Hypernuclear Spectroscopy

F. Garibaldi¹, O. Hashimoto², J. J. LeRose³, P. Markowitz⁵, S. N. Nakamura², J. Reinhold⁵, and L. Tang³,⁴

¹ Istituto Nazionale di Fisica Nucleare and Istituto Superiore di Sanità, I-00161 Roma, Italy
² Tohoku University, Sendai, 980-8578, Japan
³ Jefferson Lab, Newport News, Virginia 23606, USA
⁴ Hampton University, Hampton, Virginia 23668, USA
⁵ Florida International University, Miami, Florida 33199, USA

Abstract. A program of hypernuclear spectroscopy experiments encompassing many hypernuclei has been undertaken in both Halls A and C using complimentary approaches. Spectra with sub-MeV resolution have been obtained for $^9\Lambda Li$, $^{12}\Lambda B$, and $^{16}\Lambda N$ in Hall A, while results from Hall C include $^7\Lambda He$, $^{12}\Lambda B$, and $^{28}\Lambda Al$ with new data still under analysis for $^7\Lambda He$, $^9\Lambda Li$, $^{10}\Lambda Be$, $^{12}\Lambda B$ and $^{52}\Lambda V$. High resolution and high precision in the determination of the single $\Lambda$ binding energy at various shell levels has been the key success of these experiments using the $(e,e'K^+)$ reaction to produce $\Lambda$ hypernuclei.

1. Introduction

Since the first observation of hypernuclei in 1953 [1], spectroscopic investigation of hypernuclei has been considered to be a unique method to provide invaluable information on many-body hadronic systems by utilizing the new degree of freedom – “strangeness”. This impurity can be used as a probe to study both the structure and properties of baryons in the nuclear medium and the structure of nuclei as baryonic many-body systems [2, 3, 4]. Without Pauli blocking, the $\Lambda$ can penetrate into the nuclear interior and form deeply bound hypernuclear states. Therefore, new nuclear structures or unknown properties of the baryonic interaction, which cannot be seen from the investigation of ordinary nuclei with conventional probes, may manifest themselves in hypernuclei, providing indispensable information on the flavor SU(3) basis for baryonic systems.

To create a unified description of the baryonic interaction within the flavor SU(3) basis, one must understand baryonic interactions beyond nucleon-nucleon (NN) interactions, such as hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions. Spectroscopic investigation of $\Lambda$ hypernuclei, a nuclear many-body system containing one $\Lambda$ particle, provides a unique and currently the only practical tool to study the $\Lambda N$ interaction, since direct $\Lambda N$ scattering experiments are technically difficult. Since the $\Lambda$ decays only weakly and has a relatively long lifetime, $\Lambda$ hypernuclei feature narrow states commonly described by coupling of low-lying core states to a $\Lambda$ in low level shell states (s, p, ...) with widths ranging from a few to $\sim 100$ keV depending on the decay channels (weak decay, EM transitions, and nucleon emissions or breakup at high excitation levels). This makes spectroscopic studies possible.

One novel feature of the $\Lambda N$ interaction is that the $\Lambda$ has isospin 0. This prevents one-pion exchange (OPE) due to the isospin conservation requirement for the strong interaction. This means that the OPE which is the long range component in the NN interaction is missing in the
\[ \Lambda N \text{ interaction. This makes the study of the } \Lambda N \text{ interaction more attractive in exploring the short-range components in the strong interaction.} \]

However, going from spectroscopic investigation to a full understanding of the \( \Lambda \) hypernuclear structure and \( \Lambda N \) interaction is a complicated process which requires solving the baryonic many-body problem. This process is well outlined and summarized in the introduction section in the structure and \( \Lambda N \) interaction is a complicated process which requires solving the baryonic many-body problem. This process is well outlined and summarized in the introduction section in the structure and \( \Lambda N \) interaction. This makes the study of the \( \Lambda N \) interaction more attractive in exploring the elementary two-body interactions.

\[ \text{where } H_{\text{CoreNucleus}} \text{ is the Hamiltonian for the core nucleus, } t_\Lambda \text{ is the kinetic energy of the } \Lambda \text{ hyperon and } V_{\Lambda N}^{\text{effective}} \text{ describes the effective } \Lambda N \text{ interaction. The effective interaction can be constructed via a G-matrix calculation, starting from the two-body interactions in free space. One-boson exchange models such as the Nijmegen [7] and J"ulich interactions [8] (which were constructed by extending NN interaction models on the basis of flavor SU(3) symmetry with scarce } \Lambda N \text{ and } \Sigma N \text{ scattering data used to adjust parameters) are widely used to describe the elementary two-body interactions.} \]

Analytical forms of the effective potentials are often given in the form of a three-range Gaussian,

\[ V_{\Lambda N}(r) = \sum_i (a_i + b_i k_f + c_i k_f^2) \exp(-r^2/\beta_i^2) \]  

A wide variety of hypernuclear properties such as level structure and reaction cross sections are calculated using this potential and compared directly with experimental data. These calculations are reasonably reliable, in part, because the \( \Lambda N \) interaction is much weaker than the NN interaction and no anti-symmetrization against the nucleon is required. It is to be noted that few-body hypernuclear systems with \( \Lambda \leq 5 \) can be calculated directly from the two-body interactions, in which the calculated binding energies of ground and excited states are compared precisely with experimental data. In such studies, information on \( \Lambda \) hypernuclear structure obtained by spectroscopic studies plays an essential role in testing and improving YN interaction models.

There is also a phenomenological approach to the effective interaction [9, 10] in which the \( \Lambda N \) effective interaction in p-shell \( \Lambda \) hypernuclei is written in the form

\[ V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)s_\Lambda s_N + V_\Lambda(r)I_{\Lambda N}s_\Lambda + V_N(r)I_{\Lambda N}s_N + V_T(r)S_{12} \]

where \( S_{12} = 3(\sigma_N \hat{r})(\sigma_N \hat{r}) - \sigma_N \sigma_N \). Low-lying level energies of p-shell hypernuclei can be described with radial integrals over the \( s_\Lambda p_N \) wave function for each of the five terms in Eq. (3). These integrals, denoted as \( \tilde{V}, \Delta, S_\Lambda, S_N \) and \( T \), can be determined from p-shell \( \Lambda \) hypernuclear data, then compared with theoretical predictions given by free \( \Lambda N \) interactions through G-matrix calculation.”

This passage outlines the general approach applied in hypernuclear physics with which one attempts to understand the baryonic interactions beyond nucleons. On the other hand, it also shows that experimental precision in spectroscopic studies is crucially important, which is the main reason for the development of the Jefferson Lab hypernuclear spectroscopy program as well as the high precision \( \gamma \) spectroscopy program developed at KEK-PS/BNL-AGS in the last decade.

Traditionally, hypernuclei have been studied via their production using secondary mesonic beams, \( \pi \) or \( K \), through various strangeness producing reactions, such as \( (K^-, \pi^-), (\pi^+, K^+) \), etc. For the reaction mass spectroscopy, the secondary nature of the initial beam forces a limit on the energy resolution for the observed hypernuclear states. Resolution has been limited to above
1.5 MeV (FWHM). The low-lying states were difficult to observe clearly and their corresponding binding energies could not be accurately extracted. Although the high precision Λ spectroscopy experiments at these facilities have been able to provide precision level spacing information for many light hypernuclei, there is no determination of the binding energy for the ground states. Therefore, high precision mass spectroscopy still has an important and irreplaceable role in providing valuable information for finding the correct models.

The Jefferson Lab accelerator provides a unique opportunity to produce hypernuclei using the \((e,e'K^+)\) reaction with high precision. The high energy resolution is achieved by the combination of (1) precision high intensity beam; (2) high resolution of both scattering angles and momenta in spectrometers for scattered electrons and kaons; and (3) thin target foils which minimize target straggling effects. It was anticipated that the energy resolution for the Jefferson Lab hypernuclear spectroscopy program could be at the sub-MeV level with the ultimate goal of 300–400 keV (FWHM). The absolute mass scale depends on the method and technique applied in the \((e,e'K^+)\) kinematics calibration which determines the level of precision in determination of binding energy of the observed hypernuclear states.

