cross sections to bound state are reduced.

The incident K^- in the reaction (K^-, π^-) will strongly interact with nucleons through various resonant states in the case of small transferred momentum to the

hyperon. It will attenuate rapidly in nuclear matter. Therefore, the reaction will most likely convert an outer shell neutron to a hyperon with small recoil momentum. On the other hand, the π^+ in the reaction (π^+, K^+) and the γ in the reaction $p(\gamma, K^+)\Lambda$ can have a longer mean free path in nuclear matter. They can interact with interior nucleons, convert the nucleons to hyperons with larger momentum, and form deeply bound hypernuclear states. All of these features are illustrated in Figures 1.4 and 1.5.

Figure 1.4 schematically shows the typical cross sections versus momentum transfer for some of the reactions used in the spectroscopic investigation of hypernuclei. The associated production reactions have smaller cross section than the strangeness exchange reactions.

The in-flight reaction (K^-, π^-) for the ground states of light Λ has a large cross section of the order of 10 mb/sr, while that of the reaction (π^+, K^+) is on the order of $10 \mu\text{b/sr}$ and that of the reaction $(e, e'K^+)$ is on the order of 10 nb/sr [20].

Figure 1.4. Hypernuclear production cross section for typical reactions versus momentum transfer [20].

Figure 1.5 gives the calculated excitation spectra [20] for the three production reactions on a ^{12}C target. In the $^{12}\text{C}(K^-, \pi^-)^{12}_{\Lambda}\text{C}$ reaction, the peak with the largest strength corresponds to the substitutional ($\Delta L = 0$), natural parity state near the

nucleon emission threshold. In the (π^+, K^+) and (γ, K^+) reactions, the peaks corresponding to deeply bound state (1^-) and doublet states (1^- and 2^-), respectively, have relatively higher population.

Figure 1.5. Comparison of the excitation functions to be observed in the (K^-, π^+) , (π^+, K^+) and (γ, K^+) reactions on a ^{12}C target [20].

1.3 Weak Decay of Λ Hypernuclei

The Λ particle cannot decay strongly due to the conservation law that the strangeness is conserved in the strong interaction. The free Λ hyperon dominantly decays by the mesonic weak mode as [21]:

$$\begin{aligned} \Lambda &\rightarrow p + \pi^- \quad (63.9 \pm 0.5)\% \quad p \sim 101 \text{ MeV}/c, \\ \Lambda &\rightarrow n + \pi^0 \quad (35.8 \pm 0.5)\% \quad p \sim 104 \text{ MeV}/c, \end{aligned} \tag{1.3.1}$$

where p is the momentum of the recoil nucleon. The energy released in such decay is approximately $Q = 40$ MeV. These mesonic weak decay (MWD) modes are strongly suppressed when a Λ is embedded in a nucleus because the momentum of the recoil nucleon is below the typical Fermi Momentum in nuclear matter (~ 250 MeV/c).

There are still other decay modes, though less relevant, with much smaller branching ratios [22],

$$\Lambda = \begin{cases} n\gamma (\text{B.R.} = 1.75 \times 10^{-3}); & p\pi^-\gamma (\text{B.R.} = 8.4 \times 10^{-4}); \\ p\pi^-\gamma (\text{B.R.} = 8.4 \times 10^{-4}); & p\mu^-\bar{\nu}_\mu (\text{B.R.} = 1.57 \times 10^{-4}). \end{cases}$$

When a Λ is embedded in a nucleus, it interacts with one (or more) of the surrounding nucleons. The non-mesonic weak decay (NMWD) channels ($\Lambda N \rightarrow nN$, $N = p, n$) are promoted, since the momenta of two outgoing nucleons are relative large (~ 420 MeV) [23]. The energy released in this decay mode is ~ 120 - 135 MeV. The one meson-exchange (OME) model of the NMWD is schematically represented in Figure 1.6.

Figure 1.6. Schematic representation of Λ hypernuclei nonmesonic-weak decay. **Left:** exchange of nonstrange-mesons; **Right:** exchange of strange-mesons. W : a weak vertex; S : a strong vertex.

1.4 Historic Overview

In 1952, the first hypernuclear decay event (illustrated in Figure 1.7) was observed[24]. It was the birth of hypernuclear physics. Since then, the experimental study of hypernuclei has known four main generations of development.

In the first generation experiments, Λ hypernuclei were studied by the emulsion technique[15, 25] at the European Organization for Nuclear Research (CERN) and Brookhaven National Laboratory (BNL). During this era, the light Λ hypernuclei ($3 < A < 16$) were observed from the production via K^- mesons stopped in emulsion followed by their π^- -mesonic weak decay. The experimental data were limited to the binding energies of the light Λ hypernuclei ground states and a few excited states. It was found that the Λ potential well depth is approximately 2/3 of the nucleon potential.

For the second generation, counter experiments started at CERN and later at BNL in the early 1970s with high intensity and low momentum K^- beams. During this era, the spectroscopic study including excited states of hypernuclei became possible with the (K^-, π^-) reaction.

The first experiment in this stage measured the excitation energies of ${}^4_\Lambda\text{He}$ and ${}^4_\Lambda\text{H}$ from γ rays observed via the $(K^-_{\text{stop}}, \pi^-)$ reaction. The beam was stopped in the nuclear targets ${}^6\text{Li}$ and ${}^7\text{Li}$. The results of this experiment as well as the Λ binding energy (B_Λ) from the emulsion data [15] are shown in Table 1.2. The comparison of the two mirror hypernuclei ${}^4_\Lambda\text{He}$ and ${}^4_\Lambda\text{H}$ suggested the possibility of charge symmetry breaking [26].

Table 1.2. Data on the ${}^4_\Lambda\text{He}$ and ${}^4_\Lambda\text{H}$ [15].

Hypernucleus	$J^\pi(\text{gs})$	B_Λ	J^π	$E_x(\text{MeV})$
${}^4_\Lambda\text{H}$	0^+	2.04(4)	1^+	1.04(5)
${}^4_\Lambda\text{He}$	0^+	2.39(3)	1^+	1.15(4)

Figure 1.7. First observed hypernuclear decay event. Track P is the incident cosmic ray, which interacts at A, forming a hypernuclear track f, decaying at B into track 1,2 and 3[24].

The first spectroscopic experiment with a magnetic spectrometer was carried out for the $^{12}\text{C}(\text{K}_{\text{stop}}^-, \pi^-)^{12}\text{C}$ reaction at CERN [27]. After that, the study of Λ hypernuclei continued with the in-flight (K^-, π^-) reaction near the magic momentum (see Section 1.2) producing the almost recoilless Λ hypernuclei up to the mass number of 209 at CERN[28, 29, 30, 31, 32] and BNL[33] in the 1970s and 1980s. The p -shell hypernuclei were intensively investigated and it was found that the spin-orbit splittings of Λ orbits are quite small[30].

In the third generation, the (π^+, K^+) reaction took over as an effective tool for the Λ spectroscopic studies at the Alternating Gradient Synchrotron (AGS) of BNL and the 12 GeV Proton Synchrotron(PS) of the High Energy Accelerator Organization (KEK, Japan) since the mid 1980s. The spectroscopic study extended to the heavier hypernuclei up to $A=89$ at BNL[34] and to $A=208$ at KEK[35, 36, 37]. In addition to that, the identification of the deeply bound states, such as s_Λ and p_Λ , of various spectra, especially the core excited state of $^{12}_\Lambda\text{C}$ and $^{10}_\Lambda\text{B}$, provided various input constraints to understand ΛN interaction by precise comparisons with configurations mixing shell model calculations[38].

In the last twenty years, the study of Λ hypernuclei came into the fourth generation, which is about the γ -ray spectroscopy on hadronic hypernuclei production and the hypernuclear spectroscopy with the $(e, e'\text{K}^+)$ reaction. The earliest measurements of the γ -ray spectroscopy were made with NaI detectors [39]. Since 1998, the superior (few keV) resolution of Ge detectors has been exploited in the form of the Hyperball which was a large-acceptance Ge detector [40]. So far, the high-precision γ spectroscopy experiments at KEK and AGS have reported a total of 22 precisely measured transitions for several p -shell hypernuclei[20]. The results enabled a detailed theoretical study of p -shell Λ hypernuclei with shell model. However, the ground-state binding energies cannot be obtained from this type of measurement. Over the last decade, two independent experimental programs in JLab Hall A[41]

and Hall C [1, 42, 43] on hypernuclear spectroscopy were developed and successfully carried out with encouraging results [44, 45, 46, 47, 48].

The Λ hypernuclei which have been identified experimentally are summarized in Figure 1.8.

Figure 1.8. Chart of the Λ hypernuclei. It was presented in Jefferson Lab Hypernuclear Workshop by S. N. Nakamura (May 27, 2014, USA) and was updated from Ref. [20].

1.5 Λ -Nucleon Interaction

The Λ has isospin 0. The direct Λ -nucleon (ΛN) interaction does not contain one-pion exchange (OPE) contributions due to the isospin conservation. Two pion exchange processes, along with a heavier boson exchange, are assumed to account for the ΛN interaction, as illustrated in Figure 1.9. For this reason, the ΛN interaction is relatively weak.

A hypernucleus can be considered as a conventional nuclear core with a hyperon in a single-particle state of the hyperon-nucleon effective potential [17]. The Hamiltonian

Figure 1.9. Schematic representation of ΛN interaction. **Left:** the process of two pion exchanges; **Right:** the process of boson exchange.

for the particle-hole shell model configuration can be expressed as [49, 50]:

$$H = H_N + H_\Lambda + V_{\Lambda N}, \quad (1.5.1)$$

where, the H_N is an empirical Hamiltonian for the p-shell core, $V_{\Lambda N}$ is the $\Lambda - N$ interaction, and H_Λ is the Λ single-particle term. In the weak-coupling basis [51], H_Λ and H_N are diagonal and the energies can be taken from the experiment. Effective interactions for use in a nuclear medium are derived through a G-matrix procedure [52, 53], and the $V_{\Lambda N}$ can be expressed in the form:

$$V_{\Lambda N}(r) = V_0 + V_s(\vec{S}_N \cdot \vec{S}_\Lambda) + V_t S_{12} + V_{ls}(\vec{L} \times \vec{S}^+) + V_{als}(\vec{L} \times \vec{S}^-), \quad (1.5.2)$$

where $S_{12} = 3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) - \vec{\sigma}_1 \cdot \vec{\sigma}_2$ is the spin-tensor operator and $\vec{S}^\pm = 1/2(\vec{S}_N \pm \vec{S}_\Lambda)$ are the symmetric and antisymmetric combinations of nucleon and hyperon spin operators.

For the case of p-shell hypernuclei with the Λ in an s orbit, the $p_N s_\Lambda$ interaction can be expressed in terms of five radial integrals V , Δ , S_Λ , S_N and T , assumed to be constant across the p-shell and associated with the average central, spin-spin, Λ spin-orbit, induced nucleon spin-orbit and tensor terms in the potential as [5]:

$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\vec{s}_N \cdot \vec{s}_\Lambda + V_\Lambda(r)\vec{l}_{N\Lambda} \cdot \vec{s}_\Lambda + V_N(r)\vec{l}_{N\Lambda} \cdot \vec{s}_N + V_T(r)S_{12}. \quad (1.5.3)$$

The shell-model calculations for ${}^7_\Lambda\text{Li}$ used p-shell ($0\hbar\omega$) wave functions from the Cohen and Kurath (8-16)2BME interaction [54] for ${}^6\text{Li}$ core with parameter set [22]:

$$\Delta = 0.430, S_\Lambda = -0.015, S_N = -0.390, T = 0.030.$$

Doublet splittings are determined mainly by Δ , S_Λ and T . The separation for ${}^6\text{Li}(3^+) \otimes s_{1/2\Lambda}$ then is [22]:

$$\delta = \frac{7}{6}\Delta + \frac{7}{3}S_\Lambda - \frac{14}{5}T$$

Thus $\delta = 383 \text{ keV}$.

1.6 Electroproduction of Λ Hypernuclei via $(e, e'\text{K}^+)$ Reaction

1.6.1 Kinematics and Amplitude

The kinematics of electroproduction $A(e, e'\text{K}^+)Y$ reaction is sketched in Figure 1.10. The incident electron is scattered from the target with an angle θ_e , and creates a virtual photon γ^* with a four-momentum $q = (\omega, \vec{q})$, where the energy and momentum are defined by $\vec{q} = \vec{p}_e - \vec{p}_{e'}$ and $\omega = E_e - E_{e'}$, respectively. The transferred momentum $\vec{q}$ is directed along the z-axis. This photon interacts with the target to create the meson K^+ and hyperon or hypernucleus Y . The scattering plane is defined by the incident and scattered electrons. The reaction plane contains the target and the produced

K^+ and Λ . The azimuthal φ_K defines the angle between the scattering and reaction planes. The transferred momentum $\vec{q}$ is directed along the z-axis.

Figure 1.10. Kinematics of electroproduction.

The elementary process of electroproduction, an electron scattered off a target of a proton, can be written as the following equation:

$$e(p_e) + p(p_p) \rightarrow e(p_{e'}) + \Lambda(p_\Lambda) + K^+(p_{K^+}). \quad (1.6.1)$$

The four-momentum for each particle are

$$\begin{aligned} p_e &= (E_e, \vec{p}_e), \\ p_{e'} &= (E_{e'}, \vec{p}_{e'}), \\ p_p &= (m_p, 0), \\ p_K &= (E_K, \vec{p}_K), \\ p_\Lambda &= (E_\Lambda, \vec{p}_\Lambda). \end{aligned} \quad (1.6.2)$$

The triple differential cross section in the laboratory frame for the elementary electroproduction can be written as [18]:

$$\frac{d^3\sigma}{d\Omega_{e'}d\Omega_{K^+}dE_{e'}} = \Gamma \left\{ \frac{d\sigma_T}{d\Omega_{K^+}} + \epsilon_L \frac{d\sigma_L}{d\Omega_{K^+}} + \epsilon \frac{d\sigma_p}{d\Omega_{K^+}} + \cos(2\varphi_K) \sqrt{2\epsilon_L(1+\epsilon)} \frac{d\sigma_I}{d\Omega_{K^+}} \right\}, \quad (1.6.3)$$

where σ_T , σ_L , σ_p and σ_I are the unpolarized transverse and longitudinal, polarized transverse and interferences cross section, respectively. Γ is the virtual photon flux factor in the lab frame. It measures the number of virtual photons per unit photon energy, per unit electron solid angle and per incident electron. It has the form:

$$\Gamma = \frac{\alpha}{2\pi^2 Q^2} \frac{E_\gamma}{1-\epsilon} \frac{E_{e'}}{E_e}, \quad (1.6.4)$$

where $Q^2 = -q^2$. The virtual photon transverse polarization factor (ϵ), the longitudinal polarization factor (ϵ_L) and the effective photon energy (E_γ) can be written as:

$$\epsilon = \left[1 + 2 \frac{|\vec{q}|^2}{Q^2} \tan^2 \frac{\theta_e}{2} \right]^{-1}, \quad (1.6.5)$$

$$\epsilon_L = \frac{Q^2}{\omega^2} \epsilon, \quad (1.6.6)$$

$$E_\gamma = \omega + \frac{q^2}{2m_p}, \quad (1.6.7)$$

where θ_e is the electron scattering angle in the laboratory frame. For the case of real photons, only the un-polarized transverse term is nonvanishing since $Q^2 \rightarrow 0$. In the experimental setup of E05-115, the virtual photon can be treated as almost a real photon since Q^2 is quite small ($Q^2 \sim 0.01 [GeV/c]^2$).

Notice that Γ has an extremely forward peaking distribution shape. To maximize the virtual photon acceptance, the ideal case is to detect 0° scattered electrons. However, at very forward angles there are also high electron rates from Bremsstrahlung and Møller scattering. The “tilt Method” is used in the experiment E05-115 to get

the balance between the virtual photon yield and the background rate, which will be discussed in the next chapter.

The cross section shown in Equation 1.6.3 is also applied to the electroproduction of hypernuclei:

$$e + A \rightarrow e' + K^+ + H, \quad (1.6.8)$$

with the proton (hyperon) four-momentum, mass, etc, replaced by those of the nucleus A (hypernucleus H).

1.6.2 Merits of the $(e, e'K^+)$ Reaction

Electroproduction via the $(e, e'K^+)$ reaction using the high-intensity, continuous-wave, and small-emittance beam at the Jefferson Lab accelerator provides a unique opportunity to study hypernuclear spectroscopy with high precision. An energy resolution at sub-MeV level can be achieved by the combination of (1) the beam with the precise energy, (2) high resolution of both scattering angles and momenta in spectrometers for scattered electrons and kaons, and (3) thin target foils which minimize target straggling effects. The precision of the absolute mass scale depends on the method and technique applied in the kinematics and spectrometer optics calibrations.

Other than the attractive high precision, electroproduction brings in additional new features to the overall investigation of hypernuclei. First of all, the $(e, e'K^+)$ reaction produces the Λ from a proton in the nucleus, creating a core state with a proton hole to which the Λ couples. This can produce either mirror hypernuclei to those produced by the hadronic reactions (K^-, π^-) and (π^+, K^+) or states with different isospin. In other words, electroproduction provides neutron-rich hypernuclei which are suitable candidates to investigate the $\Lambda N - \Sigma N$ coupling contribution as well as the contribution from the effective ΛNN three-body force. Furthermore, besides the large 3-momentum transfer, electro-production via absorption of a virtual

photon involves large spin-flip transition amplitudes from the initial nuclear to the final hypernuclear states while the non-spin-flip amplitude remains non-negligible. Thus, deeply-bound hypernuclear states with both natural and unnatural parities may simultaneously appear. This provides a rich and new spectroscopy complementary to that produced by the hadronic reactions. As a result of the high resolution, the spectroscopy may contain states from an s_Λ coupling to $1\hbar\omega$ core states (such as states with an sd -shell nucleon) that could not be confirmed by low resolution experiments or γ spectroscopy investigations.

To compensate for the small cross sections in electroproduction, a high beam intensity and detection at small forward angles for both the scattered electrons and the reaction kaons are needed.

SECTION 2

EXPERIMENTAL SETUP AND DATA ACQUISITION

The E05-115 experiment is the third generation hypernuclear physics experiment in JLab Hall C for measuring the spectroscopy of Λ hypernuclei with high resolution using the $(e, e'K^+)$ reaction. Compared to the second generation HKS experiment (E01-011), there are four major changes and upgrades in the experimental configuration. First of all, the beam energy is increased from 1.854 GeV to 2.344 GeV to reduce the background single rate in the electron arm. Secondly, a pre-chicane beam line is used instead of a post-chicane beam line to align the post beam to the beam dump to reduce the operational difficulty. Third, a new spectrometer, the High Resolution Electron Spectrometer (HES) replaced the Enge spectrometer to gain larger angular acceptance. Finally, a new splitter magnet (SPL) with an “H” shape was built to replace the previous one with a “C” shape for better field uniformity and optics quality. Detailed information on the experiment will be given later in this chapter.

2.1 Overview

The E05-115 experiment is a coincidence type experiment. The incident electron beam scatters off the target nucleus, and Λ hypernuclei and K^+ are associatively produced. The positively and negatively charged particles are separated by a splitter magnet (SPL). After the interaction, the K^+ was detected in coincidence with an inelastically scattered electron using the two spectrometers, the High Resolution Kaon Spectrometer (HKS) and the HES, respectively.

The E05-115 experiment was carried out in 2009. The experiment aimed to measure energy levels of bound Λ states in the s- and p- shell region with variety of targets including ^7Li , ^9He , ^{10}B , and ^{12}C and beyond the p-shell by the electromagnetic re-

action with the ^{52}Cr target. Data were taken also on the targets CH_2 and H_2O for calibration purposes by the elementary process $p(e, e'K^+)\Lambda/\Sigma^0$.

2.2 Kinematic Conditions

The reaction $(e, e'K^+)$ is illustrated in Figure 2.1. The incident electron with energy of 2.344 GeV scatters off the target nucleus. The scattered electrons (e') are detected at forward angles from 3 to 9 degrees, with a central momentum of 0.844 GeV/c for the scattered electron (e'). This process can be described by the exchange of a virtual photon which approximately carries a momentum of 1.5 GeV/c. The virtual photon interacts with a proton in the target nucleus and creates a strange quark-antiquark pair. As a result, the proton can be converted into a Λ (or Σ^0) with the quark content uds , and emitting a K^+ with quark content $u\bar{s}$ at forward angles and momentum around 1.2 GeV/c. The converted Λ has a momentum of $\sim 350 \text{ MeV}/c$ and has a high probability to remain with the nucleus and form a hypernucleus.

Figure 2.1. Electroproduction of hypernuclei by the $(e, e'K^+)$ reaction.

Kinematic conditions listed in Table 2.1 were chosen in order to have the best physics yield-to-background ratio. The total Λ photoproduction cross section as a function of photon energy, was measured by the SAPHIR group [55], as shown in Figure 2.2. A maximum can be seen in the region of 1.1-1.5 GeV for the photon

energy. 1.5 GeV was chosen for both the E05-115 and E01-011 experiments [1]. This allows the central momentum of K^+ to be at 1.2 GeV/c, high enough to optimize the K^+ survival rate but low enough to apply conventional techniques for clean particle identification.

Figure 2.3 illustrates the correlations within the HKS and HES acceptances for the mass of single Λ and Σ^0 particles produced from the proton, and that of the ground states of hypernuclei ${}^{12}_{\Lambda}\text{B}$ from ${}^{12}\text{C}$ targets. The spread of the events comes from the angular acceptance of the spectrometers. The dash lines show the expected correlation at the central angles. Since Λ and Σ^0 are light, they have large recoil angles, thus wider spread, i.e., stronger angular dependence. In contrast, such spread becomes much smaller for heavy systems, such as hypernuclei with mass $A > 6$, as seen for the ${}^{12}_{\Lambda}\text{B}$ ground state distribution in Figure 2.3.

Figure 2.2. Total cross section of the $p(\gamma, K^+)\Lambda$ reaction [55].

For the kinematics condition of HES, two important factors were considered: (1) maximizing the electroproduction rate and at the same time (2) minimizing the background electron rate from Bremsstrahlungs and Møller scattering.

As discussed in Section 1.6, the electroproduction differential cross section can be suitably written as a product of virtual photon flux and the differential cross section of kaon photoproduction (γ, K^+). The virtual photon flux has the maximum in the

Figure 2.3. The mass correlations of free Λ and Σ^0 from proton and the ground state of ${}_{\Lambda}^{12}\text{B}$ from ${}^{12}\text{C}$ by the $(e, e'K^+)$ reaction.

electron scattering angle θ_e for the following value:

$$\theta_e = \arcsin\left(\frac{m_e \omega}{4E_e^2 E_{e'}^2}\right). \quad (2.2.1)$$

It is obvious that this value is essentially zero due to the small electron mass. Thus flux factor maximization is naturally expected for very forwardly scattered electrons, as seen in Figure 2.4.

Figure 2.5 shows the theoretically predicted K^+ angular dependence of the differential cross section for the photo production of the ${}_{\Lambda}^{12}\text{B}$ ground state doublet ($J^P = 1^-$ and 2^- states) with a DWIA calculation [56].

The conclusions from Figure 2.4 and Figure 2.5 are that, in order to achieve the highest possible yield of Λ hypernuclei production, both the scattered electron and the reaction K^+ need to be detected at very forward angles. Further discussion on the angular dependence of electrons associated with the virtual photon flux, Møller

Figure 2.4. Angular dependence of the Virtual photon flux factor for ^{12}C target. Plot is obtained with the following kinematics: $E_e = 2.344 \text{ GeV}$ and $\omega = 1.5 \text{ GeV}$ [2].

Figure 2.5. Angular distribution of the photo production cross section of the $^{12}_{\Lambda}\text{B}$ ground state doublet with a DWIA calculation [56].

scattering and Bremsstrahlung electrons will be given in Section 2.4.4.2, where the new configuration of the HES spectrometer and its implications are discussed.

Table 2.1. The basic kinematic and spectrometer parameters of the E05-115 experiment.

Beam energy		2.344 GeV
Beam energy precision		$\leq 8 \times 10^{-5}$
HES		
Configuration	QQD (EQ1+EQ2+ED, horizontal bend)	
Central $E_{e'}$	0.844 GeV	
$\Delta E_{e'}$	$\pm 10.5\%$	
$E_{e'}$ precision	2×10^{-4}	
$\Delta\Omega_{e'}$	7.0 msr	
average central E_γ	1.5 GeV	
HKS		
Configuration	QQD (KQ1+KQ2+KD, horizontal bend)	
Central momentum P_K	1.2 GeV/ c	
ΔP_K	$\pm 12.5\%$	
Precision	$\pm 2 \times 10^{-4}$	
θ_{eK} range	$1 - 13^\circ$	
$\theta_{\gamma K}$ range	$0 - 12^\circ$	
Average $\theta_{\gamma K}$	6.8°	
$\Delta\Omega_K$	8.5 msr	
K^+ survival rate	$\sim 27\%$	

2.3 CEBAF Electron Accelerator Facility

2.3.1 The Accelerator Overview

The Continuous Electron Beam Accelerator Facility (CEBAF) at JLab can deliver electrons in almost a 100% continuous wave (CW) to three experimental halls, Halls A, B and C as illustrated in Figure 2.6. In June 2010 [57], construction began for an additional hall, Hall D, on the opposite end of the accelerator from the other three halls, as well as an upgrade which doubles the maximum beam energy up to 12 GeV.

