**A NEW HYPERNUCLEAR EXPERIMENT WITH
THE HIGH RESOLUTION KAON SPECTROMETER (HKS)
AT JLAB HALL C**

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As a natural extension of the first successful hypernuclear spectroscopy through the $(e,e'K^+)$ reaction (JLab E89-009), a new experiment with a newly developed High resolution Kaon Spectrometer (HKS) and new configuration of the electron spectrometer was proposed. The high performance of the HKS and the new electron spectrometer configuration (tilt method) enables us to improve the energy resolution by a factor of 2, the hypernuclear yield by a factor of 50 and the signal to noise ratio by a factor of 10.

1. Experimental configuration

1.1. Introduction

Spectroscopic study of Λ hypernuclei by the $(e,e'K^+)$ reaction has unique advantages over those through meson-induced reactions such as (π^+, K^+) and (K^-, π) . Contrary to the meson-induced reactions, the $(e,e'K^+)$ reaction favorably excites spin-flip Λ hypernuclear states and produces neutron rich Λ hypernuclei converting a proton to a Λ hyperon. From the experimental point of view, it is also of significant importance that the reaction allows us to improve the energy resolution down to sub-MeV taking advantage of a high-quality primary beam.

The first $(e,e'K^+)$ hypernuclear spectroscopy experiment was carried out successfully at Jefferson Lab's (JLab) Hall C in the spring of 2000 by the E89-009 collaboration. This pioneer experiment demonstrated the great potential of the $(e,e'K^+)$ reaction, obtaining a hypernuclear mass spectrum with an energy resolution of about 900 keV(FWHM) in the $^{12}\text{C}(e,e'K^+)_{\Lambda}^{12}\text{B}$ reaction¹. However, the result suffers from poor signal to noise ratio (~ 1) and statistics. It is clear that an improvement of this hypernuclear spectrometer system is essential to fully explore the potential of the new reaction to study hypernuclear structure.

1.2. Experimental principle

As seen in Fig. 1, the basic configuration of the new experiment is similar to that of E89-009. The beam energy (1.8 GeV) was chosen as low as possible not to open unnecessary reaction channels and virtual photon energy becomes ~ 1.5 GeV, since the $p(\gamma, K^+)\Lambda$ cross section decrease for $E_\gamma > 1.5$ GeV².

The scattered electron (e') and K^+ are separated by the dipole magnet (Splitter) located just behind the target. The scattered electron is measured by the Enge split-pole spectrometer which was used also for the E89-009 experiment and K^+ by the newly developed high resolution kaon spectrometer (HKS).

The two key experimental conditions which were improved from the previous experiment are:

- The HKS was newly designed to have 3 times greater solid angle than the previous kaon spectrometer and simultaneously to achieve a momentum resolution of 2×10^{-4} .
- A new experimental configuration, "Tilt method", that will max-

imize hypernuclear production rates has been proposed. In this configuration, the Enge electron spectrometer is tilted vertically to the splitter dispersive plane so as to choose electron scattering angles of 4-5 degrees. This avoids the intense 0-degree bremsstrahlung electrons but still allows detection of the scattered electrons at a sufficiently forward angle. Therefore, the “Tilt method” inherits the advantageous aspects of the “0 degree tagging method” employed in the E89-009 experiments, but it is relatively free from the huge background rate of bremsstrahlung electrons at the focal plane of the electron spectrometer. This will allow us to use beam currents as high as a few tens μA . The new configuration makes it possible to measure hypernuclear spectra even with higher Z targets.

Employing the proposed new experimental configuration and with the high-resolution kaon spectrometer (HKS), we expect to achieve hypernuclear yields more than one order of magnitude higher and the signal-to-accidental ratio one order of magnitude better compared to the previous E89-009 experiment. The proposal of the new experiment with the HKS and the tilt method was accepted by JLab PAC19³.