To compensate the small cross sections in electroproduction, not only high beam intensity is needed but also both the scattered electrons and kaons must be detected at small forward angles. This makes the experimental design with double spectrometers difficult. The issues are associated with (1) the level of virtual photon flux, (2) the solid angle acceptance and (3) the short-lived kaon survival rate. The most obvious technical challenges for both the experiment and the data analysis are from the extremely high particle singles rates.

Other than the attractive high precision, electroproduction of hypernuclei brings in additional new features to the overall investigation of hypernuclei. First of all, electroproduction with the \((e,e'K^+)\) reaction produces a Λ from a proton in the nucleus creating a nuclear core state with a proton hole to which the Λ couples. This can produce either mirror hypernuclei to those produced by the hadronic reactions \((K^-, \pi^-)\) and \((\pi^+, K^+)\) or states with different isospin. In other words, electroproduction provides neutron rich hypernuclei which are suitable candidates to investigate the Λ-Σ coupling contribution in the effective potential as well as the contribution from the ΛNN three-body force with two \(\pi\) exchanges. Furthermore, the large 3-momentum transfer electroproduction via absorption of a virtual photon promotes large spin-flip transition amplitudes from the initial nuclear to the final hypernuclear states while the non-spin-flip amplitude remains non-negligible. Thus, deeply bound hypernuclear states with both natural and unnatural parities may simultaneously appear. This provides rich and new spectroscopy complementary to that produced by the hadronic reactions.

Over the last decade, two independent hypernuclear experimental programs in Halls A [11] and C [12] were developed and successfully carried out. In the following sections, the programs from both halls, their applied technique, the achievements in physics results, and future prospects will be described.

2. The Hall C experimental technique and development – three distinct phases

After the first production of \(^3\Lambda^+H\) hypernuclei with electron beams was confirmed in Hall C [13], \((e,e'K^+)\) hypernuclear spectroscopy was initiated by the Hall C Collaboration at Jefferson Lab. Beginning in 2000 when the Hall C Collaboration successfully carried out the first spectroscopy experiment (E89-009/HNSS) at Jefferson Lab with electroproduction, the program in Hall C has gone through three phases with two major spectrometer upgrades, HKS and HES, funded by JSPS (Japanese Society for Promotion of Science, 16GS0201, 12002001) through the Tohoku University group, as well as modification of the experimental technique in tagging the scattered electrons (see illustration in Fig. 1). These upgrades and the introduction of new techniques continued to improve energy resolution and precision in determination of absolute mass, to increase the physics production yield rate, and to widen the mass range of the produced
hypernuclei in spectroscopic studies in a variety of nuclear shell levels.

![Schematic illustration of the experimental setup, technique and equipment upgrades for the three Hall C hypernuclear spectroscopy experiments: E89-009, E01-011, and E05-115/E08-002.]

Figure 1. Schematic illustration of the experimental setup, technique and equipment upgrades for the three Hall C hypernuclear spectroscopy experiments: E89-009, E01-011, and E05-115/E08-002.

2.1. A common splitter magnet

The central element of the Hall C experiment is the charge separation splitter magnet (SPL). With the target located at the SPLs upstream effective field boundary (EFB), this dipole magnet bends the oppositely charged particles away from the beam in opposite directions. This common splitter magnet technique allows the subsequent spectrometers for forward peaked electrons and $K^+$ mesons to be located at angles sufficiently large with respect to the beam line. Therefore, it is easier to locate the double spectrometer system to detect extremely forward-angled particles. Furthermore, a single common splitter magnet immediately behind the target makes larger solid angle acceptance, which is important to compensate low yield due to the small production cross sections with an electromagnetic probe. The overall kinematics and the spectrometer optics thus depend on the design and application of this magnet.

Introduction of the splitter magnet configuration presents unavoidable challenges to the design of the experiment. First of all, the unused primary beam that passes through the SPL is deflected. Therefore, this magnet is simultaneously handling the beam, the scattered electrons, and the reaction kaons at the same time. The beam must be carefully handled to avoid a serious radiation problem. From the view point of kinematics, it couples the beam and the two spectrometer systems together in a fixed kinematics space. It is impossible to perform
an absolute calibration for each individual system separately. A special calibration method is necessary to ensure the high quality of the spectra and high accuracy in determining the \( \Lambda \) binding energy.

Secondly, the magnetic field right after the target can also direct the background particles near zero degrees into the spectrometers causing high particle singles rates and high accidental coincidence rates. In the electron arm, this background comes from bremsstrahlung and Möller scattered electrons with extremely high rates at very forward angles. They are the sources of the accidental background in the hypernuclear spectra obtained in the Hall C experiments. Positrons from pair production at near zero degrees can come into the kaon spectrometer. In general, they are not in the kaon spectrometer solid angle acceptance. However, some of them hit the dense materials in the exit area of the spectrometer and can create subsequent showers with low energy electrons going toward the detector system aided by the fringe field of the last dipole magnet. This can cause a high particle flux leading to high singles rates as well as jeopardizing the tracking efficiency and position precision of the focal plane wire chambers. This is particularly serious for heavy targets such as \(^{52}\text{Cr}\) used in 2009 for E05-115.

### 2.2. Kinematics considerations and calibration

The central virtual photon energy was chosen to be 1.5 GeV, i.e. \( \omega = E - E' = 1.5 \) GeV, at which the elementary \( \Lambda \) production cross section is at a plateau. At small forward angles, the corresponding central momentum of the kaon arm (SOS for the experiment in 2000, HKS for the runs in the 2005 and 2009 experiments) was at 1.2 GeV/c. Fixing the virtual photon energy and the kaon momentum, the beam energy is determined by the spectrometer used for the electron arm. In the Phase I (HNSS/2000) and II (HKS/2005) experiments the Enge Split-Pole spectrometer was used to tag the scattered electron at zero degrees in HNSS/2000 and at about 4.5° in the HKS/2005 experiments. The central momentum of the Enge was chosen to be 0.34 GeV/c, thus the beam energy was then 1.85 GeV. For the 2009 HKS-HES experiment, the introduction of the newly developed HES increased the electron central momentum to 0.84 GeV/c, therefore the beam energy was increased to 2.34 GeV.

The relatively lower energy kinematics made it easy to design and construct short orbit spectrometers (SOS and later HKS) which maximized the survival rate against the short lifetime of kaons (\( c\tau \sim 3.6 \) m) and allowed the use of conventional spectrometer techniques for kaon detection. The conventional detector techniques, like time-of-flight, aerogel/water Čerenkov detectors and conventional drift chambers, are able to identify and momentum-analyze the 1.2 GeV/c kaons.

With this kinematics design, the physics yield rate depends on the solid angle and momentum acceptances of the two spectrometers. Figure 2 illustrates the kinematic acceptance using the 2005 HKS setup as an example. The large momentum acceptances of both the electron and kaon arms allow allocation of the events of free \( \Lambda \) and \( \Sigma^0 \) production from the CH2 target and events from the production of various hypernuclei and hypernuclear states from different nuclear targets in a single kinematics space without changing any setting of the spectrometers. The events of the ground state of \(^{12}\text{B}\) hypernuclei are illustrated in the figure. The dash lines show the events with central angles. The distributions of \( \Lambda \) and \( \Sigma^0 \) in Fig. 2 are spread due to the recoil angles of the produced hyperons. This spread becomes smaller for heavier systems, i.e. hypernuclei with mass \( A > 6 \) are less affected by uncertainty from finite angular resolution. Figure 2 also shows the reconstructed one-dimensional mass spectrum for the correlated events. The shaded area is due to events from accidental \( e' \) and \( K^+ \) coincident events which is the main background of the Hall C experiments. The distribution away from the \( \Lambda \) and \( \Sigma^0 \) peaks and above the accidental background is due to the quasi-free hyperon production from C in the CH2 target.