In 2009, the CEBAF accelerator was capable of delivering a CW electron beam at a fundamental frequency of 1497 MHz in the energy range between 0.6 GeV and 6 GeV and average beam currents up to $200 \mu\text{A}$. The beam could be delivered to the

Figure 2.6. Schematic view of CEBAF electron accelerator.

experimental halls as un-polarized or polarized. The polarization can be up to 75%. The relative momentum spread of the beam is of the order of 10^{-5} with a geometric emittance of 10^{-9} mrad. The high energy, high intensity and high energy resolution of the beam makes CEBAF unique for a high resolution hypernuclear spectroscopic experiment via the $(e, e'K^+)$ reaction.

2.3.2 The Hall-C Beamline

Figure 2.7 shows a schematic view of the Hall-C beamline. The arc and alcove beamline deliver the electrons to the experiment hall and diagnose the beam quantities by the attached apparatuses, which are described as following. The super-harp which is a wire scanner and can move across the beam provides the absolute beam position, reading out using a shaft encoder [58]. The Beam Position Monitor (BPM) measures the relative beam position at various locations along the beam line. The Beam Current Monitor (BCM) is designed for stable, low noise, non-intercepting beam current measurements. The Fast feedback system (FFB) is a system used for beam energy and position stabilization [59].

Figure 2.7. Schematics of Hall-C beamline. Upper figure shows the schematic view of Hall-C arc and alcove. Lower figure shows inside of the hall.

The other part of the beam line is the beam line section in the experimental hall before the experimental target. The SPL needs to be considered as a part of the beam line, since it bent the post-beam.

The post-beam has to be sent to the Hall-C beam dump, so that the bending power of the SPL needs to be compensated. In contrast to experiment E01-011 that used a post-chicane after the SPL, a pre-chicaned beam line was used for the E05-115 experiment. This new method avoided the difficulty in handling the post-chicaned beam which contained a large beam halo from the target. In addition, the post-chicaned beam line appeared to generate a large number of background particles to the HKS detectors. The radiation level was also significantly affected by the post-chicaned beam line. In the pre-chicane method, the beam coming from Hall-C arc is bent to the HES side by the DZ magnet placed at the entrance of Hall-C. Then, the beam is bent by two FZ magnets aiming at the experimental target in front of the SPL. The incident angle matches the bending angle of the SPL so that the post beam aims straight at the Hall C dump after the SPL. Due to the small beam profile, low halo and tiny emittance, the pre-chicaned beam was easily tuned and operated. An additional photon dump was installed at the direction of the incident beam for the Bremsstrahlungs generated from the target.

A fast beam raster was used to reduce the heat effect generated by the high intensity beam on the targets which have a low melting temperature. The beam position variation at the target with a frequency around 25 kHz was monitored by the CEBAF 150 ohm BPM.

The beam raster was applied in the CH_2 and ^7Li target runs, as shown in Table 2.2. The Y-axis size was three times larger than that of the X-axis. This is because that X is the momentum dispersion direction and the smaller raster size was to reduce residual beam position uncertainty in the optics after correction for the beam position variation.

Table 2.2. The beam raster sizes applied during the experiment. The raster sizes are shown as (vertical) $\times$ (horizontal).

Target	Nominal Beam Current [μA]	Raster Size [mm(v) $\times$ mm(h)]	Target beam Pattern [mm(v) $\times$ mm(h)]
CH_2	2	3×1	4.95×1.65
^7Li	35	1×1	1.65×1.65

2.4 E05-115 Spectrometer System

The spectrometer system for the E05-115 experiment consists of the SPL, the electron spectrometer HES and the kaon spectrometer HKS, as shown in Figure 2.8 and Figure 2.9. The SPL is used to direct particles at forward angles to HES and HKS at larger physical angles. The configuration allows the detection of kaons in the angles ranged from 1° to 13° with respect to the incident electron beam. The HES is tilted by 6.5° in the vertical plane pivoted at the virtual target point and is vertically displaced downward by 5.6 cm. This method avoids the Bremsstrahlung and Møller scattering electrons at and near zero degrees and dramatically reduces the electron singles rate in HES.

To minimize the multiple scatterings of the whole system, the entire system was under a vacuum, including the beam line up to the exit windows of the spectrometers in both arms.

2.4.1 Splitter Magnet

A common charge separation splitter magnet (SPL) is the general technique applied by all of the Hall C hypernuclear experiments. The experimental target is located at the SPL's front effective field boundary and the SPL bends the oppositely charged particles (e^- and K^+) away from the beam direction to opposite directions.

Figure 2.8. Schematic illustration of the experimental setup.

Figure 2.9. Picture of the entire setup.

This technique makes it easier for the subsequent spectrometers (1) to be physically located at angles sufficiently large with respect to the beam line while detecting particles from small forward scattering angles; (2) to have minimized orbit path length for short lived particles such as K^+ ; and (3) to achieve large solid angle acceptance. All of these are crucial factors in achieving a high production yield rate. However, the common SPL configuration also gives unavoidable challenges for the hypernuclear spectroscopy experiments in Hall C in terms of the single rate in HES and the accidental background rate.

The new SPL magnet is a dipole magnet, as shown the picture in Figure 2.10 and schematic view in Figure 2.11. The specification of the SPL magnet is summarized in Table 2.3. Figure 2.12 shows the excitation curve by the measurement and the TOSCA calculation, and the TOSCA calculated field map was then used in the GEANT simulations to have a full volume field map.

Figure 2.10. Picture of the SPL magnet.

The SPL magnet is dedicated to HES+HKS configuration and has a complicated shape, because the SPL must have four exits (Figure 2.13). These exits are for (from right to left) HKS, Bremsstralungs (real photons), post-beam and HES. In reality,

Figure 2.11. Schematic view of the SPL magnet.

Figure 2.12. Excitation curve of the SPL magnet. The measured values were taken before and after the beam time [2].

Table 2.3. Parameters of the SPL magnet.

Pole Gap Height [mm]	190
Max. Ampere Turns [A turns]	214200
Number of Turns	210
Conductor Size [mm]	17×17 ($\phi 11$ hole)
Max. Field [T]	1.74
Max. Current [A]	1020
Total Magnet Weight [ton]	31.7

the SPL had significant magnetic field cross talk to the magnets in HKS and HES due to the large gap, sharp wedge (see Figure 2.10 and 2.11) and tight spacing of the spectrometers (see Figure 2.8 and 2.9).

2.4.2 Target System

The targets are placed at the entrance of the SPL. Table 2.4 is a summary of the experimental targets used in the E05-115 experiment. Among them, the BeO target was used only to check the beam position on the targets.

Table 2.4. List of the targets used in the E05-115 experiment.

Target	Hyperon or Hypernucleus	Thickness [mg/cm ²]	Density [g/cm ³]	Purity	Radition Length [mg/cm ²]
CH ₂	Λ/Σ^0	450.8	0.92	-	44.77
	$\Lambda^{12}\text{B}$				
H ₂ O	Λ/Σ^0	500	1.00	-	36.08
	$\Lambda^{16}\text{N}$				
⁷ Li	$\Lambda^7\text{He}$	184.0	0.54	99.9	82.78
⁹ Be	$\Lambda^9\text{Li}$	188.1	1.848	100.0	65.19
¹⁰ B	$\Lambda^{10}\text{Be}$	56.1	2.16	99.9	
^{nat} C	$\Lambda^{12}\text{B}$	112.5	2.25	¹² C : 98.89	42.70
⁵² Cr	$\Lambda^{52}\text{V}$	134.0	7.15	99.9	15.3
		154.0		99.9

Figure 2.13. Inside view of the vacuum chamber in the gap of the splitter magnet.

The complete target system, as shown in left of Figure 2.14, consists of the target ladder, the driving mechanism and the base. The water-cell target is attached to the target ladder through the water-flowing pipe. All other solid targets are mounted on the target ladder (see the right of Figure 2.14). A driving mechanism is used to move the target ladder and adjust the target position. The base is used to mount the system to the SPL magnet vacuum chamber.

Both H_2O and CH_2 are elementary process targets, with the $p(e, e'K^+)$ kinematics to generate Λ and Σ^0 . There are three reasons to use the H_2O target. First, it can keep the temperature by the flowing water, so it does not need the raster. The uncertainty from the raster can be avoided. Second, it will also be possible to perform the spectroscopic study of the $^{16}_\Lambda\text{N}$ by using the ^{16}O component of the target. Third, the beam energy is raised from 2.344 GeV to 2.364 GeV for part of the H_2O runs, which

Figure 2.14. Target system. **Left:** Schematic view of the whole target system; **Right:** Picture of the target plate attached in the target ladder.

enlarge the Λ coverage on the kinematic space. This change helps to improve the uniformity of the optical description on the kinematic space, which will be explained in detail in Section 5.4. The H_2O target was not used as the main target to produce the calibration data because the S/N ratio of the spectra of Λ and Σ^0 obtained from the H_2O target is much worse than from the CH_2 target (see Table 5.4 in Section 5.4).

2.4.3 High Resolution Kaon Spectrometer

The High resolution Kaon Spectrometer (HKS) was constructed and first used in the E01-011 experiment in 2005, aiming to improve momentum resolution and angular acceptance. In the E01-011 experiment, the HKS performed as expected [60, 61, 62]. The spectrometer consists of two quadrupole (KQ1 and KQ2), one dipole (KD) and a detector package.

2.4.3.1 HKS Magnets

The HKS magnets are normal conduction magnets, KQ2 and KQ1 are used as vertical and horizontal focusing quadrupole magnets, respectively, and KD is a dipole

magnet with a 70-degree bending angle. The basic characteristics of HKS magnets are listed in Tables 2.5 and 2.6. The typical magnetic field is summarized in Table 2.7.

Table 2.5. Parameters of the HKS Q1 and Q2 magnets.

	KQ1	KQ2
Bore Radius [mm]	120	145
Pole Length [mm]	840	600
Max. Ampere Turns [A turns]	224000	144000
Number of Turns	256	320
Conductor Size	8×8 ($\phi 6$ hole)	13.5×11.5 ($\phi 6.3$ hole)
Coil Winding	Double Pancake Winding	Solenoid Winding
Max. Field Gradient [T/m]	6.6	4.2
Max. Current [A]	875	450
Resistance [$m\Omega$]	181 (at 55°C)	119 (at 45°C)
Cooling Water Flow Rate [l/m]	49.6	17.3
Pressure Drop [MPa]	0.36	0.38
Number of Coolant Circuits	16	8
Total Magnet Weight [ton]	8.2	10.5

The HKS magnets were aligned to the new SPL magnet which had a bending angle of 32.53° , as seen in Figure 2.15.

2.4.3.2 HKS Detector Package

The HKS detector package consists of two drift chambers (HDC1 and HDC2), three layers of time of flight (TOF) counters (KTOF1X, 1Y and 2X), two types of Čerenkov counters, three layers of aerogel Čerenkov (AC1, AC2 and AC3) and two layers of water Čerenkov (WC1 and WC2); see the picture in Figure 2.16. The purpose of these detectors is to track the particles and identify the kaons. The tracking was done by the drift chambers and the TOF counters. The reference plane (focal plane, defined at $z=0$) of the tracking is defined as shown in Figure 2.17. Kaons were identified from the background of positrons, pions and protons by the Čerenkov detectors.

Table 2.6. HKS dipole parameters.

Pole Gap Height [mm]	200	
Pole Length [mm]	1560	
Max. Ampere Turns [A turns]	291840	
Number of Turns	256	
Conductor Size [mm]	22×22 (ϕ 12 hole)	
Max. Field [T]	1.53	
Max. Current [A]	1140	
Resistance [m Ω]	145 (at 47.5°C)	
	Gap Side	Yoke side
Cooling Water Flow Rate [l/m]	66.3	68.8
Pressure Drop [MPa]	0.32	0.35
Number of Coolant Circuits	8	8
Total Magnet Weight [ton]	210	

Table 2.7. HKS magnetic field summary.

Magnet (Dipole)	Path length(l) [m]	Typical magnetic field(B) [T]	$\int B \cdot dl$ [T · m]
SPL	1.60	1.7	1.85
KD	4.50	1.4	4.95
Magnet (Quadrupole)	Path length (l) [m]	Magnetic field gradient [T/m]	$\int B \cdot dl$ [T·m]
KQ1	1.14	4.5	4.22×10^{-2}
KQ2	0.90	2.8	1.96×10^{-2}

Figure 2.15. Alignment of the HKS to the SPL magnet. Unit is mm.

Figure 2.16. Picture of the HKS detector system.

Figure 2.17. HKS detector setup.

Drift chambers

The HKS drift chambers are at the front end of the entire detector system. They measure the particle trajectory across the focal plane (FP) of the HKS spectrometer and find the FP coordinates. For each uniquely identified particle, its momentum and scattering angle are reconstructed from the FP coordinates using the reconstruction matrices that represent the spectrometer optics. Three sets of drift chambers were built by the Hampton University group for the 2005 HKS experiment E01-011 [60]. Two of these chambers, named HDC1 and HDC2, were used at the HKS FP with a 1.0 meter separation distance in Z direction (along the optical axis). A Helium bag with about one atmosphere of pressure was inserted in the gap between the two chambers to minimize multiple scatterings which affect the precision of the FP coordinates. This is also the reason for the drift chambers being at the front and closest to the

HKS dipole. Their performance and tracking method in E05-115 will be given in Section 3.2.

TOF counters

The HKS time of flight (TOF) counters are important detectors with multiple applications. They were involved in both the online trigger and the offline particle identification analysis, such as the online hadron trigger, the trigger timing determination, the particle velocity (β) measurement, start time reference for the drift chambers, and the two spectrometer coincidence time calculation. The velocity information is important for the particle identification.

The HKS TOF counters consist of three planes of segmented plastic scintillation counters (KTOF-1X, 1Y and 2X). Figure 2.18 shows the schematic views of the HKS TOF counters and Table 2.8 gives the detailed parameters. The KTOF-1X, 2X consists of 17 and 18 vertical scintillator segments, respectively. KTOF-1Y consist of 9 horizontal segments. The distance between the KTOF-1X and 2X is 1.5 m; TOF of π^+ , K^+ and p are given in Figure 2.19. On the left Figure 2.19 shows the momentum dependence of β in the HKS acceptance for the particles π^+ , K^+ and p . On the right it shows the momentum dependence of the TOF of π^+ , K^+ and p between the KTOF-1X and 2X in HKS acceptance. At the HKS central momentum, the TOF difference between π^+ and K^+ is 380 ps. As shown in the bottom of Figure 2.18, a 5 mm overlap was made between the neighboring segments of KTOF-1Y in order to avoid missing acceptance.

Each scintillation counter has Hamamatsu H1949-50 photomultiplier tubes (PMT) on both ends. The timing resolutions were measured by the cosmic ray test before the experiment. The results were $\sigma = 50$ ps for KTOF-1X and KTOF2X counters and $\sigma = 70$ ps for KTOF-1Y. This corresponds to a better than 4σ separation between kaons and pions between 1X and 2X at 1.2 GeV/c.

Aerogel Čerenkov counters

Figure 2.18. Schematic view of the TOF counters. **Top Left:** KTOF-1X, **Top Right:** KTOF-2X, **Bottom:** KTOF-1Y.

Table 2.8. KTOF parameters.

KTOF-1X	
Effective area	$125^W \text{ cm} \times 30^H \text{ cm} \times 2^T \text{ cm}$
Segments	$7.5^W \text{ cm} \times 17 \text{ segments}$
PMT	H1949-50 (2 inch)
Scintillator	BC408
KTOF-1Y	
Effective area	$125^W \text{ cm} \times 27.5^H \text{ cm} \times 2^T \text{ cm}$
Segments	$3.5^W \text{ cm} \times 9 \text{ segments}$
PMT	H1949-50 (2 inch)
Scintillator	BC408
KTOF-2X	
Effective area	$170^W \text{ cm} \times 35^H \text{ cm} \times 2^T \text{ cm}$
Segments	$9.5^W \text{ cm} \times 18 \text{ segments}$
PMT H1949-50	(2 inch)
Scintillator	BC408

Figure 2.19. Momentum vs. β and TOF. **Left:** Momentum dependence to β of the particles π^+ , K^+ and p within the HKS acceptance, **Right:** Correlations between momentum of π^+ , K^+ and p and their TOF between KTOF-1X and -2X.

The Aerogel Čerenkov (AC) counters are designed to reject pions and positrons from kaons and protons. Figure 2.20 shows the relationship between the number of Čerenkov photons per centimeter of radiator and the momentum of π^+ , K^+ and p . The index of the AC radiator, silica aerogel ($n(\text{SiO}_2) + 2n(\text{H}_2\text{O})$), is $n = 1.05$. Therefore, protons and kaons cannot generate Čerenkov light within the HKS momentum acceptance ($1.2 \text{ GeV} \pm 12.5\%$). Positrons and pions can be suppressed using AC as veto in the online trigger level and a more sophisticated analysis on the AC was applied in the offline analysis to fully remove these backgrounds.

Figure 2.20. Number of Čerenkov photons per centimeter vs. momentum in the aerogel medium [63].

There are three layers of AC counters (see the schematic view in Figure 2.21) to achieve a high rejection ratio of 10^4 . Each layer has a common diffusion box. Inside it is optically separated into seven independent segments by the Tedlar film sandwiched between two layers of Millipore paper. The effective area of each layer is $169^{\text{W}} \text{ cm} \times 46^{\text{H}} \text{ cm} \times 31^{\text{T}} \text{ cm}$, where W means width, H means height, and T means thickness. Each segment is filled with 5 layers of 4 by 2 silica aerogel tiles ($1136^{\text{H}} \times 113^{\text{W}} \times 10^{\text{T}} \text{ mm}^3$ for each tile). Two types of PMTs were used: 28 Hama-

matsu R1250 PMTs for the first and the second AC layers and 14 Photonis XP4572B/D1 PMTs for the third layer.

Figure 2.21. Schematic side and top views of the HKS aerogel Čerenkov detector.

Water Čerenkov counters

The HKS Water Čerenkov detectors (WC) are used to suppress protons. Figure 2.22 shows the relationship between the number of Čerenkov photons per centimeter of water radiator and the momentum of π^+ , K^+ and p . The index of the deionized water is $n = 1.33$. The water Čerenkov detectors are able to separate protons from other particles by choosing an optimized threshold of the number of photoelectrons.

There are two of layers of WC (WC1 and WC2), as seen the schematic view in Figure 2.23. Each layer consists of 12 independent segments. The parameters of WC are summarized Table 2.9. In the E05-115 experiment, two kinds of boxes were used. Box-A was newly constructed with new material to further enhance the light collection efficiency [64], and were used in the high momentum portion of the WC plane where the β difference between protons and kaons is small, thus requiring

Figure 2.22. Number of Čerenkov photons per centimeter vs momentum in the water medium. [63].

higher separation power [2]. For the low momentum side, the original boxes (Box-B) built for the E01-011 experiment were used [61].

Bucking coil

Due to the large gap in the HKS dipole for a large angular acceptance with the highest designed momentum, the dipole yoke was saturated and a fringe field up to 5.5 Gauss was detected in the axial direction at the photomultiplier (PMT) tubes of the Čerenkov detectors. A PMT cannot work within its expected performance in the presence of such a magnetic field. This is because the field distorts the trajectory of the photo-electrons during the multiplication processes inside the PMT and causes a significant loss of collection efficiency.

To solve this problem, the bucking coil technique was applied as in the previous E01-011 experiment. The bucking coil creates a magnetic field in the opposite direction and cancels the fringe field from the HKS dipole (see the picture in Figure 2.24). From the test of WC with a magnetic field of ~ 5 Gauss parallel to the PMT axis, it was found that the gain was reduced by 60% (relative gain of 0.40).

Figure 2.23. Schematic view of the HKS water Čerenkov detector.

Table 2.9. WC parameters.

layer information		
Effective area	$184.8^{\text{W}}\text{ cm} \times 35^{\text{H}}\text{ cm} \times 8^{\text{T}}\text{ cm}$	
Segments	$15.6^{\text{W}}\text{ cm} \times 12\text{ segments}$	
Layers	2	
counter information		
Segment	Box-A 1-6	Box-B 7-12
Size	$15.2^{\text{W}}\text{ cm} \times 37.6^{\text{H}}\text{ cm} \times 8.5^{\text{T}}\text{ cm}$	
Box material	White acrylic	
Reflection material	Teflon sheet	White acrylic
Window material	Quartz glass (3mm thick)	UVT acrylic
PMT	H7195UV (2inch)	H7195 (2inch)
Čerenkov radiator	Deionized water $n = 1.33, \rho \sim 18.2\text{ M}\Omega \cdot \text{cm}$	
Light shielding material	Black curtain	

For the E05-115 experiment, the bucking coils of 40 turns and a current of 2 A were used for each of the WC counters, while 40 turns and a current of 8 A were used for each of the AC counters. With this technique, a relative gain of more than 0.70 and 0.75 for each of the WC and AC counters, respectively, was achieved. A detailed description of the bucking coil technique and performance can be found in Ref. [63]. The proton and pion rejection powers of WC and AC will be shown in Section 2.6.3.

Figure 2.24. Picture of the bucking coils. **Left:** Bucking coils implemented on the PMTs of the aerogel Čerenkov. Bucking coils are wound around the photo-cathodes of each PMT, **Right:** Bucking coils implemented on the PMTs of the water Čerenkov. A bucking coil of 40 turns was used for each PMT.

2.4.4 High Resolution Electron Spectrometer

The features of HES are the high momentum resolution ($\delta p/p = 2 \times 10^{-4}$), the large angle acceptance (7 mrad with the SPL), the capability of the application of the “tilt method” for the background reduction, and kinematic matching with HKS [2]. This spectrometer consists of two quadrupole magnets (EQ1 and EQ2), one dipole magnet (ED) and a detector package.

2.4.4.1 HES Magnets

The HES magnets used in the E05-115 experiment for the first time can be seen in Figure 2.25. EQ1 and EQ2 are vertical and horizontal focusing quadrupole magnets, respectively. ED is a dipole magnet with a bending angle of 50 degrees. The basic characteristics of the HES magnets are listed in Tables 2.10 and 2.11. The typical magnetic field is summarized in Table 2.12.

Figure 2.25. Schematic view of the HES magnets. They consist of two quadrupole and one dipole magnet (EQ1, EQ2, ED). The unit is mm.

Table 2.10. Parameters of the HES Q1 and Q2 magnets.

	EQ1	EQ2
Bore Radius [mm]	100	125
Pole Length [mm]	840	600
Max. Ampere Turns [A turns]	144000	144000
Number of Turns	180	180
Conductor Size	9×9 ($\phi 6$ hole)	9×9 ($\phi 6$ hole)
Max. Field Gradient [T/m]	7.8	5.0
Max. Current [A]	800	800
Total Magnet Weight [ton]	2.8	3.1

Table 2.11. HES dipole parameters.

Pole Gap Height [mm]	194
Pole Length [mm]	1560
Max. Ampere Turns [A turns]	289680
Number of Turns	136
Conductor Size	17 ($\phi 11$ hole)
Max. Field [T]	1.65
Max. Current [A]	1065
Total Magnet Weight [ton]	36.4

Table 2.12. HES magnetic field summary. The $\int B \cdot dl$ for EQ1 and EQ2 are calculated along a line 10 cm apart from the center of the magnet [2].

Magnet (Dipole)	Path length(l) [m]	Typical magnetic field(B) [T]	$\int B \cdot dl$ [T · m]
SPL	1.90	1.70	1.76
ED	3.20	1.14	2.50
Magnet (Quadrupole)	Path length (l) [m]	Magnetic field gradient [T/m]	$\int B \cdot dl$ [T·m]
EQ1	0.90	5.6	3.88×10^{-2}
EQ2	0.80	4.1	2.45×10^{-2}

2.4.4.2 The Tilt Method

One of the challenges of the E05-115 experiment is the extremely high electron rate from Bremsstrahlung and Møller scattering electrons. The left top panel in Figure 2.26 shows the angular distribution of the cross section of the electrons associated with the Bremsstrahlung process and the bottom panel shows that of the electron rate associated with the Møller process [2]. These background electrons at forward angles are bent by the SPL toward the electron spectrometer.

Figure 2.26. Angular distribution of the electron rate. **Top:** Associated with the Bremsstrahlung process. **Bottom:** Associated with the Møller process [2].

Both of these distributions shown in Figure 2.26 are sharply peaked at zero degrees. This feature makes it possible to avoid the high background rate by applying the “tilt method”. Pivoting at a distance of about 43 cm upstream of the virtual target point, the electron spectrometer HES is tilted up with an angle of 6.5° off the bending plane of the SPL (see Figure 2.27). This is equivalent to a rotation plus a shift of the spectrometer. In such a configuration, the scattered electrons near zero degrees are blocked by the spectrometer yokes and, thus, cannot enter the spectrometer acceptance. The tilt angle corresponding to a cut-off in the electron scattering angles of $\sim 6.5^\circ$ was chosen by a Figure of Merit (FoM) optimization between the yield rate and the accidental background rate that could be handled by the experiment as seen in Figure 2.28. The FoM in the figure was defined as $S/\sqrt{N}$, where S is the number of electrons associated with virtual photons, and N is the number of the electrons associated with Møller and Bremsstrahlung.

Figure 2.27. Schematic view of HES with its tilt angle of 6.5°

Figure 2.28. A Monte Carlo simulation results of rates of electrons associated with photon, Bremsstrahlung and Møller scattering as functions of HES tilt angle [65].

2.4.4.3 HES Detector Package

The HES detector package consists of two drift chambers (EDC1 and EDC2), and three layers of time of flight (TOF) counters (ETOF-1, ETOF-2 and ETOF-3), shown in Figure 2.29. The purpose of these detectors is to obtain the focal plane parameters for momentum and angle reconstruction and the time reference for coincidence to the detected K^+ by HKS. The reference plane (focal plane, defined at $z=0$) of the tracking is defined as shown in Figure 2.30.

