Doctor thesis

Spectroscopic study of Λ hypernuclei
by the $(e,e'K^+)$ reaction

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Abstract

Hypernuclear spectroscopy study via the $(e,e'K^+)$ reaction has been carried out for the first time, establishing a new technique to study Λ hypernuclei. The high quality electron beam at Jefferson Lab made it possible to measure Λ hypernuclear spectra with an energy resolution better than 1 MeV (FWHM). The present experiment was designed to make full use of the virtual photon flux, which peaks at very forward angles, by detecting scattered electrons at 0 degrees. Scattered positive kaons were also detected near 0 degrees, where the cross section of kaon photo-production is maximized. This unique kinematical configuration was realized with the HyperNuclear Spectrometer System (HNSS), which consisted of the Short-Orbit Spectrometer, the Enge Split-Pole Spectrometer, and the splitter magnet. The ${}_{\Lambda}^{12}\text{B}$ mass spectrum was measured in the ${}^{12}\text{C}(e,e'K^+){}_{\Lambda}^{12}\text{B}$ reaction with 0.9 MeV (FWHM) energy resolution. The averaged binding energy of the ${}_{\Lambda}^{12}\text{B}$ ground state doublet was obtained to be 11.7 ± 0.1 (statistical) ± 0.3 (systematic) MeV, which is consistent with emulsion data. The general spectral structure of the ${}^{12}\text{C}(e,e'K^+){}_{\Lambda}^{12}\text{B}$ reaction was found to be similar to that of the ${}^{12}\text{C}(\pi^+,K^+){}_{\Lambda}^{12}\text{C}$ reaction, showing characteristic peaks corresponding to s_{Λ} and p_{Λ} orbits, as well as a few core-excited states. The cross section of the ${}_{\Lambda}^{12}\text{B}$ ground state doublet was derived to be 117 ± 13 (statistical) ± 14 (systematic) nb/sr. The theoretical prediction of the cross section was consistent with the present result, validating DWIA calculation for hypernuclear yields. The present study proved the effectiveness of the $(e,e'K^+)$ reaction for future Λ hypernuclear spectroscopy studies.

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Chapter 1

Introduction

1.1 Significance of hypernuclear spectroscopic study

A hypernucleus is a many-body system composed of not only nucleons but also hyperons. Hyperons, having a strangeness degree of freedom, do not obey Pauli exclusion principle for the nucleus. Thus, one can probe deep inside the nucleus which is hardly investigated in the framework of an ordinary nucleus consisting of protons and neutrons.

The Λ hypernuclei, which are bound systems of an ordinary nucleus and a Λ hyperon, have been extensively studied in the past years. In recent experimental investigation, hypernuclear spectroscopy played unique role and has been greatly explored thanks to the progress of experimental and related theoretical studies.

The Λ hypernuclear states are usually formed as nucleon-hole Λ -hyperon-particle states in direct reactions converting a nucleon to a Λ hyperon. It has been theoretically shown that the Λ bound states have narrow spreading widths of less than a few 100 keV even above nucleon emission thresholds [1, 2]. This is in contrast with the case of ordinary nuclei where highly-excited deep-hole states have spreading widths larger than a few MeV. The reason lies in the fact that (1) the interaction between Λ and a nucleon, called the ΛN interaction, is much weaker than the nucleon-nucleon (NN) interaction, (2) no exchange term is required for the Λ -nucleon system, and (3) Λ isospin is 0. The narrow spreading widths allows one to perform precision study of many-body baryon systems with the strangeness degree of freedom through hypernuclear spectroscopy.

In addition, the study of Λ hypernuclei (indirectly) provides information on the strong interactions in the SU(3) framework with strange baryons (hadrons). Ideally, hyperon-nucleon (YN) and hyperon-hyperon (YY) scattering experiments could directly give information on the YN and YY interactions. However, these experiments are not easy because the lifetimes of hyperons are of the order of 10^{-10} s. Consequently, hypernuclear structure information obtained through hypernuclear spectroscopy plays a key role in the investigation of the YN and YY interaction.

Theoretically, hypernuclear properties can be derived starting from One-Boson-Exchange (OBE) models of ΛN interaction such as the Nijmegen potential models [3]. The effective ΛN interaction obtained by the G-matrix calculation and expressed in analytical forms

(called YNG) [4] is particularly useful in investigating hypernuclear properties such as binding energies, level structure, reaction cross sections and polarizations, etc. Such experimental information obtained through hypernuclear spectroscopy experiments can be connected to the models of hypernuclear structures, and YN and YY interactions. Such calculations are thought to be more reliable than in the case of ordinary nuclei, partly because of the weakness of the ΛN interaction.

1.2 Historical overview

The first Λ hypernucleus was discovered in an airborne emulsion in 1952 [5]. The early studies of Λ hypernuclei with kaon beams at CERN and BNL were mostly carried out with emulsion. Light hypernuclei with mass number less than 16 were produced in emulsions as hyperfragments after K^- absorption, and identified by detecting charged particles such as a π^- and/or a proton emitted via weak decay processes [6]. The binding energies of their ground states were determined through kinematical constraints of these decay particles. As a result, it was found that the well depth of the Λ -nucleus potential was $\sim 2/3$ of that in the nucleon case. However, this technique is restricted mostly to the study of the ground states of light Λ hypernuclei.

Counter experiments for the reaction spectroscopy started at CERN in the 70s by using K^- beam.

The γ -rays from the stopped (K^-, π^-) reaction were first measured at CERN ascribing them to the γ transitions of ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$ [7]. The stopped (K^-, π^-) reaction was employed for reaction spectroscopy with a magnetic spectrometer [8] and then taken over by the in-flight (K^-, π^-) reaction, although it was later revisited at KEK [9].

The in-flight (K^-, π^-) reaction, with the beam energies where the momentum transfer is small to enhance a sticking probability of a Λ hyperon into a nucleus, was intensively carried out in the 70s and 80s. The reaction converts a neutron to a Λ hyperon with the same orbital angular momentum and favorably populates substitutional states.

By the in-flight (K^-, π^-) reaction, several hypernuclei up to a mass number of 209 were studied at CERN [10–16] and BNL [17, 18]. Especially, p-shell Λ hypernuclei were intensively investigated. For example, by comparing the observed ${}^{12}_\Lambda\text{C}$ and ${}^{16}_\Lambda\text{O}$ spectra, it was shown that the ls splitting of Λ orbits is small [13, 14]. Various p-shell hypernuclear spectra were compared in detail with theoretical calculations based on a configuration-mixing shell model [19]. These studies demonstrated that the spin-dependent ΛN interaction was weak [20], and that weak coupling between a Λ hyperon and a core nucleus was a good approximation for Λ hypernuclei. Compared to the in-flight (K^-, π^-) reaction, the stopped (K^-, π^-) reaction has an advantage in its larger momentum transfer. However, there are some ambiguity and complexity originating in the K^- atomic structure [21].

In the 80s, the (π^+, K^+) reaction was proposed to be an effective tool for spectroscopic studies over the entire mass number range up to heavy hypernuclei such as ${}^{208}_\Lambda\text{Pb}$ [22]. Because of a large momentum transfer (more than 300 MeV/ c), the reaction can excite deeply bound states even for heavier Λ hypernuclei. In contrast, it is difficult to observe

the states of heavy hypernuclei in the (K^-, π^-) reaction because the reaction mostly converts a neutron in an outer orbit into a Λ in the same orbit. In addition, the (π^+, K^+) reaction excites the highest-spin states with the maximum aligned angular momentum. Therefore, it selectively excites the series of states in which the Λ single particle orbitals ($s, p, d, f, g, \dots$) couple to the high-spin valence neutron-hole states produced when a neutron is transformed into a Λ hyperon [23, 24].

Experiments with the (π^+, K^+) reaction have been intensively carried out at BNL [25–27] and KEK [28–31]. Hypernuclear mass spectra up to a mass number of 208 were obtained with an energy resolution of 1.45–2.0 MeV (FWHM) in the experiments with the Superconducting Kaon Spectrometer (SKS) at KEK [32]. The Λ binding energies of major shell-model orbitals up to heavy hypernuclei were derived, and the A dependence of the binding energies was investigated experimentally over a wide mass number range. In addition, from the ${}^{12}_{\Lambda}\text{C}$ hypernuclear mass spectrum, core-excited states have been identified for the first time and was discussed from the view points of hypernuclear structure and also characteristics of the ΛN interaction [29].

From these experimental data, it was found that the Distorted Wave Impulse Approximation (DWIA) calculation of the strength function including quasifree continuum contribution reproduces general features of the experimental results [33]. A phenomenological Λ -nucleus potential based on a spherical Skyrme-Hartree-Fock approach beyond a simple Woods-Saxon potential has been studied in order to reproduce the mass-number dependence of the measured Λ binding energies [34].

Hypernuclear γ -ray spectroscopy for p-shell hypernuclei was first performed at BNL [35, 36] in the 80s. High precision γ -ray spectroscopy with germanium detectors has recently been developed at KEK and derived the splitting of the hypernuclear states associated with spin-dependent ΛN interactions which is very small to be resolved by the reaction spectroscopy [37–39]. For example, γ transitions from excited states of ${}^7_{\Lambda}\text{Li}$ hypernucleus have been observed using the large acceptance germanium and BGO system (Hyperball) [37, 38]. The experimental result also showed shrinkage of the hypernuclear size compared to the non-strange system.

In summary, Λ hypernuclear study has made great progress by the reaction and γ ray spectroscopy and demonstrated the significance for the investigation of hypernuclear system.

1.3 Importance of resolution in spectroscopic study

As mentioned above, precise spectroscopic data using K^- or π^+ beam help investigating many-body system with the strangeness degree of freedom.

However, in the reaction spectroscopy, the best energy resolution of 1.45–2.0 MeV (FWHM), which has been achieved by experiments using the SKS at KEK [29, 31], is insufficient to resolve narrower splitting of hypernuclear states such as core-excited states of Λ hypernuclei. Figure 1.1 shows the hypernuclear mass spectra of ${}^{12}_{\Lambda}\text{C}$ obtained at BNL [26] and KEK [29]. In the KEK experiment, core-excited states (#2 and #3) were

observed between the s_Λ (#1) and p_Λ (#4) states because the energy resolution was improved from the BNL experiment. Additionally, in the E369 experiment at KEK [31], the f_Λ state in the hypernuclear mass spectrum of ^{89}Y was split into two peaks, which possibly carry information on the spin-orbit splitting of Λ hypernuclei. However, such structures were not observed in the previous experiment which had an energy resolution of 3 MeV [26]. The results mentioned above indicate that the improvement of energy resolution makes hypernuclear structure more clear and therefore results in extraction of deeper information on the role of strangeness embedded in the nuclear matter.

Figure 1.1: Hypernuclear mass spectrum for ^{12}C via the (π^+, K^+) reaction obtained in BNL [26] (left) and KEK [29] (right) experiments.

To improve the energy resolution, higher quality incident beam is required. In the previous studies, incident beams limit the energy resolution, because the K^- and π^+ beams are secondary beams, thus making their emittance poor and energy spread large.

The γ -ray spectroscopy is suitable for observation of level splitting in specific states with a few keV of energy resolution. However, this technique is limited to excited states below a particle decay threshold and also the binding energy of ground state can not be measured with the technique. The reaction spectroscopy is indispensable to directly observe global level structure.

The present experimental study presented in this thesis uses a primary electron beam for producing hypernuclei. In the next section, we will discuss the features of electromagnetic production of hypernuclei.

1.4 Photo- and electro-production of Λ hypernuclei

1.4.1 Elementary amplitude

A Λ hypernucleus can be produced by photon- or electron- induced reaction. The cross sections are related to the elementary amplitudes of the elementary reactions:

$$\begin{aligned}\gamma + p &\rightarrow \Lambda + K^+, \\ \gamma + n &\rightarrow \Lambda + K^0, \\ e + p &\rightarrow e' + \Lambda + K^+, \text{ and} \\ e + n &\rightarrow e' + \Lambda + K^0.\end{aligned}$$

The electro-production cross section of Λ is often expressed in terms of the (virtual) photo-production because an electron generates a virtual photon which is absorbed in the nucleus during the scattering process. The triple differential cross section of the electro-production can be related to the (virtual) differential photo-production cross section ($d\sigma_\gamma^*/d\Omega_K$) because all of the leptonic dependence in the phase space can be factorized as follows [40]:

$$\frac{d^3\sigma}{d\omega d\Omega'_e d\Omega_K} = \Gamma \frac{d\sigma_\gamma^*}{d\Omega_K}, \quad (1.1)$$

where ω , Ω_e and Ω_K are the energy transfer, the solid-angles of scattered electron and produced kaon, respectively. The virtual photon flux, Γ , depends only on the kinematics and can be calculated [41]:

$$\Gamma = \frac{\alpha}{2\pi^2 Q^2} \frac{E_\gamma}{1 - \epsilon} \frac{E'_e}{E_e}, \quad (1.2)$$

where the definitions and the relations of Q , q , $\mathbf{q}$, ω , E_e , E'_e , p_e , and p'_e are described in Figure 1.2. E_γ is the photon energy in the proton-photon system,

$$E_\gamma = \omega + \frac{q^2}{2 m_p}, \quad (1.3)$$

where m_p is the proton mass.

The polarization factor, ϵ , is given as:

$$\epsilon = \left[1 + \frac{2|\mathbf{q}|^2}{Q^2} \tan^2 \left(\frac{\theta_e}{2} \right) \right]^{-1}. \quad (1.4)$$

The elementary cross section of the photon-induced reaction in the lab frame can be expressed as [21, 42]:

Figure 1.2: Kinematics of the $A(Z)(e,e'K^+)_{\Lambda}B(Z-1)$ reaction

$$\left. \frac{d\sigma}{d\Omega_K} \right|_{lab} = \frac{(2\pi)^4 p_K^2 E_K \omega E_{\Lambda}}{q \{ p_K (E_{\Lambda} + E_K) - q E_K \cos \theta_L \}} |M|^2, \quad (1.5)$$

where E_{Λ} is the energy of Λ . M is the elementary transition matrix of the photon-induced reaction:

$$\begin{aligned} M &= \langle q - p_K | t | q, 0 \rangle_L \\ &= a_1(\boldsymbol{\sigma} \cdot \boldsymbol{\epsilon}) + a_2(\boldsymbol{\sigma} \cdot \hat{\mathbf{q}})(\hat{\mathbf{p}}_K \cdot \boldsymbol{\epsilon}) + a_3(\boldsymbol{\sigma} \cdot \hat{\mathbf{p}}_K)(\hat{\mathbf{p}}_K \cdot \boldsymbol{\epsilon}) + a_4\{(\hat{\mathbf{q}} \times \hat{\mathbf{p}}_K) \cdot \boldsymbol{\epsilon}\}, \end{aligned} \quad (1.6)$$

where $\boldsymbol{\sigma}$ is the baryon Pauli matrix, $\boldsymbol{\epsilon}$ is the photon polarization, and $\hat{\mathbf{q}}$ and $\hat{\mathbf{p}}_K$ are unit vectors of the photon momentum and the kaon momentum in the lab frame, respectively. There are 4 independent amplitudes for an on-mass-shell. For an off-mass-shell case such as the electron-induced reaction, additional 2 amplitudes, $a_5(\boldsymbol{\sigma} \cdot \hat{\mathbf{q}})(\hat{\mathbf{q}} \cdot \boldsymbol{\epsilon})$ and $a_6(\boldsymbol{\sigma} \cdot \hat{\mathbf{p}}_K)(\hat{\mathbf{q}} \cdot \boldsymbol{\epsilon})$, are required. Electron-induced reaction has been discussed in Ref. [43].

For the hypernuclear production on a nuclear target, the differential cross section is usually calculated by a DWIA method. In the impulse approximation, the transition matrix (T-matrix) of the hypernuclear production, within the “frozen-nucleon” approximation, is related to the elementary transition matrix M [42] which can be decomposed in the spin-independent term (f_0), the spin-dependent terms ($g_0, g_{\pm 1}$), baryon Pauli matrices ($\sigma_0, \sigma_{\pm 1}$) and the photon polarization (ϵ_0, ϵ_x):

$$M = \epsilon_0(f_0 + g_0\sigma_0) + \epsilon_x(g_1\sigma_1 + g_{-1}\sigma_{-1}). \quad (1.7)$$

Components of the photon polarization, $\epsilon_0 = \epsilon_z$ and ϵ_x are defined in a coordinate system where $\hat{\mathbf{x}} = \hat{\mathbf{y}} \times \hat{\mathbf{z}}$, $\hat{\mathbf{y}} \parallel \hat{\mathbf{q}}$, $\hat{\mathbf{z}} \parallel \hat{\mathbf{n}}$, and $\hat{\mathbf{n}} = \mathbf{q} \times \mathbf{p}_K / |\mathbf{q} \times \mathbf{p}_K|$. In the T-matrix calculation, the summation over photon-polarization components is performed. The elementary amplitudes f_0 , g_0 , and $g_{\pm 1}$ are determined by diagrammatic technique or phenomenological approach following Schorsch *et al* [44]. For example, they can be obtained by fitting the available elementary photoproduction data, although their cross sections are a little different from each other. The results indicate that spin-dependent terms are larger than the spin-independent terms. Eventually, the property of a sizeable spin-dependent term is reflected to hypernuclear spectra of the (e,e'K⁺) reaction.

1.4.2 Features

The (γ , K⁺) reaction transfers a large momentum to a recoil hypernucleus (~ 350 MeV/ c at $\theta_K = 0^\circ$, where θ_K is the kaon angle in the laboratory frame). The (K⁻, π^-) reaction has a small momentum transfer, and thus substitutional states with small angular momenta are preferentially populated as already mentioned. On the other hands, the (π^+ , K⁺) reaction which also transfers a large momentum to a recoil hypernucleus selectively excites the high-spin natural-parity state with maximum aligned angular momentum ($J = L_{max} = l_n + l_\Lambda$ in the case of $J_{target} = 0^+$). The (γ , K⁺) reaction, which has a large recoil momentum, is also expected to selectively excite the high-spin states. Moreover, because of the intrinsic spin of photons, spin-flip states are also strongly excited in this reaction [42].

The two characteristics, the large momentum transfer and sizeable spin-flip amplitudes, cause unique excitation possibilities of hypernuclear high-spin states with unnatural parity. Figure 1.3 shows a calculated excitation spectrum of $^{28}_\Lambda\text{Al}$ hypernuclei via the (γ , K⁺) reaction at $E_\gamma = 1.3$ GeV and $\theta_K = 3^\circ$, with an energy resolution of 300 keV (FWHM). The highest-spin states with unnatural parity such as $[d_{5/2}^{-1}s_{1/2}^\Lambda]_{3+}$, $[d_{5/2}^{-1}p_{3/2}^\Lambda]_{4-}$ and $[d_{5/2}^{-1}d_{5/2}^\Lambda]_{5+}$ are most strongly excited. These lambda-particle-proton-hole states have a configuration with $J = J_{max} = l_p + l_\Lambda + 1 = L_{max} + 1$. Such states are not populated in the (K⁻, π^-) and (π^+ , K⁺) reactions because of the smaller spin-flip amplitude. Additionally, the splittings of p_Λ - or d_Λ - orbits, which have information on the spin-orbit splitting of Λ hypernuclei, may be observed.

The (γ , K⁺) reaction converts a proton into a Λ hyperon. It can produce mirror hypernuclei of those which are produced by the (K⁻, π^-) and (π^+ , K⁺) reactions. For example, $^{10}_\Lambda\text{Be}$ can be produced by the (γ , K⁺) reaction, which is compared with the mirror-partner $^{10}_\Lambda\text{B}$ [46].

