Future hypernuclear experiments at JLab

S.N. Nakamura[a]

Graduate School of Science, Tohoku University, Japan

Abstract. At Jefferson Laboratory, a new way of the hypernuclear spectroscopy with the (e,e'K+) reaction has been explored. The first generation experiment E89-009 at Hall C proved a potential of the (e,e'K+) hypernuclear spectroscopy. The second generation experiments, E94-107 at Hall A and E01-011 at Hall C, start to provide new physics information. The approved third generation experiment E05-115 at Hall C is in preparation. The Hall A and Hall C collaborations start to consider future experiment together.

PACS. 21.80.+a – 21.10.Dr – 21.60.Cs

1 Introduction

The hypernuclear spectroscopy provided numerous information to the strangeness physics. So far, hypernuclei have been produced mainly by the meson induced reactions, such as (K^-,π^-) and (π^+,K^+) reactions.

At Jefferson Laboratory (JLab), a new method to produce hypernuclei, the (e,e'K^+) reaction, has been developed. The (e,e'K^+) reaction has unique features as a method to produce hypernuclei:

1. (e,e'K^+) reaction converts a proton into a Λ and produces mirror hypernuclei to those which were well studied by the (K^-,π^-) and (π^+,K^+) reactions.
2. various multiplet states can be populated since the (e,e'K^+) reaction provides a large momentum transfer similar to the (π^+,K^+) reaction and furthermore there are spin flip as well as non-flip amplitudes even at very forward angles.
3. JLab CEBAF can provide a high quality, high intensity electron beam whereas it is difficult to have very good emittance and high intensity simultaneously for the secondary meson beams like π^+ and K^-. Thanks to the high quality electron beam, we can expect much better energy resolution (sub MeV) for the (e,e'K^+) hypernuclear spectroscopy.

Therefore, the (e,e'K^+) reaction can produce various states of new hypernuclei with a better energy resolution. Furthermore, a high intensity electron beam allows us to use very thin targets (<100mg/cm^2). This contributes to the good energy resolution and allows the usage of enriched targets such as ^{6}Li, ^{7}Li, ^{10}B, ^{11}B, ^{28}Si, *etc.* Only CEBAF at JLab can provide such a high quality electron beam which can be used for hypernuclear spectroscopy until MAMI-C starts to deliver a 1.5 GeV electron beam.

[a] On behalf of JLab E89-009, E94-107, E01-011, E05-115, Hall A and C hypernuclear Collaborations.

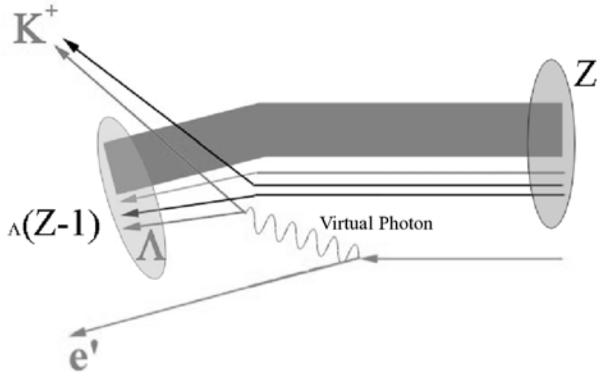

Fig. 1. The (e,e'K^+) reaction.

2 The first generation experiment

After the first production of the $^{3,4}_{\Lambda}$H hypernuclei by the (e,e'K^+) reaction [1], the (e,e'K^+) hypernuclear spectroscopy was initiated by the E89-009 experiment at JLab Hall C [2,3]. Though the (e,e'K^+) reaction has many unique features as explained in the previous section, we have to overcome following challenges to realize the (e,e'K^+) hypernuclear spectroscopy:

1. The hypernuclear production cross section in (e,e'K^+) reactions is orders of magnitude smaller than it is for meson induced reactions.
2. Coincidence measurements between scattered electrons and produced kaons should be performed.
3. Background originating from bremsstrahlung and Møller scattering is very severe.