Drift chambers

The HES drift chambers measure the particle trajectory passing through the HES focal plane (FP), from which the FP coordinates for each detected particles are obtained. Using the measured FP coordinates and the known spectrometer optics represented by the reconstruction matrices, the particle momentum and angle at the

Figure 2.29. Picture of the HES detectors.

Figure 2.30. HES detector setup.

target can be calculated. EDC1 and EDC2 are different types of drift chambers. As mentioned previously, EDC2 is the same chamber built for the HKS (identical to the HDC1 and the HDC2). Its function will be discussed in Section 3.2.

EDC1 is a drift chamber with a honeycomb cell configuration and its specification is summarized in Table 2.31. The sense wires are gold-plated tungsten with a diameter of $20\text{ }\mu\text{m}$ and the cathode wires are gold-plated aluminum with a diameter of $80\text{ }\mu\text{m}$. The sense wires and the cathode wires are placed to form a honeycomb-like cross section shape as shown in Figure 2.31. The sense wires are connected to the ground through the amplifier-discriminator circuit, and the cathode wires are connected to the negative high voltages of about -2200 V . The operational parameters are summarized in Table 2.13.

The Nanometric N277L amplifier-discriminator (16 channels per card) was used for all the drift chambers in the HES and the HKS.

Table 2.13. EDC1 parameters.

Effective area	$100^{\text{W}}\text{ cm} \times 12^{\text{H}}\text{ cm} \times 32^{\text{T}}\text{ cm}$
Number of Layers	10 (xx' , uu' , xx' , vv' , xx')
Number of Cells	114 (x , x'), 107 (u , v'), 106 (u' , v)
Distance between Layer	7.5 cm
Cell Size	0.5 cm
Angle of uu' , vv' for xx'	+30 deg, -30 g
Material	
Window Aluminized Myler	($12.5\text{ }\mu\text{m}$)
Anode Wire W-Au coated	($20\text{ }\mu\text{m}\phi$)
Cathode Wire Al-Au coated	($80\text{ }\mu\text{m}\phi$)
Resolution	
Position Resolution (horizontal: x)	$\sigma=86\text{ }\mu\text{m}$
Position Resolution (vertical: y)	$\sigma=210\text{ }\mu\text{m}$
Angular Resolution (horizontal: x')	$\sigma=0.7\text{ mrad}$
Angular Resolution (vertical: y')	$\sigma=2.8\text{ mrad}$

TOF counters

Figure 2.31. Coordinate system and wire configuration of EDC1.

Table 2.14. Operational parameters for EDC1.

HV	-2200 V
Disc. Threshold	4.0 V
Gas Content	Ar/C_2H_6 50:50(%)

There are three layers of the TOF counters (ETOF-1, -2 and -3) in the HES. The first two layers were used for the charged particle trigger from the HES side and for the coincidence time with the HKS. ETOF-3 is a single scintillator detector that was oriented normal to ETOF-1 and -2. Its length covers the full range of the focal plane and was used for the time calibration of ETOF-1 and ETOF-2 but not in the trigger.

All of the HES TOF counters are made of plastic scintillators. The time reference of the HES detectors was determined by ETOF-1. ETOF-1 and -2 were used in coincidence to make the trigger for the HES side as well as to make the coincidence with that from the HKS side. Both ETOF-1 and -2 consist of 29 horizontal segments of scintillators, as seen in the schematic view in Figure 2.32. The detailed parameters are summarized in Table 2.15. The timing resolution of each segment of ETOF-1

and -2 is about 92 ps [66], which is measured by cosmic rays. The time resolution of ETOF-3 is about 115 ps [66].

Figure 2.32. Schematic view of ETOF-1 and 2.

Table 2.15. ETOF-1 and 2 parameters

Effective area	$117^{\text{W}} \text{ cm} \times 30^{\text{H}} \text{ cm} \times 1^{\text{T}} \text{ cm}$
Segments	$5^{\text{W}} \text{ cm} \times 29 \text{ segments}$
Layers	2
PMT	Hamamatsu H6612 (1 inch)
Scintillator	BC408

2.5 Sieve Slit and Collimator

The sieve slit (SS) is a HEAVIMET (alloy of tungsten, nickel and copper) plate which has many small holes and the collimator is also made of the same material.

Technical drawing of a beam cross-section showing three views: Front view, Bottom view, and Side view.

Front view: Shows a cross-section of a beam with a central rectangular hole. The overall width is 203.2. The hole has a width of 152.4 and a height of 161.14. The distance from the top edge to the top of the hole is 142.24, and from the bottom edge to the bottom of the hole is 150.98. The hole is offset from the centerline by 15.24 on the left and 20.31 on the right. The hole has a diameter of $\varnothing 6.32$. The beam has a diameter of $\varnothing 3.18$ at the top and bottom edges.

Bottom view: Shows the beam from below, with a central circular hole. The overall width is 203.2. The hole has a diameter of $\varnothing 6.32$.

Side view: Shows the beam from the side, with a total height of 415.93. The beam has a diameter of $\varnothing 3.18$ at the top and bottom edges. The hole has a diameter of $\varnothing 6.32$ and a height of 50.8.

The SS and the collimator are made on the same plate and the position of the plate can be changed by an electric motor-driver device with a positioning accuracy

Figure 2.34. CAD drawing of the HES SS and collimator. Unit is mm. This figure is upside-down.

Figure 2.35. The design of the HKS and HES SS. One hole is missing on the HKS SS on purpose to identify easily up/down and left/right. Asymmetric pattern and different hole sizes are designed to identify easily up/down and left/right.

of 0.1 mm. The HES collimator position can be adjusted according to the need for optimization of the HES single rate and signal/accidental (S/A) ratio. Three collimator positions were applied during the experiment, as shown in Figure 2.36, SS = -300.2 mm used for the low rate runs (lower yield but better S/A ratio), -330.2 mm for the high rate runs (higher yield but poorer S/A ratio), and -347.2 mm for the none-physics runs.

Figure 2.36. The positions of the HES collimator during experiment.

2.6 Triggers

The E05-115 experiment used a coincidence type of trigger formed by the time coincidence of the single-arm trigger determined by the HKS and HES detector packages separately. During the E05-115 experiment, five types of triggers were made available: HKS CP0, HKS single, HES single, COIN and pedestal. These triggers are put into the software-controlled Trigger Supervisor (TS), as shown in Figure 2.37. Through the Data Acquisition (DAQ) system, trigger types can be selected as well as pre-scaled individually. The Pedestal trigger is a trigger generated by the clock generator for random triggers without physical events for determination of the pedestal removal cut for each channel of the Analog-Digital-Converter (ADC) units. It is used automatically for only the first one thousand triggers of all runs.

Figure 2.37. E05-115 main trigger logic.

2.6.1 HKS Trigger and Grouping Trigger

On the HKS side, two types of triggers were set up, the CP0 trigger and the HKS single trigger.

CP0 trigger

$$(CP0) \equiv (KTOF1X) \otimes (KTOF1Y) \otimes (KTOF2X), \quad (2.6.1)$$

where $\otimes$ means “AND” in the trigger logic. It is an unbiased trigger for a charged particle detected by the HKS without identification of its type. Events accepted (with proper pre-scale) by this trigger were used for various studies using the background particles, for example, the ratios of signals of pions and protons over kaons.

HKS single trigger

$$(HKS) \equiv (CP0) \otimes (\overline{AC}) \otimes (WC), \quad (2.6.2)$$

where

$$(AC) \equiv (AC1) \otimes (AC2) \oplus (AC2) \otimes (AC3) \oplus (AC3) \otimes (AC1), \quad (2.6.3)$$

$$(WC) \equiv (WC1) \otimes (WC2), \quad (2.6.4)$$

where $(\overline{AC})$ means “veto” and “ $\oplus$ ” means “or” in trigger logic. This is a trigger with less rigorous kaon identification but optimized in reduction of the background single rates at the online DAQ level. The positron and pion rejections were achieved by the AC veto which requires particle detection by two out of three AC counters from different layers. The coincidence of two WC counters from different layers ensured detection of kaons, while the proton rejection at a less rigorous level was accomplished by a proper threshold to the WC counter analog signal. These preliminary conditions combined to CP0 for charged particles, formed a HKS single trigger with kaon identification.

Grouping Logic

In the HKS single trigger, AC responds only to positrons and pions. Thus it was used in VETO mode in the trigger. Since the combined single rate of positrons and pions can be close to $\sim 10^7/\text{sec}$, the probability for detecting a positron or a pion by the AC counter system with a kaon accidentally passing also within the coincidence time window is significant. Therefore, this VETO can over “kill” some kaons while rejecting background particles.

To solve this potential problem, an electric grouping logic unit (programmable TUL module [61]) was applied. Utilizing the segmentation of the HKS detector system, six groups of individual and localized HKS single trigger was formed based on the GEANT simulation studies, as shown in Figure 2.38. In each of these grouped triggers, only the signals from limited counters are taken into account. Thus, the rate of accidental coincidence between the positrons (or pions) and kaons is minimized.

The finalized HKS single trigger is the OR of the six groups.

Figure 2.38. Schematics of an HKS grouping for trigger.

2.6.2 HES Single Trigger

On the HES side, the negatively charged particles are dominated by the scattered electrons with a factor of 10^4 over the other types. Misidentified particles cause negligibly a small accidental coincidence background. Therefore, the HES single trigger is formed by the coincidence of ETOF counters from two separate layers as follows:

$$(HES) \equiv (ETOF1) \otimes (ETOF2). \quad (2.6.5)$$

2.6.3 Coincident Trigger

Coincidence trigger is defined by the coincidence of the HKS and HES singles as:

$$(COIN) \equiv (HKS) \otimes (HES). \quad (2.6.6)$$

The reference time of this trigger was determined by the HKS single trigger. The width of the coincidence time window was set at 40 ns, taking into account the safety margin and accidental background trigger rate.

2.6.4 Trigger Supervisor and Typical Trigger Rate

The Trigger Supervisor (TS) is a central control point for the acquisition activities. Input signals to the TS were controlled during the experiment as shown in Figure 2.37. The role of the TS can be summarized as follows:

1. Accept and pre-scale the triggers from multiple sources.
2. Maintain the DAQ system as busy while a trigger is determined and data is being processed by the DAQ.
3. Generate signals used for the ADC gates and the Time-Digital-Converter (TDC) starts.

4. Coordinate the actions of multilevel trigger systems.
5. Communicate triggering information to the system's read-out controllers.
6. Keep track of the number of events currently in the buffers of the front-end modules (ADCs and TDCs).

Each signal, except for the pedestal trigger signal, was made in coincidence with the “EN” signal, and the “GO” signal, which are sent from the CODA (see section 2.7). “GO” means that the run has started, and EN means that the run has started and that data taking has been enabled. The pedestal trigger was made in coincidence with “ $\bar{\text{EN}}$ ” and “GO”. During the experiment, the first 1000 events are taken by the pedestal trigger and subsequent events were taken as physics events.

The TS is enabled to put pre-scale factors (PS) for each type of trigger run-by-run. During the experiment, these triggers were mixed by applying individual PS to ensure that the total trigger rate did not exceed the limit of 2 kHz to low computer dead time, while including singles triggers for background studies. The PS of the COIN trigger is always 1 because the events are what we aim to take. The typical trigger rate is shown in Table 2.16.

Table 2.16. Typical CP0, HKS single, HES single and coin trigger rates.

target	current [μA]	CP0 [kHz]	HKS single [kHz]	HES single [MHz]	COIN [kHz]
CH ₂	2.0	220	1.8	1.2	0.10
H ₂ O	2.8	1100	20	1.5	1.5
⁷ Li	35	540	7.3	2.2	0.96
⁹ Be	40	710	1.0	2.5	1.5
¹⁰ B	40	190	2.0	1.6	0.17
^{nat} C	20	160	1.3	1.5	0.97
	35	630	7.9	2.3	1.3
⁵² Cr	8.0	980	11	2.5	1.8

2.7 Data Acquisition System

All the signals from the detectors are sent to the counting room and digitized by the ADCs and TDCs. The FASTBUS ADC (LeCroy 1881M) and the VME TDC (JLab F1TDC) for the PMTs signals, and the FASTBUS TDC (LeCroy 1877) for the signals of drift chambers (HDCs and EDCs) were used. The digitized electronic signals were converted to physics data set and written on disk by the CEBAF On-line Data Acquisition (CODA) system [67]. The data flow of CODA is illustrated in Figure 2.39. The front-end modules (TDCs and ADCs) are arranged on crates. Each front-end crate is managed by a Read Out Controller (ROC) processor. The ROCs read the event data and sent event fragments to the Event Builder (EB). Combined data fragments from the EB are buffered into the Event Transfer (ET) system. The ET system limits the rate of the DAQ [68]. The computer dead time was kept less than 10%. The ET distributes data to an online monitoring system according to the user's requirements and sends data to the Event Recorder (ER). Finally, the ER writes events to the disks. Ethernet interfaces connect the various CODA components, and the user controls the data acquisition through a GUI interface.

Scaler information was recorded by the VME scalers. Scaler data were stored in every 2 seconds during data taking.

Information such as the spectrometer settings, accelerator and target status were read out from the Experimental Physics and Industrial Control System (EPICS). The EPICS is a slow readout control system [69] and the EPICS information in this experiment was read every 2 seconds.

2.8 Data Summary

Experimental data were taken from a total of seven different targets and Table 2.17 provides a summary of the data which are grouped by 10 sets.

Figure 2.39. CODA flow chart.

Table 2.17. Data summary.

Data set	Target	Thickness [mg/cm ²]	Beam current		Total charge [C]	Run time [hours]
			Nominal [μ A]	Average [μ A]		
1	CH ₂	450.8	2	1.990	0.281	39.24
2	H ₂ O	500.0	2.5	2.681	0.204	21.13
3	⁷ Li	184.0	35	32.01	4.839	41.98
4	⁹ Be	188.1	40	38.28	5.332	38.69
5	¹⁰ B	56.1	40	38.71	6.253	44.88
6	^{nat} C	112.5	10	8.07	0.142	4.9
7			20	19.41	1.076	15.4
8			35	32.90	4.659	39.3
9	⁵² Cr	134.0	7.5	7.66	0.825	29.9
10		154.0	7.5	7.61	5.525	201.4

SECTION 3

TRACKING IN THE HKS SPECTROMETER

The HKS tracking is carried out by the HKS drift chambers and the TOF counters. The TOF counters provide the time reference, i.e., the start time for measuring the drift time of the emitted electrons in the drift chambers. The drift time is then converted into the position according to the chamber geometry. The positions measured on the planes of the drift chambers can then be used to reconstruct the particle trajectory, from which the focal plane (FP) position and angles can be determined.

3.1 Drift Chamber

A drift chamber is a wire detector to obtain the spatial information by measuring the drift time of the electrons coming from an ionization event. When a charged particle passes through the gas in a chamber, it will interact electromagnetically with the gas molecules, and create electron-ion pairs along the path of the particle by ionization. In the electric field established within a chamber cell (formed by the cathode foils, field wires and sense wire), these electrons will drift through the gas towards the sense wire at the center of the cell, undergoing repeated collisions with the gas molecules and creating more ionized electrons. A Near constant drift velocity and gain of the number of electrons are the result of the continued collisions during the drift. The positive ions drift in the opposite direction and are collected by the cathodes. However, their drift speed is much less than that of the electrons. Near the sense wire surface where the electric field becomes extremely strong ($E \sim 1/r^2$), electrons gain energy fast and electron density becomes high quickly. The number of collisions and ionizations increase exponentially in an extremely short time; an avalanche takes place. A pulse-like current fluctuation occurs due to the collection of

these electrons by the positive sense wire in a cell in a short time. The pulsed current is converted into a pulsed voltage drop by the resistor to the ground in an amplifier through which it becomes a measurable pulsed signal. The total collected charges by the wire before amplification is proportional to the number of initial ionizations and the multiplication dominated by the avalanche. The ratio between these two is called the “gas gain”, which depends on the type of gas, cell geometry and applied potential between the sense wire and the cathodes of a drift cell unit [70].

If the drift velocity, u , of the electrons in the gas and the arrival time of the particle are known, the normal distance between the sense wire and the particle trajectory is obtained by the equation as following:

$$x = \int_{t_0}^{t_1} u dt, \quad (3.1.1)$$

where t_1 is the time when the pulse appears at the anode, while t_0 is the reference time when the particle passes through the cell. Figure 3.1 shows the basic operating principles of a drift chamber.

3.2 HKS Drift Chambers

Each of the two drift chambers HDC1 and HDC2 has 6 planes, named as x , x' , u , u' , v , and v' planes, as shown in Figure 3.2. The geometrical parameters are shown in Table 3.1. The sense wires are made of gold-plated Tungsten, $25 \mu\text{m}$ in diameter, connected to the ground through the amplifiers. The cathode field wires are made of Beryllium Copper alloy, $60 \mu\text{m}$ in diameter, connected to a negative high voltage source. The flat cathode foil planes are made of Mylar coated on both sides with $1200 \text{ \AA}$ of Cu. The gap between the two cathode foils is 0.635 cm . The same HV was applied to the cathode foil as to the field wires. The separation between the two sense wires (same as that for the two field wires), is 1.0 cm , which results a maximum drift

Figure 3.1. Basic operation of a drift chamber [71].

distance of 0.5 cm. The number of sense wires on the x , and x' planes is 122, while u , u' , v , and v' planes have 87 wires. The wire orientations of the drift chambers are defined to measure positions in three directions x , u and v . With respect to the x -axis, the u -axis is tilted by 60° (clockwise) and v -axis by -60° (counter-clockwise) (see Figure 3.2).

Table 3.1. Geometrical parameters of HDC1 and HDC2.

Dimension($W \times H \times T$)	$59.25'' \times 22.75'' \times 3.0''$
Active Region	$48.2'' \times 12.0''$
Wire Plane Configuration	$u, u'; x, x'; v, v'$

A nanometric N277L amplifier-discriminator is used for pulse amplification and conversion to a logic signal with the discriminator. Each card carries 16 channels. For each of the drift chambers HDC1 and HDC2, 40 cards are needed with equal numbers mounted on both sides of the chambers. The output signals from the cards

Figure 3.2. Schematic view of the HKS drift chamber.

are fed into FASTBUS TDCs via 33 ft. flat cables. The discriminator thresholds were set separately for the HDC1 and the HDC2 to avoid the high rate of the electric background. They were monitored and adjusted during the experiment based on the rate of the hit on the HDC1 and the HDC2. The typical value was 3.0 V for both the HDC1 and the HDC2.

During the experiment, the high particle rates caused high leakage currents on the cathode HVs, which led to instabilities of the HV power supplies. Thus the cathode HVs were adjusted and lowered to the tested plateau value of 2000 V to 2200 V to maintain stable operation of the HV power supplies while still achieving acceptable detection efficiency ($>95\%$) (see Section 3.3.2). Table 3.2 gives a typical “online” single-plane detection efficiency for the HKS drift chambers. The data is from the ^{52}Cr target run with a $7.3\mu\text{A}$ beam current, the worst case. The HV for the HDC1

was -1930 V, and -1970 V for the HDC2. The HDC1 is closer to the spectrometer exit and, thus saw a higher particle flux than the HDC2.

Table 3.2. Typical HKS drift chamber single-plane detection efficiency defined.

HDC1 plane ID	u	u'	x	x'	v	v'
efficiency(%)	97.0	96.7	97.4	98.7	96.3	96.1
HDC2 plane ID	u	u'	x	x'	v	v'
efficiency(%)	97.9	98.3	98.1	99.4	98.1	97.1

3.3 HKS Drift Chambers Tracking

3.3.1 Algorithms of HKS Tracking

Tracking for an event aims to determine a ray by combining and fitting the measured local coordinates of both chambers. The algorithms are illustrated in detail in Ref. [72] for the same set of chambers.

With the wire coordinates and drift distance information from each plane of the two HKS drift chambers, the particle trajectory can be calculated by the tracking algorithm with the assumption that particle trajectories have a small angular spread with respect to the z-axis. In the HKS, the angular spread is within $\pm 14^\circ$ in the momentum dispersive plane ($X-Z$ plane) and within $\pm 2^\circ$ in the out-of-plane ($Y-Z$ plane); see the Xp and Yp distributions in Figure 3.3.

For all of the experimental runs with low multiplicity conditions (i.e., the mean multiplicity of hits per drift chamber plane is 1), the tracking algorithms with the small angular spread approximation were applied and they worked well. The procedure is the following:

Figure 3.3. Typical distribution of the HDC focal plane parameters for unbiased events from CH_2 target. Xp and Yp are angles defined by X/Z and Y/Z , respectively.

First, for each K^+ trigger, the starting reference time for tracking is calculated by:

$$t_0 = t - z/(\beta_{K^+} * c) \quad (3.3.1)$$

where t is the time of the hit on the plane of the KTOF-1X counters, z is the perpendicular distance between the KTOF-1X plane and the FP, and β_{K^+} corresponds simply to the relative velocity of K^+ assumed with a central momentum of $1.2 \text{ GeV}/c$. Momentum varies across the focal plane to the tracking precision, and position resolutions are small and negligible.

Second, space points of the hits on each chamber are identified by assuming that all the tracks are parallel to the z axis [72] and using only the sense wire position without involvement of the drift time. The angular resolution in this step is about 50 mrad [72], comparable with the angle dispersion. All the tracks are assumed parallel to the z -axis.

In this step, all hits on each chamber are treated by combinations of pairs. Each two nonparallel wires form a pair with their intersection giving the x and y coordinates of the pair. Pairs with the squared distances between the intersections less than the combination test criterion are assigned to a combination. The coordinates of the combination are the average of the coordinates of all the pairs in the same combination. Again, combinations with the squared distances between the combinations less than the space point test criterion are assigned to a space point. The coordinates of each space point are the average of the coordinates of the combinations. There may be more than one space point on one of the chambers from one trigger. Lists are made to record the separated space points, as well as the hits linked to each space point.

Third, the drift distances to all of the sense wires associated with a space point are obtained by conversion of the drift times using the drift maps. The following subsections will describe this process in more detail.

Fourth, the left-right ambiguity is determined by picking the best χ^2 fit from all combinations of positions of a stub containing at least 5 hits from different wire planes for a space point.

Fifth, linking a pair of space points, one from each of the two chambers, forms a trail track. In this step, if there is more than one space point from a chamber, multiple trail tracks can be found. The number of possible tracks depends on the tightness of the test criteria in obtaining the combinations and space points. The particle single rate also affects the number of tracks. In the HKS tracking, these cuts are loose to prevent kaon loss from losing tracking efficiency, although it means accepting certain levels of backgrounds.

Sixth, fitting all the positions of hits for each of the identified trail track from the two chambers. Good tracks are selected by a more restrictive requirement on the χ^2 . From each good track, a set of FP coordinates labeled by the corresponding track

number is determined from the fitting. The tracking residuals and the χ^2 are used to evaluate the quality of the fit.

Single-plane tracking residuals were used to calculate the difference between the measured coordinate and the coordinate obtained by the tracking algorithm. The distribution was used to evaluate the single-plane position resolution. Figure 3.4 illustrates an example of the plane 1u1 from a CH₂ target run, i.e., from the first 16 wire group of the HDC1.

Figure 3.4. Typical tracking single-plane residual distribution. It is for the plane u' of HDC1 from a CH₂ target run (run#76312).

3.3.2 HKS Drift Chamber Calibration

Drift distance calibration

A drift map is needed to convert drift time to drift distance, i.e., the shortest distance from the particle trajectory to the sense wire that measured the signal. The drift time distribution for each plane of the two chambers (see Figure 3.5) was used to obtain this time-to-distance map. A proper time window cut for each channel (one channel for each sense wire) was set according to the drift range. The start offset of drift time for each channel was corrected to move the front edge of the distribution to

zero because the cable delays and distances of each plane of the chambers to the FP were different. The drift chamber should be uniformly illuminated over each half drift cell range (0.5 cm) after averaging over all wires from one plane. This corresponds to a uniform drift distance distribution. Based on this assumption, the drift map is obtained by:

$$D(T) = D_{max} \frac{\sum_{t_i=t_{min}}^T F(t_i)}{\sum_{t_i=t_{min}}^{t_{max}} F(t_i)}, \quad (3.3.2)$$

where D is the drift distance, D_{max} is the maximum drift distance, T is the drift time, $F(t_i)$ is the measured drift time distribution (as seen in Figure 3.5) and the interval $[t_{min}, t_{max}]$ is the properly chosen time window which rejects noise hits but maintains good detection efficiency. Applying the drift map, the drift time can be converted to the drift distance. Figure 3.6 shows the typical drift distance distribution plane-by-plane.

The drift map is correlated to the drift velocity of the electrons, which depends on the electric field of the drift cell. The electric field is determined by the applied HV but also can be influenced by the event rate per cell. This is because the positive ions drift slowly and can pile up around the cathode wires so that the potential is lowered if the event rate exceeds the rate limit set by the required recovery time. Therefore, the experimental data collected under various experimental conditions are thus separated into groups accordingly. Drift maps must be obtained separately for each group (see Table 3.3).

Plane center coordinates alignment

The precision of the wire plane coordinates is essential for the resolutions of the reconstructed FP coordinates. Mis-alignment between planes can cause the “left-right” ambiguity to be resolved incorrectly by the tracking procedure discussed previously (see Figure 3.7). As a result, the distributions of drift distance are asymmetric and non-uniform. Therefore, a geometric alignment of the wire planes is necessary.