A disadvantage of the photo- and electro-production is their small cross section compared with hadronic productions. Typical values of the differential cross sections of hypernuclear bound states are of the order of 10^3 $\mu\text{b/sr}$, 1 $\mu\text{b/sr}$ and 0.1 $\mu\text{b/sr}$ for the (K⁻, π^-), (π^+ , K⁺) and (γ , K⁺) reactions, respectively. Such small cross sections have to be overcome by intense electron beams.

Figure 1.3: Expected $^{28}_{\Lambda}\text{Al}$ energy spectrum calculated by Sotona *et al* [45].

1.4.3 History

Several experiments in the photo- and electro-production of hyperon(s) were performed in the 90s and 2000s. The elementary process of the photo-production of hyperon(s) has been intensively studied by the SAPHIR group at ELSA (Bonn) [47]. They measured cross sections and polarization of Λ and Σ^0 up to 2 GeV in the $\gamma p \rightarrow \Lambda K^+$ and $\gamma p \rightarrow \Sigma^0 K^+$ reactions. The first ever hypernuclear photo-production experiment on carbon was carried out at the Institute for Nuclear Study (INS, Tokyo) [48, 49]. It is claimed that events corresponding to the production of hypernuclear bound states were observed, although discrete peaks for hypernuclear states could not be observed. Recently, the Neutral Kaon Spectrometer (NKS) has been installed at the Laboratory of Nuclear Science (LNS, Sendai), where the K^0 photo-production experiment is currently in progress [50].

The electro-production of hyperon(s) has also been studied at Jefferson Lab (JLab) in recent years. Experiments on hydrogen, deuterium and helium targets have been carried out in the Experimental Hall C [51–58]. A feasibility study of Λ electro-production on carbon has been demonstrated and confirmed the formation of hypernuclear bound states, although with very low statistics [57, 59].

1.5 Goal of the present study

The present study is the first intensive investigation of Λ hypernuclei via the $(e,e'\text{K}^+)$ reaction. The high intensity and high quality electron beam at JLab provides us with the opportunity to perform a precise measurement of the hypernuclear excitation function, for which an extremely good resolution of sub-MeV can be achieved. The properties of the $(e,e'\text{K}^+)$ reaction are investigated and its effectiveness is demonstrated by observing sub-MeV hypernuclear mass spectra, measuring the excitation energies and cross sections of hypernuclear states.

The present thesis consists of 6 chapters. Chapter 2 describes the experiment including kinematics and experimental apparatus and Chapter 3 the design and performance of the detectors operated under high-rate condition, which is a key for the success of the experiment. Chapter 4 focuses on the data analysis, analysis procedure, detector performance, evaluations of efficiencies and acceptances. Chapter 5 shows the results and discusses the hypernuclear structures and cross sections of the observed hypernuclear states. The conclusion is given in Chapter 6.

Chapter 2

Experimental Conditions and Apparatus

2.1 Overview

The hypernuclear experiment, E89-009 [60], has been carried out in the experimental hall C at Jefferson Lab (JLab) from February to May 2000. The aim of the experiment was to verify the effectiveness of hypernuclear spectroscopy via the $(e,e'K^+)$ reaction by measuring binding energies and cross sections of hypernuclear states with sub-MeV energy resolution.

High luminosity is necessary to overcome the small cross section of the electro-magnetic interaction. To achieve this, the Continuous Electron Beam Accelerator Facility (CEBAF) was an essential tool since it provided high luminosity and high quality electron beams. The beams are provided with 100% duty factor (“continuous wave”, CW), corresponding to an effective micro-structure of the beam of 1,497 MHz short bursts (1.67 ps). Each of the three experimental halls receives one third of these bursts with an “effective” frequency of 499 MHz. A typical beam emittance is 2×10^{-9} m·rad with an energy spread of $\Delta E/E \leq 10^{-4}$. This beam quality is far better than that of meson beams produced at KEK or BNL where the beam emittance is a few tens cm·rad and energy spread around a few %. A detailed description of the CEBAF machine and the beam line components is given in Appendix A.

The experimental setup to measure Λ hypernuclei is discussed in Section 2.2, the experimental equipment in Section 2.3, trigger logic, Hall C data acquisition system, and expected rate and energy resolution of mass spectra are described in Section 2.4, 2.5, and 2.6, respectively. Finally, we will conclude this chapter with the data summary in Section 2.7.

2.2 Experimental setup

This section explains the experimental settings, which were required to obtain reasonable hypernuclear yields.

The reaction used is:

$$e + {}^A_Z \rightarrow e' + {}^A_{\Lambda}(Z-1) + K^+.$$

A virtual photon generated by an incident electron is absorbed in a target nucleus, producing a hypernucleus, a scattering electron and a positive kaon. The measured experimental observables are the energy of the incident electron and the momentum vectors of the scattered electron and kaon. Our kinematics are shown in Figure 1.2. The triple-differential cross section is described in terms of a virtual photon flux factor Γ and the (virtual) photon-induced cross section σ_γ as discussed in Section 1.4 [40, 43].

Figure 2.1(a) shows the virtual photon flux as a function of the electron scattering angle (*theta*) calculated by C. E. Hide-Wright *et al* [41]. It reaches its maximum at very forward angles and rapidly decreases when the angle increases. Therefore, the detection of scattered electrons at 0 degrees maximizes the virtual photon flux. On the other hands, Figure 2.1(b) shows the cross section of ${}^{12}_\Lambda\text{B}$ ground state doublet as a function of the scattered kaon angle obtained from a DWIA calculation [61]. The maximum cross section is given at a scattered kaon angle of 0° and gradually decreases. Consequently, both the scattered electrons and electro-produced kaons should be detected at forward angles.

The beam energy should be chosen to maximize Λ electro-production and to avoid superfluous kaons. Figure 2.2 shows the total cross sections of Λ and Σ production as a function of the incident γ energy obtained by the SAPHIR group [47]. The cross section of Λ production is almost constant for a γ energy range between 1.1 and 1.6 GeV. Additionally, superfluous kaons such as $K^*(892)$ are generated above a γ energy threshold of 1.87 GeV. Therefore, the incident beam energy was chosen to produce virtual photon with energies around 1.4 GeV.

Beam current and target thickness were constrained by the production rate of bremsstrahlung photons generated at the target. Figure 2.3 shows the angular distribution of bremsstrahlung photons compared to the virtual photon flux. The bremsstrahlung photon rate reaches the maximum at 0 degrees, which complicated our coincidence experiment. They dominated the counting rate of the focal plane counters in the electron spectrometer. To keep the signal-to-accidental ratio acceptable, the counting rate at the focal plane must be suppressed down to 2×10^8 Hz [41]. The bremsstrahlung photon rate increases with the beam current and target thickness. Therefore, a thin target (~ 20 mg/cm²) and a low beam current (< 2 μA) were used.

The experimental setup required for E89-009 is summarized in Table 2.1

(a) Angular distribution of the virtual photon flux, $E_e = 1.864$ GeV and $\omega = 1.484$ GeV. Theta is the scattered electron angle.

(b) Kaon angular distribution of the photo-production cross section of $^{12}_{\Lambda}\text{B}$ ground state doublet in a DWIA calculation by Motoba [61].

Figure 2.1: Angular distribution of the (a) virtual photon flux and (b) photo-production cross section of $^{12}_{\Lambda}\text{B}$ ground state doublet.

Table 2.1: Summary of the experimental setup for E89-009.

Item	requirement
Target thickness	$\sim 20 \text{ mg/cm}^2$
Beam current	$< 2 \mu\text{A}$
Electron scattering angle	0°
Kaon scattering angle	0°
Virtual photon energy	$1.1 - 1.6 \text{ GeV}$

Figure 2.2: γ energy dependence of the total cross section of the $p(\gamma, K^+)\Lambda/\Sigma^0$ reaction [47]. The distribution of the cross section of Λ production is basically flat in a region of $1.1 < E_\gamma < 1.6$ GeV.

Figure 2.3: Angular distribution of bremsstrahlung photons compared to the virtual photon flux ($E_e=1.864$ GeV and $E_\gamma=1.484$ GeV).

2.3 HyperNuclear Spectrometer System - HNSS

The HyperNuclear Spectrometer System (HNSS) was constructed to satisfy the experimental conditions described in the previous section. It consisted of a splitter magnet, the Enge Split-Pole Spectrometer (ESPS), and the Short Orbit Spectrometer (SOS) as shown in Figure 2.4.

Figure 2.4: Top view of the HNSS experimental setup.

The incident electron interacted with a target nucleus, producing a hypernucleus, a scattered electron and a positive kaon. Scattered particles were deflected just after the target by the splitter magnet in order to detect the particles at forward angles. The produced kaons were deflected, enlarging the angle from 2° to 16° , and entered the SOS. Scattered electrons were deflected by 33° to the ESPS. The unscattered beams went to the beam dump.

2.3.1 Splitter magnet

A splitter magnet was used to deflect charged particles to the electron/hadron spectrometers. It is a C-type dipole with 7.62 cm gap. The pole area is 60.96 cm by 33.02 cm with a maximum field of 1.8 T. The vacuum chamber with the target ladder is installed in the gap. The ladder is made up of aluminium, which can hold six targets with an area of 2.2 cm by 1.3 cm. It was moved by remote control and monitored by a camera. The targets installed in the ladder are summarized in Table 2.2.

Table 2.2: The list of targets used in E89-009.

Target Type	Thickness(mg/cm ²)	Remarks
BeO	28.6	purity = 99.5%
CH ₂	8.8	covered with 1.85 mg/cm ² of Be
Nat. C	22.0	purity = 99.99%
⁷ Li	19.0	⁷ Li(92.5%)/ ⁶ Li(7.5%)
⁶ Li	16.1	
⁹ Be	9.25	
Nat. ²⁸ Si	5.16	²⁸ Si(92.23%)/ ²⁹ Si(4.67%)/ ³⁰ Si(3.1%)

2.3.2 Enge Split-Pole Spectrometer (ESPS)

The Enge Split-pole Spectrometer (ESPS) was used to detect the scattered electrons. Figure 2.5 shows a schematic drawing of the ESPS. Its specifications are shown in Table 2.3. Originally, the ESPS was developed in the 60s to obtain two-directional focusing over the full momentum range of $p_{max}/p_{min} \sim 2.8$ (energy range $E_{max}/E_{min} \sim 8$) [62]. The second order aberration at the focal plane is zero or small over the entire energy range. This property makes the detection at the ESPS focal plane easier, because vertical position information is not required. The ESPS achieves a good resolution, $dp/p \sim 10^{-4}$. The contribution to the energy resolution of hypernuclear mass spectra is smaller than that from the SOS when the desired focal plane detectors are properly used.

Figure 2.5: A schematic drawing of the ESPS.

Table 2.3: The ESPS specifications.

central momentum	283 MeV/ c
solid angle acceptance	1.6 msr
horizontal acceptance	25 mr
vertical acceptance	20 mr
total length	~ 5 m
momentum bite	$\pm 20\%$
focal plane dimension	74 cm
$\delta p/p$	5.0×10^{-4} (FWHM)

2.3.3 Short Orbit Spectrometer (SOS)

The Short Orbit Spectrometer (SOS) was used to detect the electro-produced kaons. For a detail information, we refer the reader to the *Hall C SOS handbook* [63]. Figure 2.6 shows a schematic drawing of the SOS. Table 2.4 lists its specifications.

The SOS consists of a quadrupole (Q) magnet followed by two dipoles (D and $\overline{D}$) which share a common yoke and a detector package. The first dipole bends the central ray upward by 33° , and the second dipole bends the ray back downward by 15° , for a total of an 18° upward deflection. The distance from the target to the last hodoscope is ~ 10 m. This feature of the short length enables the measurement of short-lived particles such as kaons. A HEAVYMET (machinable Tungsten with 10% CuNi, density = 17 g/cm³) collimator can be installed in front of the SOS Q magnet. Two types of collimators were used for the experiment: one was the SOS collimator for a better definition of the solid angle acceptance, and the other a sieve slit for optics studies. Figure 2.7 shows a schematic view of the SOS collimator.

Table 2.4: SOS specifications.

Maximum central momentum	1.8 GeV/ c
solid angle acceptance	for point target ~ 7.5 msr
Angular acceptance	scattering angle ± 60 mr
	out of plane ± 40 mr
Total length	~ 10 m
momentum bite	$\pm 20\%$
dispersion	< 0.92 cm/%
$\delta p/p$	5×10^{-4} (FWHM)

The detector package of the SOS is shown in Figure 2.6. The detected particles pass through two drift chambers, two pairs of hodoscope planes, three Cherenkov detectors (gas, lucite and aerogel) and a shower counter.

Figure 2.6: A schematic view of the SOS.

Figure 2.7: Front view of the SOS collimator.

SOS Drift Chambers

The two drift chambers (DCs) measure the particle tracks.

Momentum, initial angles and initial positions at the target point are reconstructed by using the two drift chambers (DCs) information which measure the particle tracks and a transport matrix. Figure 2.8 and 2.9 show a side view and a geometrical diagram of the DCs. Each of the DCs has six wire planes with multiple orientations in the plane transverse to the central trajectory of the particles. Wire orientations are perpendicular to the scattering angles (x, x') , and tilted by 30° (u, u') and -30° (v, v') with respect to the x wires, respectively. A pair of planes with the same orientation has an offset in half cell size of 0.5 cm from each other to resolve the left-right ambiguity. Each wire plane has a set of anode wires connected to the ground and a set of potential wires and cathode foils set at negative high voltages. The wire material is gold plated tungsten and the cathode foils are made up from 1/2 mil of mylar coated with 1,200 Å of Cu on each side. The wires are separated by 1 cm, and the maximum of the drift distance is 0.5 cm. The DCs are filled with a mixture of 50:50 (by weight) argon-ethane. Charged particles passing through a wire plane ionize the gas molecules, and free electrons drift toward the nearest anode wire and are then amplified with the strong electric field around the wire. Each anode wire on each plane was directly connected to a Nanometrics or LeCroy 2735DC preamplifier card mounted on the detector assembly. These cards amplify and discriminate the signals. Discriminated signals of ECL were sent to a FASTBUS multihit TDC (LeCroy 1877). Up to 16 hits can be stored with a time resolution of 500 ps.

Figure 2.8: A side view of one SOS drift chamber.

Figure 2.9: The geometry of the SOS drift chamber.

SOS Hodoscopes

The SOS hodoscopes measure the time-of-flight (TOF). Figure 2.10 shows the geometrical configuration of the hodoscope elements. The SOS is equipped with four planes of plastic scintillator hodoscopes, each plane being composed of 9 or 16 elements. Planes are grouped into Y-X pairs (S1Y,S1X) and (S2Y,S2X), which are separated by 2.15 m (distance from the center of S1Y to that of S2X).

Figure 2.11 and 2.12 show the schematic diagrams of two types of the planes. The scintillators are overlapped with each other to prevent gaps between them. Photo multiplier tubes (Philips 2282) are connected on both sides of each scintillator bar. All signals are sent to the FASTBUS ADC (LeCroy 1881) and TDC (LeCroy 1875) through a discriminator after split. One part of the discriminated signals is “or” ed for triggers.

Figure 2.10: Geometrical position of the SOS hodoscope elements.

Figure 2.11: SOS hodoscope S1X alignment. S2X alignment is the same except for the number of scintillators (16).

Figure 2.12: Alignment of the SOS hodoscope S1Y or S2Y.

SOS Cherenkov counters

Cherenkov counters were used for Particle IDentification (PID). Three types of Cherenkov materials, aerogel, lucite and Freon 12 Gas (CCl_2F_2), were used. The indexes of gas, aerogel and lucite are 1.001, 1.034 and 1.4, respectively, which can distinguish electron/hadron, pion/kaon and kaon/proton, respectively. Figure 2.13 shows a schematic view of the aerogel Cherenkov counter. Generated Cherenkov lights in the gas and aerogel are diffused in a diffusion box, where some of the PMTs will receive the emitted lights. The lucite counter consists of 8 lucite bars with two PMTs at both ends.

All signals from the Cherenkov counters were split for the FASTBUS ADCs (LeCroy 1881) and the trigger logic after they are “or”ed in each counters. The trigger is set to require or reject Cherenkov photons above (or below) each threshold which is decided to separate kaon with the other particles.

Figure 2.13: The aerogel detector box.

SOS shower counter

The SOS shower counter is used to reject positrons. It is a set of four layers of 11 $10\text{ cm} \times 10\text{ cm} \times 70\text{ cm}$ lead glass blocks. High energy positrons traveling through a dense material radiate bremsstrahlung photons that in turn create $e^+ e^-$ pairs if they are energetic enough. When electromagnetic shower is created, Cherenkov photons from the positrons and electrons in the shower are collected. The number of photons is correlated with the total amount of energy deposited in the block. On the other hands, hadrons deposit only a small fraction of their energy. Therefore, the shower counter distinguishes positrons from hadrons. All signals from the shower counter are “or”ed for triggers. They are also sent to the FASTBUS ADCs.

2.4 Trigger

The main trigger was basically made by the SOS detector package. The ESPS detector package was not used for trigger because of its high counting rate. Outputs from the detectors, except drift chambers and SSDs, traveled up from the experimental hall to a counting house located about 100 feet above the hall, and were processed and utilized in the trigger.

Figure 2.14 shows the main part of the trigger. Trigger timing was determined by the SOS hodoscopes. Logic modules collected signals from the hodoscope planes to create the SOS signals, $S1X$, $S1Y$, $S2X$ and $S2Y$. A basic trigger was created by 3 or 4 out of the 4 hodoscopes (3/4 or 4/4). Signals from the gas, aerogel and lucite Cherenkov detectors and shower counters (GC , AC , LC and SH) were used to identify particles. The signals were collected and discriminated by a reasonable threshold to be sent to logic modules. The GC , AC and SH were used as VETO (labeled $\overline{GC}$, $\overline{AC}$ and $\overline{SH}$). The LC was used as a part of the trigger. The trigger logic is summarized in Table 2.5.

Figure 2.14: The HNSS trigger logic.

The main trigger types are summarized in Table 2.6. Trigger 4, 5 and 6 were used for the study of particle singles rate. Trigger 9 was to collect the $(e,e'e^+e^-)$ events for the HNSS hodoscope calibration. The random (pulser) trigger (trigger 10) was used to

Table 2.5: Signal meanings.

Signal	Meanings
4/4	Coincidence signal of 4 TOF planes
3/4	Signal in which 3 out of 4 TOF planes have a hit
$\overline{GC}$	Signal VETO from the Gas Cherenkov counter
$\overline{AC}$	Signal VETO from the aerogel Cherenkov counter
LC	Signal from the lucite Cherenkov counter
$\overline{SH}$	Signal VETO from the shower counter
$\overline{S1X}$	“or”ed signal VETO from S1X1, 2, 8 and 9
$LCHI$	Signal from lucite Cherenkov counter with the higher discriminator threshold (corresponding to a number of photo-electron = 4)

measure all ADC pedestals and monitor the SSD noise level.

Table 2.6: Trigger definitions.