With angular resolution and central angle precision at a level of 2–3 mr (r.m.s.), the dominant
Factors crucial to the precision of the absolute reconstructed missing masses are the precise knowledge of the absolute central beam energy and the absolute central momenta of the two spectrometers shown as 0% in Fig. 2 for ΔPe' and ΔPk. These three kinematic parameters should be precisely calibrated, however, it should be noted that there remain only two degrees of freedom for a fixed missing mass.

The large acceptance of the kaon and electron spectrometers that simultaneously includes both Λ and Σ^0 production is a major advantage of this setup. The masses of the Λ and Σ^0 are sufficiently well known that an absolute energy calibration is possible. This is impossible for the (π, K) or (K, π) reactions. The Λ and Σ^0 peaks can also be used to calibrate the kinematical parameter combination since the right combination will give the correct masses as well as the narrowest peak widths for both the Λ and the Σ^0. The resultant kinematic precision (a part of the systematic error in the Λ binding energy) depends on the statistics of the Λ/Σ^0 events and the knowledge of the line shapes which are affected by the optics tune and the radiative tail. The later can be obtained from detailed simulation studies. For the three conducted experiments, E89-009/HNSS, E01-011/HKS, and E05-115/HES, the kinematic accuracy continuously improved due to the dramatic increase of the physics yield rate with each upgrade. It was at the ∼300 keV level for HNSS. It was then improved to < ∼100 keV for HKS. The HES data are currently under analysis and the accuracy is anticipated < ∼50 keV.

2.3. Optics optimization

Because of the application of the common splitter magnet, the optics of the two spectrometers can only be optimized by using well defined physical events from the (e,e'K^+) reaction. These events include those from Λ and Σ^0 production. However, due to their light recoil mass, even small angular uncertainties can cause large momentum uncertainties. Furthermore, as illustrated by Fig. 2, events from these two processes do not fully cover the entire momentum acceptances. Therefore, events from well observed hypernuclear states were also selected in the process of the optics optimization. Hypernuclei with A > 6 have heavy recoil masses so that the momentum uncertainty from these events is very small even with large angular errors. The quality of the optics in the two dimensional space in Fig. 2 could be translated into the width of the observed peak in the one dimensional mass spectrum. Therefore, a \( \chi^2 \) was defined for each selected event for its reconstructed mass from momentum matrices with respect to the observed mean in the
spectrum. The elements of the matrices were optimized using a non-linear least squares process using the summed $\chi^2$ from events selected from various well observed hypernuclear states and different production target masses. The basic requirement is a simultaneous minimization of the width of all the observed peaks including those not involved in the event selection. Iteration is required between this optics optimization and the kinematics calibration until both reach stable results.

A blind analysis of simulation data was carried out to evaluate the systematic errors originating from the optics optimization processes. Calibration data as from $\Lambda$ and $\Sigma^0$ elementary production and data from physics states with arbitrary masses were generated by a Monte Carlo simulation with various statistics following the conditions of the actual experiment. The same level of background was also added accordingly. The arbitrarily assumed masses of states in the simulation were hidden and the same optimization process was applied to these simulated data.

The obtained result was then compared to the assumed masses of the states. The signal/accidental background (S/A) ratio is certainly the major factor that limits the achievable optics quality. The optics qualities like uniformity in the kinematics space, absolute missing mass (or $\Lambda$ binding energy) accuracy as a function of statistics and S/A ratio, and the actual line shape of a single particle state affected by the tuning process were evaluated by this blind analysis of the simulated events.

2.4. Phase I Experiment: E89-009/HNSS (2000)
This was an important pioneering experiment that proved the feasibility of high precision spectroscopy using the CEBAF electron beam. The basic layout is shown in Fig. 1. In the experiment scattered electrons were tagged by an existing Enge split-pole spectrometer at zero degrees to maximize the virtual photon flux. However, bremsstrahlung and Møller scattered electrons are also highly peaked near zero degrees thus the electron arm singles rate was extremely high. When using $22 \text{ mg/cm}^2 \text{ C}$ as the production target and applying $0.6 \mu\text{A}$ beam current which was the maximum usable luminosity, the electron arm single rate reached 200 MHz. With the Enge split-pole spectrometer, position information at the focal plane (FP) was enough to give the required resolution and thus tracking was not necessary. Since electrons from various processes are all highly peaked at $\sim 0^\circ$, neglecting the angular information of the electrons resulted in only $\sim 2 \text{ mrad}$ angular uncertainty. To measure the FP position under such a high rate, a special silicon-strip-detector (SSD) system was developed by the Tohoku-Houston collaboration [14] and successfully applied.

The existing Short-Orbit-Spectrometer (SOS) in Hall C was used as the kaon spectrometer. Its short orbit is an advantage in the detection of short lived particles such as the kaon but the solid angle acceptance with the front splitter magnet was limited to $\approx 4.5 \text{ mrad}$. In addition, its momentum resolution was $6 \times 10^{-4}$ (FWHM) which was the major limitation to the overall experimental energy resolution. The existing SOS detector system, including TOF, aerogel and Lucite Čerenkov detectors, and shower detectors, was utilized for kaon identification. A detailed description of the experimental technique as well as the spectrometers and detector systems can be found in Ref. [15].

The most important achievement of this experiment was proving the feasibility of hypernuclear spectroscopy with an electron beam. The obtained missing mass spectrum for $^{12}_\Lambda \text{B}$ demonstrated the first sub-MeV hypernuclear reaction spectroscopy with a resolution of 800 keV (FWHM) [16] (see Fig. 3), a factor of two better than the best resolution achieved by the $(\pi^+, \text{K}^+)$ experiments at KEK. However, the production yield rate was low, $\sim 0.9 \text{ counts/hour}$ from the ground state doublets of $^{12}_\Lambda \text{B}$, and the accidental background was high with a S/A ratio of $\sim 1:1$ at the peak from the ground state doublets. Two major peaks corresponding to $\Lambda$s in s and p orbits were clearly seen with the sub-MeV resolution achieved for the first time in hypernuclear reaction spectroscopy.
2.5. Phase II Experiment: E01-011/HKS (2005) with the first upgrade
The major equipment upgrade, inspired by the first successful experiment, was the design and construction of the High resolution Kaon Spectrometer, HKS. The HKS consists of normal conducting Q-Q-D magnets and this new spectrometer featured three times better momentum resolution, $2 \times 10^{-4}$ (FWHM), and three times larger solid angle acceptance, 15 msr, with the front splitter magnet. Centered at a reaction angle of $7^\circ$ it covers a reaction angle range from $1^\circ$ to $13^\circ$.

Another essential improvement in the experimental technique was the optimized configuration of the electron spectrometer, “tilt method”. The Enge split-pole spectrometer, which was used in the first phase experiment, was tilted off the splitter’s dispersion plane by an angle of 7.75° and aimed at a virtual target point below the dispersion plane by a small vertical shift ($\sim 5.6$ cm). This created an optical acceptance away from scattering angles below $4^\circ$, so that bremsstrahlung and Møller electrons were blocked by collimators and the magnet iron reducing the electron singles rate by a factor of $5 \times 10^{-5}$ while reducing the integrated virtual photon flux acceptance by only a factor of $2 \times 10^{-2}$. By the combination of increasing the luminosity and increasing the HKS solid angle acceptance, the physics yield rate was increased by almost a factor of 10.

Since the kaon arm singles rate also increased significantly, a more sophisticated detector system was designed and built. This new system included two sets of wire chambers for tracking, three layers of timing detectors for TOF, three layers of Aerogel Čerenkov detectors for pion and positron rejection, and two layers of water Čerenkov detectors for proton rejection. These detectors are segmented and grouped with sophisticated trigger modules with an FPGA (TUL-8040) to avoid accidental vetoes of kaons due to the high background single particle rates and to the reduced background from events out of the spectrometer optics by using the right combination of segmented counters. By introducing the “tilt method”, angles and momentum of scattered electrons must be fully reconstructed using the measured focal plane parameters from trajectory tracking. Therefore, a new wire chamber with a honeycomb-cell structure and timing counters was designed and constructed. Due to the significant improvement of the resolution of the kaon arm, the energy resolution was improved to the level of $\sim 500$ keV (FWHM).

