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HYPERNUCLEAR SPECTROSCOPY WITH ELECTRON BEAMS AND FUTURE PROSPECTS

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Hypernuclear spectroscopy with electron beams was initiated by JLab E89-009 at JLab Hall-C in 2000. After the successful pilot experiment, improved experiments introducing new experimental techniques such as RICH, new spectrometers (HKS, HES) and optimized configuration of electron spectrometer were performed at JLab Hall-A and Hall-C. In this article, progresses of the hypernuclear spectroscopy with electron beams in this decade are reviewed and future prospects of this research subject at JLab and MAMI-C are discussed.

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1. Introduction

Hypernuclear physics plays a unique role in our understanding of the strong interaction which is described by QCD in short range and meson exchange models in long range interaction. Though recent progress of lattice QCD is significant, phenomenological meson exchange models, which are based on a lot of nucleon-nucleon scattering data, are quite important. A typical energy and size scales of hypernuclear physics are GeV and 0.1 fm which exist between scales for perturbative QCD and meson models. We can extend our knowledge from the nuclear force to the baryon force based on flavor SU(3) symmetry by studying hypernuclei since they contain s-quark in addition to u and d quarks which make up our world.

After the first discovery of a hypernucleus in emulsion more than half a century ago, hypernuclei have been extensively studied experimentally as well as theoretically. Most of hypernuclear study has been carried out for Λ hypernuclei which contain the lightest hyperon, Λ. So far over 40 species of Λ hypernuclei, a Σ hypernucleus and a few double hypernuclei ($S = -2$) were studied. Λ is free from nucleons' Pauli exclusion principle and thus it serves as a probe in deep inside of a nucleus where investigation with normal nucleons is very difficult. It is a fundamental question whether we can treat a Λ as a single particle even in deep inside of a nucleus, or we should take quark degree of freedom into account explicitly. At the same time, nuclear structure could be modified by inclusion of Λ as an impurity. Hypernuclear study gives a chance to investigate behavior of matter under ultra-high density (nuclear density).

From the 1970s, the spectroscopic studies of Λ hypernuclei have been carried out extensively by using meson beams at CERN-PS, BNL-AGS and KEK-PS. It is very important to have a good energy resolution for spectroscopic study. With the (K^-, π^-) reactions, a few MeV energy resolution was achieved at BNL and it was improved to be 1.5 MeV at KEK-PS with a new superconducting kaon spectrometer (SKS) by the (π^+, K^+) reaction. The gamma-ray spectroscopy was established by the introduction of the HYPERBALL for p-shell hypernuclei produced by meson beams in late 90s. The hypernuclear gamma-ray spectroscopy achieved a few keV resolution for level spacings of p-shell hypernuclei. Study for hyperon-nucleon potential for p-shell hypernuclei progressed greatly by the hypernuclear gamma-ray spectroscopy. However, the importance of the reaction spectroscopy, which gives absolute binding energies of Λ, and production cross sections, increased more as a complementary measurement and thus its energy resolution needs to be improved.

In the last year of the 20th century, a novel technique of the hypernuclear reaction spectroscopy with an electron beam was initiated at Thomas Jefferson National Accelerator Facility (JLab).

In the following sections, features of the (e,e'K^+) spectroscopy, and its progress in this decade are explained.

2. *The (e,e'K^+) reaction*

Spectroscopic study of Λ hypernuclei by the (e,e'K^+) reaction (Fig. 1) has unique advantages over those through meson-induced reactions such as (π^+, K^+) and (K^-, π^-).

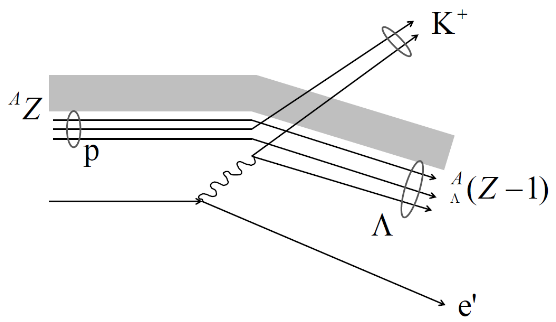

Fig. 1. Feynman diagram of the hypernucleus production with the (e,e'K^+) reaction.

- The (e,e'K^+) reaction produces strangeness by the electromagnetic interaction while meson induced reactions do it by the strong interaction. Electromagnetic interaction is well known and thus the electro-magnetic production of strangeness can be cleanly studied separating well known parts.