No.	Signal	Remarks
1	$3/4 \times \overline{GC} \times \overline{AC} \times \overline{SH} \times LCHI$	for production runs
2	$3/4 \times \overline{GC} \times \overline{AC} \times \overline{SH} \times LC$	for production runs
3	$3/4 \times \overline{GC} \times \overline{AC} \times \overline{SH} \times LC \times \overline{S1X}$	for production runs
4	4/4	for study
5	$4/4 \times \overline{GC}$	for study
6	$4/4 \times \overline{GC} \times \overline{AC}$	for study
7	$4/4 \times \overline{GC} \times \overline{AC} \times LC$	for production runs
8	$4/4 \times \overline{GC} \times \overline{AC} \times \overline{SH}$	for production runs
9	$4/4 \times \overline{GC} \times \overline{AC} \times \overline{SH} \times LC$	for production runs
9	$4/4 \times GC$	for calibration runs
10	pulser (random)	for ADC pedestal and SSD noise scans

All triggers were sent to a programmable logic module called 8LM (LeCroy 2365) and controlled by a Trigger Supervisor (TS) which has been built at Jefferson Lab. Figure 2.15 shows a logic diagram of the TS. The 8LM received $TS\ BUSY$, $TS\ EN1$, or $TS\ GO$ signals and pretriggers. The $TS\ GO$, $TS\ EN1$ and $TS\ BUSY$ mean ‘run has started’, ‘run has started and data taking is enabled’ and ‘run has started but data taking is disabled’, respectively. The 8LM produced $TRIG$ and $PRETRIG$ signals, the only difference being whether the $TS\ BUSY$ signal is affected ($TRIG$) or not ($PRETRIG$). All outputs in the 8LM were sent to the scalers and TDCs to be recorded. The 8LM sent the selected $TRIG$ signals to the TS, producing a pair of long gates (more than 100 μs). All the ADC

and TDC gates were generated by coincidence between the selected *TRIG* signals and the long gate.

Figure 2.15: The TS logic.

2.5 Data acquisition

The conversion from a collection of electronic signals to a physics event data written on disk was managed by the CEBAF On-line Data Acquisition (CODA) system. Figure 2.16 shows a flowchart of the CODA system.

Figure 2.16: A flowchart of CODA.

Information for each event was temporarily stored in the FASTBUS TDCs and ADCs, and scaler information was stored temporarily in VME scalers. Each front-end crate was managed by a Read Out Controller (ROC) processor. The signals for valid triggers were sent from the TS to the ROCs. The ROCs read the event data and sent event fragments along the Event Builder (EB). The EB checks the condition of the fragments and the synchronization of the data stream if running in buffered mode where fragments for 1,000 events are read at a time rather than building one event after another. If synchronization is lost over the past 1,000 events, the EB resets the synchronization. The EB sends the combined fragments for each event on to the Event Recorder (ER), which organizes each event into a standard format and writes it to the disk. A fast FDDI network interface connected the various CODA components, and the user controlled the data acquisition through a GUI interface.

At the beginning of each run, a pedestal trigger was applied to determine the value and width of all ADC pedestals. The physics data were stored until the maximum data size set (1 Gbyte/run). Scaler data were stored every 2 seconds during data taking. Values

such as spectrometer settings, accelerator settings and target status variables were read out from the CEBAF EPICS database by a script CODA every 2-30 seconds.

2.6 Expected singles rate and energy resolution

Singles particle rates in the SOS expected for E89-009 were calculated and are summarized in Table 2.7. Hadron singles rate was estimated by the program EPC [64]. Positron singles rate was estimated using the cross section formula of pair production, which was dominant for the SOS rate. Background in the hadron arm was rejected in the trigger by the Cherenkov counters and the shower counter. The SOS trigger rate was reduced to be less than 2 kHz. All the scattered electrons within the TDC time window (200 ns) were recorded for each SOS trigger. Bremsstrahlung electrons were rejected in the offline analysis. The singles rate of particles in the SOS was measured during the experiment. The results are discussed in appendix B.

Table 2.7: Calculated singles rates ($I_e = 1.6 \mu\text{A}$, $\theta_e = 0^\circ$, $\theta_K = 3^\circ$ and 10 mg/cm^2 of ^{12}C).

Hadron arm	Singles rate (/sec)
e^+	10^5
π^+	10^3
p	10^2
K^+	0.4
Electron arm	
e^-	10^8

The expected energy resolution of bound states in $^{12}_\Lambda\text{B}$ mass spectrum is shown in Table 2.8. Beam energy is measured with a precision of 10^{-4} . The ESPS momentum resolution was estimated by the electron momentum and SSD channel acceptance. A contribution of kinematical broadening is proportional to the inverse of the target mass number and depends on the angular resolution of the SOS spectrometer. The contribution for the carbon target is 0.2 MeV. Contribution from target thickness was also small because thin targets (22 mg/cm^2 for ^{12}C) were used. A contribution from the SOS momentum was dominant for the overall energy resolution. Eventually, a resolution of less than 1 MeV was expected.

2.7 Data summary

Data were taken in 4 separated cycles. Two electron beam energies were used, 1.864 GeV in the 1^{st} and 2^{nd} cycles and 1.721 GeV in the 3^{rd} and the 4^{th} cycles, respectively. Settings were changed many times in each cycle (Table 2.9). The ^{12}C and CH_2 targets were used

Table 2.8: Expected energy resolution for bound states in ${}^{12}_{\Lambda}\text{B}$ mass spectrum ($I_e = 1.6 \mu\text{A}$, $\theta_e = 0^\circ$, $\theta_K = 3^\circ$ and 22 mg/cm^2 of ${}^{12}\text{C}$).

Components	Resolution (keV)
Beam energy	180
ESPS momentum	130
SOS momentum	800
Kinematical broadening	200
Target thickness	< 100
overall	860

from the 1^{st} to the 3^{rd} cycles. The ${}^7\text{Li}$ target was used in the 4^{th} cycle. In the end of the 4^{th} cycle, a steel shield (2.2 mm or 4.4 mm thick) was put at the entrance of the ESPS to test a blocking effect of bremsstrahlung electrons at 0 degree. Results of the 4^{th} cycle are not discussed here. Several studies such as rate, target and trigger were done during the beam time and are not shown in the table.

Table 2.10 shows a run summary with target thickness. In this thesis, a combined result of carbon target runs from the 1^{st} to 3^{rd} cycles, except some runs at 1.8 GeV (data set no. 1) and the 1.7 GeV high current run (data set no. 11), is shown. As for the results from the CH_2 runs data, data from set 8 and 10 are shown.

Table 2.9: Data acquisition settings. Here $^{12}\text{C}(1)$ and $^{12}\text{C}(2)$ mean carbon target run with 2.2 mm and 4.4 mm absorber (steel shield) at the entrance of the ESPS (a point of $\theta'_e = 0^\circ$), respectively.

Data set No.	Cycle	Beam energy (GeV)	Beam current (μA)	Target	Trigger ($\overline{GC} \times \overline{AC} \times \alpha$)	Beam charge (mC)
1	1	1.864	0.3-0.6	^{12}C	$\alpha = 3/4 \times \overline{SH} \times LC HI$	30
2	1	1.864	0.4	^{12}C	$\alpha = 3/4 \times \overline{SH} \times LC$	21
3	1	1.864	0.5	^{12}C	$\alpha = 3/4 \times \overline{SH} \times LC$	81.6
4	2	1.864	1.0	CH_2	$\alpha = 3/4 \times \overline{SH} \times LC \times \overline{S1X}$	71.5
5	2	1.864	0.6	^{12}C	$\alpha = 3/4 \times \overline{SH} \times LC \times \overline{S1X}$	67.2
6	2	1.864	0.6	^{12}C	$\alpha = 4/4 \times \overline{SH} \times LC$	55.7
7	2	1.864	0.3	^{12}C	$\alpha = 4/4 \times \overline{SH} \times LC$	43.0
8	2	1.864	0.5	CH_2	$\alpha = 4/4 \times LC$	231.5
9	3	1.721	0.2	^{12}C	$\alpha = 4/4 \times \overline{SH}$	97.6
10	3	1.721	1.0	CH_2	$\alpha = 4/4 \times \overline{SH}$	122.9
11	3	1.721	0.6	^{12}C	$\alpha = 4/4 \times \overline{SH}$	207.9
12	4	1.721	0.8	^7Li	$\alpha = 4/4 \times \overline{SH}$	368
13	4	1.721	0.6	$^{12}\text{C}(1)$	$\alpha = 4/4 \times \overline{SH}$	52
14	4	1.721	1.5	$^{12}\text{C}(2)$	$\alpha = 4/4 \times \overline{SH}$	265

Table 2.10: Run summary.

Beam energy (GeV)	Target	Thickness (mg/cm ²)	Beam charge (mC)
1.864	^{12}C	22	269
1.721	^{12}C	22	308
1.864	CH_2	8.8	317
1.721	CH_2	8.8	154
1.721	^7Li	19	368
1.721	$^{12}\text{C}(1)$	22	52
1.721	$^{12}\text{C}(2)$	22	265

Chapter 3

Performance of the ESPS Detectors Under High Rate Condition

3.1 The ESPS detectors

During the E89-009 experiment, scattered electrons at 0° were detected with the 74 cm-long focal plane of the ESPS. Since electrons were expected to enter the focal plane with a vertical size as small as a few mm (because of the good focusing property of the ESPS), only one-dimensional readout was required for the focal plane detectors. However, the features of the ESPS resulted in a concentration of the radiation dose into a small area. Consequently, the rate at the focal plane could be as high as 10^8 Hz, dominantly due to bremsstrahlung electrons. Therefore, the requirements of the detectors in the focal plane were:

- (1) good position resolution (0.5 mm) corresponding to the energy resolution of ~ 100 keV,
- (2) high count rate operation (10^8 Hz/74 cm), and
- (3) radiation hardness as a expected radiation dose is ~ 10 kGy for a detector element.

To satisfy the above requirements, Silicon Strip Detectors (SSDs) were chosen to form the position detector at the focal plane. Additionally, plastic scintillators were used to measure timing with a precision of a few hundred ps.

Figure 3.1 shows the detector alignment at the focal plane of the ESPS. 10 groups of detectors (plane 1, 2, 3 ...,10) were used and one group consisted of one SSD and 8 scintillators. Each plane was tilted almost vertically to receive electrons coming to the focal plane with an average angle of about 48 degrees.

In this section, the design and performance of the SSDs and scintillators are discussed.

Figure 3.1: The detector alignment at the ESPS focal plane.

3.2 Silicon Strip Detector (SSD)

3.2.1 Design

The SSD was designed to satisfy the requirements mentioned previously. Figure 3.2 is a schematic drawing of one SSD and the specifications are summarized in Table 3.1.

Table 3.1: SSD specifications.

Effective area	72 mm $\times$ 50 mm
Strip pitch	0.50 mm
P ⁺ strip width	0.36 mm
Al electrode width	0.352 mm
Thickness	0.325 ± 0.015 mm
Number of channels	144
poly-Si resistance	10 M Ω
Strip capacitance	≤ 20 pF
Maximum applicable voltage	150 V

A single-sided SSD was employed for one-dimensional readout. The effective area was determined to be 50 mm (height) by 74 mm (width), taking into account the vertical size of the trajectories at the focal plane. The strip pitch of the SSD was chosen to be 0.5

mm, which corresponds to 100 keV (FWHM) of energy resolution. Its contribution was much smaller than that of the SOS (800 keV (FWHM)).

The SSD structure was designed to tolerate large leakage current due to the surface damage. Generally, two types of radiation damages, “bulk” and “surface”, must be considered for silicon detectors [65]. The “surface damage” is due to charge accumulation on the silicon surface. The “bulk damage” should be seriously considered in the case of hadron irradiation such as protons and neutrons, but it is less important in the case of electron irradiation.

The features of the SSD design are the following:

- (1) Metal-Oxide-Semiconductor (MOS) AC coupling structure (coupling capacitance $> 1,000$ pF) to reduce the effects of expected large leakage current into the adopted amplifier-shaper-discriminator (ASD) circuit.
- (2) $P^+N^-N^+$ structure [66].
- (3) Bias voltage applied to the N^+ side to avoid potential difference between the metal layer and the P^+ side.
- (4) A grounded bias ring.
- (5) A floating guard ring to reduce the surface leakage current from the surrounding N (sub) to P^+ area [67].
- (6) $10\text{ M}\Omega$ poly-Si resistors.
- (7) Optimized width of P^+ strip to take into account the inter-strip capacitance.
- (8) Optimized width of Al electrode to avoid micro-discharges at the edges of the strip [68].

The SSD was mounted on the front-end board (FEB). Aluminium electrodes were wire-bonded by $40\text{ }\mu\text{m}$ Al wires to the FEB, on which three ASD chips (TEKZ) were mounted. The bias voltage was applied to the rear side of each SSD through the FEB.

(a) The SSD top view

(b) The SSD side view

Figure 3.2: A schematic drawing of one SSD.

3.2.2 Readout electronics

The SSD signals were transferred in parallel to a multi-hit-TDC through TEKZ and an ECL driver, as shown in Figure 3.3 [69].

Figure 3.3: SSD readout system block diagram.

Figure 3.4 shows a diagram of the FEB. Three TEKZs were mounted on a FEB to read the signals of 144-ch SSD. The TEKZ is a low power, bipolar preamplifier having a shaping time of 20 ns [70–72]. It has 64 parallel ASD channels, and each channel has its own single-ended, discriminated output. The threshold voltage for TEKZ can be controlled not only internally but also externally to optimize thresholds in any time when SSD noise increases during beam time.

The discriminated output signals from each TEKZ were coupled to the ECL Driver Boards (EDBs). The EDB clocked the ASD outputs into the TDC using a 50 MHz clock. Each EDB had its own clock generator, which asynchronously drives the signals to reduce sensitivity of the system to resonant oscillation [69]. These lines were connected to 15 FASTBUS multi-hit TDCs (LeCroy 1877). The EDBs were separated from the FEB in order to reduce noise coupling from the large ECL transient signals to the low noise FEBs.

3.2.3 Performance

Figure 3.5 shows a typical hit pattern of the SSD. Low SSD channels correspond to the lower momentum. The apparent discontinuity along the SSD channel number was due

Figure 3.4: A diagram of FEB.

to the overlapped region of adjacent SSDs. The lower momentum region received higher radiation because of the optics of the splitter-ESPS system.

Assuming that the irradiated area of the 300 MeV electron beam on a SSD was $1 \text{ mm} \times 72 \text{ mm}$, an estimated total dose for approximately two months was 22-33 kGy, which depended on the focal plane position. Radiation damage caused an increase in the SSD leakage current, and consequently of the noise level as well. This may cause a decrease of the SSD efficiency and required a change in operation condition of the SSD. Thus, the SSD performance was checked by monitoring efficiency, leakage current and noise level during the experiment.

Leakage current

SSD leakage current has been monitored a few times per day during the experiment. Figure 3.6 shows (a) day and (b) integrated charge dependence of the leakage current. Plane 3 was the most irradiated position and plane 10 was out of the momentum acceptance. As shown in Figure 3.6(b), leakage current increased steeply at the very beginning of irradiation, and eventually a linear increase with dose was observed. During beam-off periods lasting for several days, the leakage current temporarily dropped. However, when the beam was restored, it quickly returned to the last beam-on value. In plane 3, the total irradiated dose was $\sim 33 \text{ kGy}$, and the leak current increased by $7 \mu\text{A}$.

Figure 3.5: A typical SSD hit pattern.

Figure 3.6: Time and integrated charge dependence of SSD leakage current in plane 3 and plane 10. Assumed the irradiation area in plane 3 was $72 \text{ mm} \times 1 \text{ mm}$, average dose was evaluated to be 33 kGy.

Noise level

The noise level (noise sigma, σ_N) was extracted by measuring the number of random noise counts during short beam-off periods of the experiment. It is known that the noise count, N , is well described by an exponential function of the ratio of the threshold voltage (V_{th}) subtracted by the offset voltage ($V_{off} = 177$ mV) to the noise sigma [73] :

$$\ln N = \ln N_0 - \frac{(V_{th} - V_{off})^2}{2G^2\sigma_n^2}, \quad (3.1)$$

where G is the charge gain of 160 mV/fC. A clock signal was used for triggering the DAQ to record the random noise count. N was measured by changing V_{th} and the distribution was fit to equation 3.1 to extract the σ_N . Figure 3.7 shows (a) distributions of the σ_N and (b) the differences before and after irradiation, respectively (pre-rad and post-rad). The noise level increased by 10% due to radiation damage.

Figure 3.7: Pre-rad and post-rad noise sigma distribution.

Efficiency

The SSD detection efficiency was evaluated using particle trajectories which hit two scintillators behind the SSD as seen in Figure 3.1. The details of the calculation method of SSD efficiency are discussed in appendix E.

Figure 3.8 shows the rate dependence of the SSD efficiency. The efficiency drops with an increase of the background rate mainly due to electronics dead time. From the double-pulse resolution of the TEKZ, the efficiency was expected to follow the 100 ns curve in Figure 3.8. In the most high-rate case, SSD rate per strip was ~ 200 kHz, corresponding to 2% of efficiency drop from that at a background rate which is close to 0.

Figure 3.8: SSD efficiency versus the rate. The four lines correspond to the expected rate dependence of SSD efficiency for TEKZ double pulse resolution of 60, 80, 100 and 120 ns.

Figure 3.9 shows the bias and the TEKZ threshold dependence of the SSD efficiency. Operational bias voltage was higher enough than the depletion voltage (~ 60 V). Operational threshold corresponded to ~ 1.1 fC, which was four times higher than the noise level (~ 0.25 fC) and a fourth of the signal from minimum ionizing energy loss in silicon (~ 4 fC). The SSD leakage current increased and thus the noise level also increased due to radiation damage. However, there was no significant change for both dependences. After all, SSD operated normally for the entire experiment.

3.3 ESPS Hodoscope

3.3.1 Design

Plastic scintillation counters with time resolution of < 250 ps were required for coincidence between a scattered electron and a kaon, because the time resolution of the SSD was not good enough (11 ns in r.m.s), due to synchronized operation with the 50 MHz clock in the ECL driver. The scintillator size was 50 mm (height) $\times$ 11 mm (width) $\times$ 8 mm

Figure 3.9: (a) Bias and (b) TEKZ threshold dependence of the SSD efficiency before and after irradiation.

(thickness). Each scintillator was connected to a PMT (3/4" Hamamatsu R3478) through a light guide. Each PMT was surrounded with an iron house for magnet shielding. The shape of the light guide was optimized to be connected to a PMT assembly. Signals were amplified before being sent to the counting house, and then fed to the FASTBUS ADC (LeCroy 1881) and discriminated for the FASTBUS TDC (LeCroy 1875).

3.3.2 Performance

About sixty scintillators were irradiated by the scattered electrons. The high-rate condition caused pile-up of the ESPS hodoscope signals and eventually generated decrease of the efficiency.

The ESPS hodoscopes received electrons at the rate of 1-5 MHz. Under the higher rate (> 3 MHz), the shape of the PMT output signal for some scintillators changed due to the signal pile-up. Figure 3.10 shows the comparison of the raw ADC spectra for a scintillator at low and high rate runs. The pile-up occurred when two signals came in a very close timing. The baseline of the PMT output pulse increased at the high-rate runs.

The high-rate condition affected the hodoscope efficiency. The efficiency decreased for some scintillators. However, (weighted) average efficiency of the ESPS hodoscope was kept more than 93%. The details of the efficiency are described in Appendix E.

Figure 3.10: Raw ADC spectra of a scintillators at the low(up) and high(down) rate runs

Chapter 4

Data Analysis

4.1 Analysis Overview

Figure 4.1: E89-009 analysis flow chart.