With these upgrades, in 2005 the E01-011/HKS experiment was successfully carried out. It aimed to study beyond p-shell hypernuclei and obtained an $^{28}_{\Lambda}$Al spectrum for the first time, observing states corresponding to the $\Lambda$ in s, p, and d shells coupling to low lying nuclear core states. In addition, spectra from two additional hypernuclei, $^7_{\Lambda}$He and $^{12}_{\Lambda}$B, were obtained, from a short test run on light hypernuclei and the necessary calibration data, respectively. Discussion of the obtained spectra is given in a later section on the physics outlook and a detailed description.
of the experimental setup can be found in Ref. [17].

2.6. Phase III Experiment: E05-115/HES (2009) with the second upgrade

For the kinematics of the second upgrade, the photon energy $\omega$ was kept at about 1.5 GeV while the beam energy $E$ and the energy of the scattered electrons $E'$ were increased by the same amount. With the higher energy $E$ (2.34 GeV) and $E'$ (0.84 GeV), the background from Bremsstrahlung and Møller scattering are more forward and thus we can make the electron spectrometer tilt angle smaller where the virtual photon flux factor $\Gamma$ is larger. The upgrade replaced the Enge Split-Pole spectrometer with a new spectrometer, the High resolution Electron Spectrometer (HES). In addition, a newly designed and constructed splitter magnet (SPL) replaced the old one in order to better handle higher energy beams and scattered electrons (see schematic view in Fig. 1). These new magnets were designed and constructed by the Tohoku University group as HKS.

By optimized matching between the HKS and the HES, including the SPL magnet with the tilt method used successfully in the second generation experiment, E01-011, the solid angle acceptances are increased, therefore, the total integrated virtual photon flux (virtual photon tagging efficiency) increases by a factor of $\sim 10$. However, the new splitter magnet, being larger than the previous one, reduced the HKS solid angle acceptance by a factor of two. So, the new system was expected to increase the overall physics yield rate by another factor of five.

With this new upgrade, the experiment E05-115/E08-002 tried to study hypernuclear spectra over a wide mass range, including the medium heavy hypernucleus $^{52}_{\Lambda}$V, and a variety of p-shell hypernuclei $^{7}_{\Lambda}$He, $^{3}_{\Lambda}$Li, $^{10}_{\Lambda}$Be, and $^{12}_{\Lambda}$B. With the improved momentum resolution by the HES for the electron arm, the overall resolution is expected to reach 400 keV (FWHM) or better, a further improvement from the 2005 HKS experiment. The data taking for the experiment was successfully carried out in 2009 and proved the yield rate increase factor using the $p(e,e'K^+)_\Lambda\Sigma^0$ reactions. With better resolution and three times higher statistics, the p-shell hypernuclei including the previously studied hypernuclei, $^{7}_{\Lambda}$He and $^{12}_{\Lambda}$B. Their level structures, especially the core excited states will be studied in detail. The first medium heavy hypernucleus $^{52}_{\Lambda}$V, produced by an electron beam will give precious information about the single particle energy of the $\Lambda$, core-configuration mixing and ls splitting. A detailed shell model calculation with DWIA was recently performed for the $^{52}_{\Lambda}$Cr$(e,e'K^+)^{52}_{\Lambda}$V reaction [18].

3. The Hall A experimental technique and setup

The E94-107 experiment in Hall A [11] started a systematic study of high-resolution hypernuclear spectroscopy on 1p shell nuclei, specifically $^9$Be, $^{12}$C, $^{16}$O. Moreover a very useful $(e,e'K)$ experiment on hydrogen was possible at the same kinematics allowing the study the elementary reaction at the same kinematics as the hypernuclear spectroscopy experiments. The results on $^{12}$C and $^{16}$O have been published [19, 20] and preliminary results are available for $^9$Be and hydrogen.

Hall A at Jefferson Lab is well suited to perform $(e, e'K^\mp)$ experiments. Scattered electrons can be detected in the HRS electron arm while coincident kaons are detected in the HRS hadron arm [21]. Kinematics for the first experiment, utilizing a $^{12}$C target, were set to particle detection at $6^\circ$ for both electrons and kaons, incident beam energy of 3.77 GeV, virtual photon energy of 2.2 GeV, scattered electron momentum of 1.56 GeV/c, kaon momentum of 1.96 GeV/c, and $Q^2 = 0.079$ GeV$^2$. This choice was driven by several factors. Since the cross section depends strongly on $Q^2$ (through the virtual photon flux as determined by the electron kinematics), to get reasonable counting rates the measurements have to be made at low $Q^2$. Hence, the electron scattering angle must be small, and the kaon angle must be close to the virtual photon direction in order to minimize the momentum transfer. However, to keep a reasonable kaon survival fraction the kaon momentum must be fairly high. A superconducting septum magnet
was added to each HRS to allow detection of particles at central scattering angles as small as 6°. This new spectrometer configuration (Septum + HRS) provides a general purpose device that extends the HRS features to small scattering angles while preserving the spectrometer optical performance [22]. Funding for the septum magnet pair was provided by Istituto Nazionale di Fisica Nucleare, INFN.

Good energy resolution together with a low level of background is mandatory for these experiments. Energy resolution depends on the momentum resolution of the HRS spectrometers, on the straggling and energy loss in the target, and on the beam energy spread. A momentum resolution of the system (Septum + HRS magnets) of $\delta p/p = 10^{-4}$ (FWHM) and an incident beam energy spread as small as $6 \times 10^{-5}$ (FWHM) are necessary to be able to get an excitation energy resolution of 600 keV or less. To reduce the background level in produced spectra, a very efficient PID system is necessary for unambiguous kaon identification. For all these reasons significant modifications were needed to the Hall A spectrometers setup.

3.1. Septum magnets
A pair of superconducting septum magnets, each providing a 6.5° horizontal bend was introduced into the HRS spectrometer configuration. A very nice feature of this septum magnet setup was that the two arms were essentially independent and could be tuned and optimized separately. Due to their small bend angle and relatively short length (80 cm) the septum magnets made only a small perturbation on the standard HRS optics that was easily corrected by a small modification of the settings of the three quadrupoles in each arm. The quality and exact character of the optics transformation tensor were measured with a series of elastic scattering measurements using a 2 GeV electron beam on C and Ta targets. Measurements were also made using a sieve-like mask in front of each spectrometer to optimize and calibrate the angular reconstruction. The results of the calibration and optimization effort are illustrated in Fig. 4. For details of the design and construction of the septum magnets see Ref. [23].

![Figure 4](image-url)

**Figure 4.** Elastic $^{12}$C scattering spectrum as seen in one arm of the HRS + Septum configuration after optimization. The width of all the peaks, elastic and inelastic, is $\leq 10^{-4}$ (FWHM).
3.2. Waterfall target
The waterfall target system provides a target for experiments on $^{16}$O. Using a waterfall for oxygen experiments has many advantages. Pure oxygen is difficult to handle, as it is highly reactive. The use of other oxygen compounds requires additional measurements to subtract the non-oxygen background, whereas the hydrogen in water can be used for calibration purposes. The technique of using continuously flowing water as an electron scattering target was first developed by Voegler and Friedrich [24], and later refined by Garibaldi et al. [25].

3.3. Detectors
The detector packages of the two spectrometers are designed to perform various functions in the characterization of charged particles passing through the spectrometer. These include: providing a trigger to activate the data-acquisition electronics, collecting tracking information (position and direction), precise timing for time-of-flight measurements and coincidence determination, and identification of the scattered particles. The timing information is provided from scintillators, as well as the main trigger. The particle identification is obtained from a variety of Čerenkov type detectors (aerogel and gas) and lead-glass shower counters. A pair of VDCs provides tracking information. The main part of the detector package in the two spectrometers (trigger scintillators and VDCs) is identical. For details of the tracking see Ref. [21].