- While the (π^+, K^+) and (K^-, π^-) reactions convert a neutron to a Lambda, the (e,e'K^+) reaction converts a proton to a Lambda. Therefore, new species of hypernuclei can be produced. Comparing hypernuclei produced by the (e,e'K^+) reaction to the ones produced by the (π^+, K^+), (K^-, π^-) reactions, charge symmetry breaking of YN interaction can be studied.

- The electromagnetic interaction can populate both spin-flip and spin-nonflip states while spin-zero particles such as π and K populate only spin-nonflip states in forward angles.

- Electrons are obtained as a primary beam, but meson beams need to be produced as secondary beams from a proton beam. High intensity and high quality primary beam contributes to good energy resolution of the missing mass spectroscopy.

In 1990s, hypernuclei were already electromagnetically produced in the ES132 experiment at the Institute for Nuclear Study (Univ. of Tokyo) [1] by ^{12}C (γ, K^+) $^{12}_{\Lambda}$B reaction and in the E91-016 experiment at the JLab Hall-C by ^{3,4}He(e,e'K^+)$^{3,4}_{\Lambda}$H reactions [2], but resolutions were very poor and spectroscopic study could not be applied.

The sub-MeV energy resolution is the key for the successful hypernuclear spectroscopic experiments at present. The first (e,e'K^+) hypernuclear spectroscopic experiment was carried out successfully at the Jefferson Lab's (JLab) Hall C in the spring of 2000 by the E89-009 (HNSS, HyperNuclear Spectrometer System) collaboration in order to prove the principle of the (e,e'K^+) hypernuclear spectroscopy.

3. *Spectroscopic studies of hypernuclei at JLab*

There are many advantages for the (e,e'K^+) hypernuclear spectroscopy, but its experimental feasibility had not been unanimously accepted before the success of the E89-009 at JLab. Difficulties of the experiment can be summarized as follows:

- Huge electron background from bremsstrahlung and Møller scattering is expected in the electron spectrometer.

- Electromagnetic production cross section of production of hypernuclei is much smaller than the mesonic production.

- Coincidence measurement is necessary of the scattered electron and electroproduced K^+.

Severe electron background deteriorates signal-to-noise ratio and detectors operating under very high background are needed. Small cross section and coincidence measurement result in low statistics. Therefore, careful design of the experiment and high quality continuous electron beam are essential.

Before the upgrade of MAMI-C at Mainz, only CEBAF at JLab could provide such a high-quality electron beam which could be used for the (e,e'K^+) hypernuclear spectroscopy. Here are the requirements for the electron beam:

- The electron energy should be higher than $\simeq$1.5 GeV to produce hypernuclei.
- In order to obtain a hypernuclear mass as a missing mass, the electron beam must have well defined energy, and its energy and the momenta of scattered electron and K^+ should be measured precisely. Coincidence measurement of e' and K^+ limits statistics and further measuring of the beam energy causes a serious production-rate problem. Therefore, the electron beam energy needs to be precisely known without measuring it by a spectrometer.
- A continuous beam is required for the coincidence measurement. A pulsed beam which gives very high instantaneous intensity makes too large accidental coincidence rate and the detector operation under such an environment limits the average beam intensity significantly.

CEBAF provides high energy (up to 6 GeV), high intensity (up to 100μA), small emittance (better thas 10^{-9}m·rad) continuous electron beam. The electron beam energy is known with a precision better than 10^{-4} which corresponds to a few 100 keV and thus it is not necessary to be measured by a beamline spectrometer.

Taking advantages of CEBAF's electron beam, the JLab E89-009 experiment was performed in 2000. The existing spectrometer, Short Orbit Spectrometer (SOS), was used as a kaon spectrometer and an ENGE type split-pole spectrometer was installed in JLab Hall-C as a scattered electron spectrometer (Fig. 2).

The E89-009 experiment demonstrated the potential of the (e,e'K^+) reaction, obtaining a hypernuclear mass spectrum in the ^{12}C(e,e'K^+)$^{12}_{\Lambda}$B reaction [3, 4]. It achieved sub-MeV energy resolution for the first time in hypernuclear reaction spectroscopy (Fig. 3).