The E89-009 experiment used existing spectrometers for the K^+ arm and the e' arm. The data accumulation was performed in the year 2000 and clear hypernuclear peaks were observed for $^{12}_{\Lambda}$B. For a reaction hypernuclear spectroscopy, sub-MeV mass resolution was achieved for the first time. This experiment proved that (e,e'K$^+$) reaction can be used for hypernuclear study and that it is a quite promising method to study hypernuclei. However, the resolution was limited by the existing K$^+$ spectrometer. Furthermore, high background rate (200 MHz) originating from bremsstrahlung and Møller scattering in the e' arm limited the primary electron beam current to less than 0.7 μA. The small solid angle of the K$^+$ spectrometer and the low electron beam current resulted in a low hypernuclear yield ($<$ 1/h for $^{12}_{\Lambda}$B).

In order to explore the full potential of (e,e'K$^+$) hypernuclear spectroscopy, it is essential to replace the K$^+$ spectrometer and to reduce the background rate in the e' spectrometer.

3 The second generation experiments

After the first (e,e'K$^+$) hypernuclear spectroscopy, the Hall C hypernuclear collaboration decided to design and fabricate a new high resolution K$^+$ spectrometer (HKS) dedicated to the (e,e'K$^+$) hypernuclear spectroscopy. In order to reduce the e' background rate drastically, a new e' spectrometer configuration was introduced (tilt method). The new experiment with the new HKS spectrometer and the tilt method was approved as E01-011 by JLab PAC19.

Another hypernuclear project, E94-107, was started by the Hall A hypernuclear collaboration. The Hall A collaboration decided to use the existing HRS spectrometers at Hall A as an electron spectrometer as well as a K$^+$ spectrometer. In order to cover forward angles, the Hall A collaboration developed new superconducting septum magnets. The kinematics are summarized in table 2 for Hall A and Hall C experiments. Both configurations have advantages and disadvantages. The virtual photon energy for Hall A and Hall C are 2.4 GeV and 1.5 GeV, respectively. Higher virtual photon energy results in higher K$^+$ momentum. The path length of the existing HRS spectrometer is over 20 m. High K$^+$ momentum is essential for the Hall A experiment, since the K$^+$ lifetime ($c\tau$) is only 3.7 m. High K$^+$ momentum requires good K$^+$ identification detector. Hall A collaboration chose a Ring Image Čerenkov counter (RICH, fig 2). Higher virtual photon energy will result in smaller Λ hyperon production cross-section, but larger Λ capture rate.

Vise versa, a 1.5 GeV virtual photon energy means a smaller capture rate but a larger Λ production rate. Merits for lower virtual photon energy are: 1) unnecessary reaction channel will not open and 2) low momentum K$^+$ identification is easier than high momentum K$^+$. However, the kaon decay loss is severer for lower momenta. Therefore, a very short orbit high resolution kaon spectrometer, HKS, should be newly designed for the Hall C experiment.

Higher beam energy has an advantage in bremsstrahlung and MØller electron background, since those events are concentrated at more forward angles. The HRS spectrometers with septum magnets select K$^+$ and e' angles at 6 degrees. A higher energy electron beam with large K$^+$ and e' detection angles