3.3.1. Time of flight (TOF) 
The long path from the target to the HRS focal plane (25 m) allows accurate time-of-flight identification in coincidence experiments if the accidental rate is low. After correcting for differences in trajectory lengths, a TOF resolution of $\sim 0.5$ ns ($\sigma$) is obtained. The time-of-flight between the S1 and S2 planes is also used to measure the speed of particles, $\beta$, with a resolution of 7% ($\sigma$).

3.3.2. Shower counters Two layers of shower detectors [26] are installed in each HRS. The blocks in both layers in HRS-L and in the first layer in HRS-R are oriented perpendicular to the particle tracks. In the second layer of HRS-R, the blocks are parallel to the tracks. Typical pion rejection ratios of 500:1 are achieved using two-dimensional cuts of the energy deposited in the front layer versus the total energy deposited.

3.3.3. Gas Čerenkov A gas Čerenkov detector filled with CO2 at atmospheric pressure [27] is mounted between the trigger scintillator planes S1 and S2. The detector allows electron identification with 99% efficiency and has a threshold for pions of 4.8 GeV/c. The detector has ten spherical mirrors with 80 cm focal length, each viewed by a PMT (Burle 8854). The lightweight mirrors were developed at INFN [28]. The length of the particle path in the gas radiator is 130 cm (80 cm) for the gas Čerenkov in the HRS-R(L), leading to an average of about twelve (seven) photoelectrons. The combination of the gas Čerenkov and shower detectors provides a pion suppression above 2 GeV/c of a factor of $2 \times 10^5$, with a 98% efficiency for electron selection in the HRS-R.

3.3.4. Aerogel Čerenkov detectors There are two aerogel Čerenkov counters available with different indices of refraction, which allow a clean separation of pions, kaons and protons over the full momentum range of the HRS spectrometers. The aerogel is continuously flushed with dry CO$_2$ gas. The two counters (A1 and A2) are diffusion-type aerogel counters. The 6 cm thick aerogel radiator used in A1 has a refractive index of 1.015, giving a threshold of 2.84 (0.803) GeV/c for kaons (pions). The average number of photoelectrons for GeV electrons in A1 is $\sim 8$. The 9 cm thick aerogel radiator used in A2 has a refractive index of 1.055, giving a threshold of 1.55 (2.94) GeV/c for kaons (protons). Trigger logic is used to require that A1 not fire (e.g.,
rejecting pions) but that A2 does fire (requiring kaons). Rejection factors of 70:1 for rejecting pions and > 60:1 for protons were achieved using the aerogels in the hardware trigger.

3.3.5. Ring imaging Čerenkov detector (RICH) The need for an unambiguous identification of kaons has driven the design, construction, and installation of a Ring Imaging Čerenkov (RICH) detector in the hadron HRS focal plane detector package. The layout of the RICH is conceptually identical to the ALICE HMPID design [29]. It uses a proximity focusing geometry, a CsI photocathode, and a 15 mm thick liquid perfluorohexane radiator. A detailed description of the layout and the performance of the RICH detector can be found in Ref. [30]. The fundamental role of the RICH in identifying the kaons is shown in Fig. 5. In the left panel the unfilled timing spectrum of coincidences between the electron and the hadron spectrometers, obtained by selecting for kaons using the two threshold aerogel counters, shows a barely visible kaon signal with a dominant contribution from misidentified pions and protons. The flat part of this spectrum is given by random coincidences. The 2 ns structure is a reflection of the pulse structure of the electron beam. The filled spectrum and its exploded version (right panel), is obtained by adding the RICH to the kaon selection. Here, all contributions from pions and protons completely vanish. The crucial role of the RICH detector can be understood also from Fig. 6. A background free spectrum shows up after RICH cuts. The core excited state peaks clearly emerge from background.

Figure 5. Hadron plus electron arm coincidence time spectra. Left panel: the unfilled histograms are obtained by selecting kaons with only the threshold Aerogel Čerenkov detectors. Filled histogram (expanded in the the right panel) also includes the RICH kaon selection. The remaining contamination is due to accidental (e,e') and (e,K+) coincidences.

4. Physics outlook from both the Hall A and C experiments
During a decade of effort, the Jefferson Lab hypernuclear program has been fruitful, even though the (e,e'K+) hypernuclear spectroscopy has proven to be very challenging technically for both performing the experiments and analyzing the data in order to achieve high precision spectroscopy.

4.1. The elementary process, Λ and Σ⁰ electroproduction
The study of p(e,e'K⁺)Λ/Σ⁰ is important not only for the understanding of strangeness electroproduction but also for absolute missing mass calibration of the spectrometer systems by using the well known Λ and Σ⁰ masses (see Fig. 7 from the 2009 HKS experiment). Due to the lack of a neutron target, an absolute mass calibration with hyperon production is impossible for the (π⁺, K⁺) and (K⁻, π⁻) reactions.
Electroproduction of $\Lambda$s at very forward angles ($Q^2 \sim 0$) is important to provide reference data to isobar models which give non-consistent predictions on the $\Lambda$ production cross section at forward angles. Water and CH2 target data provide this information though the CH2 data need to be extrapolated to the point where the hydrogen escape is zero in order to deduce the cross section. High precision data on the elementary electroproduction of hyperons will be obtained with a water fall target by E07-012 scheduled to run in Hall A in 2012.

The $p(e,e'K^+)^Y$ reaction (where $Y$ is either a $\Lambda$ or $\Sigma^0$ hyperon) has also already been measured as part of the Hall A program. The measurements meet several goals. The cross section for the elementary reaction serves as input for the models of hypernuclear cross sections. The separated $\Lambda$ and $\Sigma^0$ mass peaks calibrate the excitation energy spectra. And finally, the measured $\Lambda$ and $\Sigma^0$ cross sections are inherently interesting.

The ratio of $\Lambda:\Sigma^0$ cross sections is known to drop rapidly with increasing $Q^2$. Photoproduction measurements at this invariant mass $W = 2.2$ GeV have ratios at forward angles of 0.7, while electroproduction at $Q^2 = 1$ GeV$^2$ sees a $\Lambda : \Sigma^0$ ratio of 0.1. (It should be noted that the most forward angle available for the photoproduction data is $25.8^\circ$ or $\cos \theta_{CM} = 0.9$.) The data were taken with both a 4 cm cryogenic hydrogen target and the thin waterfall foil. The
kinematics have $Q^2 = 0.07 \text{ GeV}^2$, $W = 2.2 \text{ GeV}$, and $\theta = 6^\circ$. The results are shown in Fig. 8. Plotted is the differential cross section versus center-of-mass angle, with both the hypernuclear measurements (at $Q^2 = 0.07 \text{ GeV}^2$) and the LEPS and CLAS photoproduction results ($Q^2 = 0$). Also plotted are model calculations such as the Saclay-Lyon, Regge-plus-resonance approach, and Kaon-MAID.

Figure 8. E94-107 elementary kaon electoproduction data along with various other data sets and calculations.

As can be seen, the data suggest that not only do the present models fail to describe the data over the full angular range, but that the cross section rises at the forward angles. The failure of existing models to describe the data suggests the reaction mechanisms may be incomplete. The large magnitude of the cross section, coupled with the fact that this is electoproduction, raises the possibility that longitudinal contributions may obscure the comparison to (transverse) photoproduction data. Although there are no measurements of the longitudinal response at this low $Q^2$, the entirety of the data on the kaon longitudinal response indicates that it is everywhere less than half the transverse response, and that the interference responses (longitudinal-transverse and transverse-transverse) are approximately an order of magnitude less than the transverse. Assuming that the longitudinal response is 50% of the transverse response, the measured cross section at this value of $\epsilon$ would mean that the extracted transverse cross section drops by about 25%.