Figure 4.1 shows a flow chart of the data analysis scheme used for E89-009. Raw

data or reduced data were processed by a replay software package called ENGINE [74]. The details of the ENGINE are described in appendix C. Reduced data correspond to data sets where loose cuts were applied on raw data. This procedure allows to generate smaller size data sets for speeding up the analysis routine. The results were written in ASCII text files, HBOOK histogram files and ntuple files. Calibration and optimization of the parameters were done using the output files or other codes. Cuts were applied to the data to eliminate events other than kaons in the SOS within the missing-mass range of interest. Real coincidence events between the SOS and the ESPS were chosen, and accidental coincidence events (“accidentals”) were also used for evaluation of the accidentals including the real coincidence time window. Normalizations and efficiencies, including cut efficiencies, were obtained along with the estimates of their errors. Angular acceptances for the SOS and the ESPS were evaluated by the RAYTRACE simulation [62]. Finally mass spectra and cross sections were extracted.

4.2 Kaon measurement in SOS

4.2.1 SOS tracking

Particle trajectories inside the detector hut of the SOS were determined by two drift chambers (DCs) to reconstruct the position, angle and momentum of each event at the target.

First of all, position and direction of a particle at the focal plane, $(x_{fp}, y_{fp}, x'_{fp}, y'_{fp})$, are determined. In each chamber, a series of space points are chosen based on the wire hits in each of 6 planes. More than 5 plane hits are required for a space point to be determined. Then, left-right ambiguities (on which side of a wire a particle passes) are resolved using offsets in parallel sets of the planes such as x, x' . The space point in a chamber is then linked to the one in another chamber by a track. The track that has the lowest chi-squared is chosen as the true track. With this procedure, the position resolution of a plane was $170 \mu\text{m}$ in r.m.s on average as shown in Figure 4.2(a). A distribution of tracking χ^2 per degree-of-freedom (d.o.f) is also shown in Figure 4.2(b).

The quantities at the focal plane are then transformed back to quantities at the target, $(y_{tar}, x'_{tar}, y'_{tar}, \delta)$, where δ is dp/p (%), using a matrix which is a polynomial function of the 4 corresponding quantities at the focal plane. The calculation used an assumption that initial vertical position of the target, x_{tar} , is fixed.

4.2.2 Time-of-flight measurement

In the SOS, the particle relative velocity, $\beta = v/c$, was determined using the hodoscopes. The timing of each hit of the scintillators is corrected by its pulse height, the time from the point where a particle passed through to the PMT window, and any offsets arising due to differences in the electronic delays and the cable length. The calibration was done by a set of FORTRAN codes [75]. Accidental hits are eliminated comparing tracking results to the counter position with a hit. Finally, β is obtained by fitting the corrected time at

Figure 4.2: A typical distribution of residual and tracking χ^2 per d.o.f of the DC.

the corresponding z position and correcting the track length of a particle. In E89-009, a typical β resolution was 0.022 in r.m.s for kaons.

4.2.3 Particle IDentification (PID)

To obtain true kaon events, background particles such as positrons, protons and pions were excluded using information on Cherenkov counters, shower counter (SH) and so on. Methods to exclude the background particles are discussed here.

Positron cut

Positrons were the higher-rate particles in the SOS: about 100 kHz at a beam current of $0.5 \mu\text{A}$ on the ^{12}C target and for the beam energy of 1.7 GeV. They were rejected by the Gas Cherenkov (GC) and the SH. Figure 4.3 shows a scatter plot of the Number of PhotoElectron (NPE) in the GC and the energy deposit (dE/E) in the SH (a) without and (b) with the GC VETO in the trigger level. More than 99% of the positron events were rejected with GC VETO in the trigger. However, some positrons remained around $dE/E = 1$ in Figure 4.3(b) even after the GC VETO was applied. As a possible reason, a part of the positrons did not pass through the GC but though the SH. Therefore, the SH cuts were also required to exclude more positrons (see accepted region in Figure 4.3(b)).

Figure 4.3: Scatter plots of NPE in the GC v.s. dE/E in the SH.

Proton cut

Protons were rejected by the lucite Cherenkov (LC) and β cut. Figure 4.4(a) shows a distribution of the LC NPE for protons with and without the LC in the trigger. Since the threshold of the LC was set at a safe value of less than 1 NPE to avoid unwanted kaon loss, the LC rejected only a part of the protons. Therefore, other cuts were required to reject the remaining protons.

Most protons were rejected by the SOS β cut. To explain the method, it is convenient to use β_{TOF} and β_x ($x = K, e, \pi, p$). β_{TOF} is obtained from the TOF measurement and β_x from the particle mass, m_x ($x = K, e, \pi, p$), and the momentum (p):

$$\beta_x = \frac{p}{\sqrt{p^2 + m_x^2}}. \quad (4.1)$$

For instance, this is called β_K for kaons, β_p for protons and β_π for pions. Since the measured momenta in the SOS were more than 1 GeV/ c for positrons, one gets a value of $\beta_e \sim 1$. The difference of β between a proton and a kaon in an energy region around 1.2 GeV is more than 0.1, and the β resolution in the present TOF measurement less than 0.022. The protons were excluded using a window of $\beta_{TOF} - \beta_p > 0.075$ (more than 3σ), as shown in Figure 4.4(b).

(a) LC NPE spectra for protons with and without the LC in the trigger

(b) A scatter plot of the SOS $\delta p/p$ v.s. β_{TOF}

Figure 4.4: Spectra of the LC NPE and a scatter plot of the SOS $\delta p/p$ v.s. β_{TOF} .

Pion cut

Pion events were rejected using signals from the aerogel Cherenkov (AC), the TOF hodoscopes and RF from the accelerator.

A loose AC NPE cut ($NPE = 7$) was applied in the trigger to avoid unwanted kaon loss. Figure 4.5 shows the scatter plots of NPE for the AC and the LC (a) without and (b) with the AC VETO in the trigger.

A tight AC NPE cut ($NPE = 2$) was applied in the offline analysis. The accepted region is shown in Figure 4.5(b). However, pions still remain after the AC NPE cuts because the velocity of kaons is close to that of pions at ~ 1.2 GeV/ c . Therefore, RF time cuts and a tight β cut were additionally used for a better rejection of the pions.

Figure 4.5: Scatter plots of the AC NPE v.s the LC NPE .

The RF time (rft) is given by a prescaled ($1/8$) RF signal (499 MHz) from the accelerator. Figure 4.6(a) shows a scatter plot of the $rft - t_{sos}(tar)$ and the $\beta_{TOF} - \beta_K$, where the $t_{sos}(tar)$ is the particle time at the target reconstructed using the SOS path length, the TOF calculation and the kaon mass. Kaon events are aligned in the figure and the other particle events are not aligned due to the misuse of the particle mass at the reconstruction. A resolution of the time spectrum for true kaon events was 160 ps in r.m.s. shown in Figure 4.6(b). Therefore, each peak in the figure was selected within 1 ns to reject more pions. Eventually, the RF time cut was expressed as a set of $|rft - (time\ centers\ in\ each\ peak)| < 0.5$ ns. The effect of the RF time cut are shown in Figure 4.7(a).

Finally, to obtain more clean kaon events, a tight β cut ($|\beta - \beta_K| < 0.035$) was applied as shown in Figure 4.7(b).

Figure 4.6: RF time cut for kaon.

Figure 4.7: RF time cut and β cut for kaon

4.3 Scattered electron measurement in ESPS

Electrons were dominant for scattered particles in the ESPS. A momentum and a time for each event were determined by a hit position of the SSDs and timing information of the hodoscopes, respectively.

A time offset of the SSD was corrected plane by plane, and the SSD cluster hits were identified as a single hit. A time of the scintillators was corrected by a pulse height and any offsets associated with cable length and hit position. Electrons were identified by a coincidence between the SSDs and the hodoscopes. Figure 4.8 shows a scatter plot of hit pattern of the SSDs and the hodoscopes. Geometrical and time cuts were applied to select the coincidence events. Sets of SSD hits and scintillator times were stored in the data stream.

Figure 4.8: A geometrical correlation between the SSDs and the hodoscopes.

4.4 Two-arm coincidence

The $(e, e'K^+)$ reaction was identified by detecting in coincidence a scattered electron in the ESPS and a kaon in the SOS. The coincidence time (t_{coin}) is calculated in the offline analysis and is defined as:

$$t_{coin} = t_{SOS}(tar) - t_{ESPS}(tar), \quad (4.2)$$

where $t_{SOS}(tar)$ and $t_{ESPS}(tar)$ are the times at the target reconstructed from the SOS and ESPS time measurements, respectively. The kaon t_{coin} is defined using the kaon mass

to calculate the $t_{SOS}(tar)$. Figure 4.9 shows a scatter plot of the $\beta_{TOF} - \beta_K$ and the kaon t_{coin} (a) and a distribution of the kaon t_{coin} (b). Since a bunch of the electron CW beam is delivered to the Hall C every 2 ns, a spectrum of the kaon t_{coin} also shows the beam structure due to the timing resolution in E89-009. The true coincidence events (true peak) are included in one of the bunches. On the other hands, accidental random coincidence events appear in all the bunches. The number of the true events were derived from the number of counts in the true peak subtracted by the number of the accidental counts calculated by summing the number of events in 8 accidental bunches and dividing the result by 8.

In the case of the E89-009 experiment, some pion events were included in the true peak, and true events with pile-up of HNSS hodoscope signal leaked to an adjacent region. They were taken into account and the details for the precise evaluation of the true events are discussed in Appendix D.

Figure 4.9: Kaon coincidence time.

4.5 Missing mass reconstruction

After applying all cuts, the missing mass M_{HY} of the $(e,e'K^+)$ reaction was reconstructed using the following equation:

$$\begin{aligned}
M_{HY}^2 &= (E_e + M_A - E_K - E_{e'})^2 \\
&- (p_e^2 + p_{e'}^2 + p_K^2 - 2p_{e'}p_e \cos \theta_{ee'} - 2p_e p_K \cos \theta_{eK} + 2p_{e'}p_K \cos \theta_{e'K}), \quad (4.3)
\end{aligned}$$

where E_e , E_K and $E_{e'}$ are the energies of the incident electrons, kaons, and scattered electrons, respectively; p_e , p_K and $p_{e'}$ are the momenta of the incident electrons, kaons, and scattered electrons, respectively, M_A is the target nuclear mass or proton mass and $\theta_{ee'}$, θ_{eK} and $\theta_{e'K}$ are the angles between incident and scattered electrons, incident electron and produced kaon, and scattered electron and kaon, respectively. Since the scattering angles of the outgoing electrons were not measured, $\cos \theta_{ee'}$ was set to 1. Thus, $\cos \theta_{e'K}$ is equal to $\cos \theta_{eK}$.

A binding energy of Λ to the ^{11}B core (B_Λ) is described by the following equation:

$$-B_\Lambda = M_{HY} - M_{^{11}\text{B}} - M_\Lambda, \quad (4.4)$$

where $M_{^{11}\text{B}}$ is the nuclear mass of ^{11}B and M_Λ is the Λ mass. The M_{HY} was calculated with $M_A = M_{^{12}\text{C}}$, where $M_{^{12}\text{C}}$ is the nuclear mass of ^{12}C . Physics constants used for the present analysis are shown in Appendix G.

4.6 Momentum calibration

Momenta of incident electrons, scattered electrons and produced kaons were calibrated to reconstruct the mass spectra. The incident beam energy was measured with a precision of less than 10^{-4} in Hall C. Figure 4.10 shows the procedure of the momentum calibration for each arm.

4.6.1 SOS momentum calibration

A particle momentum in the SOS was extracted with a transport matrix and the focal plane quantities obtained by using the drift chambers. The matrix combines the SOS and the splitter magnetic elements.

The SOS matrix has been generated by the computer program COSY INFINITY [76] on the basis of measured field maps and the spectrometer design specifications. All coefficients of the SOS matrix elements were optimized by analyzing optics calibration data with the sieve slit mentioned in subsection 2.3.3. Figure 4.11 is a schematic diagram of the sieve slit. It is 3.175 cm thick with small holes drilled through it. All the holes except the central hole are 0.508 cm in diameter, and all the positions of the holes are known. Missing holes are used to confirm the proper left-right and up-down orientation, and the central hole is smaller to evaluate the angular resolution.

During sieve-slit runs, particles passing through the holes were detected. The transport matrix was tuned to reconstruct events back to the holes. Figure 4.12 shows a pattern of the sieve slit at $E_e = 1.7$ GeV.

Figure 4.10: A flow chart of the momentum calibration procedure.

The tuned SOS matrix was multiplied by the splitter matrix using the focal plane quantities for full tracking. The splitter matrix was generated by the RAYTRACE simulation code to reproduce hit patterns at the focal plane [62].

Finally, a matrix of splitter+SOS system was optimized by the peaks of Λ and Σ^0 in the reconstructed mass spectrum from data of the CH_2 target runs.

Figure 4.11: SOS sieve slit.

Figure 4.12: Reconstructed sieve slit pattern.

4.6.2 ESPS momentum calibration

To extract the momentum of the scattered electron, the SSD channel number (ch_{ssd}) was converted to a momentum ($p_{e'}^{pl}$) using a polynomial function:

$$p_{e'}^{pl} = a^{pl}(ch_{ssd})^2 + b^{pl}(ch_{ssd}) + c^{pl}, \quad (4.5)$$

where pl is SSD plane number. The parameters, a^{pl} , b^{pl} and c^{pl} , were determined for each SSD plane. They were first generated by RAYTRACE. Figure 4.13 shows a scatter plot of ESPS momentum and SSD channel number obtained from RAYTRACE. The parameters, a , b , c for each plane were derived from the RAYTRACE pattern (lines on Figure 4.13).

Figure 4.13: A scatter plot of the ESPS momentum obtained from RAYTRACE and the SSD channel number.

Parameters were then tuned by using the Λ/Σ mass. Figure 4.14 shows a scatter plot of the ESPS momentum calculated using the measured SOS momentum and SSD channel number. The ESPS momentum was derived from equation 4.3, requiring $M_Y = M_\Lambda$. Dense distributions in the scatter plot show a “belt” for both Λ and Σ^0 . The parameters were tuned by fitting the Λ belt.

In adjacent planes, such as plane 4 and 5, functions must reveal the same value in the overlapped region. Events corresponding to electrons passing through two SSD planes are shown in Figure 4.15(a). For example, Figure 4.15(b) shows an SSD plane 3 hit pattern with a hit in channel 134 of plane 2. A peak in the figure means hits at channel=134 of

Figure 4.14: A scatter plot of the reconstructed ESPS momentum and SSD channel number. The lines in the figure shows the polynomial functions.

plane 2 and at channel ~ 28 of plane 3 were identical. Figure 4.15(c) shows the obtained correlation of overlapped SSD channels. Pairs of function for the adjacent planes were connected to each other in the overlap region.

(a) A example of electron events passing through two planes

(b) A hit pattern in plane 3 with hits at channel 134 of plane 2

(c) The overlap pattern of adjacent SSDs

Figure 4.15: Relationship between SSDs.

4.6.3 Systematic errors of mass scale

Figure 4.16 and 4.17 show the missing mass spectra of the $p(e,e'K^+)\Lambda/\Sigma^0$ reactions for 1.8 GeV and 1.7 GeV, respectively. The proton mass was used as the target mass in the calculation of the M_X . Λ peak is at 0 MeV/ c^2 and Σ^0 peak is at 77 MeV/ c^2 . Broad background below the Λ and Σ^0 peaks included events from accidental coincidence and quasi-free production of hyperons on ^{12}C in CH_2 . A fitting result by a polynomial and 2 Gaussian functions was also shown in the same figure and Table 4.1. The mass resolution was 2 MeV/ c^2 (FWHM). In the elementary process, kinematical broadening is dominant for the resolution. It decreases with the target mass number.

The systematic errors in the mass scales were determined by using the fitting errors of the peak centered on Λ and Σ^0 . From Table 4.1, the systematic error for each energy setting were 0.2 MeV for 1.8 GeV runs and 0.3 MeV for 1.7 GeV runs.

Table 4.1: Fitting results of Λ and Σ^0 in the missing mass spectra.

$E_e=1.8$ GeV runs	Λ	Σ^0
$M_x - M_\Lambda (\text{MeV}/c^2)$	0.0 ± 0.1	77.0 ± 0.1
width(MeV/ c^2 ,FWHM)	2.2 ± 0.1	1.4 ± 0.4
$E_e=1.7$ GeV runs	Λ	Σ^0
$M_x - M_\Lambda (\text{MeV}/c^2)$	0.0 ± 0.2	77.0 ± 0.1
width(MeV/ c^2 ,FWHM)	2.2 ± 0.4	1.1 ± 0.1

(a) Overall

(b) Λ fitting result in the Λ region

(c) Σ^0 fitting result in the Σ^0 region

Figure 4.16: Missing mass spectrum ($M_X - M_\Lambda$) of $p(e,e'K^+)\Lambda/\Sigma^0$ for 1.8 GeV low current ($0.5 \mu\text{A}$) CH_2 runs. Fitted lines by a polynomial and 2 Gaussian functions are also shown in the lower figures. The error is statistical only.

(a) Overall

(b) Λ fitting result in the Λ region

(c) Σ^0 fitting result in the Σ^0 region

Figure 4.17: Missing mass spectrum ($M_X - M_\Lambda$) of $p(e,e'K^+)\Lambda/\Sigma^0$ for 1.7 GeV high current ($1.0 \mu\text{A}$) CH_2 runs. Fitted lines by a polynomial and 2 Gaussian functions are also shown in the lower figures. The error is statistical only.

4.7 Cross Section

The cross section of the (γ^*, K^+) reaction is calculated from the experimental yields divided by the experimental efficiency,

$$\overline{\left(\frac{d\sigma}{d\Omega}\right)} = \frac{1}{N_T} \frac{1}{N_\gamma} \sum_{i=1}^{N_K} \frac{1}{\epsilon_{total} d\Omega}, \quad (4.6)$$

where N_T is the number of target centers, N_γ the number of virtual photon, $d\Omega$ the solid angle acceptance of SOS, N_K the yields of Λ , Σ or a hypernuclear state, and ϵ_{total} the correction factor. ϵ_{total} is defined as the following:

$$\begin{aligned} \epsilon_{total} = & \epsilon_{trk} \cdot \epsilon_{trig} \cdot \epsilon_{AC} \cdot \epsilon_{LC} \cdot \epsilon_{SH} \cdot \epsilon_{bk} \cdot f_{VETO} \\ & \cdot f_{abs} \cdot f_{decay} \cdot \epsilon_{SSD} \cdot \epsilon_{hodo} \cdot f_{block} \cdot f_{comp} \cdot \epsilon_{red}, \end{aligned} \quad (4.7)$$

where the symbols are defined in Table 4.2.

Table 4.2: List of the experimental efficiency factors and typical values.

Factors and efficiencies	Meanings	Typical value and error
SOS		
ϵ_{trk}	SOS tracking efficiency	0.965 ± 0.005
ϵ_{trig}	Trigger efficiency	0.992 ± 0.002
ϵ_{AC}	AC cut efficiency	0.96 ± 0.01
ϵ_{LC}	LC cut efficiency	0.96 ± 0.02
ϵ_{SH}	SH cut efficiency	0.96 ± 0.01
ϵ_{bk}	$\beta_{TOF} - \beta_K$ cut efficiency	0.89 ± 0.02
f_{VETO}	Accidental VETO factor	0.988 ± 0.001
f_{abs}	Kaon absorption factor	0.962 ± 0.005
f_{decay}	Kaon decay factor	0.37 ± 0.03
Enge		
ϵ_{SSD}	SSD efficiency	0.960 ± 0.005
ϵ_{hodo}	ESPS hodoscope efficiency	0.96 ± 0.03
f_{block}	Coincidence time blocking factor	0.92 ± 0.02
Others		
f_{comp}	Computer dead time factor	0.923 ± 0.001
ϵ_{red}	Reduction efficiency	0.91 ± 0.02
Total		0.18 ± 0.018

As for cut efficiency, table 4.3 shows the offline cut condition to obtain a clean kaon sample. In the table, x'_{tar} , y'_{tar} and y_{tar} are the particle positions and angles at the target. Kaon losses by cuts of NPE in the GC, RF time, β_{pr} and target geometry were negligible.