Table 1. Specification of the HKS

Configuration	QQD and horizontal 70° bend
Central momentum	1.2 GeV/ c
Dispersion	4.7 cm/%
Momentum acceptance	$\pm 12.5\%$ (1.05 – 1.35 GeV/ c)
Momentum resolution ($\Delta p/p$)	2×10^{-4}
Solid angle	30 msr without Splitter 16 msr with a splitter
Kaon detection angle	Horizontal : 7 degrees (0 – 14°)
Flight Path Length	10 m
Maximum Magnetic Field	1.6 T (normal)

2. Spectrometer Design

2.1. High resolution Kaon Spectrometer (HKS)

The HKS consists of two quadrupole magnets (Q1 and Q2) and one dipole magnet (D). Due to two degrees of freedom of the quadrupole doublet, the horizontal and vertical focusing can be adjusted simultaneously. The HKS

Figure 1. Experimental setup of the E01-011 experiment.

is designed to achieve both 2×10^{-4} momentum resolution and 16 msr solid angle acceptance at the same time when it is used with the Splitter. The HKS is positioned at an angle of 7° , covering from 0 to 14 degrees, with respect to 1.2 GeV/c zero degrees scattered particle to avoid scattered positively charged particles at 0 degrees, mostly positrons.

The basic specification of the HKS spectrometer is given in table 1.

The construction and field mapping of the HKS magnets (Q1, Q2 and D) were finished in Japan (Kobe, Mitsubishi). They are ready for shipping to USA.

Figure 2. The assembled HKS magnets. From left to right, Q1 (8.2 ton), Q2 (10.5 ton) and D (210 ton) magnets are shown.

2.2. Enge split-pole spectrometer and the tilt method

In the pilot (e,e'K) hypernuclear experiment, E89-009, the electrons associated with bremsstrahlung dominated the background in the scattered electron spectrometer (Enge). The idea to suppress the bremsstrahlung background is to use the difference of the angular distributions between bremsstrahlung electrons and scattered electrons associated with the virtual photons which contributes to kaon production. The tilt of the Enge spectrometer off the bending plane of the Splitter magnet allows us to avoid the extremely high rate electrons originating from bremsstrahlung and Møller scattering. However, increasing the tilt angle, the number of the accepted virtual photons will decrease. Therefore, we need to take following rates into account to optimize the tilt angle:

- (1) virtual photons associated with hypernuclear production,
- (2) electrons associated with bremsstrahlung, and
- (3) Møller scattering electrons.

Figure 3 shows the electron scattering angle distributions at the target. The electron distributions associated with Bremsstrahlung, virtual photons and Møller scattering are plotted. Since the beam energy is fixed, the scattering angle and momentum for Møller scattering electrons have one to one correspondence, and thus a ring shaped distribution results from the Møller scattering within momentum acceptance of the Enge spectrometer.

Using a RAYTRACE Monte Carlo simulation, the events which passed through the tilted Enge spectrometer without hitting the pole or collimators were selected. Figure 3 shows that the acceptance of the *tilted* Enge spectrometer locates just out side of the Møller ring, and thus *hyper*-forward Bremsstrahlung background and Møller electrons are blocked while the electrons associated with virtual photons passed through the Enge spectrometer.

Figure 3. The scattering angle of the electrons ($p = 316 \pm 40\%$ MeV/c) at the target calculated by RAYTRACE optics code. The very forward Bremsstrahlung electrons and Møller electron rings are observed. The acceptance of the *tilted* Enge spectrometer locates just outside of the Møller ring.

This tilt configuration of the Enge spectrometer drastically suppress the electron background at the electron detector. In the E89-009 experiment, the electron rate was over 200 MHz and it limited the beam intensity and the target thickness. The virtual photon yield will be reduced by the tilt method, however, it can be easily got back by increasing the beam intensity and target thickness.

Tilt method will reduce the electron rate from 200 MHz to a few MHz even with 5 times thicker target and ~ 50 times stronger beam.