Though the E89-009 experiment was a great success as a pilot experiment to prove the principle of the (e,e'K^+) spectroscopy, it made clear that an improvement of the hypernuclear spectrometer system is vitally needed to explore fully the potential of this new experimental technique. A new high-efficiency high-resolution kaon spectrometer and a method to reduce electron background had to be developed.

Two different experimental approaches were taken as the second generation hypernuclear experiments at JLab. One is the E94-107 experiment in Hall A [5] and the other is the E01-011 experiment in Hall C [6].

The E94-107 experiment used two high-resolution spectrometers (HRS) which are the standard spectrometers at the JLab Hall A for both kaons and electrons. The E01-011 experiment designed a new high-resolution kaon spectrometer (HKS),

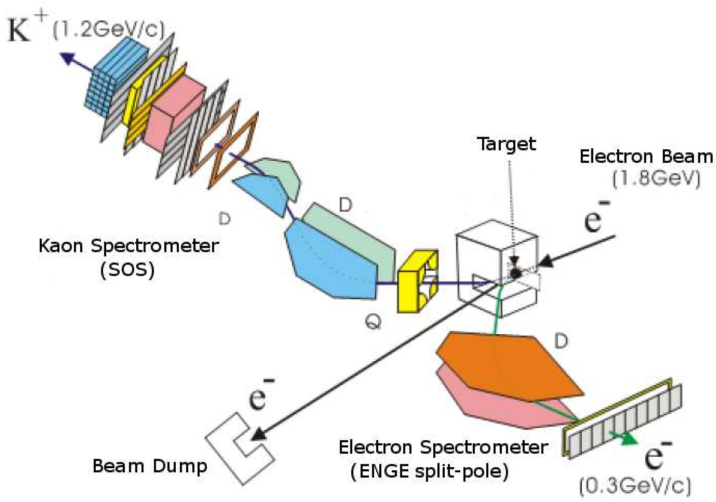

Fig. 2. Experimental setup of the E89-009 (HNSS) experiment. Hall-C's standard spectrometer SOS was used as a kaon spectrometer. As an electron spectrometer, the ENGE-type split-pole spectrometer was installed. The target was placed in a charge separation dipole magnet (splitter).

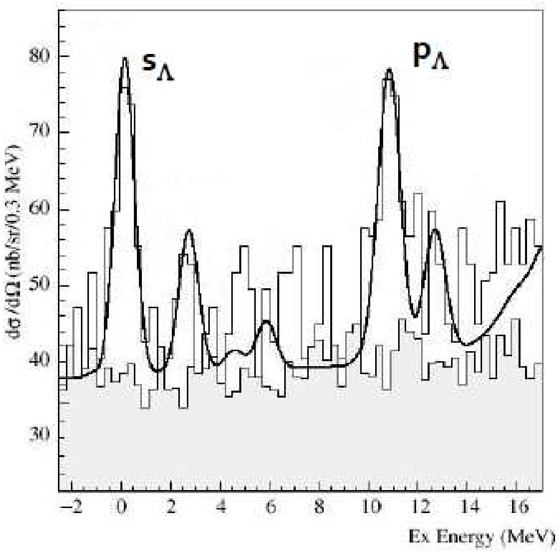

Fig. 3. Missing mass spectrum of ${}^{12}_{\Lambda}B$ obtained by the JLab E89-009 experiment [3, 4].

dedicated to this program and the ENGE split-pole spectrometer used in the first generation experiment was re-used in Hall C.

They were based on basically the same experimental principle, but different choices of spectrometer system resulted in different kinematic conditions (see Table 1).

TABLE 1. Kinematic conditions for the second generation hypernuclear experiments, E94-107 and E01-011 at JLab (vertically tilted to the dispersion plane).*

Experiment	E_e (GeV)	E_γ (GeV)	$P_{e'}$ (GeV/c)	P_K (GeV/c)	$\theta_{e'}$	θ_K
E94-107	4.0	2.2	1.8	2.0	6°	6°
E01-011	1.8	1.5	0.3	1.2	*4.7°	1°–13°

HRS has a longer orbit compared to SOS and HKS. Therefore higher kaon momentum (2 GeV/c) is required to avoid serious K^+ decay loss ($c\tau \sim$ 4m). In order to place both kaon and electron spectrometers at forward angles where the virtual photon yield is maximum, E94-107 adopted super-conducting septum magnets and E01-011 used a normal-conducting splitter magnet. These magnets were similarly used to separate different charged particles. The septum magnets allow to separate optically e' and K^+ spectrometers at the cost of solid angles. On the other hand, the single splitter magnet has large solid angles, but e' and K^+ spectrometer systems are optically connected and thus their tuning is more complicated.

