

## HYPERNUCLEAR PHYSICS AT JEFFERSON LAB

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### 1 Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF) has been successfully carrying out hadronic physics studies since 1996 at the Thomas Jefferson National Accelerator Facility (JLab) in Virginia, USA. The characteristics of this electron beam, together with those of the experimental equipment, offer a unique opportunity to study the electro-production of hypernuclei through the reaction  $A(e, e' K^+) B_\Lambda$ , where the hypernuclear production is tagged by the detection of the scattered electron in coincidence with the produced kaon. The kaon is a part of the associated strangeness pair production with a  $\Lambda$  hyperon remaining embedded in the nuclear medium to form the hypernucleus.

The hypernuclear physics program will cover an important part of the JLab experimental program over the next few years. This short review will

focus mainly on a few subjects, and some experimental details of the Hall A experiment, where the authors have primary responsibilities, will be presented.

## 2 CEBAF and the experimental Halls

The accelerator simultaneously delivers three high duty factor electron beams into three experimental halls (Halls A, B and C) with correlated energies and independent intensities. The maximum energy now available is nearly 6 GeV and the maximum current is  $200\mu A$ , allowing very high luminosity experiments.

Hall A is a 53 m diameter circular experimental area equipped with a pair of High Resolution Spectrometers (HRS) ( $\delta p/p \sim 10^{-4}$ ) for detection of electrons and hadrons with maximum momenta of 4 GeV/c. The minimum (maximum) angle is  $12.5^\circ$  ( $130^\circ$ ) and the momentum and angular acceptances are 10% and 7.0 msr, respectively.

The focal plane detection system is composed of drift chambers (for tracking), hodoscopes to provide a fast trigger, and two threshold Čerenkov detectors (with different radiators: gas  $CO_2$  and aerogel) for particle identification. The electron arm is also equipped with a shower counter to provide very high rejection of pions when used in combination with the gas Čerenkov detector.

Similar to the Hall A setup, the Hall C is equipped with two "asymmetric" spectrometers: one is able to detect particles up to 6 GeV/c (the High Momentum Spectrometer) with moderate resolution ( $\delta p/p \sim 5 \times 10^{-3}$ ), the other one has a short flight path (the Short Orbit Spectrometer - SOS) being mainly conceived to detect decaying particles (such as kaons) with a maximum momentum of 1.8 GeV/c.

The detector assembly of Hall B is conceptually different. The CEBAF Large Acceptance Spectrometer (CLAS) is employed to detect (at lower luminosity,  $\leq 10^{34} cm^{-2} s^{-1}$ ) multiple particles in the final state. It is composed of a toroidal magnet optimized to track charged particles with momenta between 250 MeV/c and 4 GeV/c from 8 to 140 degrees.

Hence, both Hall A and C are well suited to carry out coincidence ( $e, e'K^+$ ) experiments of associated production of  $K$ -*Hyperon* pairs on both nuclei and protons.

In Hall C this reaction can be best investigated at low and moderate energies (due to limitations on the highest measurable kaon momentum). Hall

$\Lambda$  is better suited to detect kaons of high momenta whose longer life time compensates for the longer flight path of an HRS spectrometer with respect to the SOS.

### 3 Physics Motivations and Experimental Goals

One of the main goals of studying hypernuclei is to improve our knowledge of the hyperon-nucleon interaction, as a natural extension of N-N physics to systems with strangeness. Moreover, complex systems such as hypernuclei could provide further insights on new types of nuclear structures, with new degrees of freedom. In the electro-weak sector, the question of whether the empirical rule involving the dominance of the  $\Delta I = 1/2$  transition in weak decays, also applies in the non-mesonic decays of  $\Lambda$  hypernuclei, is also of considerable interest <sup>1)</sup>.

Although a direct study of the  $\Lambda$ -N interaction has been attempted with  $\Lambda$  beams scattering on nucleons <sup>2)</sup>, the quality of the data is poor and the experiments are very difficult due to low beam intensities and short lifetimes.  $\Lambda$ -hypernuclei thus provide a convenient laboratory where the  $\Lambda$ -N interaction can be studied in an indirect but more practical way.