Figure 3.5. Typical HDC drift time distribution plane-by-plane.

Figure 3.6. Typical HDC drift distance distribution after applying the drift maps.

Table 3.3. E05-115 data grouped by the tracking calibration conditions.

Run	Target	Beam (μ A)	HV DC1(V)	HV DC2(V)	Map file
75884-75885	Carbon	1.0-4.0	1900	1910	75885
75886-75918	H ₂ O	2.5	1900	1910	75902
75919-75920	Carbon	2.5	1900	1910	75885
75921-75950	H ₂ O	2.8	1900	1910	75928
75951-75961	Carbon	35.0	1900	1910	75952
75962-75967	Carbon	35.0	1900	1910	75952
75968-75969	Carbon	10.0	1900	1910	75968
75970-75976	H ₂ O	2.8	1900	1910	75928
75977-75984	⁵² Cr	2.8	1900	1910	75988
75985	Carbon	10.0	1900	1910	75968
75986	H ₂ O	2.8	1900	1910	75968
75987-76052	⁵² Cr	8.0	1900	1910	75988
76050-76052	Carbon	10.0	1900	1910	75988
76053-76068	Carbon	35.0	1900	1910	76053
76069-76075	Carbon	37.0	1900	1910	76069
76076-76078	Carbon	40.0	1900	1910	76076
76079-76084	Carbon	40.0	1920	1950	76080
76085-76086	Carbon	10.0	1920	1950	76087
76087	Carbon	10.0	1920	1950	76087
76088-76091	Carbon	2.0	1920	1950	76088
76092-76104	Carbon	35.0	1920	1950	76097
76105-76112	Carbon	40.0	1920	1950	76110
76113-76117	BeO	2.0	1920	1950	76110
76118	BeO	2.0	1970	1970	76110
76119-76170	¹⁰ B	4.0	1970	1970	76125
76171-76192	¹⁰ B	45.0	1970	1970	76176
76193-76277	⁷ Li	35.0	1970	1970	76197
76278-76284	¹⁰ B	45.0	1970	1970	76176
76285-76290	¹⁰ B	40.0	1970	1970	76125
76312-76574	CH ₂	2.0	1970	1970	76315
76575-76645	⁹ Be	40.0	1970	1970	76584
76646-76649	⁵² Cr	6.0	1900	1910	76647
76650-76659	⁵² Cr	7.5	1930	1970	76651
76660-76737	⁵² Cr	7.5	1930	1970	76665
76738-76771	⁵² Cr	5.0	1930	1970	76753
76772-76789	⁵² Cr	7.5	1935	1970	76665
76790-76802	⁵² Cr	7.5	1920	1970	76665
76772-76789	SS	5.2	1920	1970	76803
76813-76824	CH ₂	2.0	1920	1970	76818
76825-76829	Carbon	20.0	1920	1970	76826
76830-76844	Carbon	20.0	1970	1970	76830
76845-77124	⁵² Cr	8.0	1910	1970	76857

Figure 3.7. Typical drift distance distribution before the wire chamber geometry alignment from run#75409(SS run).

This alignment was first done in the local coordinate system, self-defined by the geometry of the HKS chambers. A relative offset was assumed to exist at the center coordinates (X_{center} , Y_{center}) of each plane. These offsets were scanned plane-by-plane within a half cell size in x and y directions separately. The reference of the scan is the absolute sum of the mean of the tracking residuals for all of the 12 HKS drift chamber planes. Figure 3.8 shows an example of the scan result for the X_{center} . The point corresponding to the smallest tracking residual was chosen as the real X_{center} for that plane. Table 3.4 gives the alignment offsets in the local tracking coordinates. New drift maps were then generated and the left-right ambiguity was well solved, as shown in Figure 3.9 for the drift distance distribution.

Table 3.4. Offsets of the central positions of the HKS chamber planes after first alignment. The uncertainties of the offsets are 0.001 cm, which were extracted from the step of the scan.

plane	$X_{\text{center}}(\text{cm})$	$Y_{\text{center}}(\text{cm})$
1u	-0.029	-0.016
1u'	0.018	0.013
1x	-0.010	0.006
1x'	-0.003	0.004
1v	-0.035	-0.004
1v'	0.022	0.000
2u	0.031	0.002
2u'	0.000	0.034
2x	-0.001	0.000
2x'	0.003	0.000
2v	0.032	-0.029
2v'	0.011	-0.001

These relative coordinates were then aligned with respect to the absolute coordinates defined by the HKS spectrometer (the geometric survey data) (see Table 3.5). In the following, this process is named as “survey projection”. The difference between the real and the aligned center can be compared in $x-z$ and $y-z$ planes, as illustrated by Figure 3.10. To achieve the absolute alignment, which is needed for momentum

Figure 3.8. The alignment scan of the HKS drift chamber plane central position. This is for the $textx'$ plane of HDC1. The right is an enlarged view of the left for the region where the sum residual is smaller than 0.08.

and scattering angle reconstruction using the spectrometer optics, additional offsets were simply obtained by calculation from the geometric difference. This alignment does not affect the tracking quality as seen from the comparison of tracking χ^2 before and after alignment (see Figure 3.11). However, it is significant to the optical reconstruction. The alignment ensured good pattern agreement of the sieve slit (SS) holes at the SS plane, as seen in Figure 3.12, where the SS data were analyzed and reconstructed from the measured FP coordinates by the matrices obtained from a GEANT simulation with the magnetic field map from a TOSCA calculation.

After this absolute alignment, the relative alignment was repeated and small adjustments were needed (compare Figure 3.13 to Figure 3.8). The final offset of each plane is summarized in Table 3.6.

3.3.3 Improvement for High Multiplicity Tracking

Source of high multiplicity

Figure 3.9. Typical drift distance distribution after the wire chamber geometry alignment from run#75409.

Table 3.5. Survey values of central positions of the HKS chambers.

DC ID	$X_{\text{center}}(\text{cm})$	$Y_{\text{center}}(\text{cm})$
HDC1	-0.065	-0.160
HDC2	-0.768	0.740

Figure 3.10. Comparison of projected tracking results to survey data. **Left:** In the xz plane. **Right:** In the yz plane.

Figure 3.11. χ^2 comparison before and after survey data projection. This is for plane 1x2 (the second x plane in the first HKS chamber).

Figure 3.12. Reconstructed SS $Y - X$ pattern from FP. **Left:** SS distribution before survey projection. **Right:** SS distribution after survey projection.

Figure 3.13. Wire chamber plane center point scan after alignment to the survey data.

Table 3.6. Offsets of the central position of the HKS chamber planes. The uncertainty for both X_{center} and Y_{center} are 0.00001 cm, which were extracted from the step of the scan.

plane	$X_{\text{center}}(\text{cm})$	$Y_{\text{center}}(\text{cm})$
1u	0.01703	0.1641
1u'	0.07080	0.1593
1x	0.04627	0.1594
1x'	0.06260	0.1611
1v	0.03477	0.1573
1v'	0.09939	0.1645
2u1	0.73794	-0.7377
2u'	0.76208	-0.7313
2x	0.76928	-0.7331
2x'	0.78698	-0.7331
2v	0.76032	-0.7336
2v'	0.79795	-0.7357

Multiplicity is defined as the number of detected particles per detector plane from one trigger. Figure 3.14 shows the average multiplicity on the 1x1 plane. The HKS chambers are the closest detectors to the exit of the HKS Dipole, and their multiplicities are higher than those of the subsequent detectors. Multiplicity can influence the resolution and efficiency of the tracking. Most of the HKS data were taken under high multiplicity conditions. The source of the higher multiplicity is the background of the positrons which is not in the HKS kinematics acceptance.

The HKS had its kinematic (momentum and angles) acceptances set to avoid positively charged particles emitted at zero degrees. However, there was still a probability that the particles emitted at or near zero degrees with momenta slightly lower than the momentum acceptance can pass through the full length of the spectrometer. They are then outside of the detector acceptance; thus, should pass on the low momentum side of the detector system without detection. However, they do have to pass through the wall of the vacuum chamber extension box, on which a vacuum port made of alu-

Figure 3.14. The average multiplicity on HDC1 x plane.

minum was added for mounting the NMR probe which measures and monitors the dipole field. A large background of positrons was observed that apparently scattered off this part of the vacuum extension, which has been confirmed by a GEANT simulation [65]. The background of positrons scattered off the detectors with a relative large angle. Figure 3.15 shows the event rate on HDC1 which was found to be double that of the HDC2.

The high dark current resulting from this background forced a reduction of the HV applied to the HDCs to the edge of the efficiency plateau, in order to maintain operational stability. Most importantly, the high multiplicity made the previously discussed tracking procedures ineffective, i.e., significantly lowered the tracking efficiency and position resolution. Therefore, a special technique had to be developed for handling the high multiplicity data.

As mentioned above, there may be several types of particles which transversed the drift chambers in one “K⁺” trigger. Variation of their time references due to the TOF is not negligible, thus the start time calculated by Equation 3.3.1 using the assumption of only one type of particle introduces offsets to the calculation of the

Figure 3.15. Event rate on different planes of HKS chambers. **Left:** The data is from the CH_2 target run. **Right:** The data is from the ^{52}Cr target run.

start time. The purpose of this study is to obtain the individual start time for the hits associated with the same space point with the help of the TOF counters, with the result that the accidental hits on the HDC1 and the HDC2 can be reduced.

In the modified procedure, the start time is projected to the center plane of both the HDC1 and the HDC2 by the TOF instead of the FP which is in the mid-point of the two. The full path length is taken into account instead of the simplification using Z differences only. Furthermore, kaons are no longer assumed for every possible track, i.e., the TOF is not simply estimated from the estimated kaon momentum. The actual measured TOF is used. The interval cut $[t_{\min}, t_{\max}]$ applies to the time distribution of all the TOF counters to reject noise hits. A typical time distribution of KTOF counters is shown in Figure 3.16. The start time calculation is detailed into five steps.

First of all, a tracking was done on the pairs of KTOF-1X and 2X, 1X and 1Y, and 1Y and 2X. One hit on one layer of the TOF counters was selected to make a combination between the pair. One line was determined by one combination. This process was defined as “pre-tracking”. The number of combinations was counted, defined as ntof_{1x2x} , ntof_{1x1y} , and ntof_{1y2x} by looping over all the hits. The pre-tracking for the pair of KTOF-1X and 2X can be used as an example to explain this algorithm.

Figure 3.16. Typical time distribution of the KTOF-1X (run#76315, CH₂ target).

Using the FP as reference for the center of the relative coordinates, the path length of the particle is determined by the central position (X_{center} , Y_{center} , Z_{center}) of the fired timing counters then projected to the Z direction to find the corresponding time difference, i.e., tof_1x2x . Since the separation in Z between 1X and 2X is 1500 mm, and the β range of all particles is from 0.7 to 1.2, the cut for tof_1x2x is set to be [4.1670 ns, 7.1478 ns] to eliminate some of the accidental background.

The second step is projecting the time from the timing counter to the HDC1 and the HDC2, separately. If all of the $ntofs$ are equal to one, $h1times$ and $h2time$ are set as the start time for all the hits on HDC1 and HDC2, respectively, and the following steps can be ignored.

Thirdly, all the space points on the HDC1 and the HDC2 are linked to make tracks with all possible combinations. For each of the possible tracks, a straight line path is traced onto every TOF layer and to find the projected position.

Fourth, the distance between the center position of the TOF counter that registered a “hit” and the track projected position was used to determine the validity of

the track. An allowance range was given to the TOF counters based on its width but optimized by the study of the distribution of this distance at each of the TOF layers (1X and 2X) under different singles rates. Events from the CH₂ target run have the lowest multiplicity, while those from the ⁵²Cr target run have the highest multiplicity. Outside of this cut range, the track was considered not valid and is thus removed.

Table 3.7. The tracks of space points with overlapping hits on TOF counters.

x1 hit ID	x2 hit ID	DC1 SP ID	DC2 SP ID	trk _i
4	1	1	6	1
5	1	2	8	3

In the final step, the start time is calculated by projecting the time on the KTOF counters to the HDC1 and the HDC2 for each track constructed from space point combinations. Some tracks may have non-overlapped space points by overlapped TOF counter hit, such as the example track shown in Table 3.7 from one of the CH₂ target runs. These tracks will share the time information of the overlapped TOF counter. On the other hand, some tracks may have overlapped space points but associated with un-overlapped TOF counters. In this case, the average time of the multiple projections will be used as the start time for the overlapped space point.

The top panel in Figure 3.17 shows the improvement in the tracking residuals, while the bottom panel compares the χ^2 before and after application of this start time modification. It improves the position resolution and the kaon tracking efficiency which were affected by high multiplicity. Figure 3.18 shows the σ width of tracking single residuals for different targets and beam currents.

Figure 3.17. Comparison of the tracking quality before and after start time improvement.
Top: Gauss- σ of tracking single residual distribution. The red markers are the results before start time improvement; the blue markers are the results after the TOF cut; the magenta markers are the results after start time improvement.
Bottom: Tracking χ^2 distribution.

Figure 3.18. HDC residual distribution for various targets and beam currents.

SECTION 4

DATA ANALYSIS

4.1 Analysis Overview

Figure 4.1. Flow chart for data analysis.

The raw data was processed by the Hall C analysis software named ENGINE [60, 73, 74], which decodes the raw data of TDCs and ADCs, converts the TDC and ADC data of each counter into physical information, performs the HES and HKS tracking analysis (see Section 3), and sorts the counter information with recognized tracks. This part of the analysis prepares the raw data to be physically analyzed.

The subsequent analysis includes the HKS kaon identification, which eliminates the background particles, the coincidence of the HES and HKS that builds the $(e, e'K^+)$ events, and the optical and kinematic analyses to reconstruct the momentum vectors on the target plane, and to reconstruct the missing mass of events from the

($e, e'K^+$) reaction. In the E05-115 experiment, the “target plane” is optically defined as a plane which is perpendicular to the beam direction at the mean scattering vertex. The initial focal plane to target plane (F2T) and focal plane to sieve slit plane (F2S) matrices were fitted from GEANT simulation with the field map calculated by the TOSCA model.

The spectrometer optics and overall kinematics must be carefully calibrated in order to achieve the best possible precision. This is a separate analysis and is the most important and crucial part of the overall analysis procedure. Thus this part of the analysis will be presented separately in Section 5. A flow chart of the overall data analysis procedure for the E05-115 experiment is illustrated in Figure 4.1.

The cross sections were calculated after the mass spectra were finalized and the background spectra determined. This requires additional analyses on detector efficiencies and simulations for spectrometer and kinematics acceptances.

4.2 HES Tracking

The HES tracking aims to obtain position and angle information for the scattered electrons in the focal plane (FP) of the spectrometer. This information is then used to reconstruct the electron momentum vector at the target.

On the HES side, the mean multiplicity of hits per drift chamber plane is 1; thus, the tracking procedure is similar to that of HKS drift chambers under low multiplicity conditions (see Section 3.3.1).

The start time reference used in the HES tracking was obtained from the HES timing counters. A pre-trajectory was calculated from wire positions without considering drift distances. The mean time of ETOFs on the pre-trajectory was defined as time zero.

Time-to-distance maps for EDC1 and EDC2 were obtained by the same procedure as for the HKS drift chambers. However, because the honeycomb structure of

the EDC1 cells [62] have less electric field uniformity, these maps needed further adjustment. This was achieved by an iterative procedure that employed a fitted track position to extract an improved drift distance and to update the time-to-distance map. Figure 4.2 gives the typical correlation between drift distance and drift time of the EDC1 plane-by-plane.

Figure 4.2. Correlation between drift distance and drift time of EDC1 plane by plane.

The EDC2 was installed to improve the position and angle resolutions. A tracking was first done by the EDC1. A position on the EDC2 was then projected by the EDC1 tracking and the hits on EDC2 far from the projected position were rejected. The

final step was to fit a track to the hits on both the EDC1 and EDC2 planes and obtain the FP position and angles information. Figures 4.3 and 4.4 illustrate the typical reconstructed FP parameters and tracking quality. The typical single plane tracking resolution for the EDC1 and the EDC2 are about $200\ \mu\text{m}$.

Figure 4.3. Typical distributions of the HES focal plane parameters, examples from the CH_2 target runs: **Top left** - X ; **Top right** - X' ; **Bottom left** - Y ; and **Bottom right** - Y' .

4.3 Kaon Particle Identification

Kaons were identified from the background particles such as pions, positrons, and protons with the use of detectors in the HKS spectrometer, including time-of-flight (TOF) counters, Water Čerenkov (WC) counters and Aerogel Čerenkov (AC) counters. The following will discuss the procedures of particle identification using data from the ^{10}B target runs.

TOF calculation

Figure 4.4. Tracking residual of EDC1 (left) and EDC2 (right).

Particle velocity can be calculated by

$$\beta = \frac{l}{\Delta t \cdot c}, \quad (4.3.1)$$

where Δt is the TOF between two layers of TOF counters, and l is the trajectory length. The TDC values of the TOF counters were corrected for time jitter caused by pulse height variation and for time offsets caused by cable length and electronic variations between counters, and hit position variation on the scintillation counters. Since each of the TOF counters has a photomultiplier (PMT) mounted on both ends of the scintillator, the time used from each counter in calculating TOF is the mean time of the TDC values measured from the TOP and BOTTOM ends.

Particles can then be identified by calculating the square of their mass from the measured β and particle momentum p :

$$m^2 = p^2(\beta^{-2} - 1). \quad (4.3.2)$$

Typical particle β and corresponding m^2 distributions are shown in Figure 4.5. The background particles (positrons, pions, and protons) have already been greatly suppressed at the trigger level.

Figure 4.5. Typical β and m^2 distribution before any software PID.

As shown in the figure above, it is possible to separate kaons from protons and pions by using the reconstructed m^2 . However, the separation power becomes more effective when additional detectors are also utilized.

Offline Pion rejection

Figure 4.6 shows (left panel) a typical distribution of the number of photoelectrons $N_{p.e.}$ of AC (layer 1) and (right panel) a two-dimensional correlation between the mass squared of the particles and the $N_{p.e.}$ sums from all three layers of the AC. The light particles such as pions and positrons can be effectively suppressed by a cut on $N_{p.e.}$. This is derived by first summing the response of all three layers and then requiring this sum to be below a certain threshold value,

$$N_{AC1} + N_{AC2} + N_{AC3} \leq X_{AC}, \quad (4.3.3)$$

where X_{AC} is this threshold.

Figure 4.6. Typical AC $N_{p.e.}$ distribution and scatter plot with m^2 distribution. **Left:** $N_{p.e.}$ distribution of first layer of AC counters; **Right:** Correlation between the $N_{p.e.}$ summed of all three layers and m^2 .

The m^2 distribution was fitted with two pseudo-Voigt functions (see Equation 4.3.5) and one Gaussian, as shown in Figure 4.7 and described in Equation 4.3.4. Pseudo-Voigt functions ($V(x)$) were used to evaluate the number of pions and protons while Gaussian ($G(x)$) was used to evaluate the number of kaons. The X_{AC} value was optimized to 20 and the cut removes about 80% of the pions and positrons while keeping the kaon survival rate (cut efficiency) typically at 90% [2]. The evaluated percentage value of the cut efficiency was normalized with the number of pions and positrons (kaons) without the AC cut.

$$F(x) = V(x)_P + G(x)_{K^+} + V(x)_{\pi^+} \quad (4.3.4)$$

$$V(x) = c_1 \left[\frac{2}{\pi} \frac{c_2 c_3}{4(x - c_4)^2 + c_3^2} + (1 - c_2) \frac{\sqrt{4Ln2}}{\sqrt{\pi} c_3} \exp\left(-\frac{4Ln2}{c_3^2} (x - c_4)^2\right) \right] \quad (4.3.5)$$

Figure 4.7. Fitted m^2 distribution before and after the AC $N_{p.e.}$ cut.

The remaining pions and positrons will be rejected by cuts on the m^2 and coincidence time distribution.

Offline Proton rejection

As mentioned in Section 2.4.3.2, two types of WC counters were used in the same layer and have different light collection efficiencies from each other. To unify the application, the kaon peak in the $N_{p.e.}$ distribution of each counter was normalized to 1. Figure 4.8 shows a typical normalized $N_{p.e.}$ distribution for the first layer of the WC and the correlation between the mass square of the particles and the two layers sum total $N_{p.e.}$. The proton can be effectively suppressed by a cut on $N_{p.e.}$, i.e. above

a certain threshold value,

$$N_{WC1} + N_{WC2} \geq X_{WC}, \quad (4.3.6)$$

where X_{WC} is this threshold. The efficiency of the cut is again evaluated by fitting the m^2 distribution as described previously (see Figure 4.9). The optimized X_{WC} value was 1.0, which rejects $\sim 80\%$ of the protons, while keeping the kaon survival rate about $\sim 95\%$ [2]. The remaining protons are then easily rejected by cuts on m^2 and the coincidence time distribution.

Figure 4.8. Typical normalized $N_{p.e.}$ distribution of a layer of WC and the scatter plot with m^2 distribution. **Left:** normalized $N_{p.e.}$ distribution of first layer of WC counters; **Right:** Correlation between the $N_{p.e.}$ sum of both layers and m^2 .

m^2 cut

Figure 4.10 shows the same mass square distribution as that in Figure 4.9, except subtraction of the kaon mass square after application of the previously discussed cuts on the AC and WC. The kaon peak is centered at 0. A distribution of the kaon is then obtained by requiring the following condition:

Figure 4.9. Fitted m^2 distribution before and after WC $N_{p.e.}$ cut.

$$|m^2 - m_{K^+}^2| < 0.3. \quad (4.3.7)$$

The kaon efficiency from this cut is more than 99.0% except for the ^{52}Cr and H_2O targets [2], which had much higher background rates.

Coincidence time cut

Focal plane time represents the time when the particle passes the focal plane. The HKS (HES) focal plane time can be calculated by:

$$t_{fp} = t_1 - l/v, \quad (4.3.8)$$

where t_1 is the reference time determined by the KTOF-1X (ETOF1) counters. The path length l between the KTOF-1X (ETOF1) plane and the focal plane is obtained by tracking. The velocity of the particles were obtained from the reconstructed momenta.

Figure 4.10. Typical fitting result of $m^2 - m_{K^+}^2$ distribution after AC and WC cut.

The focal plane times were then projected to the target plane, employing a spectrometer optical matrix which calculates the full path length between target and the focal plane from the measured focal plane position and angles. This yields the target times for K^+ and e' , T_{HKS} and T_{HES} . The coincidence time is then simply defined as:

$$T_c = T_{\text{HKS}} - T_{\text{HES}}. \quad (4.3.9)$$

Figure 4.11 shows a typical coincidence time distribution before and after the AC, WC and m^2 cuts, and also the correlations between m^2 and T_c without and with the m^2 cut. The real coincidences are defined by the time window:

$$-1 \text{ ns} \leq T_c \leq 1 \text{ ns} \quad (4.3.10)$$

The prominent peak in the coincidence time distribution contains contributions from both real and accidental coincidences. The accidental coincidence arises from the random coincidence between K^+ and e' , not from the same $(e, e'K^+)$ reaction. The contribution from accidentals in the real coincidence peak is assumed to have the same strength as that observed in each of the accidental coincidence peaks as

seen in the “ACC” peaks in Figure 4.11. Since the typical timing resolution in the coincidence time spectrum is about 280 ps, the cut efficiency is more than 99.9%.

4.4 Accidental Background and Mixed Events Analysis

Due to the clean identification of kaons by the aforementioned PID and timing cuts, the background in the reconstructed missing mass spectrum comes only from the accidental coincidence events (see Figure 4.11). This is because the e' singles rate is still high at small forward angles when a high-intensity beam was applied to achieve a maximized production rate.

In order to precisely obtain the background shape and height in the mass spectrum, a mixed event analysis was performed. The events of e' and K^+ from the same as well as from the different accidental peaks (see Figure 4.11) were randomly selected and mixed to create a mass spectrum by the accidental coincidence with substantial statistics, as seen in Figure 4.12. The real coincidence peak was skipped in this selection. The right figure in Figure 4.12 shows a comparison between the spectra analyzed by this mixed event analysis and events selected from only one accidental peak from the $^{12}_\Lambda\text{B}$ production. The spectrum resulting from the mixed events analysis was scaled down by the corresponding multiple factor. With the background spectrum precisely measured, spectroscopic analysis can be carried out without additional background statistical uncertainty. This accidental mass spectrum can be overlaid with the spectrum obtained by the events selected only from the real e' and K^+ coincidence peak (see Section 6.1).

Figure 4.11. Typical coincidence time spectrum and correlation with m^2 . **Top left:** The coincidence time spectra with a sequence of the kaon identification cuts. **Top right:** Typical coincidence time spectrum. The 2 ns time interval of the CE-BAF beam pulse separation can be clearly seen. The True + Acc. peak is aligned to zero, and is fitted by one Gaussian function ($\sigma = 283$ ps). **Bottom left:** The correlation between m^2 and the coincidence time without any cut. **Bottom right:** The correlation between m^2 and the coincidence time after AC, WC, and m^2 cuts.

Figure 4.12. Mixed event analysis for the accidental background. **Left:** Concept of the mixed event analysis. **Right:** result of the mixed event analysis. The hatched region shows the result from the mixed event analysis and the histogram with red line shows the result from normal background analysis that selects the events from only one accidental coincidence peak.