3. Detectors Development

Table 2. Detectors for HKS spectrometer

Nomenclature	Size	Comments
Drift chamber		
HDC1	$30^H \times 120^W \times 2^T \text{ cm}$	xx'uu'(+30 deg)vv'(-30 deg) 5 mm drift distance
HDC2	$30^H \times 120^W \times 2^T \text{ cm}$	xx'uu'(+30 deg)vv'(-30 deg) 5 mm drift distance
Time of flight wall		
HTF1X	$30^H \times 125^W \times 2^T \text{ cm}$	$7.5^W \text{ cm} \times 17\text{-segments}$, H1949
HTF1Y	$30^H \times 125^W \times 2^T \text{ cm}$	$3.5^W \text{ cm} \times 9\text{-segments}$, H1949
HTF2X	$35^H \times 170^W \times 2^T \text{ cm}$	$9.5^W \text{ cm} \times 18\text{-segments}$, H1949
Čerenkov counter		
HAC1	$46^H \times 169^W \times 31^T \text{ cm}$	n = 1.055 hydrophobic aerogel $14 \times 5''$ PMT (7 seg.)
HAC2	$46^H \times 169^W \times 31^T \text{ cm}$	n = 1.055 hydrophobic aerogel $14 \times 5''$ PMT
HAC3	$46^H \times 169^W \times 31^T \text{ cm}$	n = 1.055 hydrophobic aerogel $14 \times 5''$ PMT
HWC1	$35^H \times 184.8^W \times 8^T \text{ cm}$	$15.6^W \text{ cm} \times 12\text{-segments}$, H1161 Water with wavelength shifter
HWC2	$35^H \times 184.8^W \times 8^T \text{ cm}$	$15.6^W \text{ cm} \times 12\text{-segments}$, H1161 Water with wavelength shifter

3.1. Summary of the HKS and Enge detector packages

The HKS detector package is designed to identify K^+ s from p, π^+ , e^+ backgrounds and to measure their momentum with a resolution of 2×10^{-4} . In order to realize the requirements, the HKS detector package consists of one pair of drift chambers, three planes of time-of-flight counters, two planes of water Čerenkov counters, and three planes of aerogel Čerenkov counters. The geometry of these detectors and some of their general parameters are summarized in table 2.

Table 3. Detectors for the Enge spectrometer

Nomenclature	Size	Comments
Drift chamber		
EDC	$12^H \times 100^W \times 30^T \text{ cm}$	xx'uu'xx'vv'xx' 5mm drift (uu',vv' ± 30 deg)
Hodoscope		
EHOD1	$12^H \times 100^W \times 1^T \text{ cm}$	$4^W \text{ cm} \times 25\text{-segments}$, H6612
EHOD2	$12^H \times 100^W \times 1^T \text{ cm}$	$4^W \text{ cm} \times 25\text{-segments}$, H6612
EHOD3	$12^H \times 100^W \times 2^T \text{ cm}$	$12^W \text{ cm} \times 1\text{-segment}$, H1949

The Enge detector package is designed to achieve $(\delta p/p) = 4 \times 10^{-4}$

(FWHM) and it consists of a drift chamber for tracking and two planes of hodoscope arrays for TOF measurement. Table 3 summarizes the size of each detectors.

3.2. Counter beam test

Prototype and the final version of the counter systems (HKS TOF, aerogel Čerenkov, water Čerenkov, Enge Hodoscope) were tested with 1.2 GeV/ c unseparated p , K^+ , π^+ , e^+ beam at KEK-PS (PS-T494, 500, 530).

The Enge honeycomb drift chamber was also beam-tested with electrons of a few 100 MeV at the internal tagged photon facility of Laboratory of Nuclear Science (LNS) of Tohoku University. Most of the detectors have been constructed and shipped to Jlab in March 2003.

4. Expected performance

4.1. Energy resolution

In the proposed experiment, the hypernuclear mass resolution is governed by the following items. The contributions to the energy resolution are summarized in table 4. The proposed spectrometer system is expected to achieve an energy resolution of 300-400 keV (FWHM), depending on the choice of targets.

Table 4. The energy resolution of the HKS system

Item	Contribution to the mass resolution (keV, FWHM)			
Target	C	Si	V	Y
HKS momentum			230	
Beam momentum			≤ 180	
Enge momentum			120	
K^+ angle	134	56	32	18
Target (100 mg/cm ²)	≤ 180	≤ 171	≤ 148	≤ 138
Overall	≤ 390	≤ 360	≤ 350	≤ 345

(1) HKS momentum resolution

With a Monte Carlo simulation, the momentum resolution of the HKS was estimated to be 110 keV/ c (rms) for a spatial resolution of 200 μ m of the wire chambers. This corresponds to a missing mass resolution of 230 keV.