Table 4.3: Cut conditions for kaon ID in the SOS.

parameters	conditions
$ x'_{tar} $	< 0.04 cm
$ y'_{tar} $	< 0.1 cm
$ y_{tar} $	< 0.5 cm
NPE in GC	< 2
NPE in AC	< 2
NPE in LC	> 1
dE/E (energy deposit in shower counter)	< 0.6
$ \beta_{TOF} - \beta_K $ (a gate for kaons)	< 0.035
$\beta_{TOF} - \beta_{pr}$ (proton cut)	0.08
Kaon RF time cut	within ± 0.5 ns for each peak

4.7.1 Correction factors

The correction factors shown in Table 4.2, acceptance and the number of virtual photons are discussed in this section.

SOS tracking efficiency

The tracking efficiency (ϵ_{trk}) was evaluated by the ratio of the number of obtained tracks by the DCs to that by the hodoscopes. In the process, a particle trajectory and velocity were calculated by hodoscope information without the DC one. Tracks with velocities corresponding to protons were selected, since protons are not subject to decay compared with the other particles in SOS. Then, events in which the tracks can be traced back to the center of DCs were selected. Finally, for each selected event, a DC tracking was examined.

The efficiency was calculated run by run from data set number 3 to 11. Figure 4.18 shows the stability of the tracking efficiency during the runs. The efficiency was stable for each energy setting. The obtained values were $97.1 \pm 0.4\%$ for 1.8 GeV runs and $96.0 \pm 0.5\%$ for 1.7 GeV runs.

Trigger efficiency

The trigger logic was made by requiring hits on 3 or 4 hodoscope planes, the VETO counters and the LC. Since the SOS hodoscope efficiency by plane was 99.7%, the trigger efficiency (ϵ_{trig}) in 3 out of 4 was 100%, and in 4 out of 4, $(98.8 \pm 0.2)\%$. The contribution from the other detector elements was taken as a cut efficiency or an accidental VETO factor.

Figure 4.18: Run stability of the tracking efficiency.

AC cut efficiency

The AC cut efficiency (ϵ_{AC}) was evaluated by the ratio of the number of kaon events after AC cut to that without AC cut. Since kaons and pions overlapped each other in the β_{TOF} spectrum as shown in Figure 4.19(a), kaon events were counted after subtracting pion events. The number of π^+ events was evaluated by fitting the $\beta_{TOF} - \beta_\pi$ distribution with a Gaussian. Efficiencies were 92–98%, depending on the beam intensity. The AC cut efficiency is summarized in Table 4.4, where the error is statistical only.

Table 4.4: AC cut efficiency.

Data set no.	Efficiency (%)	Data set no.	Efficiency (%)
1	95.7 ± 2.9	7	96.6 ± 2.0
2	95.6 ± 2.0	8	97.2 ± 1.0
3	95.9 ± 1.3	9	95.6 ± 1.4
4	95.5 ± 1.7	10	94.0 ± 1.4
5	94.8 ± 1.5	11	92.5 ± 1.6
6	94.9 ± 1.4

(a) $\beta_{TOF} - \beta_{\pi}$ spectra with π^+ and K^+

(b) kaon survival ratio v.s. AC threshold in a case of 1.7 GeV high current runs

Figure 4.19: $\beta_{TOF} - \beta_{\pi}$ spectra with or without AC cut and a threshold dependence of AC cut efficiency.

LC cut efficiency

The LC cut efficiency (ϵ_{LC}) was evaluated by the ratio of the number of kaon events above the LC threshold to that without the LC cut. Runs in which the LC was not included in the trigger were used for this evaluation. Figure 4.20 shows the threshold dependence of LC cut efficiency. The LC was included in the trigger in 1.7 GeV runs while the LC was not used for the trigger in most of the 1.8 GeV runs. For both beam energy settings, an offline LC cut, $NPE > 1$, was applied. Efficiencies were $(95.7 \pm 1.9)\%$ for 1.8 GeV runs and $(95.7 \pm 0.8)\%$ for 1.7 GeV runs. The errors shown are statistical only and are higher at 1.8 GeV because of the low statistics. The efficiency in data set number 1 was $(88.2 \pm 1.8)\%$ because the LC threshold was higher ($NPE = 4$) in that period.

SH cut efficiency

The SH cut efficiency (ϵ_{SH}) was evaluated as the ratio of the number of kaons below threshold of dE/E in the SH to that with no SH cut. Since the threshold of dE/E was set to be 0.6, the efficiency was $95.8 \pm 1.2\%$, where the error is the statistical only.

(a) for 1.8 GeV runs

(b) for 1.7 GeV runs

Figure 4.20: LC cut efficiency.

Figure 4.21: SH cut efficiency

β_K cut efficiency

β_K cut was $|\beta_{TOF} - \beta_K| < 0.035$. Since β resolution for kaon was 0.022 ± 0.001 , β_K cut efficiency (ϵ_{bk}) was $88.8 \pm 1.7\%$.

Accidental VETO factor

When a VETO counter is fired in a real kaon event, the event is not recorded. It is possible that any other particle fires VETO counter when a kaon comes in. This is called accidental VETO. Accidental VETO factor was extracted from count rate of VETO counter and a width of timing gate for trigger. Count rates in the GC, AC and SH above threshold were 107/99/75 kHz at $0.5 \mu\text{A } ^{12}\text{C}$ runs, respectively. All the VETO counter timing gate were set to 40 or 50 ns with a error of 5 ns. Table 4.5 shows the probability of accidental VETO for each counter $0.5 \mu\text{A } ^{12}\text{C}$ runs. Accidental veto factor (f_{veto}) was evaluated using the probabilities for VETO counters used in trigger. The factor is summarized in Table 4.6. The error was 0.1%.

Table 4.5: Probability of accidental VETO for each counter at $0.5 \mu\text{A } ^{12}\text{C}$ runs.

Counter type	Trigger rate (kHz) above threshold	gate width (ns)	Probability %
GC	107	40	0.4
AC	99	50	0.5
Shower	75	50	0.4

Table 4.6: Accidental VETO factor.

Data set no.	Factor	Data set no.	Factor
1	0.984	7	0.992
2	0.990	8	0.996
3	0.987	9	0.995
4	0.987	10	0.987
5	0.984	11	0.984
6	0.984		

Kaon absorption correction

A kaon interacts with materials when passing through the target, the splitter and the SOS detector element. When a kaon is absorbed into a material, the event is lost and

kaon absorption must be taken into account as a correction factors. A list of materials for the SOS arm with their thickness and densities are given in Table 4.7.

Material	thickness (cm)	ρ (g/cm ³)	t (g/cm ²)	Notes
Target	-	-	< 0.03	CH ₂ , ¹² C
Target Chamber			< 0.1	
[Spectrometer]				
Air	~ 15	0.0012	0.02	
Kevlar entrance	0.0127	0.74	0.01	5 mil Kevlar
Mylar entrance	0.0076	1.39	0.01	3 mil Mylar
Kevlar exit	0.0381	0.74	0.03	15 mil Kevlar
Mylar exit	0.0127	1.39	0.02	5 mil Mylar
[Detector Hut]				
Air	~ 200	0.0012	0.24	DC1 through S2
DC Mylar cathode	0.0176	1.39	0.02	14 planes
Ar/CH ₄ gas	7.41	0.00154	0.01	
Sense Wires (W)	0.00008	19.3	< 0.01	12 × 30 μ m wires
Field Wires (W)	0.00034	19.3	< 0.01	12 × 60 μ m wires
S1Y,S2Y	2.20	1.03	2.27	1.098 for overlap
S1X,S2X	2.08	1.03	2.14	1.04 for overlap
window for GC	0.112	~ 1.39	0.16	
Freon gas	~ 100	0.0051	0.51	
Lucite	2.54	1.16	2.95	
Al (for AC)	0.13	2.70	0.35	
Aerogel	9.0	0.2	1.8	

Table 4.7: Property of the SOS materials. These parameters are used to calculate the kaon absorption factor.

Assuming n_0 particles enter a layer of material of thickness t (g/cm²), the number of particles absorbed in that layer will be:

$$n = n_0 \frac{N_A t}{A} \sigma_0, \quad (4.8)$$

where $N_A = 6.022 \times 10^{23}$ mol⁻¹ is Avogadro's number, A the atomic number, and σ_0 the absorption cross section given in [77] by:

$$\sigma_0 = 21.065 p_K^{-0.99} A^{0.79} [mb], \quad (4.9)$$

with the kaon momentum p_K in GeV/ c . Taking all materials into account gives the kaon absorption factor (f_{abs}):

$$f_{abs} = 1 - \frac{0.04489}{p_K^{0.99}}. \quad (4.10)$$

Equation 4.10 was used to correct for absorption losses, on an event-by-event basis. Figure 4.22 shows the momentum dependence of the absorption. The absorption factor was 95–97 %. The momentum acceptance of Λ , Σ^0 and the ^{12}B bound region is also shown in the figure. The uncertainty associated with this correction originates from the measurement of the detector size and the number of penetrated scintillators, which was 0.5 %.

Figure 4.22: The momentum dependence of kaon absorption. Momentum acceptance for each state are also shown.

Kaon decay factor

Kaon is an unstable particles with a mean life time $\tau = 1.2371 \pm 0.0029 \times 10^{-8}$ sec. Kaons generated at the target may decay into secondary particles before detection. Various decay channels are listed in Table 4.8.

Table 4.8: K^+ decay channels.

Decay Modes	Branching Ratio (%)
$\mu^+ \nu_\mu$	63.51 ± 0.18
$\pi^+ \pi_0$	21.16 ± 0.14
$\pi^+ \pi^+ \pi^-$	5.59 ± 0.05
$\pi^0 e^+ \nu_e$	4.82 ± 0.06
$\pi^0 \mu^+ \nu_\mu$	3.18 ± 0.08
$\pi^+ \pi^0 \pi^0$	1.73 ± 0.04

If decay particles after a kaon decays are never detected in the SOS, the number of detected kaons is deficient by the fraction (known as the main decay correction):

$$\frac{N_{detected}}{N_{at\ target}} = \exp \left(-\frac{M_K}{p_K} \frac{x}{3.709} \right), \quad (4.11)$$

where x is a distance in meters traveled from a target to the detector, p_K is the kaon momentum in GeV/c and M_K is the kaon mass in GeV/c^2 .

In fact, decay particles are sometimes detected by some or all of the detector elements. This lead to over-correction (double counting) if such events pass all the cuts and are mistaken for indecayed kaons. This is called a “mimicked” kaon. Therefore, a second decay correction is required. To evaluate it, a Monte Carlo simulation which implements decays has been done in previous kaon experiments using the SOS in Hall C [54–56]. When kaons decay prior to reaching the detector hut, decay particles are lost and are not detected. However, if decays take place within the hut, about 20% of “mimicked” kaons will be detected. The contribution of “mimicked” kaons was estimated to be $3 \pm 1\%$.

The total decay factor is written by the following equation:

$$f_{decay} = \left[\exp \left(-\frac{M_K}{p_K} \frac{x}{3.709} \right) + 0.03 \right] \pm 0.03. \quad (4.12)$$

The error comes from contributions of mimicked kaon, SOS momentum and path length. Figure 4.23 and 4.24 show scatter plots of the decay factor or the SOS path length and momentum, and the distribution of the decay factor, respectively. The path length dependence on the decay factor is small and the decay factor increases with momentum. The correction is calculated on an event-by-event basis because it depends on the path length and velocity of the detected kaon.

(a) $^{12}_{\Lambda}\text{B}$ bound region for 1.8 GeV

(b) $^{12}_{\Lambda}\text{B}$ bound region for 1.7 GeV

(c) Λ region for 1.8 GeV

(d) Λ region for 1.7 GeV

Figure 4.23: Correlation between the decay factor or the SOS path length and momentum for the (a) (b) $^{12}_{\Lambda}\text{B}$ bound region and the (c) (d) Λ region.

(a) Σ^0 region for 1.8 GeV

(b) Σ^0 region for 1.7 GeV

(c) All distributions for 1.8 GeV

(d) All distributions for 1.7 GeV

Figure 4.24: (a) (b) Correlation of decay factor to the SOS path length and momentum for the (a) (b) Σ^0 region, and (c) (d) all distributions.

SSD efficiency

The SSD detection efficiency (ϵ_{SSD}) was evaluated by using two hodoscope coincidence events (see Appendix E for details). The efficiency dropped with the count rate due to electronic dead time. Figure 4.25 shows a scatter plot of the efficiency and the SSD channels in (a) low current runs and in (b) high current runs. In the lower momentum side (around the SSD channel=300), the efficiency was lower than in the higher momentum side (around SSD channel=1000) because electron rate in the lower momentum region was higher. Figure 4.26 shows a distribution of SSD efficiency in the lower rate run (upper figure) and the higher rate run (lower figure). Consequently, the weighted average of SSD efficiency moved down to the lower because of the higher rate in plane 2 and 3, which are shown in Table 4.9. The statistical error was 1%.

(a) in low current runs

(b) in high current runs

Figure 4.25: A scatter plot of SSD detection efficiency and channels in (a) low current runs and (b) high current runs.

Figure 4.26: The distribution of SSD efficiency in lower rate runs (upper) and in higher rate runs (lower).

Table 4.9: SSD efficiency (weighted average).

Data set no.	efficiency	Data set no.	efficiency
1.8 GeV runs		1.7 GeV runs	
3	96.1	9	96.6
4	96.0	10	96.0
5	95.6	11	95.7
6	95.6		
7	96.2		
8	96.5		

ESPS hodoscope efficiency

The detection efficiency of the ESPS hodoscopes was evaluated by using events in the region where particles can pass through a SSD and two scintillators geometrically (see Appendix E for details).

Figure 4.27 shows scatter plots of the hodoscope efficiency versus the scintillator channel. The efficiency in most counters was high until high current runs (beam current $0.6 \mu\text{A}$) in the middle of the 2^{nd} cycles, as shown in Figure 4.27 (a). After changing to the lower currents ($0.3 \mu\text{A}$), the efficiency in some counters gradually dropped. The distribution of the efficiency in the end of the 3^{rd} cycle is shown in Figure 4.27(b). The decrease continued until the discriminator threshold of the scintillators was re-adjusted in the end of the 4^{th} cycles.

(a) in the middle of the 2^{nd} cycle

(b) in the end of the 3^{rd} cycle

Figure 4.27: Scatter plots of hodoscope detection efficiency and the counter number in the middle of the 2^{nd} cycle (data set number=6) and in the end of the 3^{rd} cycle (data set number=11).

Figure 4.28 shows the distribution of the efficiency, and Table 4.10 shows a weighted average in each data setting. The averaged efficiency decreased after data set number=6 because the efficiency in some counters started dropping. The error is 2–3%, which includes statistical and systematic errors.

(a) in the middle of 2nd cycle

(b) in the end of 3rd cycle

Figure 4.28: Distribution of Hodoscope detection efficiency in the middle of 2nd cycle (data set no=6) and in the end of 3rd cycle (data set no=11).

Table 4.10: ESPS hodoscope efficiency (weighted average).

Data set no.	Efficiency	Data set no.	Efficiency
1.8 GeV runs		1.7 GeV runs	
3	0.97 ± 0.02	9	0.93 ± 0.02
4	0.97 ± 0.02	10	0.93 ± 0.03
5	0.97 ± 0.02	11	0.93 ± 0.03
6	0.97 ± 0.02		
7	0.95 ± 0.03		
8	0.94 ± 0.03		

ESPS and coincidence cut efficiency

Two types of cuts, geometrical cuts and timing cuts were applied for scattered electrons. Loose geometrical cuts were applied so as to cover the electron trajectory. SSD time cut was set at ± 35 ns around the peak of true events, which is 3 times of SSD time resolution(rms). Therefore, ESPS cut efficiency was very close to 100%.

The coincidence time gate was set from -1 ns to 2 ns. Since the resolution of the coincidence time was less than 400 ps, the cut efficiency was also close to 100% .

Coincidence time blocking factor

In single-hit TDC with COMMON START type, the first STOP signal after a START signal determines the timing, and the second STOP signal coming before the next START signal is ignored. When the first STOP signal is an accidental hit and the second STOP signal is a true hit, the true hit is not detected. This is called time blocking.

In E89-009, the START signal was made by the SOS trigger and the hodoscope time in the ESPS was measured by single-hit TDC. Thus, the coincidence time blocking factor (f_{block}) is described as the following relation:

$$f_{block} = 1 - rt, \quad (4.13)$$

where r is the counting rate in a scintillator and t the time between START and STOP signal. The factor was evaluated in the event-by-event basis because each event had a different scintillator time and rate. t varied by the kaon flight time from 26 to 29 ns, and the scintillator rate varied from below 1 MHz up to 5 MHz. Figure 4.29 shows scatter plots of the blocking factor versus (a) counter number and (b) rate, and Figure 4.30 shows distributions of the blocking factor. The width came from the variation in the kaon flight time. The overall correction was widely distributed as shown in Figure 4.30. Table 4.11 lists the weighted average values of the blocking factor for each data set. The error was 1%, which came from the stability of the hodoscope rate.

Table 4.11: Coincidence time blocking factor (weighted average).

Data set no.	Factor	Data set no.	Factor
1.8 GeV runs		1.7 GeV runs	
3	0.91	9	0.96
4	0.91	10	0.91
5	0.89	11	0.90
6	0.89		
7	0.94		
8	0.96

Figure 4.29: Scatter plots of the blocking factor and hodoscope quantities, (a) counter number and (b) rate.

Figure 4.30: Distributions of the blocking factor.

Computer dead time factor

The computer dead time is a time interval when the DAQ processes a previous event. The Hall C DAQ processes the events with $\sim 400 \mu\text{s}$ time intervals or an event rate ~ 2.5 kHz. The computer dead time was calculated from the difference between the numbers of pretrigger and trigger events. Figure 4.31 shows the computer dead time versus run number. Settings are also shown in the figure. Dead time increases with trigger rate which was higher in 3 out of 4 trigger runs due to the positron background. During 4 out of 4 runs, the dead time was smaller since the trigger rate decreased because of more suppression of positrons.

Figure 4.31: Computer dead time.

Actually, the computer dead time factor (f_{comp}) was calculated as

$$f_{comp} = \frac{\sum trigger}{\sum pretrigger}. \quad (4.14)$$

Both trigger and pretrigger quantities were recorded in a scaler file for all runs. The dead time correction is summarized in Table 4.12. The error was below 0.1%.

Reduction efficiency

Raw data was reduced using a loose cut condition shown in Table 4.13 in order to speed up the analyze routine. The number of kaon events in the reduced data was compared to that in the raw data. Kaon events were selected by requiring collimator cut, β cut, PID

Table 4.12: Computer dead time factor.