4.2. $^7\Lambda\text{He}$ hypernucleus

A recent cluster calculation gives a precise prediction of the $^7\Lambda\text{He}$ mass as a system of $\alpha + n + n + \Lambda$ [31]. It has been recognized in the analysis of the $A=7$ hypernuclear isotriplet, $^7\Lambda\text{He}$, $^7\Lambda\text{Li}^* (T=1)$ and $^7\Lambda\text{Be}$, that it is quite important to study the charge symmetry breaking (CSB) effect of the $\Lambda N$ interaction which is necessary to explain mass difference between $^4\Lambda\text{H}$ and $^3\Lambda\text{He}$. However, the statistics of the existing $^7\Lambda\text{He}$ data from emulsion are too poor to give any reliable conclusion.

Preliminary analysis of the results of E01-011 [32] shows a clear peak of the $^7\Lambda\text{He}$ ground state with enough statistics for the first time. The obtained binding energy was compared with results from the cluster calculation. Surprisingly, inclusion of a CSB term in the $\Lambda N$ interaction makes the discrepancy between experiment and theory worse, though the CSB term is essential for $A=4$ hypernuclei. This indicates that current understanding of the CSB effect in the $\Lambda N$ interaction potential is still imperfect and further systematic study is necessary.
4.3. $^{12}\text{C}(e,e'K^+)^{12}_Λ\text{B}$

$^{12}_Λ\text{C}$ serves as a mass reference system in the $(\pi^+, K^+)$ and $(K^-, \pi^-)$ hypernuclear reactions so that very high statistics data have been accumulated since the ground state doublet and states with $Λ$ in the p-shell make prominent peaks with sufficient cross sections. Therefore, its mirror hypernucleus, $^{12}_Λ\text{B}$, which is expected to have the same features as $^{12}_Λ\text{C}$, can be used as a reference system for hypernuclear $(e,e'K^+)$ spectroscopy though the $(e,e'K^+)$ reaction needs no emulsion mass reference, since the well known hyperon masses can be used.

The high resolution achievable in the $(e,e'K^+)$ reaction enables us to compare the hypernuclear iso-doublet $^{12}_Λ\text{B}$ and $^{12}_Λ\text{C}$ to extract the iso-spin dependent term of $ΛN$ interaction, i.e. the CSB effect. The $^{12}_Λ\text{C}$ spectrum obtained by E336 at KEK-PS (Fig. 9 top) [33], $^{12}_Λ\text{B}$ spectrum obtained by E94-107 at Jefferson Lab Hall A (Fig. 9 middle) [19] and $^{12}_Λ\text{B}$ spectrum obtained by E01-011 in Hall C (Fig. 9 bottom) [34] are compared. One can recognize that the global structures of $A=12$ hypernuclei are similar and the $^{12}_Λ\text{B}$ excitation energies are consistent between the Hall A and Hall C data. Thanks to the high resolution of $(e,e'K^+)$ hypernuclear spectroscopy, the states with $Λ$s coupled to low-lying core excited states were clearly observed for $^{12}_Λ\text{B}$ as well as the prominent $s_Λ$ and $p_Λ$ peaks.

![Figure 9. Missing mass spectra of $^{12}_Λ\text{B}$ and $^{12}_Λ\text{C}$ [19, 33, 34].](image)

The Hall A spectrum features excellent signal-to-noise ratio due to the high performance RICH detector and the Hall C spectrum shows improved resolution through the introduction of the newly developed HKS. With the improved resolution, the positions of the two excited-state peaks and the existence of additional strength outside the major peaks are much more clearly defined than in the $(\pi^+, K^+)$ spectrum [35]. In particular, the position of the first-excited peak is in agreement with $γ$-ray data. Detailed analysis and comparison of $A=12$ hypernuclear spectra is now underway.
4.4. $^9$Be($e,e'K^+)^{\Lambda}_2$Li

There are still some unresolved problems in the spectroscopy of hypernuclei in the lower part of p-shell. The spectra of $^{10}_{\Lambda}B$ (ground state doublet splitting) and the $^{11}_{\Lambda}B$ (energy of the J=1/2+ member of the first excited doublet) as measured in precise ($K^-, \pi^-\gamma$) and ($\pi^+, K^+\gamma$) experiments are inconsistent with the standard shell model description of p-shell hypernuclei.

The electroproduction of a $^3_{\Lambda}Li$ hypernucleus from a $^9$Be target can hopefully shed new light on this problem. In this case the ground state doublet and two excited doublets of $^9_{\Lambda}Li$ (all lying below the strong neutron decay threshold) are produced with comparable cross sections. In addition, splitting of the ground-state doublet and the second excited-state doublet are predicted to be large enough to be detected ($\sim 500$ keV), while the first excited state doublet is predicted to be almost degenerate. In an electroproduction experiment with good energy resolution five hypernuclear states below the strong particle decay threshold can, in principle, be resolved in the $^3_{\Lambda}Li$ hypernucleus.

The results of the analysis of the $^9$Be($e,e'K^+)^{\Lambda}_2$Li, reported here, are still preliminary. In Fig. 10, the theoretical curve is superimposed on the fitted data. The theoretical cross sections are obtained using the Saclay-Lyon (SLA) model for the elementary p($e,e'K^+\Lambda$) reaction. Shell-model wave functions are determined using a parametrization of the $\Lambda N$ interaction that fits the precise $\gamma$-ray hypernuclear spectra of $^7_{\Lambda}Li$. A fit with three peaks is guided by the three main structures predicted by the theory. The fit procedure is described elsewhere [19]. An attempt has been made to also disentangle the different contributions coming from the multiple levels which calls for a fit with five peaks, as guided by the theoretical model.

![Figure 10. $^9$Be($e,e'K^+)^{\Lambda}_2$Li missing mass spectrum fitted with five gaussians. Also shown are the theory predictions for this spectrum.](image)

As mentioned previously the results are still preliminary. At first look it seems evident a disagreement exists between experiment and theory for the strength of the second and third doublets. This can be due both to the elementary part of the reaction and to the nuclear part (spectroscopic factors).

4.5. $^{16}$O($e,e'K^+)^{\Lambda}_{16}$N

The $^{16}$O($e,e'K^+)^{\Lambda}_{16}$N reaction was measured in Hall A. The $^{16}_{\Lambda}N$ final state is particularly interesting both because it has not been measured previously and because it allows a comparison to the mirror nucleus, $^{16}_{\Lambda}O$ whose bound energy levels were measured both with germanium detectors (allowing very precise determinations of the excitation spectra) [36] and with a variety of hadronic reactions, e.g., ($K^-, \pi^-$) [37], ($\pi^+, K^+$) [33] and ($K^+_{stop}, \pi^-$) [38] (allowing moderate determination of the ground state energy).
The presence of the hydrogen has many advantages. In particular, it permits a calibration of the missing-mass scale and thus an accurate measurement of the \( \Lambda \) binding energy in the hypernucleus. Moreover, an interesting measurement of the \((e,e'K^+)\) cross section on a proton in a kinematical region never previously measured was possible.

The kinematics for the experiment were almost the same as for the \(^{12}\text{C}\) running: particles were detected at 6° (both electrons and kaons), an incident beam energy of 3.66 GeV, virtual photon energy of 2.2 GeV, scattered electron momentum of 1.45 GeV/c, kaon momentum of 1.96 GeV/c, and \( Q^2 = 0.079 \text{ GeV}^2 \).

Figure 11, left panel, shows the \(^{16}\Lambda\text{N}\) excitation-energy spectrum as obtained after kaon selection with aerogel detectors and RICH without background subtraction. The electron kaon random coincidence contribution evaluated in a large timing widow and normalized is superimposed on the spectrum. Again, the uniquely low backgrounds can be seen. The shaded region shows the \((e,e') \times (e,K^+)\) random-coincidence background. The large broad peak observed at around 30 MeV is the mis-reconstructed binding energy due to the contribution of the hydrogen in the waterfall when the oxygen mass is used for the target mass in constructing the missing mass. The excitation region of the \(^{16}\Lambda\text{N}\) production with background subtraction is shown on the right side of the figure.