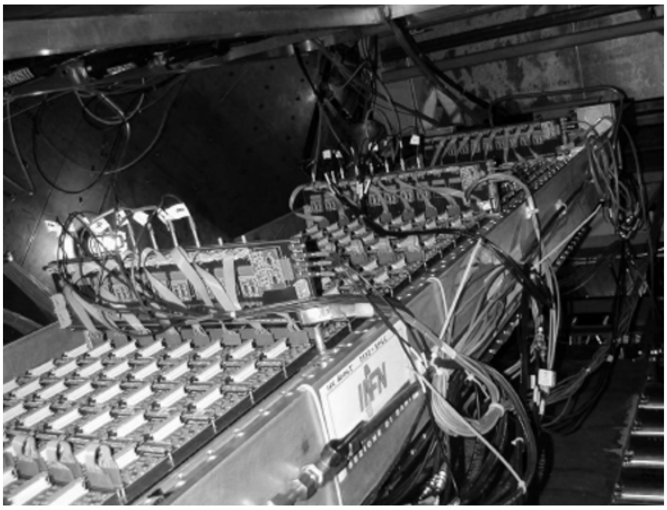

Fig. 2. The RICH detector developed for the Hall A experiments.

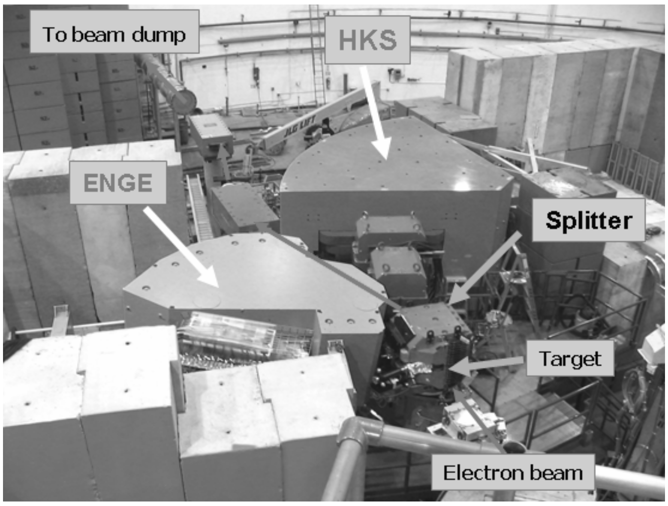

Fig. 3. The E01-011 experimental setup installed at JLab Hall C. The 1.8 GeV electron beam reacts with the target placed in the splitter magnet. Negatively charged particles (e') are deflected to left (ENGE electron spectrometer) and positively charged particles (K$^+$) go to right (HKS).

leads to very clean hypernuclear spectra for the Hall A experiment at the cost of loss of hypernuclear yield.

The Hall C configuration with lower beam energy and smaller K$^+$ and e' detection angles, results in a larger hypernuclear yield, but the background rate is higher. Therefore, a new e' spectrometer configuration was introduced for the Hall C experiment. Fig. 3 shows a picture of the E01-011 setup installed at JLab Hall C. The newly introduced Kaon spectrometer (HKS) and the vertically tilted ($\sim$8 deg) ENGE e' spectrometer can be seen. With the tilt method, the angular acceptance of the e' spectrometer is out of the Mϕller ring and also the bremsstrahlung background is suppressed (Fig. 4). The electron rate associated with the virtual photon is also reduced by the tilt method, but a higher beam intensity and thicker targets can easily compensate the loss.

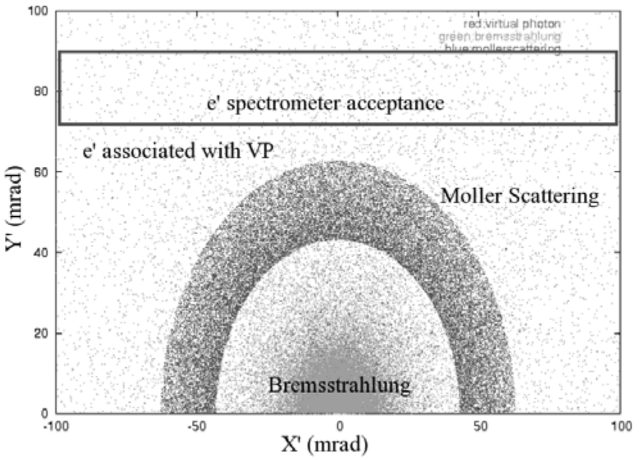

Fig. 4. The e' emission angles at the Hall C target. The electron spectrometer was tilted perpendicular to the dispersion plane to reduce electron background associated with bremsstrahlung and Mϕller scattering.