In this respect, the high resolution spectroscopy of  $\Lambda$ -hypernuclei is a powerful tool. In fact, the energy spectrum can be calculated from the  $\Lambda$ -N effective potential which is commonly written as a sum of five terms: a central part, a spin-spin interaction term,  $\Lambda$ - and N-spin-orbit interactions and a tensor part. Doublet splittings originate from the coupling of the two spin orientations of the  $\Lambda$  hyperon with the angular momentum of the parent nucleus. Due to the small excitation of one component of the doublet by hadronic probes and to the limited energy resolution reached so far the doublets have never been observed. Their identification is essential to the investigation of the spin dependence of the N- $\Lambda$  effective interaction, since the doublet splitting is mainly determined by the spin-spin,  $\Lambda$ -spin-orbit, and tensor terms. The N-spin-orbit part mainly affects the spacing between doublets.

Precise  $\Lambda$  hypernuclear spectroscopy is the primary experimental goal of the Jlab hypernuclear program, where very high energy resolutions, at the level of 350 keV, can be reached.

The  $(e, e'K^+)$  electromagnetic induced production of hypernuclei is characterized by a large momentum transfer ( $q \sim 300$  MeV/c,  $\Delta l = 2$  transitions

dominate) and a strong spin-flip term ( $\Delta s = 1$ ). This means that virtual photons may excite both natural and unnatural parity, and both low and high-spin hypernuclear states with a deeply bound  $\Lambda$  hyperon, while with  $\pi^+$  and  $K^-$  induced reactions the spin flip transitions are very weak<sup>13)</sup>. Moreover, since the  $K^+-\Lambda$  electroproduction is from the proton (while the  $\Lambda$  production is from the neutron in the case of hadronic reactions), new hypernuclei, charge symmetric to the ones generated by  $\pi^+$  and  $K^-$  beams, can be produced.

Electron beam facilities like CEBAF will therefore provide a powerful complementary approach to this field of physics where most of the data available to date come from the strangeness exchange reaction ( $K^-, \pi^-$ ) and the associated production reaction ( $\pi^+, K^+$ ).

#### 4 The JLab Experimental Program on Hypernuclear Physics

Five proposals<sup>3)-7)</sup> on the subject have been approved at JLab.

Experiment E91-016<sup>3)</sup> in Hall C has finished data taking with the standard detector package in the investigation of the production of light hypernuclei on D,  $^3\text{He}$  and  $^4\text{He}$  targets, looking for bound and narrow states. Preliminary analysis of the data on deuterium<sup>8)</sup> suggests the possibility of studying the neutron induced reaction  $e + n \rightarrow K^+ + \Sigma^-$ .

Two experiments plan to investigate 1p-shell hypernuclear spectroscopy with different experimental techniques: the high luminosity Hall A experiment E94-107<sup>7)</sup> described in detail in the next session, and the Hall C experiment E89-009<sup>4)</sup>. The latter will use a 1.645 GeV electron beam at low current (0.2 - 2  $\mu\text{A}$ ) on thin targets (10 mg/cm<sup>2</sup>) of  $^9\text{Be}$ ,  $^{12}\text{C}$  and  $^{10}\text{B}$  (or  $^7\text{Li}$ ). The low luminosity, convenient for a number of reasons, reduced background and thus simplified particle identification, for example, is possible since the electrons and kaons will be detected at almost zero degrees, thus maximizing the production rate. This is accomplished by the Hypernuclear Spectrometer System (HNSS) upgrade of Hall C which consists of a splitter magnet placed at the target position bending the kaons towards the SOS spectrometer and the electrons towards a new Enge split pole magnet.

The overall missing energy resolution is dominated by the SOS momentum resolution of  $\delta p/p \sim 5 - 7 \times 10^{-4}$  FWHM. It is expected that a resolution between 600 keV and 1 MeV will be achieved. This experiment, the first electromagnetic induced production of hypernuclei, will take data in March

2000. It will allow identification of level structures, however, the detection of doublet splitting will be very difficult with the expected resolution. It will provide an important test of the low luminosity approach.

Experiment E97-008 <sup>5)</sup>, also in Hall C, plans to extend these measurements to heavier nuclei. It will explore the possibility of direct observation of the spin-orbit splitting at higher orbits. The experiment is currently conditionally approved depending on the results obtained from E89-009.