![Figure 11](image)

**Figure 11.** The \(^{16}\Lambda\text{N}\) excitation-energy spectrum as obtained after kaon selection with aerogel detectors and RICH without background subtraction.

Figure 12 shows the six-fold differential cross section expressed in \( \text{nb}/(\text{sr}^2 \text{ GeV MeV}) \). Similarly to the \(^{12}\text{C}\) target, the background was evaluated by fitting the data obtained for random coincidences in a large timing window and subtracted, resulting in no residual background in the region on the left of the ground state. The fit to the data has been made using Voigt functions. Four isolated peaks are observed. The ground state peak gives a \( \Lambda \) separation energy of \( B_\Lambda = 13.76 \pm 0.16 \text{ MeV} \) for the \( 1^- \) member of the ground-state doublet in \(^{16}\Lambda\text{N}\). Three more peaks are observed at binding energies of 6.93, 2.84, and 3.34 MeV.

The theoretical cross sections were obtained in the framework of the distorted-wave impulse approximation (DWIA) [39] using the Saclay-Lyon (SLA) model [40] for the elementary \( p(e,e'K^+)\Lambda \) reaction. The ground state of \(^{16}\text{O}\) is assumed to be a simple closed shell and the shell-model wave functions for \(^{16}\Lambda\text{N}\) are computed in a simple particle-hole model space. As in the case of \(^{12}\Lambda\text{B}\), the energy of the first-excited peak (a doublet of \( 1^- \) and \( 2^- \) states) agrees much better with the \( \gamma \)-ray data than does the data from hadronic reactions. This gives confidence in the energies extracted for the third and fourth peaks. The largest discrepancy between theory and experiment is in the position of the fourth peak. The excitation energies of the positive-parity states depend on the spacing of the \( p_\Lambda \) and \( s_\Lambda \) single-particle energies which
Figure 12. The $^{16}\text{O}(e,e'K^+)^{16}_\Lambda\text{N}$ spectrum from Hall A expressed in nb/(sr$^2$ GeV MeV).

have to be extrapolated from $^{13}_\Lambda\text{C}$ and could therefore be uncertain by several hundred keV. The gap between the third and fourth peaks is predicted to be slightly larger (6.5 MeV) than the underlying separation (6.324 MeV) of the p-hole states in $^{15}\text{N}$, in contrast to the observed splitting of 6.18 MeV. In fact, the first clear indication that the spin-orbit splitting of the p$_\Lambda$ orbits is very small came from the observation that the separation between the 0$^+$ states is very close to the underlying core-state separation.

The $\Lambda$ separation energy of $B_\Lambda = 13.76 \pm 0.16$ MeV obtained for the first peak is important. There are few emulsion events for the heavier p-shell hypernuclei and these events tend to have ambiguous interpretations. The reactions involving the production of a $\Lambda$ from a neutron are more difficult to normalize. For example, the ($\pi^+,K^+$) data are normalized to 10.80 MeV for the $B_\Lambda$ of $^{12}_\Lambda\text{C}$ which differs considerably from the much better determined value of 11.37 $\pm$ 0.06 MeV for the mirror hypernucleus $^{12}_\Lambda\text{B}$. This difference is often cited as evidence for charge-dependent effects. However, the ($K^-_{\text{stop}},\pi^-$) reaction gives 11.38 $\pm$ 0.09 MeV for $^{12}_\Lambda\text{C}$ [38]. Within errors, the binding energy and the excited levels of the mirror hypernuclei $^{16}_\Lambda\text{O}$ and $^{16}_\Lambda\text{N}$ (this experiment) are in agreement, giving no strong evidence of charge-dependent effects. Details and references can be found in Ref. [20].

4.6. $^{28}_\Lambda\text{Si}(e,e'K^+)^{28}_\Lambda\text{Al}$

The $^{28}_\Lambda\text{Al}$ hypernucleus was studied with an isotopically enriched $^{28}_\Lambda\text{Si}$ target by E01-011 in Hall C. This is the first beyond p-shell hypernuclei studied with an electron beam and the developed technique to realize the $^{28}_\Lambda\text{Al}$ spectrum opened a door to medium heavy hypernuclear spectroscopy by the $(e,e'K^+)$ reaction in the E05-115 experiment. The mirror hypernucleus $^{28}_\Lambda\text{Si}$ was studied at KEK-PS with a natural Si target [41]. The global structures of the spectra look similar, but the binding energies of the ground states are apparently different and the excitation energy of the p$_\Lambda$ is much larger than that of $^{28}_\Lambda\text{Si}$ (see comparison in Fig. 13). Careful investigations to understand this difference are now underway experimentally as well as theoretically.

4.7. Other spectra to be analyzed – $^{10}_\Lambda\text{Be}$ and $^{52}_\Lambda\text{V}$

The main target of the third generation experiment, E05-115, in Hall C is isotopically enriched $^{52}_\Lambda\text{Cr}$. By the $^{52}_\Lambda\text{Cr}(e,e'K^+)^{52}_\Lambda\text{V}$ reaction, a spectroscopic study of a medium heavy hypernucleus was carried out for the first time with an electron beam. Precise single particle energies of $^{52}_\Lambda\text{V}$ are expected to provide important constraints to mean field theories and a systematic study of the $\Lambda$’s single particle energy will reveal the distinguishability of hadrons deep inside
of a nucleus. The precise structure of $^{52}_{\Lambda}$V will shed light on the nature (core-configuration mixing or l-s splitting of the $\Lambda$N force) of high-l $\Lambda$ states which were observed in medium heavy hypernuclei with the ($\pi^+$, $K^+$) reaction [42]. The experiment is technically challenging since the high electromagnetic background causes a high multiple hit rate in the detectors. Development of a new tracking code to handle high multi-hit events is now underway.

In addition, the p-shell hypernucleus $^{10}_{\Lambda}$Be was studied with an enriched $^{10}_{\Lambda}$B target. As mentioned previously, the naive charge symmetry breaking term in the $\Lambda$N interaction cannot explain the masses of the $A=7$ iso-triplet hypernuclei. The CSB term can be modified to explain the $A=4$ and $A=7$ systems by simultaneously introducing another degree of freedom, but the constructed CSB interaction should predict the masses of $A=10$ hypernuclei which can be treated as an iso-doublet $\alpha + \alpha + N + \Lambda$ by the same technique as the $A=7$ system in the framework of a cluster model. Therefore the results of E05-115’s $^{10}_{\Lambda}$Be spectroscopy are anxiously awaited.

5. Future prospects

In 2008, a high-intensity proton machine, J-PARC (Japan Proton Accelerator Research Complex), started operations. One of the major research subjects at J-PARC is hypernuclear spectroscopy with high intensity kaon beams. New results on $S = -2$ hypernuclear spectroscopy and high-precision $\gamma$-ray spectroscopy of $S = -1$ hypernuclei will be obtained at J-PARC. Hypernuclear spectroscopy with electron beams is complementary to research subjects at J-PARC. Therefore, combining research outputs from J-PARC and Jefferson Lab will make great progress in this research field in the next decade.