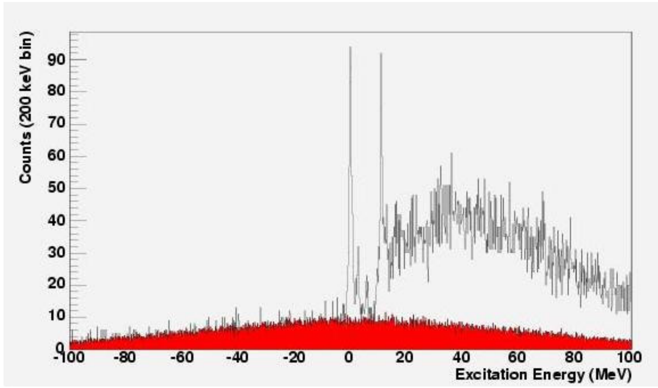

Fig. 5. The ${}^{12}_{\Lambda}$B spectra obtained by the Hall-A E94-107 experiment. Two prominent peaks which correspond to s_{Λ} and p_{Λ} states are clearly seen. The hatched region is an estimated background.

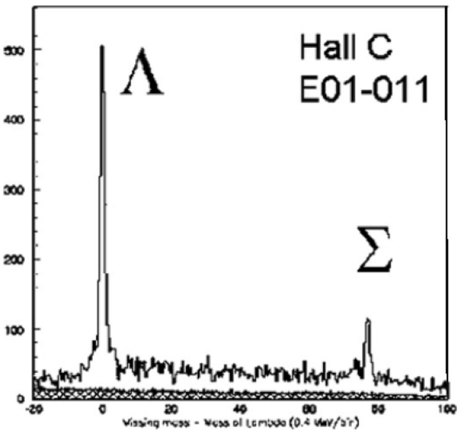

Fig. 6. The p(e,e'K$^+$)Λ, Σ^0 spectrum obtained with CH_2 target by the Hall-C E01-011 experiment. Thanks to wide acceptance of the HKS spectrometer, both of Λ and Σ_0 peaks are clearly seen in one magnetic field set.

The experiment E94-107 took data at JLab Hall A in 2004-2005 and the E01-011 at Hall C in 2005. Figure 5 shows the ${}^{12}_{\Lambda}$B excitation-energy spectrum obtained by E94-107 at Hall A. The E94-107 experiment achieved the best energy resolution of ~640 keV (FWHM) in the ${}^{12}_{\Lambda}$B spectrum in a reaction study of hypernuclear spectroscopy. E94-107 obtained also the excitation-energy spectra for ${}^{9}_{\Lambda}$Li, ${}^{12}_{\Lambda}$B, and ${}^{16}_{\Lambda}$N.

Though the analysis is still in progress, the E01-011 experiment obtained preliminary excitation-energy spectra for ${}^{7}_{\Lambda}$He, ${}^{12}_{\Lambda}$B, and ${}^{28}_{\Lambda}$Al with an energy resolution of ~700 keV (FWHM), which will be improved by further analysis.

Figure 6 shows a p(e,e'K$^+$)Λ, Σ^0 missing mass spectrum obtained by the E01-011 experiment. The wide momentum acceptance of HKS allows us to observe Λ and Σ^0 simultaneously. These two peaks are quite important for the calibration of the absolute mass scale.

The success of the second generation experiments confirmed that newly introduced sophisticated detectors and techniques worked fine such as RICH, HKS, and the tilt method. The (e,e'K$^+$) hypernuclear spectroscopy is now established and it is time to consider how we can explore the full potential of this method.

4 The future (3rd generation) experiments

The targets used for the (e,e'K$^+$) hypernuclear spectroscopy have been limited to the relatively light mass region. Figure 7 shows hypernuclear masses and the related physics topics.