4.5 Cross Section

The statistically averaged (γ^*, K^+) photoproduction differential cross section can be calculated from the experimental yields as the following:

$$\begin{aligned} \overline{\left(\frac{d\sigma}{d\Omega_K}\right)}_{|1^\circ-13^\circ} &= \frac{\int_{\text{HKS}} d\sigma}{d\Omega_K} \frac{1}{d\Omega_K} \int_{\text{HKS}} d\Omega_K \\ &= \frac{1}{N_T} \frac{1}{N_{\gamma^*}} \frac{1}{\epsilon^{\text{common}}} \sum_i^{N_{\text{HY}}} \frac{1}{\epsilon_i^{\text{HES}} \epsilon_i^{\text{HKS}} \Delta\Omega_i^{\text{HKS}}}, \end{aligned} \quad (4.5.1)$$

where N_T is the number of target nuclei, N_{HY} is the yield of hypernuclei obtained by the experimental result, and N_{γ^*} is the number of virtual photons associated with the scattered electrons detected from the HES side. $\Delta\Omega_K$ is the solid angle of the HKS, which depends on the momentum and emission angle of the particle, and was evaluated by a Monte Carlo simulation [65]. ϵ^{HES} is the experimental efficiency of

the HES side, ϵ^{HKS} is the experimental efficiency of the HKS side, and ϵ^{common} is the product of computer live time and the coincidence cut efficiency.

4.5.1 Correction Factors

The efficiencies, ϵ^{common} , ϵ^{HES} and ϵ^{HKS} are defined as:

$$\begin{aligned}\epsilon^{\text{HES}} &= \epsilon^{\text{etrig}} \cdot \epsilon^{\text{etrack}}, \\ \epsilon^{\text{HKS}} &= \epsilon^{\text{ktrig}} \cdot \epsilon^{\text{ktrack}} \cdot \epsilon^{\text{AC}} \cdot \epsilon^{\text{WC}} \cdot \epsilon^{m^2} \cdot f^{\text{abs}} f^{\text{decay}}, \\ \epsilon^{\text{common}} &= \epsilon^{\text{ctime}} \cdot \epsilon^{\text{comp}}.\end{aligned}\tag{4.5.2}$$

The meaning of each factor and their typical values for the data set #7 (^{12}C target with a beam current of $20\mu\text{A}$) are described and summarized in Table 4.1. The detailed description as well as the values of the correction factors for the E05-115 experiment were provided in Ref. [2].

Table 4.1. List of the experimental efficiencies and factors, and typical values for data #7 (see Table 2.17) [2].

Name	Meanings	Typical value and error
ϵ^{etrig}	HES trigger efficiency	98.2 ± 1.2
ϵ^{etrack}	HES drift chamber detection efficiency	91.3 ± 1.8
ϵ^{ktrig}	HKS trigger efficiency	91.4 ± 3.1
ϵ^{ktrack}	HKS drift chamber detection efficiency	98.8 ± 0.2
ϵ^{AC}	AC cut efficiency	98.9 ± 0.5
ϵ^{WC}	WC cut efficiency	96.0 ± 0.5
ϵ^{m^2}	m^2 cut efficiency	99.9 ± 0.01
ϵ^{ctime}	Coincidence time cut efficiency	99.9 ± 0.08
f^{abs}	Kaon absorption factor	95.2 ± 0.1
f^{decay}	Kaon live time factor	29.4 ± 0.8
ϵ^{comp}	Computer live time factor	99.4 ± 0.3
ϵ^{total}		23.8 ± 1.0

4.5.2 Acceptance

The angular acceptance for HKS and HES, respectively, were shown in Figure 4.13 and Figure 4.14 from real data, with the selection of $(e, e'K^+)$ events. The angular acceptance cuts used to derive the solid angle (in units of mrad) are:

for HKS, $\Delta x'_t \in (-210, -30)$, and $\Delta y'_t \in (-50, 50)$;

for HES, $\Delta x'_t \in (-20, 20)$, and $\Delta y'_t \in (30, 105)$.

Figure 4.13. Reconstructed HKS angle at the target plane.

The momentum acceptances were shown in Section 2.1 Figure 2.3. For the cross section calculation, the momentum cuts were applied both for HKS and HES, $1.1 < p_K < 1.3 \text{ GeV}/c$ and $0.8 < p_e < 0.98 \text{ GeV}/c$, respectively, since there is less uncertainty of the magnetic fields in this central region.

4.5.3 Number of Virtual Photons

The number of virtual photons, N_{γ^*} , produced at target point by electron scattering can be obtained by integrating the virtual photon flux factor Γ , over all of the acceptances. In our analysis, the actual integration was carried out by the GEANT simulation that included all of the acceptances and known spectrometer magnetic

Figure 4.14. Reconstructed HES angle at the target plane.

fields:

$$N_{\gamma^*} = \frac{Q_{\text{tot}}}{Q_e} \int d\Omega \int d\omega \Gamma(\theta, \omega), \quad (4.5.3)$$

where ω is the total energy of the virtual photon, Q_{tot} is the total charge converted by beam current monitor, Q_e is the elementary charge, and $\Gamma(\theta, \omega)$ is the virtual photon flux (see Equation 1.6.4) which was used as a probability function in the simulation. The integrated virtual photon flux is 3.54×10^{-5} (2.71×10^{-5}) [1/electron] when the HES collimator position is -7.7 (-4.7) cm (see Section 2.5) [2], with the momentum acceptance cut mentioned above.

SECTION 5

SPECTROMETER SYSTEM CALIBRATION

To obtain accurate mass spectroscopy of hypernuclei with high energy resolution, the spectrometer system must be carefully calibrated. The process of the calibration includes target straggling corrections, forward optical tuning, raster correction, and mathematical spectrometer system calibration.

5.1 Target Straggling Corrections

After applying the kaon identification and coincident time gate, the mass of the hypernucleus (M_{HY}) can be obtained by:

$$\begin{aligned} M_{\text{HY}} &= \sqrt{E_{\text{HY}}^2 - (\vec{p}_{\text{HY}})^2} \\ &= \sqrt{(E_e + M_T - E_K - E_{e'})^2 - (\vec{p}_e - \vec{p}_K - \vec{p}_{e'})^2}, \end{aligned} \quad (5.1.1)$$

where $\vec{p}$ is the three-dimensional momentum vector with the subscripts HY, T, e, K and e' meaning the Λ hypernucleus, nuclear target, the electron beam, the kaon and the scattered electron, respectively. E means the energies of the particles.

The three-momentum vectors ($\vec{p}_e$, $\vec{p}_K$ and $\vec{p}_{e'}$) in Equation 5.1.1 can be described as:

$$\vec{p}_e = (0, 0, p_e), \quad (5.1.2)$$

$$\vec{p}_K = (x'_{tK} \cdot p_{Kz}, y'_{tK} \cdot p_{Kz}, p_{Kz}), \quad (5.1.3)$$

$$\vec{p}_{e'} = (x'_{te'} \cdot p_{e'z}, y'_{te'} \cdot p_{e'z}, p_{e'z}), \quad (5.1.4)$$

where x'_t , and y'_t are the particle emission angles expressed as: $x'_t = p_x/p_z$, $y'_t = p_y/p_z$.

In the current analysis, the mass spectroscopy of the hypernucleus was expressed by the Λ binding energy of the hypernuclei defined by:

$$-B_{\Lambda} = M_{\text{HY}} - M_{\text{core}} - M_{\Lambda}, \quad (5.1.5)$$

where M_{core} is the mass of the nuclei core, and M_{Λ} is the mass of free Λ .

Energy loss in the target by the beam electron e , scattered electron e' and reaction kaon K^+ is one of several important sources that affects the accuracy of M_{HY} calculated kinematically by Equation 5.1.1. The amount of energy loss depends on the reaction point in the target. The target thickness introduces an unavoidable energy loss uncertainty which contributes to the energy resolution. One of the major advantages of electroproduction using the high intensity CEBAF beam is being able to use minimized target thickness while maintaining high production rate. This is an important factor in achieving high energy resolution. The statistical average of the energy loss due to target straggling becomes the residual kinematics off-set which is one of the essential contributions to the mass (or binding energy) precision and thus must be studied carefully and corrected.

For this experiment, the target straggling was studied utilizing a Monte Carlo simulation code Hall C SIMC [75], with the inputs including the kinematics, coordinate, and target geometry and components of the E05-115 experiment. Figure 5.1 shows the example of the SIMC simulated energy loss spectra from the CH_2 target with a thickness of 450.83 mg/cm^2 . The statistical means of energy loss were applied as the first order correction in the mass calculation by:

$$\begin{aligned} E_{\text{beam}} &= E_{\text{beam}}^{\text{measured}} - \Delta E_{\text{beam}}, \\ E_{e'} &= E_{e'}^{\text{measured}} + \Delta E_{e'}, \\ E_{K^+} &= E_{K^+}^{\text{measured}} + \Delta E_{K^+}. \end{aligned} \quad (5.1.6)$$

Figure 5.1. Energy loss spectra of the beam, e' and reaction kaon K^+ , respectively, in the CH_2 target. eeloss is for e' , keloss is for K^+ , and beloss is for e .

This correction was further optimized after the mass spectroscopy was established and the procedure will be discussed in Section 5.1.3. As expected from the Bethe-Bloch formula, the mean energy loss of the particles in the target is linearly proportional to the target thickness as shown in Figure 5.2 and summarized in Table 5.1.

Table 5.1. The linear functions used to describe the mean energy losses in the targets. x is the target thickness.

Target	$\Delta E_{e'}(\text{keV})$	$\Delta E_{\text{beam}}(\text{keV})$	$\Delta E_{K^+}(\text{keV})$
CH_2	$23.810 + 1.149x$	$10.760 + 1.155x$	$-157.9 + 1.373x$
H_2O	$-66.730 + 1.309x$	$56.120 + 1.022x$	$-14.960 + 0.931x$
^{12}C	$9.164 + 0.997x$	$10.190 + 0.9721x$	$4.968 + 0.750x$
^7Li	$6.967 + 0.718x$	$8.638 + 0.892x$	$2.667 + 0.718x$
^{10}B	$12.434 + 0.952x$	$11.508 + 0.972x$	$7.572 + 0.741x$

5.1.1 Energy Loss Corrections for CH_2 Target

Since the Λ and Σ^0 events produced from the CH_2 target using the $p(e, e'K^+)$ reaction were used for both kinematics calibration and optimization of the reconstruction matrices for the experiment, its kinematics definition must be accurate. Due to the

Figure 5.2. The linear functions used to describe the mean energy losses in the CH₂ target.

beam burning effect for the CH₂ target, its average thickness is not perfectly known. On the other hand, the CH₂ target contains a C component which can produce $^{12}_{\Lambda}\text{B}$ hypernuclei via $\text{C}(e, e'K^+)^{12}_{\Lambda}\text{B}$ reaction, the same as that from the pure ^{12}C production target for which the thickness was precisely known. This enables an effective thickness calibration for the CH₂ target by aligning its spectroscopy of $^{12}_{\Lambda}\text{B}$ hypernuclei to that obtained from the pure C target.

The straggling corrections were applied and optimized to the ^{12}C target data in obtaining the $^{12}_{\Lambda}\text{B}$ spectrum. The events from the CH₂ target were also analyzed with the $^{12}\text{C}(e, e'K^+)^{12}_{\Lambda}\text{B}$ kinematics to generate the same $^{12}_{\Lambda}\text{B}$ spectrum formed by the events from the ^{12}C component in the CH₂ target. Although the statistics are lower, the peaks of the ground state and the p -shell states are sufficiently well recognized. Energy loss corrections corresponding to various CH₂ target thicknesses were scanned to find the best simultaneous alignment of both the ground and p -shell states between the two spectra. The two peak alignments can also reduce the overall systematic uncertainty of the alignment caused by a higher statistical uncertainty for each of

two peaks in the spectrum from the CH_2 target. During the scanning, the linear functions shown in Table 5.1 were used to extract the energy loss corresponding to various target thicknesses.

Since the energy loss correction for the ^{12}C data was iterated with the mathematical spectrometer calibration until optimum, the effective CH_2 target thicknesses were also carried correspondingly in the iteration. The final best effective thickness of the CH_2 target is 380 mg/cm^2 , and the corresponding energy loss corrections are: $\Delta E_{\text{beam}} = 450 \text{ keV}$, $\Delta E_{e'} = 460 \text{ keV}$, and $\Delta E_{K^+} = 364 \text{ keV}$.

Figure 5.3 shows the alignment of the two spectra. The s - and p -shell peaks are both aligned within 10 keV. The statistical uncertainties of the s - and p -shell peaks from the ^{12}C target are $\pm 19 \text{ keV}$ and $\pm 33 \text{ keV}$, respectively. The uncertainties for those from the CH_2 target are $\pm 130 \text{ keV}$ and $\pm 190 \text{ keV}$, due to low statistics.

Figure 5.3. Alignment of the spectra of ^{12}B obtained by the $^{12}\text{C}(e, e'K^+)^{12}\text{B}$ reaction from the CH_2 and ^{12}C targets. The peaks are fitted by a single Gaussian shown as red line.

With optimized energy loss correction, the kinematics calibration for the experiment can be done using the known masses of Λ and Σ^0 produced from the CH₂ target. The statistical uncertainties in these alignment peaks contribute a systematic uncertainty to the absolute mass or binding energy of hypernuclei but not to the excitation energy relative to the ground state. By involving the two peaks in the alignment procedure, statistical uncertainty is reduced and the contribution to the systematic uncertainty of the binding energy for heavier hypernuclei is found to be ± 90 keV. Energy loss corrections were applied to all of the production targets, but separately optimized following the optics optimization iteration.

5.1.2 Energy Loss Corrections of H₂O Target

The H₂O target was also used to produce free Λ and Σ^0 during a small part of the production runs and was aimed to involve them for optics optimization. Its average thickness is also not precisely known due to the water cell geometry. In order to make sure the H₂O and CH₂ targets are under a unified kinematics, its effective thickness was calibrated by referring the mass of Λ and Σ^0 to that produced by the CH₂ target.

Similar to the alignment between the targets ¹²C and CH₂, the effective thickness of H₂O was found by the best simultaneous alignment of both Λ and Σ^0 between the two spectra from the targets CH₂ and H₂O, seen as Figure 5.4, to be 565 mg/cm², and the corresponding energy loss corrections are: $\Delta E_{\text{beam}} = 635$ keV, $\Delta E_{e'} = 674$ keV, and $\Delta E_{K^+} = 512$ keV.

5.1.3 Effective Target Thickness Scan

To optimize the target energy straggling correction, the spectra of the hypernuclei were obtained from the targets ¹²C, ¹⁰B and ⁷Li produced with various energy loss corrections corresponding to various effective target thicknesses. The linear functions shown in Table 5.1 were used to calculate the energy loss according to the thickness.

Figure 5.4. Alignment of spectra of Λ and Σ^0 obtained by the $p(e, e'K^+)\Lambda, \Sigma^0$ reaction from the CH_2 and H_2O targets.

With the optimum energy loss corrections, the kinematics of the production should be in the best known condition. Then the ground state peak in the spectra of hypernuclei should have the smallest width and the maximized number of the real events above the background. Thus, this can be achieved by maximizing the ratio of the integrated number of events above the background from the ground state peak (from a Gaussian fit) to the fitted peak width (σ). The thickness was scanned with a step size of 1 mg/cm^2 for a range from 50% and 150% of the thickness shown in Table 5.1. A function of 2nd order polynomial is used to fit the correlation of the ratio to the scanned target thickness to obtain the most optimum target thickness, as shown in Figure 5.5 for the ^{12}C target. This target thickness scan, as well as the calculation of the target straggling corrections of the CH_2 and H_2O , were iterated following the mathematical spectrometer optics calibration to be discussed in Section 5.4. Table 5.2 summarizes the final effective target thickness and the corresponding corrections for the targets $^{12}_\Lambda\text{C}$, $^{10}_\Lambda\text{B}$ and $^7_\Lambda\text{Li}$.

Figure 5.5. Target thickness scan for ^{12}C . **Top:** The spectrum of the $^{12}_{\Lambda}\text{B}$. The red line is the fitted Gaussian function. **Bottom:** The ratio of the total number of events in the ground state peak over the peak with (sigma) as a function of the scanned target thickness.

Table 5.2. The effective target thickness and corresponding mean energy loss.

Target	Thickness(mg/cm ²)	$\Delta E_{e'}$ (keV)	ΔE_{beam} (keV)	ΔE_{K^+} (keV)
^{12}C	108	117	115	86
^7Li	204	194	191	149
^{10}B	75	84	84	63

5.2 Forward Optical Tuning

Forward optical tuning is a process of the spectrometer magnetic field map study using GEANT simulation with the criteria from the data of the sieve slit (SS) and the CH₂ target runs. The purpose is to find a map that gives a close expression of the real magnetic field.

Although each of the magnets was precisely mapped individually and the TOSCA calculation could extend the field map reliably to the regions where the field mapper could not reach, the significant cross talk connected by the SPL (as mentioned in Section 5.4) introduced large unknown field asymmetries in both the HKS and the HES. This caused the initial reconstruction matrices obtained using the events generated by the GEANT simulation to deviate far from reality. Studies showed that the optics cannot be fully optimized by the mathematical method with the initial matrices too far from reality.

The SS position (x_s, y_s) distribution shown in the following was reconstructed from the measured focal plane (FP) parameters by the equation (F2S equation):

$$\begin{pmatrix} x_s \\ y_s \end{pmatrix} = \begin{pmatrix} M_{F2S} \end{pmatrix} \begin{pmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ (x_f)^2 \\ x_f \cdot x'_f \\ \cdot \\ \cdot \\ x_f'^5 \cdot y'_f \\ y_f'^6 \end{pmatrix}, \quad (5.2.1)$$

where the M_{F2S} is the matrix fitted by the data from GEANT simulation (seen in Appendix A). (x_f, y_f) is the FP position, and x'_f and y'_f are the FP angles.

5.2.1 Procedure of Forward Tuning

As mentioned above, the real field map deviated significantly from that calculated by the TOSCA model. It can be easily recognized from a comparison between the events taken experimentally by the SS runs and those generated by the GEANT simulation, as shown in Figures 5.6 and 5.7. Each plot in both figures represents the events for which the particles passed through one column of the holes on the SS plane (see Figure 5.8). The columns are labeled from c1 to c10 on the HKS side and from c2 to c10 on the HES side, corresponding to the particle positions from far from to near to the beam direction. Since only a few particles passed through columns on the two sides, events from the c1 and c11 columns on the HES side are not shown. Figure 5.8 shows also the reconstructed SS patterns for both the HKS and the HES, using the matrices fitted by the GEANT simulation data with the field map calculated by the TOSCA model.

Comparing the events colored in blue and magenta in Figure 5.6, the simulated distribution on the FP obviously does not match that from the real data, and the level of disagreement appears to increase from c1 to c10, showing a geometric dependence. This also happened to HES, as seen in Figure 5.7. Due to the application of the “tilt method”, the asymmetric pattern on the HES side is expected. In Figure 5.8, the reconstructed spots are not located at the position of the SS holes, indicating that the reconstruction matrices obtained from simulation are not properly representing the real optics. Such an effect can also be seen in the correlations between the calculated mass of Λ and Σ^0 and the reconstructed momentum and target angles. The invariant mass becomes strongly correlated to the kinematics parameters, indicating that the kinematics parameters were incorrectly reconstructed, as seen in Figure 5.9.

Figure 5.6. The HKS FP x-y correlation pattern before the forward optical tuning. The blue patterns are from GEANT simulation and the magenta ones are from the real SS data. The map in the simulation is from the TOSCA calculation.

Figure 5.7. The HES FP $x - y$ correlation pattern before the forward optical tuning. The blue patterns are from GEANT simulation and the magenta ones are the real SS data. The map in the simulation is from the TOSCA calculation.

Figure 5.8. Reconstructed SS pattern before forward tuning. **Left:** Reconstructed SS distribution from real data on the HKS side. **Right:** That on the HES side. The matrices used for reconstruction are from the GEANT simulation with the map from the TOSCA calculation. The reconstructed spots are not located at the position of the holes as the matrices used to make the reconstruction do not represent the true optics.

Therefore, there are three criteria which can be used to judge the quality of the field map: matching of the FP patterns between the simulated and real data, positions and pattern of the SS holes, and the independency of the calculated invariant mass of Λ and Σ^0 to the kinematic parameters.

The procedure of the forward optical tuning is illustrated by the flow chart in Figure 5.10. Sources of problems and solutions were carefully studied using the GEANT simulation.

The explanations of each part of the procedure are as follows:

1. The magnetic field map used in the simulation was studied for each element. The investigations included the 3-dimensional position off-sets, the field strength deviation from the assumed setting, the SPL fringe field range variation, and the position dependent asymmetry of the field map caused by the interference between the SPL

Figure 5.9. The correlations between masses of Λ , Σ^0 and the kinematic parameters before forward tuning. P_K is the momentum of K^+ , $P_{e'}$ is the momentum of the scattered electron, X'_K and Y'_K are the angles of K^+ , $X'_{e'}$ and $Y'_{e'}$ are the angles of the scattered electron.

Figure 5.10. Flow chart of the forward tuning on the field map.

and Q1 magnets in the HKS and the HES. The field asymmetry was expressed by a position dependent 3-dimensional correction factor function written in terms of 3rd order polynomials which corrects both transverse and longitudinal fields according to positions.

2. SS events were simulated for each of the changes made to the field map to study the optical character change in comparison to that from the real SS data.

3. Optical events from a point target were also generated to obtain new reconstruction matrices corresponding to the change. Then the real SS data was re-analyzed to reconstruct the pattern of SS holes on the SS plane to study the change of the optical characters represented by the matrices.

4. The CH2 data was re-analyzed by the new matrices to check the correlations between the reconstructed kinematics parameters (momentum and angles) and the invariant mass of Λ and Σ^0 to find the effect to the kinematics.

5. Each of the above sources was treated as an ingredient, and combination of them was made according to the need in meeting all three of the criteria.

6. Iterations were made until all three of the criteria were simultaneously met.

This was a massive work which is time consuming but necessary to resolve the problems. The study found that the dominant optics change from the original design of the spectrometer system comes from the field interference between the SPL and the HKS (HES) magnets. This interference leads to significant asymmetries in the magnetic field for both spectrometers. Corrections to the field map were needed in order to obtain the matrices closely representing the real optics. The correction functions were found and are shown in detail in Appendix B, as well as the other changes to the magnetic field.

5.2.2 Results of Forward Tuning

After the the above discussed forward optical tuning, the $x - y$ correlation pattern on the FP (simulation and real data comparison) and the reconstructed SS pattern (comparison to the known pattern of holes) showed close agreement to the first order. The correlations between invariant mass and kinematic parameters show good independency, as seen in Figures 5.11-5.14.

As seen in Figures 5.11 and 5.12, the cross points of the $x - y$ pattern on the FP from the simulated and real data match together, and the 2-dimensional distributions, band-by-band, overlap with each other in general. The reconstructed pattern of SS holes for the HKS and the HES SS spots are shown in Figure 5.13 and a good match was reached. These ensured that the matrices are close to the real optics and they can be further optimized by the mathematical tuning method. As shown in Figure 5.14, a small dependency between the invariant mass of Λ and Σ^0 and the kinematic parameters still exist. This comes from the part of the optics which is expressed by higher order terms in the matrices. The mathematical optimization has the ability to further improve this part of optics and will be discussed in Section 5.4.

Figure 5.15 shows the spectra of Λ and Σ^0 obtained from the CH_2 target after forward tuning. The Cauchy function is used to fit the peaks combining with a 3rd order polynomial describing the background, as the following:

$$\begin{aligned} F(x) &= C(x) + a_0 + a_1x + a_2x^2 + a_3x^3 \\ C(x) &= \frac{1}{\gamma\pi[1 + (\frac{x-x_0}{\gamma})^2]} \end{aligned} \quad (5.2.2)$$

Here $\frac{1}{\gamma\pi}$ describes the amplitude of the peak, x_0 gives the mean value, and γ gives the width (the half-width at half maximum, HWHM). The polynomial is used to describe the background shape. The fitted results are shown in Table 5.3. At the current quality of the optics and kinematics, the width (FWHM) of the ^{12}B ground

Figure 5.11. The HKS FP $x - y$ correlation pattern after forward optical tuning.

Figure 5.12. The HES FP $x - y$ correlation pattern after forward optical tuning.

Figure 5.13. Reconstructed SS distribution after forward optical tuning. **Left:** HES SS distribution of real data. **Right:** HKS SS distribution of real data. The reconstructed spots are now located at the position of the holes as the matrices used to make the reconstruction closely represent the true optics.

Table 5.3. Fitting results for the spectra on Figure 5.15.

Particle	Mean(MeV)	FWHM(MeV)
Λ	0.450 ± 0.0353	2.832 ± 0.0980
Σ^0	76.740 ± 0.0900	3.270 ± 0.2260

state peak from the ^{12}C target runs with a beam current of $20\mu\text{A}$, was still around 6 MeV.

5.3 Raster Correction

For electroproduction physics with a high intensity primary beam, particles are detected only at the FP. The momentum vector on the target must be reconstructed from the measured FP parameters, i.e., the focal plane coordinates (x_f, x'_f, y_f, y'_f) matrix, under the condition of the point target, i.e., the target plane coordinate

Figure 5.14. The correlation between missing mass of Λ , Σ^0 and the reconstructed kinematic parameters after forward tuning. P_K is the momentum of K^+ , $P_{e'}$ is the momentum of the scattered electron, X'_K and Y'_K are the angles of K^+ , $X'_{e'}$ and $Y'_{e'}$ are the angles of the scattered electron.

Figure 5.15. Spectra of Λ and Σ^0 after forward optical tuning. The fitting function is a Cauchy function plus a 3rd order polynomial.

matrix $(x_t = 0, x'_t, y_t = 0, y'_t)$. Here $(x'_t$ and $y'_t)$, the in-plane and off-plane angles, define the scattering angle. The two coordinate matrices are related uniquely by the spectrometer optics, the optical matrices.