Data set no.	Factor	Data set no.	Factor
1	0.847	7	0.968
2	0.834	8	0.977
3	0.847	9	0.982
4	0.839	10	0.949
5	0.749	11	0.924
6	0.935		

cut ($AC < 2$, $LC > 1$ and *shower* $dE/E < 0.6$) and loose coincidence time cut (± 20 ns around the true peak). The ratio (R_g) of the number of kaon events in the reduced data set to that in the raw data is regarded as the data reduction efficiency (ϵ_{red}). The efficiencies were 85–96% because of a bug in the tracking code and parameter mismatching. The efficiency for each data set is summarized in Table 4.14.

Table 4.13: Cut condition for data reduction.

Ntuple quantities	Correction
Shower $dE/E < 0.7$	0.97
$ x'_{tar} < 0.15$ cm	1.
$ y'_{tar} < 0.15$ cm	1.
$N_{track} > 0$	0.96(1.7 GeV runs), 0.97(1.8 GeV runs)
overall	0.93(1.7 GeV runs), 0.94(1.8 GeV runs)

Summary

The efficiencies and factors are summarized in Table 4.2. Relative errors of ϵ_{total} were calculated in an event-by-event basis as the root-sum-square of the relative errors of efficiencies and factors, considering that they were independent. Figure 4.32 shows the distribution of the relative error of ϵ_{total} . The weighted average value, 10%, was used for evaluating the systematic errors on the cross sections.

Table 4.14: Reduction efficiency.

Data set no.	Correction
3	0.87 ± 0.02
4	0.95 ± 0.02
5	0.96 ± 0.02
6	0.94 ± 0.02
7	0.90 ± 0.02
8	0.94 ± 0.02
9	0.85 ± 0.02
10	0.88 ± 0.02
11	0.89 ± 0.02

Figure 4.32: A distribution of the relative error of ϵ_{total} calculated in event-by-event basis.

4.7.2 Acceptance

Momentum acceptance

The SOS covered $\pm 20\%$ around the central momentum ($1.2 \text{ GeV}/c$). On the other hands, the ESPS covered $\sim 110 \text{ MeV}/c$, narrower than the SOS momentum coverage. Thus, the net SOS momentum acceptance was determined by the ESPS momentum coverage. Figure 4.33 shows the correlation between the SOS dp/p (%) and the ESPS momentum when masses of Λ , Σ^0 or binding energies of s_Λ and p_Λ states were fixed.

Figure 4.33: SOS dp/p (%) v.s. ESPS momentum(P_e) (GeV/c).

SOS solid angle acceptance

The SOS solid angle acceptance was calculated by the RAYTRACE simulation. The acceptance depended on the trigger type and beam energy setting. For some runs during 1^{st} and 2^{nd} cycles, scintillator S1X1, 2, 8 and 9 were turned off or used as VETO in a trigger logic (labeled $\overline{S1X}$) because the positron background rate was very high. The acceptance was calculated in three cases:

- (1) runs of 1.8 GeV without $\overline{S1X}$ in a trigger,
- (2) runs of 1.8 GeV with $\overline{S1X}$ in a trigger, and
- (3) runs of 1.7 GeV.

The results for each cases are shown in Figure 4.34. The SOS acceptance was almost constant ($\sim 5 \text{ msr}$) for the Λ and ${}^{12}\text{B}$ bound region. For the Σ^0 region, the variation of

the acceptance was larger. The statistical error in the acceptance was estimated to be 1%.

(a) for 1.8 GeV runs with $\overline{S1X}$ in trigger

(b) for 1.8 GeV runs without $\overline{S1X}$ in trigger

(c) for 1.7 GeV runs

Figure 4.34: SOS solid angle acceptance.

4.7.3 Number of virtual photons

The number of virtual photons generated at the target was calculated to evaluate the cross section. The virtual photon flux $\Gamma(p, \theta)$ (/MeV/electron) as a function of the angle and momentum of scattered electrons was calculated using the equations written in Ref. [41]. It was integrated over the solid angle acceptance, $W(p, \theta)$. The acceptance was calculated for the ESPS momentum by the RAYTRACE simulation. The $W/4\pi$ (%) as a function of the ESPS momentum is shown in Figure 4.35. The number of generated virtual photon are described by:

$$N_\gamma = \frac{Q}{e} \int \int \Gamma(p, \theta) W(p, \theta) d\Omega dp, \quad (4.15)$$

where Q is total charge and p is ESPS momentum. Figure 4.36 shows the momentum dependence of the number of virtual photons per electron.

Figure 4.35: The coverage of integrated (4π) virtual photon flux.

Integration range over the ESPS momentum was carefully chosen because there were regions where the SSD has no coincidence with any ESPS scintillators. Figure 4.37 shows the distribution of the ESPS momentum for the 1.8 and 1.7 GeV runs. The upper panels

show all events, while the lower panels show events used in the analysis. Momentum regions where events were ignored were not included in the integration. The detected regions were $\sim 90\%$ of the acceptance detected by the SSD. The ESPS momentum acceptance for the integration is shown in Table 4.15. The systematic error from the beam current measurement is dominant. The beam current monitors were calibrated before the beam time. It showed 5% of the systematic error. Compared with it, the errors from the flux calculation is negligible.

Figure 4.36: The number of virtual photons (/MeV/electron).

Table 4.15: The number of virtual photons.

Beam energy	from	to	the number of virtual photon per electron
1.8 GeV	233 MeV/c	344 MeV/c	3.702×10^{-4}
1.7 GeV	215 MeV/c	312 MeV/c	3.414×10^{-4}

(a) at a low momentum region (1.8 GeV)

(b) at a high momentum region (1.8 GeV)

(c) at a low momentum region (1.7 GeV)

(d) at a high momentum region (1.7 GeV)

Figure 4.37: The ESPS momentum distribution for all (upper) and selected (lower) momenta. Momentum regions where events were ignored were not included in the integration.

4.7.4 Systematic errors

The total systematic error of the cross section is summarized in table 4.16. Details are described in the previous sections.

Table 4.16: Systematic errors.

Quantity	systematic error (%)
Target thickness	5
the number of virtual photon	5
SOS acceptance	1
efficiency	10
overall	12

4.7.5 Energy resolution

The energy resolution of the spectrometer system was derived from the $(e, e'e^+e^-)$ pair production. To reconstruct the pair creation, a positron and two electrons were required in the SOS and the ESPS, respectively. Figure 4.38(a) shows a scatter plot of the SOS momentum (dp/p) versus the sum of momenta of two electrons. A dense line described by an arrow represents a correlation from the pair production. Figure 4.38(b) shows the total energy spectrum of a positron and two electrons with statistical errors. The energy resolution was (0.92 ± 0.18) MeV (FWHM).

The obtained value included contribution from two electrons and only from the higher region of the electron momentum. Since the resolution was mainly determined by the precision of the SOS momentum, a difference between the obtained value and the resolution of bound states for $^{12}_\Lambda\text{B}$ spectrum should be very small.

(a) Scatter plot

(b) Spectrum

Figure 4.38: The correlation of SOS $\text{dp/p}(\%)$ and (a) summed electron momenta and (b) a spectrum of reconstructed total energy obtained from the $(e,e'e^+e^-)$ reaction.

Chapter 5

Results and discussion

In this chapter, experimental results are presented and discussed.

5.1 Experimental results

5.1.1 Hypernuclear mass spectrum for ${}_{\Lambda}^{12}\text{B}$

Figure 5.1 shows hypernuclear mass spectrum for ${}_{\Lambda}^{12}\text{B}$ obtained in the ${}^{12}\text{C}(\text{e},\text{e}'\text{K}^+)$ reaction. The horizontal axis represents the binding energy of Λ for ${}_{\Lambda}^{12}\text{B}$ and the hypernuclear mass (M_{HY}) subtracted by the target mass (M_A). The spectrum is obtained at scattered electron scattering angle of 0° and kaon scattering angles from 0° to 4° . The data sets used are summarized in Table 5.1, which are picked up from Table 2.9. Since data of the CH_2 target runs are included, events of Λ production from hydrogen are also shown in the unbound region in the figure. Figure 5.2 shows the spectra including (a) true+accidental coincidence events (“true timing events”) and (b) accidental coincidence events only (“acc. events”) with error bars. The spectrum of the acc. events was obtained from 8 bunches in the accidental coincidence regions in Figure 4.9. Therefore, the errors of the acc. events are smaller than that of true timing events. Cross sections and binding energies of the ${}_{\Lambda}^{12}\text{B}$ states were extracted after subtracting the spectrum of the acc. events from the spectrum of the true timing events. The spectrum after subtracting the acc. events is shown in Figure 5.2(d).

Table 5.1: Data sets used for the analysis of the ${}_{\Lambda}^{12}\text{B}$ hypernuclear mass spectrum.

Data set No.	Cycle	Beam energy (GeV)	Beam current (μA)	Target	Trigger ($\overline{GC} \times \overline{AC} \times \alpha$)	Beam charge (mC)
2	1	1.864	0.4	${}^{12}\text{C}$	$\alpha = 3/4 \times \overline{SH} \times LC$	21.0
3	1	1.864	0.5	${}^{12}\text{C}$	$\alpha = 3/4 \times \overline{SH} \times LC$	81.6
4	2	1.864	1.0	CH_2	$\alpha = 3/4 \times \overline{SH} \times LC \times \overline{S1X}$	71.5
5	2	1.864	0.6	${}^{12}\text{C}$	$\alpha = 3/4 \times \overline{SH} \times LC \times \overline{S1X}$	67.2
6	2	1.864	0.6	${}^{12}\text{C}$	$\alpha = 4/4 \times \overline{SH} \times LC$	55.7
7	2	1.864	0.3	${}^{12}\text{C}$	$\alpha = 4/4 \times \overline{SH} \times LC$	43.0
8	2	1.864	0.5	CH_2	$\alpha = 4/4 \times LC$	231.5
9	3	1.721	0.2	${}^{12}\text{C}$	$\alpha = 4/4 \times \overline{SH}$	97.6
10	3	1.721	1.0	CH_2	$\alpha = 4/4 \times \overline{SH}$	122.9
overall	-	-	-	${}^{12}\text{C}$	-	366.1
	-	-	-	CH_2	-	425.9

(a) In the wider region

(b) Around the bound region

Figure 5.1: Hypernuclear mass spectrum for ${}_{\Lambda}^{12}\text{B}$ obtained with the carbon target (a) in the wider region and (b) around the bound region. The spectrum made by the accidental coincidence events is shown in the histogram. Λ production events in the CH_2 target runs are also included in the spectrum.

(a) True timing events

(b) Acc. events

(c) The spectrum for comparison

(d) The spectrum after subtracting acc. events

Figure 5.2: $^{12}_\Lambda\text{B}$ spectra with error bars.

5.2 Discussion

5.2.1 $^{12}\text{C}(\text{e},\text{e}'\text{K}^+)_{\Lambda}^{12}\text{B}$ spectrum

Figure 5.3 shows the hypernuclear mass spectrum of $_{\Lambda}^{12}\text{B}$ obtained in the $^{12}\text{C}(\text{e},\text{e}'\text{K}^+)$ reaction. The width of the ground state demonstrated an energy resolution of the present experiment to be 0.9 MeV (FWHM). This is the best resolution ever achieved in hypernuclear reaction spectroscopy. Two prominent peaks at $B_{\Lambda} \sim 12$ and ~ 0 MeV are observed. The peaks are interpreted as having the configurations with the outermost proton-hole and a Λ hyperon in the s_{Λ} -orbits, $[(p_{3/2})_p^{-1}, (s_{1/2})_{\Lambda}]$, and in the p_{Λ} -orbits, $[(p_{3/2})_p^{-1}, (p_{1/2}, p_{3/2})_{\Lambda}]$. Additionally, some small peaks are seen between the prominent peaks.

The $_{\Lambda}^{12}\text{B}$ spectrum was fitted in a region of $-25 < -B_{\Lambda} < -4$ MeV with 3 Gaussians for candidates of hypernuclear states and a constant for the evaluation of background level. In the fitting, the widths were constrained to be the same. The binding energies and the cross sections derived in the fitting are summarized in Table 5.2. The numbering of the peaks is from the ground to the excited states (#1 - #3). Background level was evaluated to be 5 ± 1 nb/sr in the over-bound region, $-25 < -B_{\Lambda} < -15$ MeV.

Figure 5.3: The observed $_{\Lambda}^{12}\text{B}$ spectrum with fitting curves described in the text.

The $_{\Lambda}^{12}\text{B}$ spectrum can be compared with the $_{\Lambda}^{12}\text{C}$ spectra via the (π^+, K^+) reaction obtained at KEK and BNL. Figure 5.4 shows the $_{\Lambda}^{12}\text{C}$ spectrum obtained in KEK-E369

Table 5.2: Results of the fitting for ${}_{\Lambda}^{12}\text{B}$ spectrum.

states	$-B_{\Lambda}$ (MeV) $\pm$ (statistic) $\pm$ (systematic)	FWHM (MeV)	Cross section (nb/sr) $\pm$ (statistic) $\pm$ (systematic)
# 1	$-11.7 \pm 0.1 \pm 0.3$	0.92 (fixed)	$117 \pm 13 \pm 14$
# 2	$-9.7 \pm 0.2 \pm 0.3$	0.92 (fixed)	$57 \pm 13 \pm 7$
# 3	$-6.8 \pm 0.3 \pm 0.3$	0.92 (fixed)	$31 \pm 14 \pm 4$

experiment[31]. The spectrum shape of ${}_{\Lambda}^{12}\text{C}$ is similar to that of ${}_{\Lambda}^{12}\text{B}$. The ${}_{\Lambda}^{12}\text{C}$ spectrum showed characteristic peaks corresponding to s_{Λ} (#1) and p_{Λ} (#5) orbits and also some core-excited states (#2, #3, and #6). The #1–#6 peaks in the ${}_{\Lambda}^{12}\text{C}$ spectrum can be compared with the yields in a corresponding energy region of the ${}_{\Lambda}^{12}\text{B}$ spectrum. More precise comparison of these spectra is expected to provide information on the hypernuclear structure and ΛN interaction, when spectra with much better quality and statistics are obtained.

Figure 5.4: The hypernuclear mass spectrum for ${}_{\Lambda}^{12}\text{C}$ via the (π^+, K^+) reaction obtained in KEK-E369 experiment [31].

Weak coupling between ^{11}B core and a Λ hyperon

A $^{12}_\Lambda\text{B}$ hypernucleus is considered to be composed of a ^{11}B core nucleus and a Λ hyperon on the basis of a weak coupling picture. For the following discussion, we use the analogy that proton-holes are made in the $(e,e'p)$ and $(e,e'K^+)$ reactions. In the weak coupling limit, $^{12}_\Lambda\text{B}$ hypernuclear states with ^{11}B excited and non-excited core configurations with a Λ hyperon in the s_Λ -orbits should be observed with the same strength and at the same excitation energy of ^{11}B states in a spectrum obtained by the $^{12}\text{C}(e,e'p)^{11}\text{B}$ reaction. Figure 5.5 shows level schemes of ^{11}B and $^{12}_\Lambda\text{B}$ (s_Λ states only) in the weak coupling limit.

$^{12}\text{C}(e,e'p)^{11}\text{B}$		The present results	
Spectroscopic factor S	Excitation energy (MeV)	Excitation energy (MeV)	$^{12}\text{C}(e,e'K^+)^{11}_\Lambda\text{B}$ cross section
0.25	$\frac{5.020}{3/2^-} \dots\dots\dots 1^- 2^-$	$\overline{\text{5.4}}$	31 nb/sr
0.26	$\frac{2.125}{1/2^-} \dots\dots\dots 0^- 1^-$	$\overline{\text{2.5}}$	57 nb/sr
1.72	$\frac{0}{3/2^-} \dots\dots\dots 1^- 2^-$	$\overline{\text{0}}$	117 nb/sr
$^{11}\text{B} \otimes S_\Lambda \longrightarrow ^{12}_\Lambda\text{B}$			

Figure 5.5: Level schemes of ^{11}B and $^{12}_\Lambda\text{B}$ in the weak coupling limit. Spectroscopic factors of the ^{11}B states in the $^{12}\text{C}(e,e'p)^{11}\text{B}$ reaction and the extracted cross sections in the $^{12}\text{C}(e,e'K^+)^{12}_\Lambda\text{B}$ reaction are also shown in the figure.

Spectroscopic factors of the ^{11}B states in the $^{12}\text{C}(e,e'p)^{11}\text{B}$ reaction are also shown in the figure [78]. In the reaction, the excited states of ^{11}B at 2.1 MeV ($1/2^-$) and 5.0 MeV ($3/2^-$), which are interpreted as multiplet members of $[^{12}\text{C}^*(4.4 \text{ MeV}) \times p_{3/2}^{-1}]$, were populated with the single-particle strengths of 10–20% relative to the ground state. No other $l = 1$ strengths such as $7/2^-$ and $5/2^-$ were observed, and therefore the total identified $l = 1$ strength amounted to only $57 \pm 6\%$ of a shell-model result in which all four valence protons are restricted to the $1p$ shell. The measured cross sections in the $^{12}\text{C}(e,e'K^+)^{12}_\Lambda\text{B}$ reaction are also shown in the figure. Since the excitation energies of the

#2 and #3 states in the $^{12}_{\Lambda}\text{B}$ are close to that of the ^{11}B $1/2^-$ and $3/2^-$ excited states, respectively, the states #2 and #3 could be identified as the core-excited states with the configurations of $[^{11}\text{B}^*(1/2^-) \times s_{\Lambda}]$ and $[^{11}\text{B}^*(3/2^-) \times s_{\Lambda}]$, respectively. The difference of the corresponding excitation energies partly results from ΛN effective interaction.

Theoretical prediction of $^{12}\text{C}(\text{e}, \text{e}'\text{K}^+)_{\Lambda}^{12}\text{B}$ reaction

Present experimental spectrum is compared with a theoretical calculation based on the DWIA and the configuration-mixed shell model [42, 79, 80].

Hypernuclear wave functions were obtained by diagonalizing the Hamiltonian,

$$\mathcal{H} = H_N^{\text{Cohen-Kurath}} + t_{\Lambda} + \xi(l_{\Lambda} \cdot s_{\Lambda}) + \sum_N v_{\Lambda N}, \quad (5.1)$$

where $H_N^{\text{Cohen-Kurath}}$ is the Cohen-Kurath shell-model Hamiltonian [81], t_{Λ} is the Λ kinetic energy, $\xi(l_{\Lambda} \cdot s_{\Lambda})$ is the spin-orbit force for Λ -orbits and $v_{\Lambda N}$ is the effective ΛN interaction. The Cohen-Kurath model well reproduces the spectroscopic factors of p-shell nuclei [81–83].

For the effective interaction part, the YNG interaction [4] deduced on the basis of the G-matrix calculation with the Nijmegen soft core model-F (NSC97f) force was used.

The theoretical $^{12}_{\Lambda}\text{B}$ spectrum at $\theta_K = 3^\circ$ is shown in Figure 5.6 and the corresponding values are listed in Table 5.3 [42, 80]. Figure 5.6(b) shows the experimental spectrum overlaid with the theoretical calculation with 0.9 MeV (FWHM) resolution.