5.1. Experiments before the 12 GeV era

A proposal (E07-012) [43] has been approved by the Jefferson Lab PAC to study the angular dependence of the $^{16}_\Lambda$(e,e$'K^+$)$^{16}$N and p(e,e$'K^+$)$\Lambda$ reactions. In the performed Jefferson Lab hypernuclear electroproduction experiments (E89-009, E94-107, E01-011, and E05-015) the $K^+$ mesons are detected at very small (few degrees) laboratory scattering angles (measured with respect to virtual photon momentum). This region of kaon scattering angles is not covered, unfortunately, by recent photo and electroproduction data on the elementary production process from CLAS [44], SAPHIR [45], and LEPS [46] Collaborations. The angular dependences of the cross section at small angles and at photon energies $E_\gamma \sim 2$ GeV predicted by different models for the $K^+$ electromagnetic production (see Fig. 8) differ drastically and this lack of relevant information about the elementary process makes an interpretation of obtained hypernuclear spectra difficult. In addition, the ratio of the hypernuclear (calculated in DWIA) and elementary cross section measured at the same kinematics should be almost model independent at very forward kaon scattering angles. The ratio therefore contains direct information on the target and hypernuclear structure, production mechanisms and, possibly on the modification of the dynamics of the p(e,e$'K^+$) process in the nuclear environment.
The Hall A experimental setup with septum magnets, the waterfall target, and virtual photons with energy $E_\gamma = 2$ GeV has a unique opportunity to solve the above mentioned problems. We will measure:

- The electroproduction cross section on the proton in $\text{H}_2\text{O}$ at lab kaon scattering angles, $\theta_{\text{lab}k} = 8.5^\circ$ and $11^\circ$ ($\theta_{\text{lab}k\gamma} = 4^\circ$ and $7^\circ$), which together with our previous measurements for $\theta_{\text{lab}k} = 6^\circ$ ($\theta_{\text{lab}k\gamma} = 2^\circ$) will cover the angular region missing in the CLAS and SAPHIR data. New precise data will clearly discriminate between various models of photo and electroproduction of strangeness, such as Saclay-Lyon and Kaon-MAID.

- The angular dependence of the hypernuclear cross section (HN) on $^{16}\text{O}$ will be determined simultaneously. These data and, especially, the ratio of HN to the elementary cross section will give new valuable information on hypernuclear structure (including spin assignment of produced hypernuclear states), reaction mechanisms and, even possibly the modification of the dynamics of the $(e,e'K^+)$ process in the nuclear medium.

5.2. Decay pion spectroscopy

So far, the $(e,e'K^+)$ hypernuclear study has been developed in missing mass spectroscopy. The production mechanism and structure of hypernuclei have been studied by this method. As an addition, a new experimental technique, hypernucleus decay pion spectroscopy, was proposed as E10-001 [47].

Utilizing the relatively weak electromagnetic probe and high momentum transfer in the reaction kinematics, “hot hypernuclei” (i.e. at highly excited states) or hypernuclei with $\Lambda$ produced directly in the s-shell then coupling to the highly excited deep particle hole states of the nuclear core (i.e. states with $\Lambda$ coupled to high lying core states) are produced in the continuum part of the overall hypernuclear production from one common nuclear target. This type of hypernucleus has high spin and some of them have masses well above the nucleon/nucleus emission threshold. The strong nuclear breakup process which produces various hyper-fragments (i.e. light hypernuclei) will take place as seen in emulsion or bubble chamber experiments. The selectivity is expected to also follow Young’s scheme [48]. Therefore, the high continuum production from hypernuclear electroproduction becomes a rich source of light hypernuclei. After a cascade (“cool down”) process to the ground state, light hypernuclei decay via weak decay modes in which the negatively charge pion decay channel is expected to have above a 10% rate for all p-shell hypernuclei. The light hypernucleus stops easily in the target due to the low release energy.

Decaying at rest, the pions from the two body decay channel have monochromatic momenta which contain characteristic information about the ground state of the decayed hypernuclei via the well known structures (to a few or below keV level) of normal nuclei involved in the two-body decay. Therefore, precisely measured pion momentum spectroscopy will provide important information about the light hypernuclei.

Wide ranging physics can be learned from the pion spectroscopy. For example (but not limited to), with resolution < 170 keV/c FWHM the ground state binding energy for a variety of simultaneously produced light hypernuclei can be determined with a precision better than 20 keV. This is particularly important to reconfirm the values obtained from emulsion data analysis and to resolve the puzzle in the CSB. Many pairs of mirror hypernuclei can be obtained at the same time. From pion spectroscopy for a specific hypernucleus the spin-parity, which is still missing for many light hypernuclei, of the initial hypernucleus can be determined. This pion decay may prove to be an unique tool in studying extremely neutron rich hypernuclei at or near drip line, such as $^6\Lambda\text{H}$ (the heavy hyper-hydrogen).

A pioneering run to prove the principle of this new technique will be carried out simultaneously with E07-012 in Hall A. Future experiments will be proposed and planned based
realistically on the outcome of this test run. The success of this test run is not only important for establishing an excellent hypernuclear program at Jefferson Lab based on this technique but also opens doors for future studies using high intensity mesonic beams and further technical development for new physics aspects which are not yet accessible, such as pion decay asymmetry with respect to the hypernuclear polarization which pin-points the exact formation mechanism of a hypernucleus and the deep interior structure of the nucleus through the production rate of specific light hypernuclei (such as $^4\Lambda H$) from different parental hypernuclear high-lying states [49].

5.3. Future hypernuclear spectroscopy with electron beams at Jefferson Lab

After the CEBAF 12 GeV upgrade, the Jefferson Lab Hypernuclear Collaboration which consists of the previous Hall A and Hall C Hypernuclear Collaborations will pursue a wide mass range of hypernuclear study. One direction of the $(e,e'K^+)$ reaction spectroscopy is to study heavier hypernuclear systems to extract $\Lambda$’s single particle energies to study hadron behavior deep inside of the nucleus. Heavier targets result in severe background and thus the experiments need to control the high background. In order to accumulate reasonable statistics in a given amount of beamtime, large acceptance and the high-resolution short-orbit spectrometers, HKS and HES, will be powerful tools for such a study.

Detailed studies of relatively light hypernuclei for which the signal-to-noise ratio is more important than the statistics could be studied by using the HRS with a higher beam energy. The clean kaon selection capability of the RICH detector will play a significant role in such programs. In a decade of electroproduction of hypernuclei studies, we have developed many tools and techniques, and thus we can choose the right tools depending on the physics program. Though its feasibility is not yet proven, the new decay pion hypernuclear spectroscopy is an interesting research subject. It might break through a limit of the $(e,e'K^+)$ hypernuclear spectroscopy which has not yet been combined with the study of the decay products. For example, hypernuclear $\gamma$-ray spectroscopy is a very powerful research technique which can be combined with $(\pi,K)$ and $(K,\pi)$ reactions, however, the Ge $\gamma$-ray detector cannot work in a high-rate electron background. If decay pion spectroscopy is proven to be feasible, a new large solid-angle spectrometer (H$\pi$S) which would concurrently serve as a splitter magnet can be introduced with the existing HKS and HES. Such spectrometers could provide data for standard $(e,e'K^+)$ spectroscopy, hypernuclear decay spectrum, and triple-coincidence information.

6. Summary

Hypernuclear spectroscopy by electromagnetic probes has been established at Jefferson Lab (Hall A and Hall C) showing that the experimental knowledge coming from hypernuclear studies by hadronic probes can be greatly improved. In a decade, a wide variety of hypernuclei, $^7\Lambda He, ^9\Lambda Li, ^{10}\Lambda Be, ^{12}\Lambda B, ^{16}\Lambda N, ^{28}\Lambda Al$ and $^{52}\Lambda V$, have been studied by the $(e,e'K^+)$ reaction. Large momentum transfer, strong spin flip, the excitation of both natural and unnatural parity states, and the creation of new species of hypernuclei not otherwise available are the characteristics of electromagnetic hypernuclear spectroscopy. Moreover, high energy resolution and precision measurements, also characteristic of the electromagnetic probe, make these experiments unique and crucial tools for this field. High accuracy determination of the $\Lambda$ binding energy for different hypernuclei has been achieved and much more is expected from the new line of research by pionic decay experiments. Systematic studies of mirror hypernuclei could shed light on charge dependence in hypernuclei and the underlying YN interaction.

These experiments were and are challenging. They have required many novel technologies and new detectors to be built in both Halls A and C. These detectors and the new technologies have served in the past and will serve in the future for other important experiments at Jefferson Lab. For these reasons, in the decade to come, the Hypernuclear Collaboration of Jefferson Lab is expected to play a key role in this research field in the framework of collaborations with other
existing or new facilities. The recent upgrade of MAMI-C has enabled it to produce hypernuclei with an electron beam and J-PARC soon starts to deliver high-intensity $\pi$ and $K$ beams. In the exploration of hypernuclear physics, the next decade looks very promising.

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