In the following part, advantages and demerits of each setup and their achievements will be reviewed.

3.1. E94-107, JLab Hall-A hypernuclear experiment

Figure 4 shows a schematic drawing of the E94-107 setup. As the electron and kaon spectrometers, well established HRSs in Hall A were used. In order to measure forward e' and K^+ simultaneously, superconducting septum magnets were constructed.

Though many technical achievements were realized to perform the experiment, two major developments should be noted here. One is the Ring Image Cherenkov counter (RICH) [7] to select 2.0-GeV/c K^+s and the other is the waterfall target.

Figure 5 shows coincidence time spectra (the time difference between electron scattering and K^+ emission at the target) without (left) and with (right) K^+ selection by RICH. They show CEBAF's 2 ns beam bunch structure as well as π^+, K^+ and p peaks. After selecting K^+ by RICH, π^+ rejection factor was about 1000. Introduction of RICH enabled to select K^+s cleanly though their momentum was much higher (2.0 GeV/c) than the kaon momentum (1.2 GeV/c) in E01-011. Combination of HRS with higher beam energy, momenta (E_e, $P_{e'}$, P_K) and clean selection of kaon by RICH made it possible to reduce accidental background. Therefore, the signal-to-noise ratio (S/N) was drastically improved comparing with E89-009 even though handling and getting better resolution of higher momenta particle is generally more difficult.

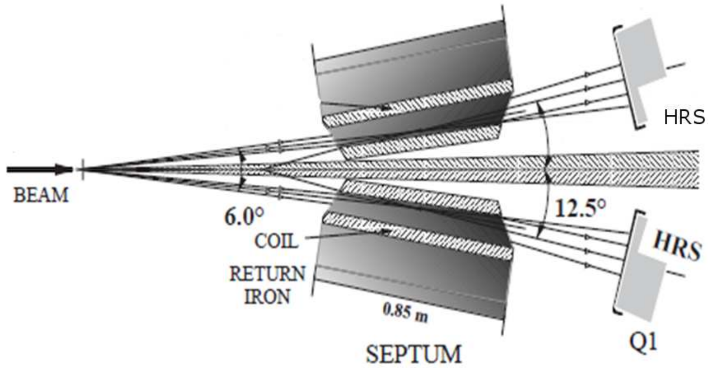

Fig. 4. Setup of E94-107 at JLab Hall A.

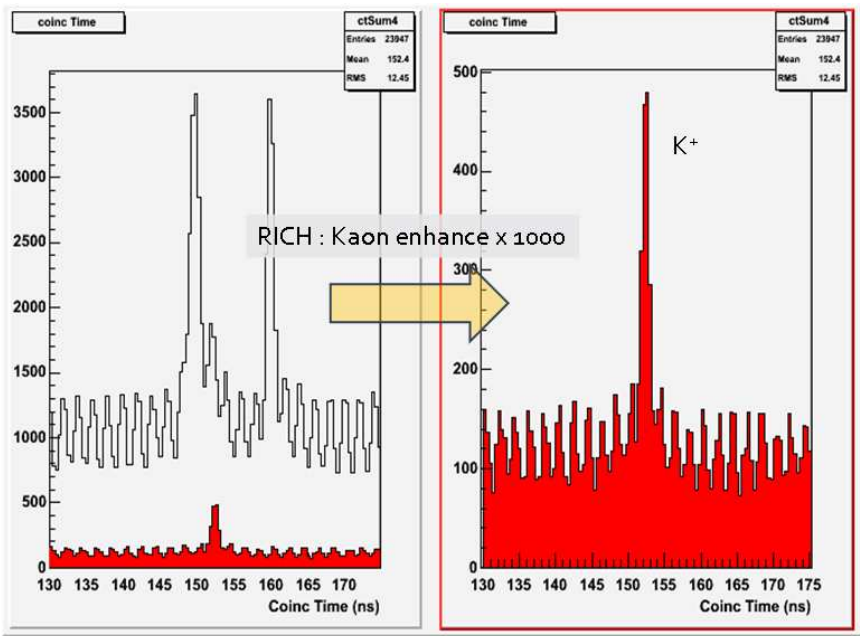

Fig. 5. Coincidence time spectra without and with RICH K^+ selection.