Weak decays of hypernuclei will be studied by experiment E95-002 <sup>6)</sup> in Hall C. The goal of the experiment is to carry out direct measurements of the lifetime of heavy hypernuclei with high accuracy (20 - 30 ps). Since the free  $\Lambda$  hyperon pionic decay channel is suppressed in a nucleus due to Pauli blocking effects (the resulting nucleon would have a momentum smaller than the typical Fermi momentum in the nucleus), the lifetime of hypernuclei is dominated by the non-mesonic weak decays which can occur in the nuclear medium via a two-body interaction with a nucleon. Measurements of the lifetimes of hypernuclei hence make it possible to investigate the weak four-fermion vertex  $\Lambda N \rightarrow NN$  which can only be studied in a nuclear medium. The dependence on  $A$  of the lifetime will also be measured with the aim of investigating the short range properties of the  $\Lambda$ - $N$  interaction.

## 5 Hypernuclear Spectroscopy in Hall A

The main goal of experiment E94-107 is to carry out high resolution spectroscopic studies on  ${}^7\text{Li}$ ,  ${}^9\text{Be}$ ,  ${}^{12}\text{C}$  and  ${}^{16}\text{O}$  target nuclei.

The experiment will use the standard HRS spectrometer pair, whose minimum detection angle is  $12.5^\circ$ . However, to maximize the cross section one has to keep the electron scattering angle as small as possible (large virtual photon flux) and the kaon angle close to the transferred momentum. Detecting both the electron and the kaon at angles smaller than  $10^\circ$  is thus a crucial requirement:  $6^\circ$  is a reasonably acceptable value. Moreover, to keep an acceptable kaon survival fraction at the spectrometer focal plane (25 m away from the target), the kaon momentum has to be fairly high and this implies also higher momenta for incident and scattered electrons in comparison with the Hall C setup.

The chosen kinematics is: 4 GeV electron beam; scattered electrons and kaons detected at  $6^\circ$  with momenta of 1.8 and 1.96 GeV/c, respectively.

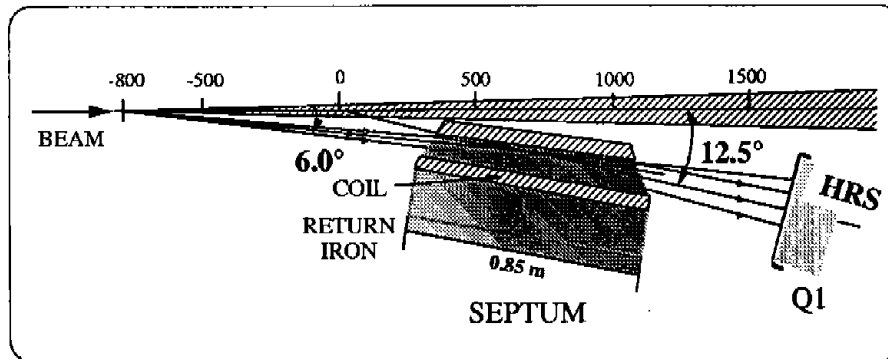


Figure 1: *Septum magnet schematical layout. Only one septum is shown, the other being placed symmetrically on the other side of the beam.*

The two main issues of concern in this experiment are: (i) as already discussed very forward angles for both the electron arm and the kaon arm must be reached to keep the counting rates at a reasonable level; (ii) high luminosity is needed implying a very high background of proton and pion random coincidence events, therefore a powerful particle identification (PID) system will be required.

Forward angle detection capability is accomplished by the use of the two septum magnets<sup>9)</sup> whose layout is shown schematically in Fig. 1. The scattering chamber is moved upstream by about 80 cm with respect to its nominal position and the two septa, placed at the sides of the beam pipe, are used to bend 6° tracks of electrons (on one side) and kaons (on the other side) to 12.5° where each HRS is placed at its minimum angle. The septum+HRS system can also be moved varying the central angle from 6° to 12.5°, independently for the two arms. It has been shown<sup>9)</sup> that the addition of the septa keeps the optimal performance of each HRS essentially unchanged. Such devices will greatly improve the Hall A experimental capabilities. Many experiments will make use of them. Two have already been approved: GDH sum rule at low  $Q^2$ <sup>10)</sup> and the parity violation experiment E99-115<sup>11)</sup>.