Light targets are suitable to study elementary process of the strangeness electro-production. The light hypernuclei (s,p shell region) data will provide information on the baryon-baryon interaction in the SU(3)$_F$ frame work with precise few-body theoretical calculations. During the last years knowledge about the light hypernuclei has drastically improved by the hypernuclear γ-ray spectroscopy [6] and it is quite important to provide complementary data by a reaction spectroscopy experiment. Recently, it is pointed out that $\Lambda-\Sigma$ coupling may play an important role in large isospin hypernuclei [7]. The (e,e'K$^+$) reaction is suitable to study such an effect with neutron-rich light hypernuclei, since the (e,e'K$^+$) reaction converts a proton into a Λ while the (π^+,K$^+$), (K$^-$,π^-) meson reactions convert a neutron into a Λ.

The hypernuclear programs at JLab have been concentrated on the light hypernuclei. Surely, a systematic study in this region is quite important. The Hall A collaboration has now submitted a new proposal (PR07-012)[8] to JLab PAC31. This experiment aims to measure most fundamental p(e,e'K$^+$)Λ reaction in very forward angle where theoretical models give inconsistent predictions. With a water fall target, the angular dependence of the ${}^{16}_{\Lambda}$N as well as Λ electro-production will be studied in detail.

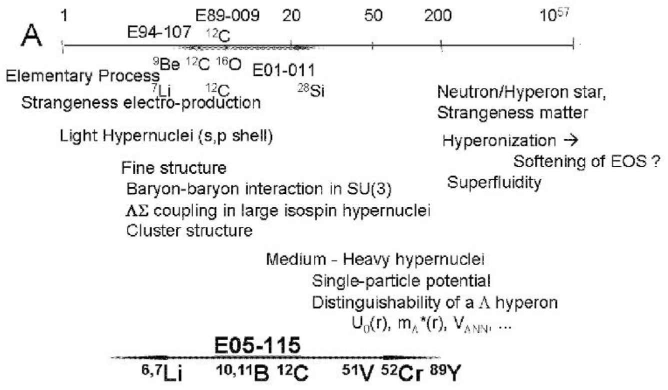

Fig. 7. Hypernuclear mass and related physics topics.

For the heavier hypernuclear study, we can expect a different kind of information. The structure of heavier nuclei is dominated by mean-field dynamics which is widely accepted in nuclear theories. However, the experimental studies for normal nuclei to test the single particle nature of a nucleon are limited only for states near the Fermi surface. The deep inside of normal nuclei is hardly studied spectroscopically since Pauli principle forbids access of a probe nucleon. This situation is totally different for hypernuclei. The Λ particle is free from nucleon's Pauli exclusion and easily accesses the deep inside of nuclei. Study of heavier hypernuclei will provide information about the depth of the Λ potential in mean-field, information on the spin-orbit splitting or possible core polarization, and so on. These information will serve to answer the fundamental question, whether a nucleon or baryon can exist as a single particle even deep inside of nuclei or whether it should be treated within a quark picture. High energy resolution of (e,e'K^+) hypernuclear spectroscopy allows us to have systematic information on medium heavy hypernuclei.

Investigation of heavier hypernuclei will open the door to study astrophysical strangeness physics, such as strangeness component of neutron or hyperon stars. However, ^{28}Si target is the heaviest target used for the (e,e'K^+) hypernuclear study, because heavier targets will produce severer bremsstrahlung background. An experiment for heavier hypernuclei should be improved in following three points:

1. Signal-to-noise ratio,
2. Energy resolution,
3. Hypernuclear yield.

In order to improve the signal-noise ratio, there is one trivial way, reducing the beam current at the cost of hypernuclear yield. Hypernuclear production yield is essentially important to study heavier hypernuclei in a limited beamtime, and thus, reducing the beam current will be applied only to the calibration data. Signal-to-noise ratio should be improved by increasing the virtual photon tagging efficiency in the e' spectrometer and by optimization of the kinematics to reduce physics background such as bremsstrahlung and Mϕller scattering.