However, in some cases the point beam must be spread over a finite area by the raster technique. In this experiment, the raster was applied to the CH_2 and ^7Li targets to protect them against damaging or melting. Figure 5.16 shows the dispersed beam position pattern observed from a typical CH_2 target run. A beam burning effect is visible at the center region.

Such a spread of the beam position on the target breaks the uniqueness of the optical matrices. In other words, the FP position is spread following the beam raster. This introduces the spread of the reconstructed momentum and angles. Therefore, the raster correction is needed. This is particularly important in the case of Λ and Σ^0 production from the CH_2 target, since the known masses of these particles are used for kinematics calibration, and the events selected from these two peaks are used also for optimization of optical matrices. Without proper correction, the spread will result in uncertainties in the kinematics and the optics and will affect the precision and resolution in reconstructing the mass of hypernuclei.

The recorded 2-dimensional raster amplitudes and the raster phases provide the information for the beam position on target with precisely known frequency.

There are two methods used to do the raster correction (1) applying the corrections on the reconstructed momentum vector on the target and (2) correcting on the FP coordinate matrix. For the first method, the corrections of momentum vector are written as functions of the beam position on the target. This method depends on the linearity of the spectrometer optics in terms of the beam position variation. For the second method, the corrections for the FP coordinates are written as functions (expressed in matrices) of the beam position on target. The corrected FP coordinates can then be used in reconstructing the momentum vector at the target as in the case of the point target.

The raster correction was studied by the GEANT simulation to determine the effectiveness of the two methods. The second method was proven more effective; see the comparison in Figure 5.17. The correction recovers the original peak shape and height. The correction appears to be able to restore the target to the FP correspondence correctly and this is critically important for the optics optimization, which depends on each selected individual event (see Section 5.4).

5.4 Mathematical Spectrometer System Calibration

The mathematical spectrometer system calibration is applied to achieve the expected sub-MeV resolution. It includes optical calibration and kinematic calibration.

In the E05-115 experiment, the SS plate was placed in front of each spectrometer and behind the common SPL which introduces momentum dispersion at the SS plane. This dispersion widens the angular acceptance correlation of each small SS hole and causes a correlation between momentum and angles for the selected events. In other words, events from a given hole cannot uniquely define a set of angles independent

Figure 5.16. Beam position distribution on the target plane from CH₂ runs. The nonuniform density distribution is caused by the beam burning effect.

of momentum. Therefore, the techniques of the 2-arm coupled calibration had to be used for both kinematics and optics.

5.4.1 Calibration Overview

The missing mass calculated by the equation given in Section 5.1 is simply the function of the known and the reconstructed kinematic parameters at the target as:

$$M_{\text{HY}} = f(E_{\text{beam}}, P_K, x'_{tK}, y'_{tK}, P_{e'}, x'_{te'}, y_{te'}), \quad (5.4.1)$$

where P_K and $P_{e'}$ are the scalar momenta of the K^+ and the scattering electrons, respectively, which will be simply mentioned as the momenta of the particles in the following discussion.

Various unknown experimental defects, such as the absolute beam energy accuracy, precision in setting the spectrometer magnets, and change of the total integral

Figure 5.17. Comparison of the mass error δM for raster correction studied by GEANT simulation. The δM for an event is defined by the difference between the generated mass and the reconstructed mass. **Left:** Raster correction was made directly to the target plane momentum vector. **Right:** Raster correction was applied to the FP parameters. “ori” is the data set without raster effect, “without correction” is the data set with raster effect but without correction, “raster correction” is the data set with raster effect and with correction.

of $B \cdot dl$ due to the field cross talk which affects the fringe field distribution, can introduce “off-sets” to the assumed central kinematics definition and cause kinematic errors in calculating the missing mass. This error can appear as an absolute mass shift, a mass scale change, and a poorer energy resolution. Effectively, due to such defects, Equation 5.4.1 is changed to:

$$M_{\text{HY}} + \Delta M_{\text{HY}} = f(E_{\text{beam}0} + \Delta E_{\text{beam}0}, (P_{Kd0} + \Delta P_{K0})(1 + \delta_K/100), \quad (5.4.2)$$

$$x'_{tK}, y'_{tK}, (P_{e'd0} + \Delta P_{e'0})(1 + \delta_{e'}/100), x'_{te'}, y'_{te'}),$$

where $\delta_{e'}$ and δ_K are the relative momentum referring to the assuming central momentum. $E_{\text{beam}0}$, P_{Kd0} and $P_{e'd0}$ are the expected beam energy, central momenta of K^+ and the scattering electron, respectively. Additional defects which are not included in this expression can come from the deviation of the defined central spectrometer

angle of the HKS and the HES. Therefore, kinematic calibration is the process to find the effective corrections of the associated kinematics parameters in order to achieve the highest possible mass precision.

Optically, the kinematic parameters from each spectrometer, momentum and angles at the target plane, were reconstructed from the measured FP coordinate vector by the 6th order transfer matrices (F2T) with a goal of reaching an accuracy level of 10^{-4} as:

$$\begin{pmatrix} x'_t \\ y'_t \\ \delta \end{pmatrix} = \begin{pmatrix} M_{angle} \\ M_{momentum} \end{pmatrix}_{F2T} \begin{pmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ (x_f)^2 \\ x_f \cdot x'_f \\ \cdot \\ \cdot \\ (x_f)^5 \cdot x'_f \\ (x_f)^6 \\ \cdot \\ \cdot \end{pmatrix} \quad (5.4.3)$$

There are a total of about 1300 matrix elements involved (more than 200 for each kinematic parameter). The optical calibration is the process to find the best matrix elements (or the best combination of them) in the F2T matrices (see in Section 5.4.2) to achieve the highest possible resolution.

Due to the application of a common SPL magnet in the experimental configuration, no single-arm calibration by elastic scattering could be performed. Thus, this experiment had to use the events from well-known reactions for calibrations on both kinematics and optics. The chosen sets of data for calibration are listed in Table 5.4.

Table 5.4. Data set for the mathematical spectrometer system calibration. BG means background, BC means the beam current, and S/N means the signal-to-background ratio.

Target	Mass	Events # above BG	S/N(in 2.5σ)
CH ₂	Λ	4988	3.54
CH ₂	Σ^0	2650	1.40
H ₂ O($p_e \sim 2.364$ GeV)	Λ	283	2.96
$^{12}\text{C}(\text{BC} = 20 \mu\text{A})$	$^{12}_{\Lambda}\text{B}_{\text{gs}}$	309	1.61

The events from $^{12}_{\Lambda}\text{B}_{\text{gs}}$, the ground state of $^{12}_{\Lambda}\text{B}$, were initially from the runs only with a $20 \mu\text{A}$ beam current for better S/N ratio. Events from $35 \mu\text{A}$ beam runs were added later when the resolution reached $\sigma = 0.5 \text{ MeV}/c^2$ to increase the statistics. The events from the dominant p-shell peak of $^{12}_{\Lambda}\text{B}$ were further added in the momentum matrices optimization when the resolution approached to $\sigma = 0.4 \text{ MeV}/c^2$ to ensure uniform precision in the optics in the mass region of the hypernuclei.

As shown in Table 5.4, the beam energy applied for the H₂O target is 20 MeV higher than that for the rest of the production targets. Figure 5.18 illustrates the mass correlation between the momenta of the scattered electron and the reaction K^+ . It can be seen that by raising beam energy from $2.344 \text{ GeV}/c$ to $2.364 \text{ GeV}/c$, the correlation line of Λ produced by the $p(e, e'K^+)$ reaction is moved near to the line of $^{12}_{\Lambda}\text{B}_{\text{gs}}$ produced by the $^{12}\text{C}(e, e'K^+)$ reaction. It enlarges the Λ coverage on the kinematic space, thus the purpose of these events was to help better define the kinematics and optics.

The kinematics calibration involved events from Λ and Σ^0 peaks only. Their masses are well-known and only the statistical means taking into account of radiative tail contribution are needed to determine the correct kinematics space.

Events from $^{12}_{\Lambda}\text{B}$ were involved only for optics calibration in optimizing the momentum reconstruction matrices. Since Λ and Σ^0 are light projectiles with a signifi-

Figure 5.18. Mass correlation between momenta of K^+ and the scattered electron, calculated at $\theta_e = 0.0$ rad and $\theta_{K^+} = 0.17$ rad. The beam energy is $E_e = 2.344$ GeV for Λ (green), Σ^0 (red), and $^{12}_\Lambda B_{gs}$ (blue and $-B_\Lambda$). The correlation in black is Λ with beam energy $E_e = 2.364$ GeV.

cant correlation between their momenta and recoil angle, their energy resolutions are almost equally sensitive to the quality in the momentum and angle reconstruction matrices. Thus, these events alone cannot separate the contributions from the two types of matrices. In contrast, hypernuclei are much heavier than Λ and Σ^0 . Simulation studies showed that their mass resolutions depend almost solely on the quality of the momentum reconstruction matrices.

$^{12}_\Lambda B$ is the best known hypernucleus studied previously by electroproduction (and well measured by emulsion), thus events from its ground state and the well-isolated dominant p -shell peak are suitable to be used for the momentum matrix optimization. In addition, their production cross sections are the largest among all the p -shell hypernuclei. Sufficient statistics can be reached within a relatively short beam time for the HKS experiments. Therefore, involving events from $^{12}_\Lambda B$ with higher weights over the events from Λ and Σ^0 is to optimize the momentum matrices only. On the other hand, these events were not involved in the optimization of the angle reconstruction

matrices since they are not sensitive to angle uncertainties (about 40 times smaller angular dependence than Λ and Σ^0).

The events from Λ and Σ^0 were kept in the optimization of the momentum matrices with an optimized low level. They were used to prevent local defects by optics to the kinematics space due to the large amount of degree of freedom from the optical matrices. Thus, they are necessary to ensure uniform precision over the full kinematics space. However, their involvement would certainly reduce the effectiveness in the optimization of the momentum matrices. Therefore, iteration is needed and the optimization of the momentum matrices took many more iteration steps than those of angle matrices. The ultimate optimization was achieved by iterations between the optimization of the angular and momentum matrices.

5.4.2 Procedures of the Calibration

The procedures of the mathematical spectrometer system calibration are illustrated by the flow chart shown in Figure 5.19.

Figure 5.19. The procedure of the mathematical optical and kinematic optimization for the spectrometer.

In the current analysis, the process of calibration starts from the iteration between angle and momentum matrices optimization, since the masses of Λ and Σ^0 had higher order dependence on the kinematic parameters (see Figure 5.14).

One loop of the procedure of nonlinear χ^2 minimization is shown in Figure 5.20, and the fitting process was carried out by Minuit [76]. The χ^2 is defined as:

$$\chi^2 = \sum \chi_i^2, \quad (5.4.4)$$

where i stands for the i th selected peaks of the masses which were included in the tuning. χ_i^2 is defined as:

$$\chi_i^2 = \frac{\omega_i}{(dof)_i} \sum_k^{N_i} \left(\frac{M_k^{\text{calc}} - M^{\text{ref}}}{\sigma_k} \right)^2, \quad (5.4.5)$$

where dof is the degree of freedom, N is the number of events used for the χ^2 calculation, ω is the statistical weight for the selected mass, and M^{ref} is the mass reference. The data from PDG [21] was chosen for Λ and Σ^0 . The fitted results from the starting point of the current loop were chosen for the ${}^{12}_{\Lambda}B$ peaks. The matrix elements were varied in searching for the minimized the χ^2 . In each loop of iterations, such minimization of χ^2 was repeated ten times, which is sufficient to achieve convergence of the χ^2 .

For the momentum matrices, the ratio of the statistical weight was adjusted between loops as needed by analyzing the peak width change of ${}^{12}_{\Lambda}B$ in comparison to that of Λ and Σ^0 . The peak width of the masses included in the tuning should become narrower. At the same time, the peak width in the spectrum of the other hypernuclei which were not involved in the calibration, such as ${}^{10}_{\Lambda}\text{Be}_{\text{gs}}$, ${}^7_{\Lambda}\text{He}_{\text{gs}}$, should follow the progress. Improperly chosen weight could result over tune, i.e. broadening of the peak width in the uninvolved spectroscopy. For this case, the weight would be

re-evaluated and adjusted. The process was then repeated from the rewind version of the F2T matrices.

Figure 5.20. Procedure of nonlinear χ^2 minimization.

The kinematics calibration involves two separated steps. The procedure of the $\Delta p_{e'}$ and Δp_{K^+} optimization was similar to the momentum and angle matrices optimization, except only the single 0th order matrix element in the reconstruction matrices were tuned by the process of minimization of the χ^2 . On the other hand, these elements were not tuned in the optics optimization. Only the events from Λ and Σ^0 were used, and $\omega_\Lambda : \omega_\Sigma = 1 : 1$.

The effective beam energy shift ΔE_{beam0} is searched by a beam energy scan with the criteria of χ_1^2 and χ_2^2 which are defined as follows:

$$\chi_1^2 = \omega_\Lambda \frac{(M_\Lambda^{\text{fit}} - M_\Lambda^{\text{PDG}})^2}{\langle \sigma_\Lambda \rangle^2} + \omega_\Sigma \frac{(M_\Sigma^{\text{fit}} - M_\Sigma^{\text{PDG}})^2}{\langle \sigma_\Sigma \rangle^2}, \quad (5.4.6)$$

$$\chi_2^2 = \omega_\Lambda \frac{(\sigma_\Lambda^{\text{fit}})^2}{\langle \sigma_\Lambda \rangle^2} + \omega_\Sigma \frac{(\sigma_\Sigma^{\text{fit}})^2}{\langle \sigma_\Sigma \rangle^2}, \quad (5.4.7)$$

where $\langle \sigma_i \rangle$ ($i = \Lambda, \Sigma^0$) are the fitted σ of the corresponding peak.

Figure 5.21 is a typical correlation between χ_1^2 and χ_2^2 from the scan. The marker in the red circle was considered as the best point, and the corresponding ΔE_{beam0} was chosen as the corrections for the needed beam energy corrections in the current cycle of iteration.

Figure 5.21. The correlation of the two χ^2 defined for the beam energy scan.

The optical and kinematic calibrations were alternated in continued iteration, until reached

$$|M_{\Lambda}^{\text{fit}} - M_{\Lambda}^{\text{PDG}}| \leq 50 \text{ keV}, |M_{\Sigma}^{\text{fit}} - M_{\Sigma}^{\text{PDG}}| \leq 50 \text{ keV}$$

and peak width of Λ , Σ^0 and ${}^{12}\text{B}_{\text{gs}}$ were the narrowest.

The procedure of the target straggling optimization was repeated after each loop of the spectrometer calibration, seen as Figure 5.22.

Figure 5.22. The iterated procedure of the mathematical system calibration and the target straggling optimization.

5.5 Calibrated Spectroscopy of Λ and Σ^0

The missing mass spectra from the CH_2 target obtained by the E05-115 and the E01-011 experiments are shown in comparison in Figure 5.23. They were calibrated independently by the same procedure presented above. There are two types of background in the spectrum of Λ and Σ^0 : accidental background and ^{12}B quasi-free from ^{12}C component data analyzed with $p(e, e'K^+)$ kinematics. The accidental background shape can be obtained precisely by the mixed event method mentioned in Section 4.4. The quasi-free background shape can be experimentally obtained from the ^{12}C target data analyzed by $p(e, e'K^+)$ kinematics, seen in Figure 5.24. The shape of the quasi-free background was fitted with a 3rd order polynomial which would be used for fitting the Λ and Σ^0 peaks.

In order to compare with the spectra before the mathematical tuning, the final spectra of Λ and Σ^0 are fitted by a Cauchy function and a background shape shown as Figure 5.25. The mass separation of Λ and Σ^0 obtained from the E05-115 experiment is $76.970 \pm 0.031 \text{ MeV}/c^2$, while that obtained from the E01-011 experiment is $76.987 \pm$

Figure 5.23. Spectroscopy of free Λ and Σ^0 by the reaction $p(e, e'K^+)$ from the CH_2 target. The mass is presented in terms of Λ binding energy.

Figure 5.24. Background of the Λ and Σ^0 spectroscopy.

$0.100 \text{ MeV}/c^2$. They are consistent with each other. The results from these two experiments are summarized in Table 5.5 for comparison.

Figure 5.25. Spectra of Λ and Σ^0 fitted by Cauchy function.

Table 5.5. The fitted results of the reconstructed mass Λ and Σ^0 from the two HKS experiments. The units for the masses are MeV/c^2 .

	$-B_\Lambda(\Lambda)$	Width (FWHM)	$-B_\Lambda(\Lambda)$	Width (FWHM)
E05-115	-0.030 ± 0.015	1.436 ± 0.036	76.940 ± 0.027	1.281 ± 0.070
E01-011	0.014 ± 0.033	1.998 ± 0.085	77.001 ± 0.094	1.946 ± 0.243

For the absolute binding energy of hypernuclei, the contribution from this calibration to the overall systematic uncertainty is found to be $\sim 27 \text{ keV}$ for the E05-115 experiment and $\sim 43 \text{ keV}$ for the E01-011 experiment from the fitting uncertainty, and the uncertainty of the free Λ mass from the PDG data was used [21]. This uncertainty is named as “ Λ mass precision” in Section 6.

5.6 Missing Mass Resolution and Optics Defect Uncertainty

5.6.1 Missing Mass Resolution

The missing mass resolution is contributed by the intrinsic mass resolution, and the mass offset due to the target energy loss uncertainty. Both of them can be evaluated by a blind analysis.

A blind analysis of simulation data was carried out to evaluate the systematic error originated from the matrix optimization processes. It was also used to study the contribution to the accuracy from each individual source, such as the FP parameter precision, target thickness and energy straggling, beam position raster size, angle and momentum uncertainties from optically optimized matrices at each stage.

Calibration data from Λ and Σ^0 elementary production and the ^{12}C target data from the physics states with several arbitrary masses and various statistics were artificially generated by a Monte Carlo simulation. The quality, including the background level, was generated to be the same as in the experiment. Other than the elementary process, the masses of the physics states were hidden to the analyzer. The same optimization analysis was carried out on the simulated physics data starting with the artificially “deformed” reconstruction matrices. The finalized results were then compared to the input masses of the states to examine the precision and systematic uncertainty in determination of the absolute missing mass (or binding energy) and excitation energy. The expected missing mass resolutions for various targets evaluated by the blind analysis are shown in Table 5.6.

The best resolution is expected for the $^{10}_{\Lambda}\text{Be}$ and $^{12}_{\Lambda}\text{B}$ spectroscopy. The resolution of $^7_{\Lambda}\text{He}$ is expected to be worse because of the larger contribution from the target straggling due to much a thicker target. The expected width of the Λ and Σ^0 is contributed by the thickness and larger recoil.

Table 5.6. The anticipated missing mass resolution evaluated by blind analysis. [65]

Hyperon Hypernucleus	Target	Intrinsic (keV)	Target Straggling (keV)	Total(FWHM) (keV)
Λ	CH_2	830	1000	1380
${}^7_{\Lambda}\text{He}$	${}^7\text{Li}$	440	260	750
${}^{10}_{\Lambda}\text{Be}$	${}^{10}\text{B}$	440	80	540
${}^{12}_{\Lambda}\text{B}$	${}^{12}\text{C}$	440	130	550

5.6.2 Optics Defect Uncertainty

The process of the optical matrices tuning may cause a shift of the missing mass in the absolute energy scale, called optics defect uncertainty. An optics defect can result from the difference of the generated missing mass (mm_{gen}) and the calculated missing mass (mm_{tuned}) by the constructed momenta and angles from the simulation data; see Figure 5.26. In order to eliminate the statistic uncertainty, a large number of events is generated. The matrices from the above spectrometer system calibration procedure is used to reconstruct the momenta and angles. The mean value of the difference for Λ is ~ 21 keV, and for ${}^{12}_{\Lambda}\text{B}$ is ~ 44 keV. The optics defect uncertainty is smaller than ~ 50 keV.

Figure 5.26. Missing mass shift caused by the optical matrix optimization. **Left:** Λ from CH_2 . **Right:** ${}^{12}_{\Lambda}\text{B}$ from ${}^{12}\text{C}$ target.

SECTION 6

RESULTS AND DISCUSSION

In this section, the mass spectra of ${}_{\Lambda}^{12}\text{B}$, ${}_{\Lambda}^{10}\text{Be}$, and ${}_{\Lambda}^7\text{He}$ hypernuclei obtained by the experiment E01-115 will be described. The mass spectroscopy of ${}_{\Lambda}^{12}\text{B}$ from the experiment E01-011 is also included in the discussion.

6.1 Spectroscopy of ${}_{\Lambda}^{12}\text{B}$ and Discussion

6.1.1 Spectroscopy of ${}_{\Lambda}^{12}\text{B}$

The spectra of ${}_{\Lambda}^{12}\text{B}$ independently obtained from the experiments E05-115 and E01-011 are shown as Figure 6.1. The accidental background (shape and height), seen as indicated by the red line in the figure, was obtained precisely with negligibly small statistical uncertainty by the method of mixed event analysis, which randomly picks e and K^+ coincidences from events selected in eight accidental time coincidence peaks (see Figure 4.12). The quasi-free distribution, seen as the blue line, is represented by a 5th order polynomial with a zero at $B_{\Lambda} = 0$. All the peak fittings to the spectra of ${}_{\Lambda}^{12}\text{B}$ to be discussed in the following are above these two backgrounds.

Using events selected within a range of $\pm 2.5\sigma$ around the mean and requiring statistical significance larger than 3.5, eight peaks can be recognized in both spectra from E05-115 and E01-011. In the case for peaks having low statistics, the statistical significance is calculated by [77]:

$$S = \sqrt{2n_0 \ln(1 + s/b) - 2s}, \quad (6.1.1)$$

where n_0 is the total number of events, s is the number of the real events, and b is the number of background events.

Figure 6.1. Spectroscopy of the $^{12}_{\Lambda}\text{B}$ obtained by the experiment E05-115 and experiment E01-011, respectively.

For the E05-115 spectrum, the ground state peak of $^{12}_{\Lambda}\text{B}$ is fitted by a single Gaussian function as shown in Figure 6.2 and found to be located at $B_{\Lambda} = 11.380 \pm 0.020$ MeV with a width of $\sigma = 270 \pm 22$ keV. In comparison, for the E01-011 spectrum, the ground state peak was found located at $B_{\Lambda} = 11.379 \pm 0.026$ MeV with a width of $\sigma = 339 \pm 33$ keV. Results from the two independent experiments are consistent.

Figure 6.2. Single Gaussian fitting for ground doublet states of the $^{12}_{\Lambda}\text{B}$ spectrum.

It is noted that the first proton breakup ($^{12}_{\Lambda}\text{B} \rightarrow ^{11}\text{Be} + \text{p}$) threshold is located at $-B_{\Lambda} = 0.9$ MeV. All states below this threshold should have decay widths less

than a few keV via γ decay. Therefore, all the observed peaks should have the same width except for peaks arising from doublets with non-negligible energy separations. In Figure 6.1, the ground state peak is obviously broader than the others. Therefore, all of the other seven peaks are fitted with Gaussian functions by assuming the same width, which was found to be $\sigma = 231 \pm 30$ keV (FWHM ~ 544 keV) with the minimum χ^2 fit. For the E01-011 spectrum, the width for the other seven peaks was found to be $\sigma = 300 \pm 50$ keV (FWHM ~ 706 keV).

Figure 6.3. Double Gaussian fit for the ground state peak in the E05-115 spectroscopy with a 1.35 MeV fitting range. Widths of Gaussian and peak amplitude ratio were fixed.

Figure 6.3 shows the close-up view of the ground state doublets from the E05-115 spectrum. With shell model description, the ground state doublet is considered to consist of $J^\pi = 1^-$ and 2^- states arising from a particle-hole to particle coupling $^{11}\text{B} \otimes j^\Lambda = [3/2^-] \otimes s_{1/2}^\Lambda$ (see Section 6.1.2). Due to low statistics, it is difficult to make a clear separation of the ground state doublets without constraint to minimize the number of fitting parameters. A double Gaussian fit study was carried out with the energy resolution held fixed at the value found for the excited peaks ($\sigma = 231$ keV for E05-115) and fixed peak amplitude ratio which was then scanned from its lower to the upper limits (1:1 to 1:4) suggested by theory [78, 79]. Although the theory-estimated

ratio depends on the interaction models and K^+ detection angles, the population of the 2^- state is consistently 3-4 times larger than that of the 1^- state for our kinematics. For each chosen ratio, the fitting was studied by various bin size with the corresponding fitting range that maintains the minimum required number of degrees of freedom to succeed a double Gaussian fitting.

Variations of χ^2/NDF and statistical uncertainties for the fitted position of states and number of counts per state were examined. It was found that the positions (fitted means) of the two states (thus their separation) are not affected and vary only a few keV by the bin size change. However, χ^2/NDF and statistical uncertainties vary depending on the background level and the remaining statistics. Thus the bin size and fitting range were chosen according to the best χ^2/NDF and minimized statistical uncertainty. Due to the high accidental background, the integrated number of counts per state has a large uncertainty ($\sim 50\%$) from the double Gaussian fit but uncertainty for the position (i.e., mean) is relatively small. Comparing state positions and separation with various chosen ratios, the variation is small, ranged from 0.16 to 0.20 MeV with almost constant χ^2/NDF and statistical uncertainty. Therefore, chosen close to the average, the ratio was selected to be 1:3.5. This gives the peak separation of 181 ± 16 keV from the E05-115 spectrum as seen in Figure 6.3. Using the same analysis, it was found to be 176 ± 18 keV from E01-011. The two independent results are consistent with each other. Therefore, their average gives the excitation energy of 2^- as 179 ± 13 keV, with the ratio chosen to be at 1:3.5. From here on, the excitation energy of all of the following states discussed later is thus referred to as the B_Λ of the 1^- ground state obtained by this double Gaussian fit.