At the luminosity of the experiment, about  $3 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ , obtained with a 100  $\mu\text{A}$  beam current on a 100  $\text{mg}/\text{cm}^2$  thick target, the  $(e, e')$ ,  $(e, p)$ ,  $(e, \pi^+)$  single rates are all at the level of 1 MHz. This gives rise to very high

rates of random coincidences  $(e, e') \otimes (e, h)$  (where  $h = p, \pi^+$ ), to be compared with the low hypernuclear production which should vary between 1 and 40 counts/hour/level.

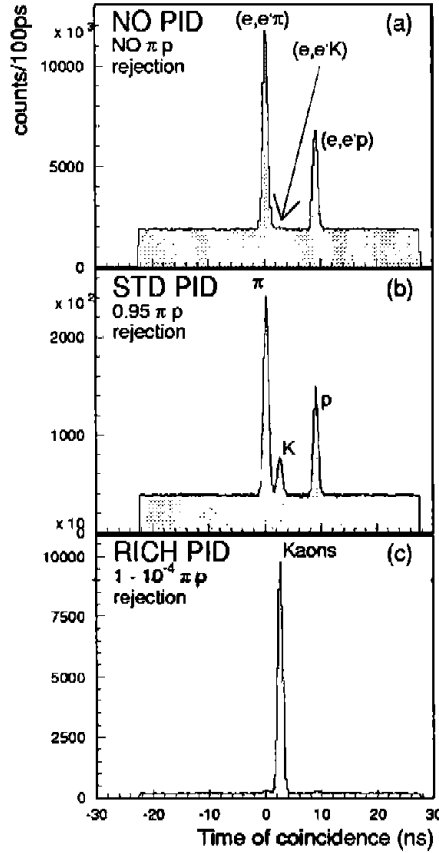


Figure 2: *Electron-hadron coincidence timing spectra.*

while true  $(e, e'h)$  events ( $h = \pi^+, k^+, p$ ) give clear peaks.

In Fig. 2(a), data are shown where no PID is applied at all. The  $(e, e'K^+)$  “trues” peak can hardly be seen, as it is hidden by a huge background mainly

To study the impact of the background on the experiment, a dedicated Monte Carlo code has been developed. Besides the reconstruction of usual phase space variables, the simulation is based on the reconstruction of the missing mass spectra and the coincidence time between the electron and the kaon, as expected when considering all possible sources (real and random coincidences of electrons with any hadron). Then, a study has been performed with different assumptions on the rejection power of background events through different PID systems.

In the simulation, any background coming from  $\pi^-$ 's detected in the electron arm is not considered since the  $\text{CO}_2$  gas Čerenkov detector and the shower counter provide a very high rejection of pions <sup>12</sup>).

In Fig. 2 the spectra of the coincidence time between electron and hadron arm triggers obtained in the  $^{16}\text{O}(e, e'K^+)$  reaction with different PID performances are shown. The random coincidences spread all over the accepted coincidence time win-

due to random  $(e, e'p)$  and  $(e, e'\pi^+)$  coincidences. In Fig. 2(b) the "standard" hadron identification based on two threshold Čerenkov detectors operating with aerogel radiators having two different refractive indexes has been assumed. In such a configuration at 2 GeV/c the high index of refraction (1.055) is used to detect both kaons and pions (while protons are below threshold) and the low index of refraction (1.015) is used to veto pions, the only particle which fires the detector. In this case, the percentage of protons and kaons misidentified as kaons was assumed equal to 5%. Such misidentification has been evaluated allowing for inefficiencies of the vetoing detector and from delta ray production by protons. In this case the kaon peak is clearly distinguished. Although most kaons in this peak come from quasifree scattering, in the missing energy spectrum these events spread above the hypernuclear bound states region, and the background below the timing peak is also spread all over the missing energy acceptance.