(2) Beam momentum resolution

Beam momentum resolution is required to be better than 1×10^{-4} . This corresponds to 180 keV/ c (FWHM) for 1.8 GeV/ c beam. It is

also necessary to monitor long term fluctuation of the beam central momentum. If these fluctuation should turn out to be significant, they will be corrected in the off-line analysis.

(3) **Enge momentum resolution**

Assuming a spatial resolution of $60\mu\text{m}$ (rms) and an angular resolution of 2 mr (rms), the momentum resolution of the Enge spectrometer is estimated to be $120\text{ keV}/c$ (FWHM).

(4) **Kinematical broadening due to uncertainty of the K^+ scattering angle**

The uncertainty of the K^+ emission angle is dominated by the multiple scattering through the materials between the target and the drift chambers (uncertainty due to the spatial resolution of the chambers are less than 0.2 mrad). Contribution of the following materials are taken into account: the target ($100\text{ mg}/\text{cm}^2$), vacuum windows (Kevlar $216\mu\text{m}$, Mylar $127\mu\text{m}$), helium bag (100 cm) and chambers (mylar $0.0045''$, argon 5.08 cm @ STP).

The total uncertainty of the K^+ angle was estimated to be 2.9 mrad (rms) for the carbon target. This angular uncertainty corresponds to 134 keV (FWHM) ambiguity to the ${}^{12}_{\Lambda}\text{B}$ mass. Similarly, this effect to ${}^{28}_{\Lambda}\text{Al}$ (Si target) will be 56 keV (FWHM).

(5) **Momentum loss in the target**

Assuming a Vavilov distribution, the average momentum loss and spread of $1.2\text{ GeV}/c$ K^+ in $100\text{ mg}/\text{cm}^2$ carbon were calculated. The corresponding contribution to the energy resolution is 180 keV (FWHM).

4.2. Yield estimation

Table 5. The hypernuclear yield comparison between E01-011 and E89-009

	E01-011	E89-009	Gain Factor
Virtual γ flux/ 10000 e^-	0.2	4	0.05
Target Thickness (mg/cm^2)	100	22	4.5
e^- acceptance, e^-K^+ momentum matching	200	120	1.7
K^+ survival rate	0.35	0.4	0.9
Solid angle of K arm (msr)	16	5	3.2
Beam current (μA)	30	0.66	45
Estimated yield (${}^{12}_{\Lambda}\text{B}_{gr}/\text{hour}$)	45	0.9	50

The expected yield of the hypernuclear states are evaluated based on the E89-009 result for the ${}^{12}_{\Lambda}\text{B}$ ground state in the ${}^{12}\text{C}(\text{e},\text{e}'K^+){}^{12}_{\Lambda}\text{B}$ reaction,

comparing the beam intensity, acceptance ratio of the virtual photons, kaon detection efficiency and so on. The E01-011 experiment is expected to increase hypernuclear yields by a factor of 50, and to improve the signal to accidental ratio by a factor of 10 (Table 5).

5. Summary

The first successful $(e,e'K^+)$ hypernuclear experiment (JLab E89-009) proves the $(e,e'K^+)$ reaction is a promising way for the high resolution hypernuclear spectroscopy, but the kaon spectrometer and extremely high background rate in the electron arm limited the resolution and yield.

In order to overcome the problems, we proposed a new experiment with the newly developed High resolution Kaon Spectrometer (HKS) and new configuration of the electron spectrometer (tilt method). The new experiment aims to improve the energy resolution by a factor of 2, the hypernuclear yield by a factor of 50 and the signal to noise ration by a factor of 10.

The development of the detector package were almost finished and the final tuning at JLab is in progress. We will be ready for the first experiment with the HKS in 2004. Lots of hot hypernuclear data will spring out from the Jlab Hall-C in the near future.

References

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