Hall C collaboration decided to introduce a new high resolution electron spectrometer (HES) to increase the virtual photon tagging efficiency and to have better momentum matching with the kaon spectrometer, HKS. The new HES will accept higher e' momenta and thus the primary beam energy can be higher keeping the same virtual photon energy. The background processes like bremsstrahlung and Mϕller scattering will be more forward distributed and physics background will be reduced.

Furthermore, the larger acceptance of HES will increase the hypernuclear yield. High statistics and better signal-to-noise ratio will allow us to calibrate the new spectrometer precisely. Better understanding of the optics will lead to better energy resolution. Above three improvements are related with each other and improving one of them will give positive feedback to others.

A new proposal to investigate a wide mass range of hypernuclei (^{6}Li, ^{7}Li, ^{9}B, ^{10}B, ^{12}C,^{51}V, ^{52}Cr, ^{89}Y targets) with a new HES spectrometer was submitted to JLab PAC28 and accepted as E05-115 [9]. Further explanation on the E05-115 experiment and HES spectrometer will be given in the next section.

4.1 High resolution electron spectrometer (JLab E05-115)

Figure 8 shows a schematic figure of E05-115 setup. A new splitter magnet and a high resolution electron spectrometer (HES) will be introduced. The most important constraint for the design of the E05-115 experiment is that the successful HKS optics should not be destroyed by the introduction of a new splitter and HES. Therefore, the new splitter magnet has pentagon shaped pole to keep the optics for the K^+ arm.

The HES consists of Quad, Quad, Dipole magnets and it is basically a smaller version of the HKS. The HES will accept e' momentum of 0.55$\sim$1.0 GeV/c while the ENGE spectrometer used for E01-011 accepts 0.35 GeV/c.

Higher e' momentum allows us to use 2.5 GeV primary electron beam keeping the virtual photon energy of 1.5 GeV. The bremsstrahlung and Mϕller scattering electron background will be reduced by the high primary electron energy.

Table 1 summarizes the HES parameters. The tilt method successfully reduced background by a factor of 10000 in the E01-011 experiment and it will be applied to the HES again. The primary beam energy change should be adjusted by the e' central momentum, since the HKS central momentum is fixed at 1.2 GeV/c. The splitter magnet's dispersion is quite large at the entrance of HES, and

Table 1. HES parameters.

Configuration	Q-Q-D (50 deg bend)
Central Momentum	0.55 - 1.0 GeV/c
Momentum acceptance	> 200MeV/c
e' angle	> 2.5 deg. (for 1.0GeV/c)
Solid angle	10 msr (with SPL)
Spectrometer tilt angle	0-10 deg.

Table 2. Evolution of the JLab Hypernuclear Experiments.

	E89-009 Hall C	E94-107 Hall A	E01-011 Hall C	E05-115 Hall C
Spectrometer	SOS+ENGE+SPL	HRS+HRS+Septum	HKS+ENGE+SPL	HKS+HES+newSPL
Beam Intensity (μA)	0.7	100	24	30-100
Target Thickness (mg/cm^2)	22	100	100	100
Hypernuclear Yield ($^{12}_{\Lambda}$B$_{gs}$/hour)	0.5-0.9	2-4	8-10	(40-100)
Resolution (keV, FWHM)	750	650	<700	(300-400)
Beam Energy (GeV)	1.8	4	1.8	2.5
Virtual Photon Energy (GeV)	1.5	2.4	1.5	1.5
K central momentum (GeV/c)	1.2	2.0	1.2	1.2
e' central momentum (GeV/c)	0.3	1.6,1.9	0.35	1.0
K detection angle (deg)	0-7	6	1-13	1-13
e' detection angle (deg)	0	6	4.5	>2.5