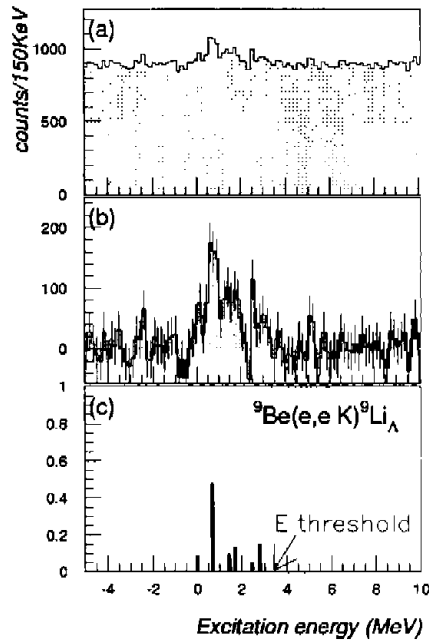


Figure 3: Excitation energy spectra for the  ${}^9\text{Be}(e, e'K^+) {}^9\text{Li}_\Lambda$  reaction

In Fig. 3 the excitation energy spectra for the reaction  ${}^9\text{Be}(e, e'K^+) {}^9\text{Li}_\Lambda$  is displayed for events selected in the kaon peak (a) and after background subtraction (b). In the simulation the "standard" hadron identification (based on two aerogel Čerenkov detectors) has been assumed. The calculation for the spectra (Fig. 3(c)) and cross sections have been taken from <sup>13</sup>.

Finally, the simulation has been carried out assuming the characteristic PID performance of a Ring Imaging Čerenkov (RICH) detector. In this case the huge background due to protons and pions becomes negligible (see Fig. 2(c)).

In Fig. 4 a comparison of the excitation energy for the reactions  ${}^9\text{Be}(e, e'K^+) {}^9\text{Li}_\Lambda$ ,  ${}^{12}\text{C}(e, e'K^+) {}^{12}\text{B}_\Lambda$



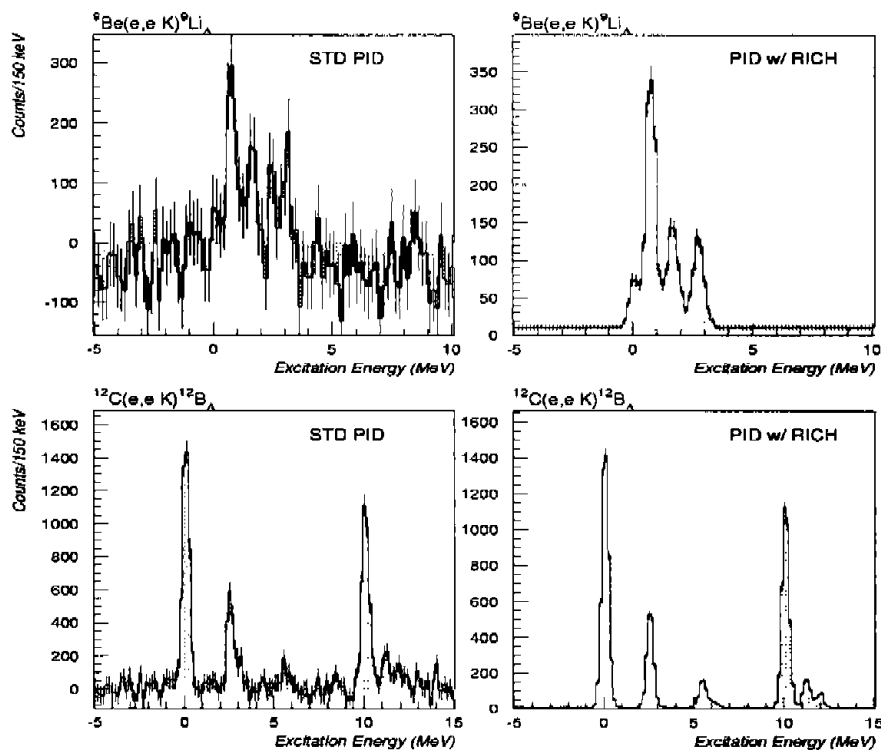


Figure 4: *Excitation energy spectra obtained under different PID performance assumptions (see text).*

is shown considering the two PID systems (the “standard” one making use of two aerogel threshold detectors, and the RICH one). The figure shows that, at least for the  $^{12}\text{C}(e,e'K^+)^{12}\text{B}_\Lambda$  reaction, the  $p, \pi$  rejection assumed for the aerogel detectors would be sufficient to have a clear identification of at least the higher counting bound levels. On the other hand, the use of a RICH detector would allow identification of many low counting levels, not visible otherwise, and to possibly discern doublets (first two peaks of the  $^9\text{Li}_\Lambda$  spectrum in Fig. 4). It was thus proposed to add to the HRS detector package a  $\text{C}_6\text{F}_{14}/\text{CsI}$  proximity focusing RICH<sup>14</sup>). This project has been approved and funded by the collaboration and the detector is now under construction.