Figure 6.4 shows the fitted spectra of the $^{12}_\Lambda\text{B}$ independently obtained from the E05-115 and E01-011 experiments. Table 6.1 lists the binding energy B_Λ of the fitted peaks (including the two from double the Gaussian fit) from the two experiments as well as their average. Although the E01-011 spectrum has a poorer resolution

and larger statistical uncertainty compared to that from E05-115, the results are consistent.

Figure 6.4. Full-fitted spectroscopy of the ^{12}B obtained by the E05-115 and E01-011 experiments.

The uncertainties listed in Table 6.1 are statistical. The contributions of systematic uncertainty are listed in Table 6.2. The systematic uncertainty for the ground state doublet should add an additional fitting uncertainty of ± 20 keV for both E05-115 and E01-011, and their total is ± 116 keV for E05-115 and ± 157 keV for E01-011, respectively. Therefore, the systematic uncertainty for B_Λ is about ± 0.12 MeV and ± 0.16 MeV for E05-115 and E01-011, respectively.

The photo-production cross sections were obtained by using the virtual photon flux factor Γ explained in Section 4.5. The cross sections of the corresponding peaks from the two independently obtained spectra are listed separately without average. For both experiments, the systematic uncertainty of the experimentally obtained cross sections is about 12% [65]. The acceptance and correction factors are also shown in Section 4.5 for experiment E05-115. The acceptance and correction factors for

Table 6.1. Measured binding energies and cross sections of $^{12}_{\Lambda}\text{B}$.

Peak	B_{Λ} (E05-115) (MeV)	B_{Λ} (E01-011) (MeV)	B_{Λ} Average (MeV)	Cross section (E05-115) (nb/sr)	Cross section (E01-011) (nb/sr)
#1-1	11.529 ± 0.012	11.517 ± 0.014	11.523 ± 0.013	83.0 ± 3.0	101.0 ± 4.2
#1-2	11.348 ± 0.012	11.341 ± 0.014	11.344 ± 0.014		
#2	8.425 ± 0.047	8.390 ± 0.075	8.415 ± 0.040	19.1 ± 3.7	33.5 ± 11.3
#3	5.488 ± 0.052	5.440 ± 0.085	5.475 ± 0.044	18.0 ± 4.6	26.0 ± 8.8
#4	2.499 ± 0.075	2.882 ± 0.085	2.667 ± 0.056	16.2 ± 5.1	20.5 ± 7.3
#5	1.220 ± 0.056	1.470 ± 0.091	1.289 ± 0.048	28.7 ± 7.2	31.5 ± 7.4
#6	0.524 ± 0.024	0.548 ± 0.035	0.532 ± 0.020	75.7 ± 10.8	87.7 ± 15.4
#7	-0.223 ± 0.039	-0.318 ± 0.085	-0.240 ± 0.035	39.0 ± 7.4	46.3 ± 10.3
#8	-1.047 ± 0.078	-0.849 ± 0.101	-0.973 ± 0.062	27.8 ± 7.9	28.5 ± 7.4

Table 6.2. The systematic uncertainty for $^{12}_{\Lambda}\text{B}$ binding energy.

Item	E05-115(keV)	E01-011(keV)
Λ mass precisions (see Section 5.5)	± 27	± 43
Target Straggling of ^{12}C	± 40	± 40
Target Straggling of CH_2	± 90	± 136
Optics defect	± 50	± 50
Total	± 114	± 156

experiment E01-011 can be found in the Ph.D theses by Okayasu and Matsumura [61, 62]. As mentioned in Section 2.2, the average $\theta_{\gamma K}$ in the E05-115 experiment is $\sim 6.8^\circ$, while it is $\sim 5.8^\circ$ in the E01-011 experiment; therefore, the measured cross sections in the E05-115 experiment are expected to be lower than those from the E01-011 experiment, due to the dependence on the $\theta_{\gamma K}$ angle. This kinematics reduction is theoretically estimated to be about 13%, while the measured reduction is about 22%. Taking into account the uncertainties, the cross sections measured by the two independent experiments are also in reasonably good agreement.

6.1.2 Interpretation of the ${}^{12}_{\Lambda}\text{B}$ Spectrum

Table 6.3 compares the measured excitation energies and cross sections to those of the theoretical calculations by John Millener [45] (omitting peaks #4 and #7 which will be discussed separately). The main structures from the theory interpretation are given in the second column, with the designation p_{Λ} meaning that there is a strong mixing of $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ configurations [45]. The angular momenta and the parity of the states are listed in the third column, where the subscript means the number of states with the same angular momentum and parity. The measured excitation energies listed in the fourth column were extracted from the average B_{Λ} in Table 6.1. The uncertainty shown in the table is the weighted average of the two statistical uncertainties from the two experiments. The systematic uncertainty of the measured excitation energies is about ± 0.07 MeV (shown in Table 6.4). The experimentally measured photo-production cross sections listed in Table 6.3 are the average from the two measurements after scaling up the E05-115 result by 22%. The theory predicted that cross sections are scaled from the available electro-production cross sections [45] by using a factor that makes the summed cross section of the ground state doublet to be 100 nb/sr. This scaling factor corresponds to the integrated virtual photon flux. Taking into account the $\pm 12\%$ systematic uncertainty, good agreement can be seen

except for that for peak #5, which is 3-4 times larger than the predicted value based only on consideration of the structure of the p_Λ states. The 1_2^+ state is predicted to have a negligible cross section and is thus omitted here.

Table 6.3. Comparison with theoretical predictions for $^{12}_\Lambda\text{B}$.

Peak	Main structure	J_n^π	E_x^{exp} (MeV)	E_x^{th} (MeV)	σ^{exp} (nb/sr)	$\frac{\sigma_i}{\sigma_{gs}}$ (%)
#1-1	$^{11}B(3/2^-; \text{g.s.}) \otimes s_{1/2\Lambda}$	1_1^-	0.00	0.00	101.1 ± 2.8	100.0
#1-2	$^{11}B(3/2^-; \text{g.s.}) \otimes s_{1/2\Lambda}$	2_1^-	0.179 ± 0.013	0.12		
#2	$^{11}B(1/2^-; 2.125) \otimes s_{1/2\Lambda}^s$	1_2^-	3.11 ± 0.04	2.59	24.7 ± 4.2	32.9
	$^{11}B(1/2^-; 2.125) \otimes s_{1/2\Lambda}$	0_1^-		2.59		
#3	$^{11}B(3/2^-; 5.020) \otimes s_{1/2\Lambda}$	2_3^-	6.05 ± 0.05	5.64	23.1 ± 4.7	12.4
	$^{11}B(3/2^-; 5.020) \otimes s_{1/2\Lambda}$	1_3^-		5.72		4.0
#5	$^{11}B(3/2^-; \text{g.s.}) \otimes p_{3/2\Lambda}$	2_1^+	10.23 ± 0.05	10.29	33.0 ± 5.7	5.1
	$^{11}B(3/2^-; \text{g.s.}) \otimes p_\Lambda$	1_1^+		10.34		2.6
#6	$^{11}B(3/2^-; \text{g.s.}) \otimes p_{1/2\Lambda}$	2_2^+	10.99 ± 0.02	10.93	90.4 ± 10.0	30.6
	$^{11}B(3/2^-; \text{g.s.}) \otimes p_{3/2\Lambda}$	3_1^+		11.01		46.8
#8	$^{11}B(1/2^-; 2.125) \otimes p_{3/2\Lambda}$	2_3^+	12.50 ± 0.06	12.80	30.5 ± 5.9	19.4
	$^{11}B(1/2^-; 2.125) \otimes p_\Lambda$	1_3^+		12.91		5.8

Table 6.4. The systematic uncertainty for $^{12}_\Lambda\text{B}$ excitation energy.

Item	E05-115(keV)	E01-011(keV)
Optics defect	± 57	± 66
Scale (by Λ & Σ^0)	± 10	± 30
Ground state doublet fitting	± 20	± 20
Ground state single peak fit	± 18	± 23
Total	± 64	± 80
Average	± 70	

The detailed interpretation of the observed spectroscopy as well as of peaks #4, #7 and the extra cross section of #5 will be discussed in the following section.

6.1.2.1 States with a Λ in the s -shell Coupled to the Low-lying ^{11}B Core States

The observed peaks #1, #2, and #3 can be interpreted as three doublets made by the coupling of a Λ in the s -shell (s_Λ) to three low-lying core states. Such an interpretation can be compared (see Figure 6.5) to the level scheme of the mirror hypernucleus $^{12}_\Lambda\text{C}$, which has been constructed from four precisely measured γ transitions by the KEK experiment E566 [80]. Other than small excitation energy differences, ^{11}C and ^{11}B have the same level structures. To a first approximation, the excitation energies of states in the excited doublets of $^{12}_\Lambda\text{B}$ can be obtained by adding the difference between the excitation energies of the core states in ^{11}C and ^{11}B .

Figure 6.5. The level structures of $^{12}_\Lambda\text{C}$ and $^{12}_\Lambda\text{B}$ for the first four doublets (energies in keV).

Separation of the ground state doublet for $^{12}_\Lambda\text{C}$ was measured to be 0.162 MeV [80], while that from the same doublet of $^{12}_\Lambda\text{B}$ measured by the HKS experiments was 0.179 MeV. Taking into account the 0.125 MeV energy difference between the first $1/2^-$ core states, the 1_2^- state in $^{12}_\Lambda\text{B}$ is expected at 2.958 MeV, close to the measured value of 3.109 MeV. The 0^- member in this doublet is not expected to be seen in

both cases due to a negligibly small cross section. Similarly, the doublet (2_2^- and 3_1^-) states corresponding to the $5/2^-$ core excitation are also predicted to have small cross sections ($< \text{few nb/sr}$) in both cases, thus unobservable.

In the case of the fourth doublet, the γ transition measured in the KEK experiment was assigned to be between the 1_3^- and 1_1^- states. However, in the $(e, e'K^+)$ experiment the lower member of the doublet, the 2_3^- state, is expected to be much more strongly populated. Thus, the two experiments should have measured different states in the same doublet. By simply adding the energy difference of $5.020 \text{ MeV} - 4.804 \text{ MeV} = 0.216 \text{ MeV}$, the upper member (i.e. the 1_3^- state) is suggested to have an excitation energy of 6.266 MeV. This simple estimate gives the separation of the two states in the fourth doublet on the order of $\sim (0.22 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{syst.}}) \text{ MeV}$, compared with 0.08 MeV from the theory in Table 6.3.

6.1.2.2 States from a Λ in the p -shell

Beyond the four s_Λ states (including the 1_1^- and 2_1^- ground state doublet members) there are five peaks (#4 to #8) that could be fitted with the confirmed resolutions (540 keV and 710 keV FWHM) for the two independent HKS spectra. Their averaged excitation energies are 8.85, 10.23, 10.99, 11.75, and 12.50 MeV with a systematic uncertainty of 0.07 MeV.

Notice that the #4 peak in the published JLab Hall A spectrum (see Table 1 in Ref. [45]) was fitted with a width that is $0.93 \pm 0.46 \text{ MeV}$ FWHM, wider than the reported resolution of 670 keV FWHM. The excitation energy was reported as $E_x = 9.54 \pm 0.16 \text{ MeV}$. However, there was still unexplainable additional strength. Such a fitted result appears to be the average ($E_x \approx 9.50 \text{ MeV}$) of peaks #4 and #5 from the HKS result. Of these two peaks in the HKS spectrum, the #5 peak is then expected to be the doublet containing the contributions from the 2_1^+ and 1_1^+ states with a Λ in the p -shell coupled to the $3/2^-$ ground state of the ^{11}B core. The

separation of the pair is predicted to be very small (see Table 6.3). The #4 peak is not predicted by theory; this will be discussed in Section 6.1.2.3.

Peak #6 is the dominant peak among the p_Λ states, consistent with the observation made by the JLab Hall A experiment. This peak can be interpreted as a doublet composed by the second (2_2^+ and 3_1^+) pair of p_Λ states (see theory prediction in Table 6.3). Peak #8 is located at about the first breakup threshold and could be due to the third (2_3^+ and 1_2^+) pair of p_Λ states. The width uncertainty for the fitting is about ± 50 keV, meaning the separation of these two doublet states is small, possibly ≤ 100 keV.

Like peak #4, peak #7 is not predicted by $0\hbar\omega$ based calculations using a p-shell core [81]. Peak #7 also appears to exist in the JLab Hall A spectrum above the dominant p -shell peak, but the remaining strength was simply fitted for one peak with a width of 1.58 MeV, more than two times wider than the claimed resolution (670 keV FWHM). Thus, peaks #5, #6, and #8 are likely to be the three pairs of p_Λ states. Their possible configurations and excitation energies are listed in Table 6.3, where they are compared with the theory.

Rather precise information on the p_Λ states of ${}^{12}_\Lambda\text{C}$ comes from analyses of proton emission from such states formed by the ${}^{12}\text{C}(\text{K}_{\text{stop}}^-, \pi^-)$ reaction in emulsion [82]. The B_Λ for a narrow 0^+ state is given as 0.14 ± 0.05 MeV and there is evidence for 2^+ states 0.06 and 0.81 MeV below the 0^+ state. Based on the predicted excitation energy of 11.08 MeV for the 0^+ state, the 2_1^+ and 2_2^+ states would be at 10.27 and 11.02 MeV in ${}^{12}_\Lambda\text{B}$, in quite good agreement with the interpretation presented in Table 6.3.

6.1.2.3 Positive-parity Core States with a Λ in the s -shell

The presence of the extra peaks #4 ($E_x = 8.85 \pm 0.06$ MeV) and #7 ($E_x = 11.75 \pm 0.04$ MeV) is not surprising. Spectroscopic investigations on ${}^{12}_\Lambda\text{C}$ [20, 83, 84] and ${}^{12}_\Lambda\text{B}$ [45] have included states both below and above the main p_Λ peak (#6 in

our case) in their fits to account for leftover strength not accounted for in the p^7p_Λ calculations. For the spectra from the JLab HKS experiments, the extra peaks were fitted with the same width as the other peaks because of the better resolution. As discussed in Ref. [45], these two peaks may correspond to states with the configuration of an s_Λ coupled to $3/2^+$ and $5/2^+$ ^{11}B core states, the positive parity states. These ^{11}B states are not strongly populated in proton removal from ^{12}C and the hypernuclear states must, therefore, pick up their excitation strength from mixing with the strong p_Λ states. The known positive parity states of ^{11}B are $5/2^+$ states at 7.286 MeV, 9.272 MeV, and 11.600 MeV, and $3/2^+$ states at 7.978 MeV and 9.873 MeV [85]. In a $1\hbar\omega$ ($s^4p^6(sd)$ plus s^3p^8) calculation for ^{11}B [86], the corresponding candidates are mostly $s^4p^6(sd)$ in character with $L = 2$ and $S = 1/2$. In addition to the simple mixing of these states with an s_Λ attached to the p^7p_Λ states, linear combinations of the s_Λ and p_Λ hypernuclear configurations are required to eliminate spurious center-of-mass motion. Both from their structure and their proximity to the strong p_Λ states, states based on the 9.87 MeV $3/2^+$ and 11.60 MeV $5/2^+$ states of ^{11}B are probably most likely to pick up formation strength in the $^{12}\text{C}(e, e'K^+)$ reaction. The excessive strength of peak #5 may come from a strong mixing of the p_Λ state and a state with a positive-parity core ($7/2^+$ at the excitation energy of 10.60 MeV [85]). Theoretical investigations with a full $1\hbar\omega$ basis are indeed needed.

6.2 Spectroscopy of $^{10}_\Lambda\text{Be}$ and Discussion

6.2.1 Spectroscopy of $^{10}_\Lambda\text{Be}$

Figure 6.6 shows the spectrum of $^{10}_\Lambda\text{Be}$ obtained by the E05-115 experiment. All the fitted peaks for spectroscopy of $^{10}_\Lambda\text{Be}$ that will be discussed in the following section are above the overlaid accidental background and quasi-free distribution indicated by the red and blue lines, respectively.

Figure 6.6. Spectroscopy of $^{10}_{\Lambda}\text{Be}$. The red line is the distribution of the accidental background from the mixed events analysis, and the blue line is the quasi-free distribution represented by a 3rd order polynomial with a zero at $B_{\Lambda} = 0$.

By selecting events within $\pm 2.5\sigma$ and requiring statistical significance higher than 3.5, twelve peaks can be recognized in the spectrum of $^{10}_{\Lambda}\text{Be}$. Due to limited statistics, the fitting started by assuming the same peak width in the region below $-B_{\Lambda} = 5$ MeV (up to peak #11). All states in this region above the ground state (peak #1) are considered stable. This common width was first examined by fitting peak #5, which appears to be a well-isolated single peak. The eleven peaks (from #1 to #11) were simultaneously fitted in this $-B_{\Lambda}$ region. The bin size (as used in the figure) was optimized by the minimized χ^2/NDF as well as by the least statistical uncertainty. The common width was further studied with the same optimization. It is easy to recognize that peaks #8 and #9 are broader, meaning a result of a mixture of multiple states. Thus, another common but broader width was applied to these two peaks in the global fitting of the eleven peaks. The first narrower common width was found to be $\sigma = 248$ keV, while the broader one was 454 keV. This fit corresponds to the best confidence level of 90% calculated by the p-value [21]. Above $-B_{\Lambda} = 5$ MeV, although there are signatures of structures in reference to the statistical averaged quasi-free distribution, only one structure appears to have sufficient statistical significance, if

only the events above the quasi-free distribution are treated as real events. Peak #12 was thus assigned to this distribution. It was fitted separately, taking into account the accidental and quasi-free background. The width was found to be $\sigma = 373$ keV. The results are summarized in Table 6.5.

Figure 6.7. Spectroscopy of the $^{10}_{\Lambda}\text{Be}$ with fitting of recognized peaks.

This fit result confirms the energy resolution concluded by the study of the $^{12}_{\Lambda}\text{B}$ spectroscopy. Since the ^{10}B target has smaller target straggling uncertainty, the energy resolution for $^{10}_{\Lambda}\text{Be}$ is expected to be about 10% better, meaning at a level of about $\sigma \approx 210\text{-}220$ keV. The obtained 248 keV single-peak width indicates that all of the peaks with this width may be doublets with a separation ranging from $\sim 50\text{-}100$ keV. Such separation is too small for this experiment to resolve. In order to extract the energy resolution of the spectrum of $^{10}_{\Lambda}\text{Be}$, a double Gaussian simulation was carried out for the first doublet (peak #1) with the same strength and the fixed separation ranging from 50-100 keV. The width (σ) of each peak of the doublet was found to be on the order of $\sim 0.22 \pm 0.20$ keV (~ 520 FWHM). In addition, although peaks #8, #9 and #12 are sufficiently broad, the limited statistics prevents further multiple

Table 6.5. Measured binding energies and cross sections of $^{10}_{\Lambda}\text{Be}$ spectrum.

Peak	B_{Λ} (MeV)	Ex (MeV)	Width (σ) (MeV)	Cross Section (nb/sr)
1	8.66 ± 0.059	0	0.248	10.3 ± 0.7
2	7.82 ± 0.094	0.84 ± 0.111	0.248	7.1 ± 0.6
3	6.24 ± 0.076	2.42 ± 0.096	0.248	10.3 ± 0.7
4	5.53 ± 0.123	3.13 ± 0.136	0.248	6.1 ± 0.7
5	4.26 ± 0.098	4.40 ± 0.114	0.248	5.2 ± 0.6
6	2.53 ± 0.109	6.13 ± 0.124	0.248	6.7 ± 0.6
7	1.52 ± 0.080	7.14 ± 0.099	0.248	9.5 ± 0.6
8	0.21 ± 0.124	8.45 ± 0.137	0.454	13.4 ± 0.5
9	-1.29 ± 0.128	9.95 ± 0.141	0.454	13.9 ± 0.5
10	-2.44 ± 0.096	11.10 ± 0.113	0.248	9.6 ± 0.7
11	-3.25 ± 0.092	11.91 ± 0.109	0.248	8.0 ± 0.7
12	-10.28 ± 0.137	18.94 ± 0.137	0.373	9.8 ± 0.8

Gaussian fitting with adequate results. The possible structures will be discussed in the following section.

The uncertainty quoted for the fitted results in Table 6.5 is statistical. The systematic uncertainty for B_{Λ} (illustrated in Table 6.6) is ± 0.11 MeV. Since a major part of this systematic uncertainty causes a constant shift for the B_{Λ} of all the peaks, the systematic uncertainty of the measured excitation energies is only about ± 0.06 MeV. The systematic uncertainty for the cross section is about 9% [65].

6.2.2 Interpretation of the $^{10}_{\Lambda}\text{Be}$ Spectrum

Shell-model calculations for the $^{10}_{\Lambda}\text{Be}$ has been performed using the same interaction as that for the $^{12}_{\Lambda}\text{B}$ [86, 87]. From the calculation, the energy separation of the p_{Λ} and s_{Λ} single-particle states in $^{10}_{\Lambda}\text{Be}$ is about 9.22 MeV [86]. The measured peaks except for #2, #5, and #7 in Figure 6.7 and Table 6.5 will be interpreted by these calculations. In addition, the observed excitation level spectrum of $^{10}_{\Lambda}\text{Be}$ can be

Table 6.6. The systematic uncertainty for ${}_{\Lambda}^{10}\text{Be}$ binding and excitation energy.

Item	Uncertainty(keV)
${}_{\Lambda}^{10}\text{Be}$ binding energy	
Λ mass precision	± 27
Target Straggling of ${}^{10}\text{B}$	± 30
Target Straggling of CH_2	± 90
Optics Defect	± 50
Total	± 110
${}_{\Lambda}^{10}\text{Be}$ excitation energy	
Optic Defect	± 57
Scale (by Λ & Σ^0)	± 10
Total	± 58

compared to that of its mirror hypernucleus ${}_{\Lambda}^{10}\text{B}$, and the charge symmetry breaking (CSB) will be discussed.

6.2.2.1 Ground State of ${}_{\Lambda}^{10}\text{Be}$

Peak #1 is considered to be the ground state peak from the coupling of the Λ in the s-shell to the $3/2^-$ ${}^9\text{Be}$ core state. This leads to two possible angular momentum states, a 1^- (non-spin flip), which is expected to be the ground state, and a 2^- (spin-flip) which together form a doublet (see Table 6.7). Due to a significant increase in the spin-flip amplitude, the $(e, e'K^+)$ reaction promotes both of these two states, and they are predicted to have similar cross sections. The separation is predicted to be ~ 0.1 MeV [87]. Such a small separation is below the limit that can be extracted by this experiment because of its resolution and the statistics of the data.

As mentioned above, due to a thinner and lighter target with less target straggling, the energy resolution is expected to be about ~ 220 keV. In the global fitting, the width used to fit peak #1 by a single Gaussian function is $\sigma = 248$ keV (see Table 6.7) with a statistical uncertainty of ~ 60 keV. Taking all of these into account, the separation of the doublet appears to be small, in the order of ~ 100 keV at most. On

the other hand, the KEK gamma-ray experiments have placed an upper limit of about 100 keV on the spacing in ${}^{10}_{\Lambda}\text{B}$ for the same doublet [36]. This appears to be consistent with our conclusion. The mean binding energy of the doublet is 8.66 ± 0.059 MeV. If the cross sections of the two states are similar and 100 keV separation is assumed, then the binding energy of the 1^- ground state could be 8.71 MeV. The result from an early emulsion experiment shows the B_{Λ} of the ground state of ${}^{10}_{\Lambda}\text{Be}$ is 9.11 ± 0.22 MeV, from only 3 events for a single decay channel [88].

For its isospin mirror hypernucleus ${}^{10}_{\Lambda}\text{B}$, the emulsion experiment found a ground state binding energy of $B_{\Lambda} = 8.89 \pm 0.12$ MeV from only 10 events observed in two step decays [88]. In contrast, the KEK experiment using the (π^+, K^+) reaction (which does produce spin-flip states) obtained a ${}^{10}_{\Lambda}\text{B}$ spectrum with an energy resolution of 2 MeV FWHM and reported $B_{\Lambda} = 8.1 \pm 0.12(\text{stat.}) \pm 0.5(\text{syst.})$ MeV [36]. There is a large disagreement between these two results.

Recently, it has been recognized that the energy calibration of the KEK experiment was incorrect and a shift of ~ 0.6 MeV should be applied to the measured B_{Λ} in all the spectra obtained from the p-shell hypernuclei up to ${}^{208}\text{Pb}$. Taking this into account, the fitted position of the first peak should be corrected to ~ 8.7 MeV. Since the (π^+, K^+) reaction dominantly populates the non-spin flip state, it should be the binding energy of the 1^- ground state of ${}^{10}_{\Lambda}\text{B}$. Therefore, a rough estimate based on comparison of the corrected B_{Λ} (${}^{10}_{\Lambda}\text{B}$ from KEK) ≈ 8.7 MeV and B_{Λ} (${}^{10}_{\Lambda}\text{Be}$ from JLab HKS) ≈ 8.71 MeV indicates that there is no charge symmetry breaking (CSB) within the uncertainty observed from this mirror pair, or is negligibly small in comparison to ~ 0.35 MeV [15] from the pair of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$. Such a result supports the theory interpretation that the large CSB in the ΛN interaction originates from the coherent Λ - Σ coupling [89], which decreases significantly for the p-shell hypernuclei. Thus, to study CSB in ΛN interaction, one must focus on few body hypernuclei.