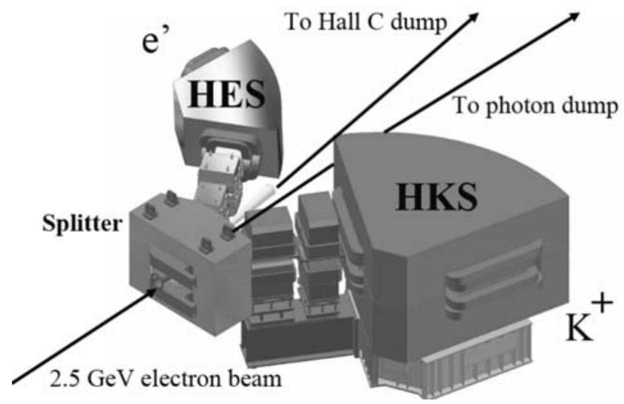

Fig. 8. The E05-115 experimental setup. The splitter magnet and e' spectrometer will be newly developed for the (e,e'K$^+$) hypernuclear spectroscopy. The 2.5 GeV primary electron beam is pre-bent in the beamline and deflected beam by the splitter will go straight to the Hall C dump.

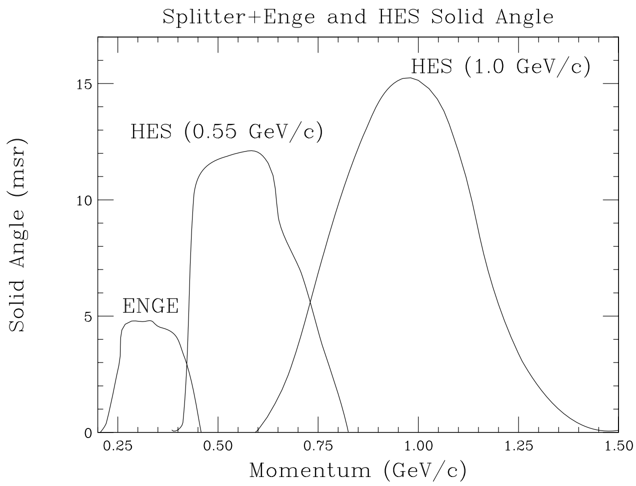

Fig. 9. Estimated HES solid angle with the ENGE spectrometer used in E01-011.

thus the HES installation position should be adjusted depending on the central e' momentum. Once a primary beam energy is determined, the position of HES is also determined. The tilt angle (0∼10 deg) will be optimized to accept the scattered electron with the emission angle of > 2.5 degrees to reduce electron background.

Using the optics code RAYTRACE, the solid angle of HES was estimated (figure 9). The expected solid angle is more than two times larger than the one of the ENGE spectrometer used in the E01-011 experiment. Furthermore, the electron associated with the virtual photon production is not uniformly but forward distributed. The gain of the virtual photon tagging efficiency is much larger than the solid angle gain. The virtual photon yield gain is expected to be as large as a factor of 8. Detail Monte Carlo simulation with a 3D magnetic field map calculated by the TOSCA is now in progress.

The HES magnets are now under construction in Japan. After the excitation test and field mapping, they will be shipped to JLab by the end of year 2007.

5 Summary and future of the JLab hypernuclear programs

The hypernuclear program at JLab was initiated by the pilot (e,e'K$^+$) hypernuclear spectroscopy E89-009 at JLab Hall C. Though E89-009 suffered from low statistics and limitations of the existing kaon spectrometer, it proved that the (e,e'K$^+$) reaction can be used for hypernuclear study and it is quite promising.

The second generation experiments were performed at Hall A (E94-107) and at Hall C (E01-011) with advanced experimental techniques such as superconducting septum magnets, a ring image Čerenkov counter (RICH), a newly designed high resolution kaon spectrometer (HKS) and a new e' spectrometer configuration (tilt method). The second generation experiments took high resolution ($<$ 700keV, FWHM) excitation energy spectra for light hypernuclei such as $^{7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{12}_{\Lambda}$B, $^{16}_{\Lambda}$N, and $^{28}_{\Lambda}$Al. For some of these data the analysis is still in a preliminary stage, discussion with theoretician starts to give interesting information.