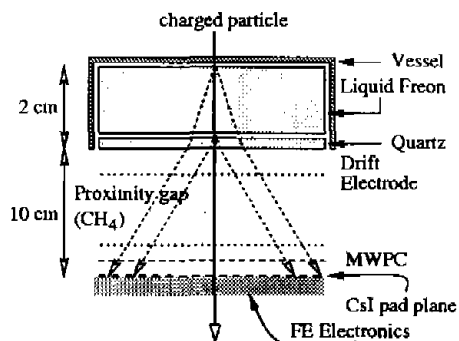


Figure 5: *Schematic layout of the proximity focusing  $C_6F_{14}/CsI$  RICH detector under construction for Hall A.*

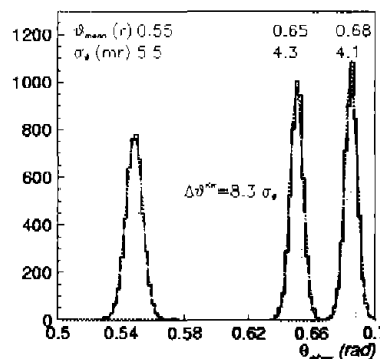


Figure 6: *Simulation of the angles reconstructions from  $p$ ,  $K$ ,  $\pi$ , at momenta of  $2 \text{ GeV}/c$ .*

### 5.1 The Ring Imaging Čerenkov upgrade for the Hall A detector package

The  $C_6F_{14}/CsI$  proximity focusing RICH has already been investigated by the ALICE HMPID RICH group <sup>15)</sup>. A schematic layout of this detector is shown in Fig. 5. The liquid radiator is  $C_6F_{14}$  and the photodetector is a classical MWPC with a pad plane coated by a 500 nm thick layer of CsI UV photoconverter, which represents the main critical component of the detector. The Monte Carlo simulation combined with the test performed by the ALICE group conservatively predicts a rejection power of  $10^4$  for  $\pi$  and several orders of magnitude less for  $p$ .

A Monte Carlo simulation based on the GEANT3 tracking package has been developed. The simulation includes realistic optical characteristics and photodetector responses. The number of produced photoelectrons ( $\sim 17$ ) is in good agreement with the test performed by ALICE <sup>16)</sup>.

A backtracing angle reconstruction algorithm has been also implemented, which determines the emission Čerenkov angle from the photon hit (clusters) positions, the track parameters (direction and entrance point), and the geometry.

The Monte Carlo generated events have been processed with the recon-

truction algorithm and the main result is summarized by Fig. 6 where the leftmost peak represents the reconstructed proton angle, the central peak is kaons and the rightmost peak is pions. The width of each peak (approx. 4.1 mrad) is the results of several contributions to the determination of the angle: the chromaticity of the radiator, the uncertainty on the emission point in the radiator, and the size of the position detector.

As shown in the figure at 2 GeV/c, the separation of  $K/\pi$  is at the level of  $8.3\sigma$ .

## 6 Conclusions

Experiments on hypernuclear physics with electromagnetic induced reactions are possible for the first time due to the CEBAF beam quality and the expected spectrometer performances. High resolution hypernuclear spectroscopy is one of the main goals of the JLab program in this field where the electromagnetic approach offers the opportunity to reach energy resolutions of a few hundred keV. New hypernuclei, charge symmetric with respect to those excited with hadronic induced reactions, can be produced, and both spin-flip and non-spin-flip transitions are excited by electron beams, providing the chance to discern spin doublets.

The JLab hypernuclear program will be able to provide in the next few years high quality and complementary data to those produced at BNL, KEK and in the near future at DAΦNE in a common effort to access nuclear systems with strangeness and to investigate the properties of the hyperon-nucleon interaction via the "hypernuclear" laboratory.

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