Table 5.3: Comparison of experimental result with theoretical prediction [80].

peak no.	Experimental results		Theoretical prediction		
	Ex (MeV)	cross section (nb/sr)	J^π	Ex (MeV)	cross section (nb/sr)
# 1	0	$117 \pm 13 \pm 14$	1_1^-	0	23.4
			2_1^-	0.19	114.5
# 2	$2.5 \pm 0.2 \pm 0.3$	$57 \pm 13 \pm 7$	1_2^-	2.40	51.4
			0^-	3.06	9.9
# 3	$5.4 \pm 0.3 \pm 0.3$	$31 \pm 14 \pm 4$	2_2^-	6.27	15.1
			1_3^-	6.39	5.8

The theoretical calculation qualitatively reproduces the global structure of the experimental result. In addition to the two pronounced peaks, three core-excited states (or its doublet) $[^{11}\text{C}^*(1/2^-) \times s_{\Lambda}]$, $[^{11}\text{C}^*(3/2^-) \times s_{\Lambda}]$ and $[^{11}\text{C}^*(1/2^-) \times p_{\Lambda}]$ are populated as small peaks.

In all states, the amplitudes of spin-flip states are larger than that of spin-non-flip states. Additionally, the separation of the doublet is calculated to be within 500 keV for

all the observed states. Therefore, all the obtained cross sections should be compared with the sum of the cross sections of the spin-flip and the spin-non-flip states. The theoretical calculation of the doublet cross sections of the #1, #2, and #3 give consistent values with the experimental results within systematic errors. It indicates that the DWIA with a phenomenological potential describes hypernuclear structures well enough to the 1st order as in the case of the (π^+, K^+) reaction.

The present results also enable us to partly discuss a validity of the calculation of Λ hypernuclear excitation energies. In the calculation, the energy levels depend on the ΛN interaction model which is used to deduce the ΛN effective interaction part. Figure 5.7 shows the level scheme of ${}^1_{{\Lambda}}C({}^1_{{\Lambda}}B)$ with the Nijmegen soft-core OBE potential models (NSC97a-NSC97f) [80]. The NSC97 has six versions corresponding to different magnitudes of the spin-spin interaction. All of the six versions gives good fits to the YN scattering data [3]. Calculated excitation energy of the 2^-_2 and 1^-_3 states are inconsistent with the excitation energy of #3 ($5.42 \pm 0.24 \pm 0.25$ MeV) obtained from the present experiment. Therefore, the excitation energy of #3 suggests NSC97c-e might be appropriate. As for the ground state doublet of ${}^1_{{\Lambda}}B$, since weak decay of the 1^- state was observed, The NSC97a-d are not suitable. Therefore, only a NSC97e might be suitable. For further detail discussion, spectra with much better quality and statistics are required.

Binding energy of ${}^1_{{\Lambda}}B$ ground state

The average binding energy of the ground state doublet was obtained to be $(11.7 \pm 0.1 \pm 0.3)$ MeV. The binding energy of the ground state of ${}^1_{{\Lambda}}B$ has been measured in emulsion experiments previously, which was (11.37 ± 0.06) MeV [84]. According to Ref. [84], 87 events were found via the decay process of ${}^1_{{\Lambda}}B \rightarrow \pi^- + \alpha + \alpha + \alpha$. The present result is consistent with emulsion data.

(a) With a fixed energy resolution of 300 keV (FWHM)

(b) The experimental spectrum overlaid with the theoretical spectrum with 0.9 MeV (FWHM) energy resolution

Figure 5.6: The theoretical prediction of ${}_{\Lambda}^{12}\text{B}$ spectrum by Motoba [80]

Figure 5.7: The level scheme of $^{12}_{\Lambda}\text{C}(^{12}_{\Lambda}\text{B})$ calculated with Nijmegen soft-core models [80].

5.3 Upgrade consideration of the (e,e'K⁺) spectroscopy

The first experiment of hypernuclear spectroscopy via the (e,e'K⁺) reaction has been conducted successfully. In the experiment, however, we encountered difficulties and limitations in the existing experimental setup as described in the following.

The ESPS scintillator can work normally at singles electron rate of less than 2 MHz/counter. When the singles rate in the ESPS exceeded the count rate limitation, the detection efficiency in the ESPS due to pile-up of the scintillator signals decreased, and the electronics dead time increased. The signal-to-accidental (S/A) ratio also decreased from 0.8 at the beam current of 0.2 μ A to 0.2 at 0.6 μ A. To keep the normal operation of the ESPS hodoscopes and a better S/A ratio, we were forced to run the experiment with lower beam currents. The $^{12}_\Lambda$ B spectrum has been obtained by spending one month of the beam time. If we run the experiment in the present experimental setup, it would take a few month or half a year to get enough ground state yield (~ 500). This is not realistic.

At the end of the beam time, carbon target runs have been carried out with 2 or 4 mm steel shield at an entrance of the ESPS. The shield helped to block the scattered electrons from bremsstrahlung at 0 degree. Since the ESPS electron rate significantly dropped, we increased the beam current up to 1.5 μ A, still keeping S/A ratio of 0.6-0.8. Although quantitative study was not done because the ESPS angular acceptance with the shield could not be obtained, this study suggested that the experimental setup in which the scattered electrons from bremsstrahlung at 0 degrees are blocked is better though a large virtual photon flux at 0 degrees is also blocked.

The SOS momentum resolution mainly determined energy resolution of hypernuclear mass spectrum. Additionally, the SOS solid-angle acceptance, 5 msr, can be improved.

Therefore, three experimental conditions have to be improved in the future (e,e'K⁺) hypernuclear spectroscopy:

- (1) lower background due to the scattered electrons from bremsstrahlung at a focal plane of an electron spectrometer (< 1 MHz/focal plane),
- (2) better momentum resolution of a kaon spectrometer ($< 2 \times 10^{-4}$) and
- (3) larger solid-angle acceptance of a kaon spectrometer (> 15 msr).

Chapter 6

Conclusion

Measurements of hypernuclear excitation spectra have been successfully carried out via the $(e,e'K^+)$ reaction for the first time. In the present study, we intended to explore a new generation of hypernuclear spectroscopy making use of the reaction with a high-quality CW electron beam available at Jefferson Lab (JLab). The $(e,e'K^+)$ reaction has advantages over the meson induced reactions such as (π^+,K^+) and (K^-, π^-) ; it converts a proton to a Λ hyperon and excites both natural and unnatural parity states with its sizable amplitudes. In addition, more important experimentally, the reaction allows us to realize sub-MeV energy resolution for Λ hypernuclear mass spectra, since a high-quality primary beam is used.

In the present experiment, the 0 degree tagging method was employed, which utilized most of the virtual photon flux by detecting scattered electrons including 0 degrees. Scattered kaons were detected also at very forward angles where Λ photo-production cross section meets the maximum. To realize the unique kinematics, the experimental setup installed in the experimental Hall C of JLab consisted of the existing Short Orbit Spectrometer (SOS) for kaon detection and Enge split-pole spectrometer that measured scattered electrons.

Net one month was spent for data taking with a carbon target. The $^{12}_{\Lambda}\text{B}$ hypernuclear spectrum was obtained with 0.9 MeV (FWHM) energy resolution, which is much better than that of the $^{12}_{\Lambda}\text{C}$ spectra obtained by the SKS spectrometer at KEK-PS and is the best ever achieved in the hypernuclear reaction spectroscopy.

From the $^{12}_{\Lambda}\text{B}$ spectrum, the ground (s_{Λ}) states, p_{Λ} states and candidates of core-excited s_{Λ} states were observed.

The elementary reaction of $p(e,e'K^+)\Lambda/\Sigma^0$ was used for calibration of the absolute scale of the missing mass, and the binding energy of the ground state of $^{12}_{\Lambda}\text{B}$ was determined within the present experiment. Thus, the average binding energy of $^{12}_{\Lambda}\text{B}$ ground state doublet was obtained to be 11.7 ± 0.1 (statistical) ± 0.3 (systematic) MeV¹. The present result is consistent with emulsion data.

The observed spectral structure was similar to that of the mirror hypernucleus, $^{12}_{\Lambda}\text{C}$.

¹The final value of the average binding energy in the analysis is 11.4 ± 0.5 MeV [85]

Precise comparison of these spectra is expected to provide information on the hypernuclear structure and ΛN interaction, when the spectra with much better quality and statistics are obtained.

The cross section of the ${}_{\Lambda}^{12}\text{B}$ ground state doublet was deduced to be 117 ± 13 (statistical) ± 14 (systematic) nb/sr². The theoretical prediction calculated by Motoba gives a consistent value with the present result. It can be said that a calculation based on the DWIA for the $(e,e'\text{K}^+)$ reaction adopting a phenomenological potential for ΛN interaction described reasonably well the hypernuclear production process as in the case of the (π^+, K^+) reaction.

The present experiment has shown the effectiveness of Λ hypernuclear spectroscopy via the $(e,e'\text{K}^+)$ reaction. The new spectroscopic technique for the investigation of Λ hypernuclei has been established by the present study.

²The final value of the cross section is 140 ± 17 (stat) ± 18 (sys) nb/sr [85]

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Appendix A

The CEBAF Accelerator and Hall C beamline

A.1 CEBAF Accelerator

The CEBAF accelerator is an electron machine, capable of delivering CW (100% duty factor) unpolarized (and polarized) electron beams of up to 6 GeV and beam currents of up to 200 μA simultaneously in three experimental halls. The microstructure of the beam consists of short (1.67 ps) bursts at 1,497 MHz. Each of the three experimental halls receives one third of these bursts, leading to “effective” frequency of 499 MHz per hall. A typical beam emittance is 2×10^{-9} m·rad with an energy spread $\delta E/E$ of 10^{-4} . The relative beam energy can be measured within 10^{-4} and the absolute beam energy to 10^{-3} .

Figure A.1 shows a schematic view of CEBAF. Electrons are generated in the injector and accelerated up to about 60 MeV. The beam is then accelerated by a pair of recirculating LINACs (the North and the South LINACs) that each use 160 0.5 m long pairs of 5-element niobium cryogenic cavities to accelerate the electrons. A “standard” energy gain for each LINAC is about 600 MeV. The beam recirculation is achieved using five pairs of recirculating arcs. The total number of magnets in the beam transport system is around 2,200. The electron beam can be extracted and sent to any of the experimental halls after one, two, ... five passes through the machine.

In E89-009, Jefferson Lab provided unpolarized CW electron beam with energies in the 1.7-1.9 GeV range and currents up to 2.0 μA .

A.2 The Hall C beamline

The Hall C arc beamline is 41.6 m long and consists of 8 dipoles, 12 quadrupoles and 8 pairs of beam correctors which transport the beam from the Beam Switch Yard (BSY) to the target. The arc is also equipped with several monitors to measure the energy, current, position and profile of the beam. Figure A.2 shows a schematic diagram of the Hall C

Figure A.1: The CEBAF accelerator.

arc.

There are three pairs of Superharps which are used for beam energy measurement and for beam profile measurement. The Superharps are made of x/y 22 μm tungsten wires that sample the beam intensity as a function of the transverse position in the beam pipe. Superharp scans are used to calibrate the Beam Profile Monitors (BPMs), to make absolute energy measurements and to study the emittance and dispersion of the beam.

Current measurements are performed by an Unser monitor and by three resonant cavity Beam Current Monitors (BCM1, 2 and 3). The Unser monitor is a parametric current transformer which calculates the absolute current. The BCMs are tuned by RF cavities which measure the RF radiation of the beam and provide relative current measurements. Rastering magnets are installed to oscillate the beam position in both the vertical and horizontal planes. They are used to avoid overheating of thin target such as CH_2 used in the E89-009 experiment. A typical raster size is 3 mm. Since the beam position at the target is monitored by the BPMs, the rastering is verified, and the central beam position is monitored and adjusted.

The beam current was calibrated as a function of the BCMs output value. In the beginning of the beam time, the calibration was done and a systematic error of 5% was obtained. In Hall C, the accelerator has been operated on average at $\sim 10 \mu\text{A}$ with a systematic error of $\sim 1\%$. In E89-009, a lower current setting was required, which caused an increase of the systematic error.

Figure A.2: The Hall C beamline.

Appendix B

Rate and Signal-to-Accidental ratio

B.1 Overview

The particle singles rate study was done with the 1.7 GeV runs. Several targets, ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$, ${}^{12}\text{C}$ and ${}^{28}\text{Si}$ were irradiated. The singles rate of scattered electrons, produced positrons and hadrons were measured. The count rate of scattered electrons determined the signal-to-accidental (S/A) ratio in the events for true coincidence. High-rate electrons also increased the multiplicity per trigger.

B.2 Particle singles rate in SOS

Particles singles rate was roughly measured by using different combination of the trigger:

$$\begin{aligned} e^+ &: (4/4) \\ \pi^+ &: (4/4) - (4/4 \times \overline{GC}) \\ p &: (4/4) - (4/4 \times \overline{GC}) - (4/4 \times \overline{GC} \times \overline{AC}). \end{aligned}$$

Table B.1 shows the results of the measurement of singles rate by visual scalers in several targets. The beam current was normalized by a scintillator counting rate in the ESPS. In our settings, positron singles rate were dominant for the SOS. The singles rate of the other particles was lower by a factor of 2. Thus, singles rate in the 4/4 trigger was regarded as positron singles rate. The result is consistent with the pair production cross section. Singles rate of pions and protons was initially estimated by the program EPC [64]. Measured values were not consistent with that of the EPC because positrons were not completely removed by VETO counters. Positron singles rate affected the accidental VETO which is described in section 4.7.

B.3 Electron singles rate in ESPS

Bremsstrahlung electrons were dominant for electron rate in the ESPS. Electron singles rate was calculated by the equations written in Ref. [86]. The number of photons $\rho(k)$ for

Table B.1: Particle singles rate in SOS.

Target	Thickness (mg/cm ²)	Beam current (μ A)	e ⁺ kHz	π^+ kHz	p kHz
⁶ Li	16.1	0.74	110	1.6	0.21
⁷ Li	19.0	0.85	120	1.6	0.19
¹⁰ B	16.3	0.80	91	1.3	0.17
¹¹ B	20.8	0.67	97	1.3	0.13
¹² C	22.0	0.47	100	1.4	0.14
²⁸ Si	5.2	1.11	120	1.4	0.11
from EPC or pair creation (¹² C)	10	1.6	100	1	0.10

$k - dk/2 < k < k + dk/2$, with the photon energy k and dk the energy width of photon after penetrating target, is described as [86]:

$$\rho(k)dkdT = \frac{dk}{k} \left(\frac{4}{3} - \frac{4}{3}y + y^2 \right) dT, \quad y = k/E, \quad (\text{B.1})$$

where E is beam energy and dT the target thickness in radiation length.

With $E=1,721$ MeV, $k=1,461$ MeV, and $dk=2$ MeV for a scintillator in the middle of the Enge focal plane, bremsstrahlung rate (R_{calc}) is calculated by the following:

$$R_{calc} = 8.26 \times 10^9 I dT, \quad (\text{B.2})$$

where I is beam current in μ A.

Fig.B.1 shows the results of electron rate measurement in the ESPS for several targets. A scintillator in the middle of the focal plane (No.38) is used for the counting rate on the visual scaler. The calculation (dashed lines) agrees with the experimental results except for ⁶Li, which may have been oxidized during the experiment. It proves that the ESPS has been operated without additional electron loss.

Figure B.1: Electron singles rate for several targets v.s beam current.

B.4 Coincidence rate and S/A ratio

A coincidence rate (R_C) depends on the experimental acceptance such as solid angles and momenta. It can be described as the following:

$$R_C = C \times R_K, \quad (\text{B.3})$$

where C is called the coupling probability and R_K is the detected kaon rate.

On the other hands, the accidental rate (A) within 2 ns around the coincidence time window is expressed as:

$$A = R_e \times R_K \times 2 \times 10^{-9}, \quad (\text{B.4})$$

where R_e is the scattered electron rate. The the S/A ratio is then:

$$S/A = R_C/A = C/(R_e \times 2 \times 10^{-9}). \quad (\text{B.5})$$

C was obtained from measuring S/A and R_e . The electron rate in the ESPS limits the beam current because a high current causes a decrease of the S/A ratio.

Figure B.2 shows the dependence of the beam current as a function of the S/A ratio and C . C changed from 0.06 to 0.10 because:

- (1) The acceptance of the total virtual photon flux was 30%,
- (2) Only half of the total momentum acceptance in the ESPS and the SOS was used, and
- (3) The detection efficiency was approximately 80%.

Therefore, the expected S/A ratios were consistent with the experimental ratios for the ESPS electron rate (10-20%).

(a) S/A ratio vs beam current

(b) Calculated C vs beam current

Figure B.2: The S/A ratio and coupling probability.

B.5 Event multiplicity

In the present experiment, trigger was made only by the SOS detectors. For the SOS, single track (multiplicity=1) was dominant since the SOS rate is a few 100 kHz for the maximum. On the other hand, multiplicity in the ESPS was larger than that in the SOS because the electron rate exceeded 200 MHz. Figure B.3 shows a multiplicity distribution at $0.6 \mu\text{A } ^{12}\text{C}$ target runs for the coincidence time window of 2 ns. The multiplicity increases when the width is wider.

Figure B.3: The distribution of ESPS multiplicity for a 2 ns coincidence window.

Fig.B.4 shows the ratio of the event in multiplicity ≤ 1 , ≤ 2 and ≤ 3 to all events. In the latter, a high efficiency is kept except for the data set No. 5 and 6 in which the highest beam current runs were taken on ^{12}C target. Inclusion of the events with larger multiplicity increases the number of accidental coincidence events. However, no multiplicity cuts were required in the present analysis, since the distribution should have no special structure and we confirmed the structures of any spectra obtained in E89-009 had no change drastically.

(a) multiplicity ≤ 1

(b) multiplicity ≤ 2

(c) multiplicity ≤ 3

Figure B.4: The ratio of the number of events for a multiplicity ≤ 1 (a) , ≤ 2 (b) and ≤ 3 (c) to all event.

Appendix C

Program ENGINE

The analysis of the raw data was accomplished using the Hall C analysis software called ENGINE [74]. The code reads raw CODA and EPICS events, decodes detector hits and extracts or reconstructs tracks and particle information for each event (Figure C.1). It also records the hardware and software scalers for each run.

The ENGINE starts by reading in a main configuration file which indicates a series of input filenames used in the program and flags which spectrometer is to be analyzed. The code is processed to open the raw data files after definition of all the run parameters and initialization of histograms and ntuples.

In the beginning of the run, ADC thresholds are determined by events from a pedestal trigger. All variables are included into a common block and registered to use appropriate calls. The CEBAF Test Package (CTP) software library is used to provide a flexible way to store and modify histograms, test conditions and scaler definitions and other analysis parameters. Finally, the main event loop starts. It reads and processes events according to their types:

1. scaler events - decode and increment all hardware scalers. This includes time and charge from the last scaler event. The total (running) time and accumulated charge are also computed.
2. EPICS (slow control) events - monitor the status of magnetic settings and beam-line diagnostics, etc. The information is stored in ASCII files to be further analyzed by the other specific programs such as the beam current calibration code and to check the stability of the beam energy.
3. physics events - consists of raw detector hits.

In the physics event loop, raw detector hits are read, decoded, and passed to the main reconstruction code, *s_reconstruction* and *k_reconstruction*. After an event is successfully reconstructed, information for appropriate particle identification is computed, saved for each spectrometer, then the physics quantities are defined.

The outputs of the ENGINE code are:

- 1 ASCII report file(s) - contain hardware and software scalers as well as calculated detector efficiencies and integrated beam charge.
- 2 An HBOOK file - contains a set of histograms in the CERNLIB's HBOOK format, which is used to check the detector performance and monitor the integrity of the data. It sometimes may be used for efficiency calculation.
- 3 Ntuple file(s) - contain a list of identical data structures for each event, which is used to reconstruct the mass spectra.
- 4 An EPICS output file - to check the stability of the spectrometer magnets and accelerator settings.
- 5 Raw data dump(s) - for TOF calibration (in the SOS).