Table 3. Time-line of the JLab Hypernuclear Programs.

Year	Hall A	Hall C
2000		E89-009 Beam
2003		HKS ship to JLab
2004	E94-107(1) Beam	JP Gov. approved HES
2005	E94-107(2) Beam	E01-011 Beam
		E05-115 approved
2006		HES Design
	HYP2006	
	Hall A, C Joint Meetings	
2007	PR07-107 submitted	HES Fabrication
200X	(E07-107 Beam)	E05-115 Beam
	4th Generation Experiment	

The third generation experiments are now in preparation making use of what we have learned from the second generation experiments. The Hall A collaboration will perform a systematic investigation about the most fundamental strangeness electro-production process: p(e,e'K$^+$)Λ reaction. Though the understanding of the elementary process is crucial for the analysis of hypernuclei, theoretical models give inconsistent predictions about p(e,e'K$^+$)Λ reaction at very forward angles. With the water fall target, ${}^{16}_{\Lambda}$N can be studied in detail concurrently with Λ electro-production. The proposal PR07-107 has been submitted to JLab PAC31.

The Hall C collaboration has decided to build a new high resolution electron spectrometer (HES) to investigate a wide mass range of hypernuclei. A proposal to investigate wide range of hypernuclei (^{6}Li, ^{7}Li, ^{9}B, ^{10}B, ^{12}C,^{51}V, ^{52}Cr, ^{89}Y targets) with a new HES spectrometer was approved as E05-115 by JLab PAC28. The wide acceptance of HES and the better matching of HKS and HES spectrometers will improve the hypernuclear yield by more than factor of 5. The tilt method which worked effectively in E01-011 will be applied to the HES in order to suppress high rate electron background from bremsstrahlung and Mϕller scattering. It is particularly important for the heavier targets.

Table 2 compiles the evolution of the JLab hypernuclear experiments from the first generation to the third generation experiments. It can be seen that better hypernuclear yield and resolution are obtained for the second generation experiments with improved experimental techniques.

The time-line of the JLab hypernuclear program is given in table 3. The Hall C collaboration will finish the fabrication of the new HES spectrometer in 2007 and HES will be shipped to JLab by the end of 2007. The E05-115 experiment will be ready for beam in year 2008. The Hall A and Hall C hypernuclear collaborations started to discuss about a possibility to merge the collaborations. The joint meetings with theoreticians are already held twice at Mainz and FIU in 2006. The forth generation hypernuclear experiments will be carried out by the merged JLab hypernuclear collaboration.

References

1. F. Dohrmann, *et al.*, Phys. Rev. Lett. **93**, (2004) 242501.
2. T. Miyoshi, *et al.*, Phys. Rev. Lett. **90**, (2003) 232502.
3. L. Yuan, *et al.*, Phys. Rev. C **73**, (2006) 044607.
4. O. Hashimoto, L. Tang, J. Reinhold, and S.N. Nakamura spokespersons, *JLab E01-011 Proposal* (2001).
5. F. Garibaldi, S. Frullani, P. Markowitz, and J.J. LeRose spokespersons, *JLab E94-107 Proposal* (1994).
6. O. Hashimoto and H. Tamura, *Progress in Particle and Nuclear Physics* **57** (2006) 564.
7. Y. Akaishi, H. Harada, S. Shinmura and K.S. Myint, *Phys. Rev. Lett.* **84** (2000) 3539.
8. F. Garibaldi, M. Iodice, P. Markowitz, and J.J. LeRose spokespersons, *JLab PR07-012 Proposal* (2007).
9. O. Hashimoto, L. Tang, J. Reinhold, and S.N. Nakamura spokespersons, *JLab E05-115 Proposal* (2005).