6.2.2.2 States with a Λ in the s -shell Coupled to the Low-lying ${}^9\text{Be}$ Core States

Besides the ground state doublet (1^- and 2^-), four additional peaks, #3, #4, #6, and #10 in Figure 6.7, appear explainable also as s_Λ states, i.e., the states with a Λ in the s -shell coupled to the low-lying ${}^9\text{Be}$ core states. Table 6.7 gives their suggested core states, spin-parity of the resulting ${}^{10}_\Lambda\text{Be}$ states, the measured excitation energies relative to the 1^- ground state, the theory [87] predicted excitation energies, the measured cross sections, and the theory calculated relative population (i.e. spectroscopic factors).

Table 6.7. Comparison with theoretical predictions on ${}^{10}_\Lambda\text{Be}$. Relative population is based on the spectroscopic factor given by the theory.

Peak	${}^9\text{Be}$ core	J_n^π	E_x^{exp} (MeV)	E_x^{th} (MeV)	σ^{exp} (nb/sr)	Relative population
#1	$3/2_1^-$	1_1^-	0	0	10.3 ± 0.7	0.538
		2_1^-		0.110		0.661
#3	$5/2_1^-$	2_2^-	2.42 ± 0.096	2.482	10.3 ± 0.7	0.737
		3_1^-		2.585		0.556
#4	$1/2_1^-$	0_1^-	3.13 ± 0.136	3.202	6.1 ± 0.7	
		1_2^-		3.228		
#6	$7/2_1^-$	3_2^-	6.13 ± 0.124	6.433	6.7 ± 0.7	0.339
		4_1^-		6.509		0.579
#10	$7/2_2^-$	3_3^-	11.10 ± 0.113	10.926	9.6 ± 0.7	0.250
		4_2^-		11.532		1.386

In the weak coupling limit, the sum of the cross sections for all of the final states based on a particular core state is proportional to the cross section for nucleon removal from the target. The core states listed in Table 6.7 in a shell-model calculation, have summed spectroscopic factors (relative population) for proton removal from a ${}^{10}\text{B}$ larger than 0.4, except for the $1/2_1^-$ core state. As for the ground state doublet built on the $3/2_1^-$ core state, these additional four peaks are all doublets. Except for peak #10, doublet separations for peaks #3, #4, and #6 are all predicted to be

about or smaller than ~ 100 keV, in agreement with the fitted width. Although the doublet separation for peak #10 is predicted to be sufficiently large, the 3_3^- state is not expected to show, because its predicted cross section (see population in Table 6.7) is small, compared to the dominant 4_2^- state.

A rough comparison can be made between the measured cross sections and the calculated spectroscopic factors. Taking into account the statistical uncertainty and the 8% systematic uncertainty, the relative yield agrees well with the prediction except for peak #4. This doublet has a negligibly small predicted spectroscopic factor [87], but the actual measured cross section is comparable to that of peak #6. The extra strength of peak #4 may result from the coupling of the s_Λ to the positive core state (see Section 6.2.2.4).

Table 6.8 gives the low-lying energy levels of the ^9Be core. The width of peaks #4 and #6 of the spectrum $^{10}_\Lambda\text{Be}$ in Table 6.7 is much narrower than the corresponding core states $1/2_1^-$ and $7/2_1^-$; this could be the lambda stabilizing them against neutron decay (see the fourth column in Table 6.8) [90]. In addition, doublets (peaks #3, #6, and #10 in Table 6.7) built on the $5/2^-$ and the two $7/2^-$ states, are close or slightly less in excitation than the core states (see the second column in Table 6.8). However, for the $1/2_1^-$ state, the corresponding doublet (peak #4 in Table 6.7) is ~ 0.4 MeV higher than the core state. This can be additional evidence that there may be an extra contribution for the strength of peak #4.

Table 6.8. The low lying energy levels of ^9Be [91].

State J_n^π	E_x (MeV)	Width(MeV)	Decay
$3/2_1^-$	0		stable
$5/2_1^-$	2.429	0.78×10^{-3}	γ , n , α
$1/2_1^-$	2.78	1.10	n
$7/2_1^-$	6.380	1.21	γ , n
$7/2_2^-$	11.282	0.575	n

6.2.2.3 States with a Λ in the p -shell

Table 6.9 shows the energies and formation strengths for p_Λ states of the $^{10}_\Lambda\text{Be}$ from the $(e, e'K^+)$ reaction [86] from the shell-model calculation. A series of angular momentum L states are obtained by coupling the core spin to the orbital angular momentum of the Λ in p -orbit states. The multiplets of the states (see the third column of Table 6.9) are obtained by coupling the $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ states to each low-lying ^9Be core state (listed in the 1st column of Table 6.9). The separation between $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ was set to be 100 keV. The two sets of $L = 3/2$ states from the coupling of the $5/2_1^-$ core state resulting from mixing with the states based on a nearby $1/2_1^-$ seen in Table 6.7. The predicted excitation energies listed in the fourth column are given relative to the lowest 1_1^+ state. The relative populations obtained from the spectroscopic factors are listed in the fifth column. All states corresponding to the ^9Be core states with a negligible population are omitted from the list.

From Table 6.9, one can recognize three significant doublets and a group of three states with close excitation energy (namely the $2_2^+/3_1^+$, $4_1^+/3_2^+$, $4_2^+/5_1^+$ and $4_5^+/4_6^+/5_2^+$ states) that have their strengths concentrated around ~ 0.8 , 3.2, 7.0 and 12.1 MeV (p -shell excitation), respectively.

Notice that the six states (forming three doublets) based on the $3/2_1^-$ ground state of the ^9Be core are spread over nearly 2 MeV and they all are expected to have moderated strengths. By adding the expected p_Λ to s_Λ spacing of ~ 9.2 MeV to their centroid in a p -shell excitation of ~ 0.8 MeV, their centroid excitation energy with respect to the ground state of $^{10}_\Lambda\text{Be}$ is ~ 10.0 MeV. The observed peaks #8 and #9 have their centroid at ~ 9.2 MeV with an energy separation of around 1.5 MeV. Thus, these peaks may be good candidates for the lowest group of p_Λ states.

The second significant group of p_Λ states may come from the $4_1^+/3_2^+$ doublet, centroid at the excitation energy of ~ 3.2 MeV + 9.2 MeV = 12.4 MeV above the ground state doublet. This predicted group is close to the observed peak #11 at $Ex =$

Table 6.9. Shell-model calculation for $p^5 p_\Lambda$ states in the hypernucleus $^{10}_\Lambda\text{Be}$ [86]. The s-shell is fully occupied by four nucleons.

^9Be core	L	J_n^π	$Ex(\text{MeV})$	Population
$3/2_1^-$	$3/2$	1_1^+	0.00	0.2663
		2_1^+	0.02	0.2278
	$5/2$	2_2^+	0.78	0.5045
		3_1^+	0.81	0.3464
	$1/2$	0_1^+	1.60	0.1644
		1_2^+	1.85	0.4165
$5/2_1^-$	$7/2$	4_1^+	3.16	0.4276
		3_2^+	3.17	0.6505
	$3/2$	1_3^+	3.31	0.0848
		2_3^+	3.42	0.1023
	$5/2$	2_4^+	3.67	0.1960
		3_3^+	3.74	0.1705
	$3/2$	2_5^+	4.26	0.2677
		1_5^+	4.28	0.1771
	$9/2$	4_2^+	6.94	0.3557
		5_1^+	6.99	0.4126
$7/2_1^-$	$5/2$	2_7^+	7.13	0.0482
		3_5^+	7.31	0.1811
	$7/2$	3_6^+	7.89	0.1084
		4_3^+	7.93	0.3078
$7/2_2^-$	$7/2$	3_{10}^+	11.43	0.1598
		4_5^+	11.71	0.7132
	$9/2$	4_6^+	12.13	0.4904
		5_2^+	12.37	1.0534
	$5/2$	2_{14}^+	12.52	0.0717
		3_{12}^+	12.84	0.1927
		3_{14}^+	13.81	0.1818

11.91 MeV. The narrow width may be due to the domination of this doublet over the other states associated with the $5/2^-$ core.

Finally, the observed peak #12 at $Ex = 18.94$ MeV with respect to the ground doublet can be considered to correspond to the triplet $4_5^+/4_6^+/5_2^+$ which has an excitation energy centroid at $\sim 12.1+9.2=21.3$ MeV. The difference in excitation energy may come from the fitting for a peak above the assumed quasi-free background. In reality, the events from these states contribute in forming the quasi-free distribution. For the same reason, such fit may also lower the observed excitation energy values for all of the peaks from peak #8 to #11.

6.2.2.4 Positive-parity Core States with a Λ in the s -shell

The current $0\hbar\omega$ based shell model calculations do not predict any structure that corresponds to peaks #2 ($Ex = 0.84 \pm 0.111$ MeV), #5 ($Ex = 4.40 \pm 0.114$ MeV), and #7 ($Ex = 7.14 \pm 0.099$ MeV). However, there exists a series of positive-parity states for ${}^9\text{Be}$ [91], especially a $1/2^+$ state at an excitation of 1.684 MeV, a $3/2^+$ state at 4.704 MeV and a $9/2^+$ state at 6.76 MeV. A Λ in the s -shell can couple to these positive-parity core states from the s -shell, s_Λ . Peaks #2, #5, and #7 may be related to these structures. In addition, the extra strength of peak #4 results from the coupling of the s_Λ to the $5/2^+$ ${}^9\text{Be}$ core state at 3.049 MeV.

These types of configurations need more complicated $1\hbar\omega$ based shell model calculations, which do not yet exist. However, the predicted cross section is small for the coupling of a s_Λ to these positive-parity states; thus, it does not expect to have high strength for these s_Λ positive-parity core states. This finding raises a challenge for theoretical investigations. The other possibility for peaks #5 and #7 to pick up extra strength will be discussed in Section 6.4.

6.3 Spectroscopy of ${}^7_{\Lambda}\text{He}$ and Discussion

6.3.1 Spectroscopy of ${}^7_{\Lambda}\text{He}$

The ${}^7_{\Lambda}\text{He}$ was first studied by emulsion experiments [88]. However, only a few events were observed for this hypernucleus and their masses spread over a wide energy region, so that no ground state binding energy could be determined. As one of the lightest p-shell hypernuclei, its ground state is one of the members of an iso-spin triplet along with the first excited state of ${}^7_{\Lambda}\text{Li}$ and the ground state of ${}^7_{\Lambda}\text{Be}$. Thus, it is one of the most interesting light hypernuclei, and the theoretical calculations of its structure are expected to be done precisely. The JLab E01-011 (HKS) experiment obtained a spectrum for the ${}^7_{\Lambda}\text{He}$ and observed its ground state for the first time [48]. However, due to limited statistics, the expected core excited states were not confirmed. The E05-115 experiment measured this hypernucleus again with a factor of four higher statistics and further improved precision, aiming to confirm the existence of the core excited states. The obtained spectrum of the ${}^7_{\Lambda}\text{He}$ is shown in Figure 6.8. All the fitted functions for the spectroscopy of ${}^7_{\Lambda}\text{He}$ are above the accidental background obtained precisely by the mixed events analysis.

Using events selected within the range of $\pm 2.5\sigma$ of the fitted peak width and requiring a statistical significance larger than 3.5, three peaks can be recognized and fitted in the spectrum; see Figure 6.8. Peak #1 was fitted as a single Gaussian with the confidence level around $\sim 95\%$ and its width is $\sigma = 0.31 \pm 0.050$ keV (FWHM 730 keV). The resolution is lower than that in the spectroscopy of ${}^{12}_{\Lambda}\text{B}$ and ${}^{10}_{\Lambda}\text{Be}$ as expected. Since its structures are relatively simple, to maximize the yield rate, a much thicker target was used; thus, the energy uncertainty from the target straggling is higher as mentioned in Section 5.1. The statistics of peaks #2 and #3 are limited and there is significant overlapping. Thus, a double Gaussian fit with a common width was used. The width was found to be $\sigma = 400$ keV, corresponding to the best confidence level

(90%). The fitted results are shown in Table 6.10 and the quoted uncertainty in the table is statistical. The systematic uncertainty for the B_Λ (illustrated in Table 6.11) is ± 0.12 MeV. This systematic uncertainty mainly causes a constant shift of the spectrum in terms of B_Λ . The systematic uncertainty of the measured excitation energies (relative to the ground state) is about ± 0.06 MeV. The systematic uncertainty for the cross sections is about 17.0% [65].

Figure 6.8. Spectroscopy of ${}^7_\Lambda\text{He}$ fitted by Gaussian functions.

Table 6.10. Measured binding energies and cross sections for the spectrum of ${}^7_\Lambda\text{He}$.

Peak	B_Λ (MeV)	E_x (MeV)	σ Width (MeV)	Cross section (nb/sr)
1	5.51 ± 0.05	0	0.31 ± 0.050	17.3 ± 0.6
2	4.00 ± 0.14	1.50 ± 0.15	0.40(fixed)	9.7 ± 0.5
3	2.78 ± 0.15	2.72 ± 0.16	0.40(fixed)	7.8 ± 0.5

6.3.2 Interpretation of the ${}^7_\Lambda\text{He}$ Spectrum

Peak #1 is considered to be the $1/2^+$ ground state of the ${}^7_\Lambda\text{He}$, and its binding energy is found to be $B_\Lambda = 5.51 \pm 0.05(\text{stat}) \pm 0.12(\text{syst})$ MeV. It has good consistency

Table 6.11. The systematic uncertainty for the ${}^7_\Lambda\text{He}$ binding and excitation energies.

Item	Uncertainty(keV)
${}^7_\Lambda\text{He}$ binding energy	
Λ mass precision	± 27
Target Straggling of ${}^7\text{Li}$	± 62
Target Straggling of CH_2	± 90
Optics Defect	± 50
Total	± 123
${}^7_\Lambda\text{He}$ excitation energy	
Optic Defect	± 57
Scale (by Λ & Σ^0)	± 10
Total	± 58

with the published result ($B_\Lambda = 5.68 \pm 0.03(\text{stat}) \pm 0.25(\text{syst})$ MeV [48]) from the E01-011 experiment. Due to improved statistics, two additional peaks in the spectrum are recognized (peaks #2 and #3) as mentioned above.

The level structure of the ${}^7_\Lambda\text{He}$ was calculated with a three-body cluster model: ${}^7_\Lambda\text{He} = {}^5_\Lambda\text{He} + n + n$ [92]. The calculated spectrum and the corresponding core nucleus ${}^6\text{He}$ are represented in Figure 6.9. Based on this calculation, the ground state of the core nucleus is only weakly bound by 0.69 MeV below the $\alpha+n+n$ threshold, while that of the ${}^7_\Lambda\text{He}$ becomes rather deeply bound by 3.02 MeV below the ${}^5_\Lambda\text{He}+n+n$ threshold. The first excited 2^+ state of the core nucleus is unbound, about 1.1 MeV above the $\alpha+n+n$ threshold. S_Λ coupling to this core state results in the doublet states. $3/2^+$ and $5/2^+$ with a small separation, and this doublet is predicted to be bound by 1.33 MeV below the ${}^5_\Lambda\text{He}+n+n$ threshold. This illustrated the glue-like role played by the Λ hyperon in this light system of ${}^7_\Lambda\text{He}$.

The predicted excitation energy of the first $3/2^+$ core excited state is 1.69 MeV. The energy separation of the $3/2^+$ and $5/2^+$ states, including both the spin-spin and spin-orbit potential terms, is predicted as only 0.08 MeV, too small to be resolved by multiple peak fittings. The measured excitation energy of peak #2 is

$1.50 \pm 0.15(\text{stat.}) \pm 0.06(\text{syst.})$ MeV. Thus, it appears that peak #2 is a good candidate corresponding to the predicted doublet states $3/2^+$ and $5/2^+$ coming from the coupling of the s_Λ to the 2^+ core state.

There is no additional structure predicted by the current theoretical works for the peak #3 ($E_x = 2.72 \pm 0.16$ MeV) in Table 6.10. The possible contribution for this peak will be discussed in the following section.

Figure 6.9. Calculated energy spectra of the low-lying states of ${}^7_\Lambda\text{He}$ [92].

6.4 States at Break-up Thresholds

For both the ${}^{10}_\Lambda\text{Be}$ and ${}^7_\Lambda\text{He}$ hypernuclei, break-up (i.e., fragmentations) can take place, even in the Λ bound region, which is defined as $-B_\Lambda < 0$. In the case of ${}^{10}_\Lambda\text{Be}$, the first break-up threshold (${}^{10}_\Lambda\text{Be} \rightarrow {}^9_\Lambda\text{Be} + n$) appears at $Ex = 4.065$ MeV, i.e., $-B_\Lambda = -4.6$ MeV, while the second one (${}^{10}_\Lambda\text{Be} \rightarrow {}^6_\Lambda\text{Be} + \alpha$) is at $Ex = 7.397$ MeV, i.e., $-B_\Lambda = -1.26$ MeV. For the ${}^7_\Lambda\text{He}$, there is one break-up threshold in the bound region, ${}^7_\Lambda\text{He} \rightarrow {}^5_\Lambda\text{He} + n + n$, at $Ex = 3.02$ MeV, i.e., $-B_\Lambda = -2.49$ MeV.

The two peaks #5 ($Ex = 4.4$ MeV) and #7 ($Ex = 7.14$ MeV) in the ${}^{10}_{\Lambda}\text{Be}$ spectrum and peak #3 ($Ex = 2.72$ MeV) in the ${}^7_{\Lambda}\text{He}$ spectrum appear located very close to these break up thresholds. These peaks might be resonances, which may also contribute extra strength to the nearby states, such as the possible positive parity states of ${}^{10}_{\Lambda}\text{Be}$ at $Ex = 4.704$ MeV, 6.76 MeV, and 7.978 MeV as discussed in Section 6.2.2.4.

SECTION 7

CONCLUSION

The unique CEBAF beam has enabled high-precision spectroscopic investigations of Λ hypernuclei which serve as a laboratory for studying the ΛN interaction.

The spectra of the ${}_{\Lambda}^{12}\text{B}$ and the ${}_{\Lambda}^7\text{He}$ independently obtained by the experiment E05-115 are consistent with those from the previous experiment E01-011. The improvements in both energy resolution and statistics for E05-115 ensure high precision spectroscopy with detailed level structures of the Λ hypernuclei. This precisely measured spectroscopy information is important and needed for theoretical investigation on the ΛN interactions.

The ${}_{\Lambda}^{12}\text{B}$ spectrum from E01-011, with a resolution of ~ 700 keV, is similar to that published by the JLab Hall A experiment [45], which claimed a similar resolution. While the Hall A spectrum contains the mystery of the origin of a narrower p_{Λ} peak width, the HKS experiments (E01-011 and E05-115) have proven uniformity of precision over the full kinematics space. With good resolution, ~ 540 keV FWHM, the spectrum from E05-115 permits double-peak fitting to separate the ground state doublet and the determination of four extra peaks (two on each side of the strong p_{Λ} peak). Of these, the peaks at 8.8 MeV and 11.75 MeV are interpreted as having the dominant structure of an s_{Λ} coupled to positive-parity states of ${}^{11}\text{B}$. All of this represents new information because of good resolution.

A rich spectroscopy of ${}_{\Lambda}^{10}\text{Be}$ is obtained for the first time. Among the 12 observed peaks, 9 peaks can be explained by the $0\hbar\omega$ based theory calculation. The remaining 3 may have to be explained by a $1\hbar\omega$ based calculation, which is not yet currently available. This certainly gives a challenge to the theory investigation.

The binding energy of the ${}_{\Lambda}^7\text{He}$ ground-state ($1/2^+$) is an important parameter in studies of the $A=7$ iso-triplet hypernuclei. The result from E05-115 shows good

agreement with the published E01-011 result [48], but with further improved precision as well as statistics. One of the two newly observed extra peaks can be interpreted by the coupling of the s_Λ to the 2^+ ${}^6\text{He}$ core. The configuration of the third peak cannot yet be confirmed. It could come from another 2^+ core state which is not experimentally seen or a resonance at the break-up threshold. This is certainly interesting and it obviously needs to be further confirmed both theoretically and experimentally.

The key technical improvement for possible future experiments in the spectroscopy of the Λ hypernuclei will be the reduction of the accidental background.

APPENDICES

APPENDIX A

SIEVE SLIT SIMULATION

Figure A.1 shows GEANT simulated HKS SS events, and the corresponding correlation between the Focal Plane (FP) parameters. One band cut from the FP $x' - x$ correlation selects the particles passing through one column of the holes in the SS plate, and one band cut from the FP $y' - y$ correlation selects the particles passing through one row of the holes in the SS plate (see Figure A.2). Therefore, the particles passing one special hole in the SS plate are selected by a simultaneous one band cut from both $x' - x$ and $y' - y$ correlations. The various HES SS simulated correlations are shown in Figure A.3.

Figure A.1. Various plots from HKS SS simulation data. xfp is x in the focal plane, xpf is the angle of x' in the focal plane, yfp is y in the focal plane, yfp is the angle of y' in the focal plane.

Figure A.2. Events selection on the SS plane. **Top:** Left is one band cut from HKS FP $x' - x$ correlation; right is the corresponding one column in the SS pattern. **Bottom:** Left is one band cut from HKS FP $y' - y$ correlation, and right is the corresponding row in the SS pattern

Figure A.3. The various plots from HES SS GEANT simulation. xfp is x in the focal plane, $xpfp$ is the angle of x' in the focal plane, yfp is y in the focal plane, and $ypfp$ is the angle of y' in the focal plane.

APPENDIX B

APPLICATIONS OF FORWARD OPTICAL TUNING

During forward optical tuning, the asymmetry function is found and optimized and applied to the x (Bx) and y (By) components of the HKS Q1 magnetic field, separately, shown as the following equations:

$$\begin{aligned} Bx &= Bx_0 \cdot F(x), \\ By &= By_0 \cdot G(x), \end{aligned} \tag{B.0.1}$$

where, Bx_0 and By_0 are the intensity of the field components from the TOSCA calculations.

At the same time, the asymmetry function was also applied to the HES Q1 magnetic field, seen as follows:

$$Bx = Bx_0 * R(x), \tag{B.0.2}$$

where the asymmetry function only on the Bx was enough to describe the asymmetry field.

On the HKS side, functions are applied separately for the area of $y \geq 0$ and $y < 0$, because of the asymmetry on the y direction, as seen in Figure 5.6.

For $y \geq 0$, the optimized asymmetry functions are shown as follows:

$$\begin{aligned} F(x) &= c1(1.0 + \frac{c2}{c5}(x + c4) + \frac{c3}{(c5)^2}(x + c4)^2), \\ G(x) &= c6(1.0 + \frac{c7}{c5}(x + c4) - \frac{c8}{(c5)^2} * (x + c4)^2). \end{aligned} \tag{B.0.3}$$

for $y < 0$, the optimized asymmetry functions are shown as follows:

$$\begin{aligned} F(x) &= c9(1.0 + \frac{c10}{c5}(x + c4) + \frac{c11}{(c5)^2}(x + c4)^2), \\ G(x) &= c12(1.0 + \frac{c13}{c5}(x + c4) - \frac{c14}{(c5)^2}(x + c4)^2). \end{aligned} \quad (\text{B.0.4})$$

where $c1, c2, c3, c5, c6, c7, c8, c9, c10, c11, c12, c13$ and $c14$ are the parameters needed to be optimized. $c1, c6, c9$ and $c12$ are the scale factors for the components Bx and By , separately. $c2, c3, c7, c8, c10, c11, c13$ and $c14$ stand for the asymmetry level, $c5$ is the action range of the functions, and $c4$ is the cross point of the asymmetry magnetic field.

The starting action point of the Bx is -15 and that of the By is -7. Currently, the values of the optimized parameters are shown in Table B.1.

Table B.1. The optimized parameters for the asymmetry functions on the HKS side.

c1	c2	c3	c4	c5	c6	c7
0.994	0.12	0.0075	7.0	17.0	1.03	0.2
c8	c9	c10	c11	c12	c13	c14
0.004	1.0	0.12	0.0075	1.03	0.2	0.004

On the HES side:

$$R(x) = a0(1.0 - a1(x - a2) - a3(x - a2)^2 - a4 * (x - a2)^3), \quad (\text{B.0.5})$$

where the currently used values of the parameters are shown in Table B.2. Due to the “tilt method”, the application only on the Bx is good enough to obtain the correction effective magnetic field.

Besides the asymmetry functions mentioned above, the intensities of the field are scaled, and the scaling factors are summarized in Table B.3.

Table B.2. The optimized parameters for the asymmetry functions on the HES side.

a0	a1	a2	a3	a4
0.98	0.0035	1.2	0.6×10^{-4}	0.17×10^{-4}

Table B.3. Scaling factors of the magnetic field of the HKS and the HES magnets.

Magnet	Scale Factor
SPL on HKS	0.9852916
HKS Q1	0.969021
HKS Q2	0.998256
HKS D	0.98678
SPL on HES	1.0
HES Q1	1.0
HES Q2	1.0
HES D	0.9925

In addition to these scaling factors, there are still asymmetry scaling factors for some of the components of the magnetic field, shown in Table B.4.

Table B.4. Additional scaling factors of the magnetic field of the HKS and HES magnets.

Magnet	Condition	Component	Scale Factor
HKS Q2	$x > 0$	B_y	1.055
HKS Q2	$x \leq 0$	B_y	1.08
HES Q2		B_y	0.9725

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