Figure C.1: ENGINE flow chart

Appendix D

Extraction of true coincidence events

D.1 Overview

To count the true number of coincidence events, the number of accidental coincidence events and pion events must be accounted for. Moreover, the true events that leaked into the adjacent peak due to the HNSS hodoscope pile-up must also be determined.

D.2 Cut condition for coincidence time

Figure D.1 shows the distribution of the kaon coincidence time (t_{coin}). A peak including the true coincidence is at 0 ns in the figure and the time windows are defined in every 3 ns as shown by the lines.

The number of events in the coincidence time between $t1$ and $t2$ [ns] is defined as $ct(t1, t2)$. In the present analysis, the time window for true coincidence is defined as $0 < t_{coin} < 2$ [ns]. The true events with the HNSS hodoscope pile-up are included in a region of $0 < t_{coin} < 2$ [ns] as shown in Figure D.2. Therefore, the time window includes all the true events.

The time windows for accidental coincidence events are defined as $-7 < t_{coin} < -1$ and $5 < t_{coin} < 23$ (8 regions in the figure). The number of true events (N_t) is described by the following:

$$N_t = CT(-1, 2) - A_p \quad (D.1)$$

$$A_p = \frac{CT(-7, -1) + CT(5, 23)}{8}. \quad (D.2)$$

However, pion events must be removed from N_t . The way to remove them is explained in the next section.

Figure D.1: Distributions of the coincidence time.

D.3 Extraction of pion events

Pion events are selected by changing AC cut condition to $AC\ NPE > 2$. An adjacent peak to the true peak includes pion coincidence events. Therefore, the pion events including the true peak is evaluated using two regions, $-1 < t_{coin} < 2$ and $2 < t_{coin} < 5$.

Figure D.3 shows the coincidence time for pion events. True coincidence events for pions are around 2 ns. The others are for accidental coincidence.

A ratio of true coincidence events for pions in $-1 < t_{coin} < 2$ to $2 < t_{coin} < 5$ [ns] (R_p) is described as the following:

$$R_p = \frac{CT(-1, 2) - A_p}{CT(2, 5) - A_p} \quad (D.3)$$

Within coincidence time for kaons, pion events included in $2 < t_{coin} < 5$ [ns] can be extracted. Therefore, the number of pion events in $-1 < t_{coin} < 2$ [ns] within the coincidence time for kaons (N_p) is described as the following:

$$N_p = (CT(2, 5) - A_p) \times R_p \quad (D.4)$$

The R_p for each data set are summarized in table D.1.

Figure D.2: Pulse height of ESPS hodoscope vs. coincidence time.

D.4 Extraction of true events for the $^{12}_{\Lambda}\text{B}$ energy spectrum

Figure D.4 shows the distributions of accidental coincidence and accidental+pions for $-30 < -B_{\Lambda} < 20$ (MeV). In this region, the ratio of the number of pion to accidental coincidence events (pion/accidental) is $(16 \pm 0.1)\%$. On the other hands, the weighted average of R_p is $46 \pm 11\%$. Therefore, a ratio of the pion/accidental in the true coincidence region is $(7 \pm 1)\%$. Figure D.5 shows the $^{12}_{\Lambda}\text{B}$ spectrum with (a) accidental coincidence only and (b) with accidental+pion coincidence. Validity of the accidental coincidence spectrum is confirmed by comparing the averaged accidental counts per 400 keV in an over-bound region, $-30 < -B_{\Lambda} < -15$ (MeV). In the present analysis, the over-bound region was used for the determination of the background.

(a) For 1.8 GeV runs

(b) For 1.7 GeV runs

Figure D.3: Coincidence time for pion events.

Table D.1: The ratio of the pion leak into the true region to that of an adjacent region.

data set no.	pion leak ratio (<i>true/adjacent</i>)	data set no.	pion leak ratio (<i>true/adjacent</i>)
1.8 GeV		1.7 GeV	
3	0.38 ± 0.10	9	0.17 ± 0.07
4	0.66 ± 0.14	10	0.10 ± 0.10
5	0.39 ± 0.12	11	0.26 ± 0.09
6	0.68 ± 0.11		
7	0.85 ± 0.17		
8	0.63 ± 0.07

Figure D.4: Accidental (circle) and accidental+pion (box) coincidence for $-30 < -B_\Lambda < 20$ (MeV).

(a) with accidental coincidence only

(b) with accidental + pion coincidence

Figure D.5: Effect of the accidental and pion coincidence on the ^{12}B energy spectrum.

Appendix E

Detection efficiency calculation of ESPS detectors

E.1 ESPS detectors

In E89-009, SSD and hodoscopes were used to detect the scattering electrons. Because of a lack of redundancy, the evaluation of the efficiency was complicated. In this chapter, the procedures and results of our efficiency calculation are discussed.

E.2 SSD detection efficiency

E.2.1 Overview

SSD detection efficiency was evaluated as the ratio of the number of events with hits in the SSD (N_{ssd}) to the number of electrons passing through the two scintillators ($N_{electron}$):

$$\epsilon_{ssd} = \frac{N_{ssd}}{N_{electron}}. \quad (\text{E.1})$$

E.2.2 $N_{electron}$

Figure E.1 shows the time difference (dt) between two overlapped scintillators when they have a hit. A true coincidence peak was $-5 < dt < 5$ (ns) in the figure. The number of coincidence in the region is defined as N_t and includes accidental coincidence events. They were evaluated from the regions $-15 < dt < -5$ and $5 < dt < 15$ (ns). The number of accidental coincidence in the region is defined as N_f . Therefore, the $N_{electron}$ is calculated from:

$$N_{electron} = N_t - N_f. \quad (\text{E.2})$$

Figure E.1: The time difference between the two scintillators in the ESPS.

E.2.3 N_{ssd}

Figure E.2 shows a correlation between SSD time (T_{ssd}) and scintillator time (T_{scin}) when selecting N_t . The T_{scin} is defined as the time average of the two scintillator hits.

A true coincidence region (true region) is $-30 < dT = T_{ssd} - T_{scin} < 30$ (ns). The number of hits in the true region is defined as T_t . The true region includes accidental coincidence between SSD and one scintillator. The number of accidental coincidence between SSD and a scintillator is defined as T_f . The T_f is evaluated with the number of hits outside of the true region.

The hit density around the true region is not the same due to the difference in the TDC types. SSD signals were measured with multi-hit TDCs, and hodoscope signals were measured with single-hit TDCs. When an event at a time $t = t_0$ of a single hit TDC is selected, the past events to a selected one ($t < T_0$) are suppressed, because a signal at $t = t_0$ means that the both detectors don't have any signal for $t < t_0$.

Because of the inconsistency of the hit density, the T_f is extracted from an average of hit densities around the true region. The hit densities for $30 < dT = T_{ssd} - T_{scin} < 40$ and $-40 < dT = T_{ssd} - T_{scin} < -30$ (ns) are described as D_+ and D_- , respectively. The area in *true* region is defined as A_t in ns^2 . The T_f was calculated as:

$$T_f = \frac{D_+ + D_-}{2} \times A_t, \quad (\text{E.3})$$

$$A_t = (\text{SSD time window}) \times (\text{scintillator time window}). \quad (\text{E.4})$$

The $T_t - T_f$ represents the number of true SSD hits in N_t . However, it is not equal to N_{ssd} . Figure E.3 shows a distribution of dt with N_t and N_f . N_t includes the accidental coincidences between the two scintillators. When a true coincidence between SSD and one scintillator exists, accidental coincidences between the two scintillators also exist. Such

Figure E.2: Correlations between T_{ssd} and T_{scin} .

events are in true region. The number of events in the *true* region (F_t) and accidental region (F_f) with N_f are also extracted using the same approach.

Finally, the SSD efficiency is written by the following equation:

$$\epsilon_{ssd} = \frac{T_t - T_f - (F_t - F_f)}{N_t - N_f}. \quad (\text{E.5})$$

Figure E.3: The time difference of the SSD time and averaged scintillator time when selecting N_f . The coincidence event peak results from a hit between the SSD and one scintillator.

E.2.4 The rate dependence of SSD efficiency

SSD efficiency depends on the electron rate as shown on Figure E.4. Offsets at the low rate limit were due to charge collection inefficiency. SSD efficiency is related to the SSD channel rate as:

$$\epsilon_{ssd}(\%) = 97.0 - 0.00777Re, \quad (\text{E.6})$$

where Re is SSD rate per channel in kHz. The equation was obtained by a linear fit of the data.

Figure E.4: Efficiency V.S. SSD channel rate

The rate dependence originated from the SSD readout electronics. Figure E.5 shows a distribution of the time interval between serial counts for each plane. Peaks in every 20 ns are due to the 50 MHz clock frequency of the ECL driver. The time width of the TDCs was set to 200 ns, and the 16th hit in each channel was recorded in a region of more than 200 ns. Figure E.6 shows a calculation of the time interval between serial counts when assuming the dead time of 60–120 ns. The result was consistent with the calculation for the dead time 100–120 ns.

Figure E.5: The time interval of the double counting from the data.

Figure E.6: The calculated time interval of the double counting.

E.3 Hodoscope detection efficiency

E.3.1 Overview

The ESPS hodoscope efficiency was evaluated using electron events passed through one SSD and one scintillator. It was done for scintillators from No. 11 to 64 (54 scintillators). The other channels were out of the momentum acceptance. Electrons passed through two scintillators or one scintillator within the ESPS momentum acceptance. In a region where electrons pass through only one scintillator, the efficiency for the scintillator can not be calculated because true electron hits can not be identified. Therefore, only the efficiency for 44 scintillators was calculated by the equation described later. The efficiency for the remaining 10 scintillators was evaluated using normalized value from the ADC gains.

E.3.2 Equation

Figure E.7 shows examples of electron hits in SSDs and scintillators. The efficiency of a scintillator (“scin1”) in a given row was evaluated with the SSD and a scintillator from another row (“scin2”).

Figure E.7: The geometry of the SSD and scintillators

Figure E.8 shows a spectrum of a scintillator time (t_{scin}). Coincidence events between the SOS and ESPS are also shown at 0 ns in the figure. The time width of “scin2” selected for the the efficiency calculation is $-15 < t_{scin} < 5$ (ns).

SSD channels were selected to cover a region where electrons should pass through two scintillators. Figure E.9(a) shows an overlap region of the selected SSD channels. The two hit patterns of the coincidence between SSD and each scintillator are shown as line and dot-line histograms.

Figure E.9(b) shows the time difference between a selected SSD channel and a scintillator (“scin2”). The number of events in the selected region in the figure is defined as

Figure E.8: Scintillator time. The peak shows coincidence events between the SOS and ESPS.

N .

Figure E.10 shows the time difference between two scintillators with selected SSD channels and time. The number of count in $-5 < t_{scin} < 5$ (ns) in the figure is defined as T . Since accidental coincidence is very small for N and T , the efficiency is described as T/N .

(a) The SSD hit pattern gate

(b) The spectrum of the time difference between a selected SSD channel and a scintillator

Figure E.9: The SSD hit pattern gate setting. “shadows” from scintillator hits are shown. SSD hit pattern gates were set to cover the overlap region.

Figure E.10: Time difference between two scintillators.

E.3.3 Calculation result

Figure E.11 - E.15 shows the time dependence of detection efficiency for 44 scintillators. The efficiency for some channels was very high. However, efficiency dropped for some channels after the beam current was changed from $0.6 \mu\text{A}$ to a lower setting.

E.3.4 Extraction of efficiency by ADC gain

The efficiency for 10 scintillators which can not be calculated by the previously mentioned equation was determined by the ADC gain. Figure E.16 shows a correlation between the ADC gain and efficiency. Here, ADC gain (G) is defined as the following:

$$G(\text{channels}) = ADC - ped, \quad (\text{E.7})$$

where ped is 800.

When the gain was more than 1000, high efficiency was kept during experiment. The efficiency for scintillators with the gain more than 1000 was $98 \pm 2 \%$.

For the other scintillators having the gain less than 1000, the ADC gain was compared with that of scintillators for which the efficiency was calculated. Figure E.17–E.19 show the correlations between the gain and run number. Though the correlation was not obvious, the efficiency was determined using the efficiency of scintillator having the same tendency for the gain. The estimated error was 4%.

E.3.5 Summary of hodoscope efficiency

Table E.1 and E.2 list the hodoscope efficiency for data set No. 1–11. The weighted average value of the efficiency for each data set was determined from the values in the tables.

Figure E.11: Time dependence of the scintillator efficiency (1).

Figure E.12: Time dependence of the scintillator efficiency (2).

Figure E.13: Time dependence of the scintillator efficiency (3).

Figure E.14: Time dependence of the scintillator efficiency (4).

Figure E.15: Time dependence of the scintillator efficiency (5).

Figure E.16: Gain v.s. scintillator efficiency

Figure E.17: Time dependence of the scintillator gain (1).

Figure E.18: Time dependence of the scintillator gain (2).

Figure E.19: Time dependence of the scintillator gain (3).

Table E.1: Calculation results of the hodoscope efficiency (1).

Scin No.	Data Set No.										
	1	2	3	4	5	6	7	8	9	10	11
11	99 ± 1								Out of acc.		
12	98 ± 2								Out of acc.		
13	99 ± 1						96 ± 2	91 ± 3			90 ± 3
14	98 ± 2							95 ± 2	93 ± 3		
15	98 ± 2	93 ± 4	91 ± 4		75 ± 5		69 ± 4	75 ± 3	83 ± 3		
16	98 ± 2								94 ± 2	97 ± 2	
17	93 ± 3			88 ± 3			93 ± 3			88 ± 2	85 ± 2
18	98 ± 2						96 ± 3	92 ± 2	98 ± 2		
19	98 ± 2										
20	98 ± 2						95 ± 2	93 ± 2	96 ± 2	95 ± 2	
21	98 ± 2	97 ± 2				92 ± 3		86 ± 3	79 ± 4	83 ± 4	
22	98 ± 2						96 ± 2	93 ± 3	88 ± 3	89 ± 3	
23	98 ± 2										
24	98 ± 2				94 ± 2	93 ± 3	91 ± 3	92 ± 2		90 ± 3	
25	96 ± 2				94 ± 2	96 ± 2	95 ± 3	93 ± 2	90 ± 2	89 ± 3	
26	95 ± 3						80 ± 3	76 ± 2	77 ± 3	76 ± 3	69 ± 6
27	98 ± 2										
28	98 ± 2										
29	98 ± 2										
30	94 ± 4								92 ± 5		
31	98 ± 2						94 ± 4		94 ± 5		
32	95 ± 5										
33	95 ± 5						85 ± 5				
34	96 ± 4						92 ± 4	92 ± 2	91 ± 5		
35	98 ± 2						96 ± 2	92 ± 2	91 ± 5		
36	98 ± 2						96 ± 2				95 ± 3
37	98 ± 2										
38	98 ± 2						92 ± 2	90 ± 2	91 ± 2	88 ± 3	86 ± 4
39	99 ± 1							98 ± 2	97 ± 2		95 ± 3
40	95 ± 5	70 ± 5	95 ± 5			90 ± 5					

Table E.2: Calculation results of the hodoscope efficiency (2).

Scin. No.	Data Set No.										
	1	2	3	4	5	6	7	8	9	10	11
41	95 ± 5										
42	98 ± 2					96 ± 2	93 ± 2	89 ± 3	84 ± 5		
43	99 ± 1										
44	98 ± 2										
45	99 ± 1					97 ± 2			96 ± 2	95 ± 2	
46	99 ± 1					98 ± 2	97 ± 2			96 ± 2	
47	99 ± 1										
48	95 ± 5										
49	95 ± 5										
50	98 ± 2										
51	98 ± 2					95 ± 2	92 ± 3	92 ± 2	89 ± 2		
52	98 ± 2					96 ± 2	94 ± 2	90 ± 3	89 ± 3		
53	99 ± 1					98 ± 2	95 ± 2	94 ± 2	93 ± 2		
54	98 ± 2										
55	99 ± 1										
56	95 ± 5										
57	95 ± 5					85 ± 5					
58	98 ± 2					95 ± 2	90 ± 2	84 ± 4	80 ± 3	76 ± 5	
59	99 ± 1					98 ± 2	97 ± 2	95 ± 2	94 ± 3		
60	98 ± 2										
61	99 ± 1										
62	99 ± 1										
63	99 ± 1								98 ± 2	97 ± 2	
64	Out of acc.								90 ± 5		

Appendix F

Elementary cross section

The elementary cross sections of Λ and Σ^0 were evaluated by analyzing the missing mass spectra from the CH_2 target data. The spectra were fitted with a polynomial and 2 Gaussians because spectra consisted of Λ , Σ^0 and a broad spectrum including accidental coincidence events and Λ/Σ^0 quasi-free production from ^{12}C . Table F.1 shows the fitting results with statistical and systematic errors. Evaluated cross sections in the Lab frame were converted to that in the CM and compared with previous experiments. The results in 1.8 GeV (data set No.8) and 1.7 GeV (data set No.10) are shown. The results in 1.8 GeV runs were inconsistent with that of 1.7 GeV runs. On the other hands, cross section of the ground state of $^{12}_\Lambda\text{B}$ in 1.8 GeV was consistent with that in 1.7 GeV (145 ± 32 and 111 ± 24 nb/sr in Lab frame, respectively)

Table F.1: Cross section of $^{12}_\Lambda\text{B}$ states.

Product	cross section (nb/sr) in CM frame $\pm$ (statistical) $\pm$ (systematic)
Λ (1.8 GeV)	$166 \pm 11 \pm 25$
Σ^0 (1.8 GeV)	$35 \pm 12 \pm 5$
Λ (1.7 GeV)	$66 \pm 13 \pm 10$
Σ^0 (1.7 GeV)	$19 \pm 15 \pm 3$

The results were compared with the experimental results obtained by the SAPHIR group which measured elementary cross section of $p(e,e'\text{K}^+)\Lambda/\Sigma^0$ for real γ energy up to 2 GeV [47]. Figure F.1 shows the measured angular distributions. In E89-009 experiment, the corresponding E_γ was 1.52-1.63 GeV for 1.8 GeV runs and 1.41-1.51 GeV for 1.7 GeV runs, and the corresponding $\cos\theta_K^\perp$ in CM was very close to 1. The obtained values of the cross section for Λ production were inconsistent. As a possible reason, the number of “H” in the CH_2 targets might decrease by evaporation in high current runs.

Figure F.1: The angular distribution of Λ and Σ^0 CM cross section measured by the SAPHIR collaboration.

Appendix G

Physics constants

Physics constants used for the present analysis are shown in Table G.1

Table G.1: Values of particle and target atomic masses used in the present analysis.

Quantity	Symbol	Value
Proton mass	M_p	0.988272 GeV/ c^2
Electron mass	M_e	0.000511 GeV/ c^2
Positive kaon mass	M_K	0.493677 GeV/ c^2
Lambda mass	M_Λ	1.115683 GeV/ c^2
Neutral sigma mass	M_{Σ^0}	1.192642 GeV/ c^2
^{12}C atomic mass	$M_{^{12}\text{C}}$	11.1780 GeV/ c^2
^{12}C nuclear mass	$M_{^{12}\text{C}}$	11.17495 GeV/ c^2
^{11}B atomic mass	$M_{^{11}\text{B}}$	10.255102 GeV/ c^2
^{11}B nuclear mass	$M_{^{11}\text{B}}$	10.252627 GeV/ c^2

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