The waterfall target was prepared as an ^{16}O target for the ^{16}O (e,e'K$^+$) $^{16}_{\Lambda}$N experiment and as a proton target for the energy calibration with the p(e,e'K$^+$)Λ reaction.

The E94-107 experiment took successfully data for p-shell hypernuclei such as $^{12}_{\Lambda}$B, $^{16}_{\Lambda}$N and $^{9}_{\Lambda}$Li with an energy resolution of $\sim$ 700 keV (FWHM) in 2004 and 2005 [8, 9].

3.2. E01-011, JLab Hall-C hypernuclear experiment (HKS)

In JLab Hall-C, an experiment with natural upgrade of the first (e,e'K^+) hypernuclear spectroscopy was carried out. The E01-011 experiment (HKS) improved the pilot E89-009 experiment in the following two points.

- A new kaon spectrometer, HKS, was designed with an intention to realize both large detection efficiency and high-resolution, simultaneously.
- A new experimental configuration, the 'tilt method', was adopted so that very forward electrons associated with bremsstrahlung process can be avoided and therefore a higher luminosity ($\propto$ target thickness $\times$ beam intensity) can be accepted.

Since the energy resolution and hypernuclear yield were limited by the kaon spectrometer in E89-009, a new kaon spectrometer (HKS) was designed for this program. It was a short-orbit spectrometer and the K^+ decay loss was less severe than with HRS. Therefore, the K^+ central momentum was set at 1.2 GeV/c. Lower momentum made kaon identification easier so that conventional aerogel and water Cherenkov counters were used in the trigger level to select kaons. Lower momentum contributes also to improve the momentum resolution. The relative resolutions of HRS in Hall A and newly developed HKS in Hall C are similar ($\Delta p/p \sim 2 \times 10^{-4}$), however, momentum resolution is twice better for HKS since its central momentum is roughly two times smaller. Construction of a large solid angle spectrometer is much easier for lower momentum since the smaller rigidity of particles allows to make the magnets smaller.

However, larger solid angles for K^+ and e' result in higher accidental coincidence rates and that would deteriorate S/N ratio. Therefore, a new technique is necessary to reduce the background rate drastically.

In the pilot experiment, zero-degree electrons were measured to maximize the virtual photon yield. However, it caused serious electron background in the electron spectrometer. The counting rate of the e' spectrometer (ENGE) in E89-009 was over 200 MHz and it limited usable beam intensity and target thickness. In E01-011, the ENGE spectrometer was vertically tilted from the dispersion plane to avoid very forward bremsstrahlung and Møller electrons (tilt method). Virtual photon yield is reduced by this tilt method, however, background rate is highly suppressed so the virtual photon loss can be compensated by higher beam current and thicker target. The 200 MHz electron background in E89-009 was reduced to be only 1 MHz in E01-011 though luminosity was more than 200 times higher.

In 2005, the second generation experiment in JLab Hall C, E01-011, took data for ${}^{12}_{\Lambda}$B, ${}^{7}_{\Lambda}$He and ${}^{28}_{\Lambda}$Al which is the first beyond p-shell hypernucleus studied by the (e,e'K^+) reaction and it proved that HKS achieved the designed performance and the tilt method successfully reduced the electron background [11]. The information about the E01-011 setup and preliminary results of E01-011 are discussed in detail in Ref. [12].

3.3. Highlights of E94-107 and E01-011, the second generation experiments

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

The ^{12}C target is frequently used as a reference for hypernuclear spectroscopy. Since there is no neutron target, n(π,K)Λ, Σ^0 reaction cannot be used for the absolute missing-mass calibration with the well-known Λ, Σ^0 masses. Therefore, all binding energies of (π,K) hypernuclear reaction spectroscopy depend on the old emulsion data of $^{12}_{\Lambda}$C.

On the other hand, (e,e'K$^+$) spectroscopy can calibrate the absolute missing-mass scale by p(e,e'K$^+$)Λ, Σ^0 reaction with the Λ, Σ^0 masses. It is quite important to check consistency of $^{12}_{\Lambda}$C and $^{12}_{\Lambda}$B emulsion data by a totally different experimental technique.

Figure 6 shows missing-mass spectra of $^{12}_{\Lambda}$C and $^{12}_{\Lambda}$B. The $^{12}_{\Lambda}$C spectrum (top)

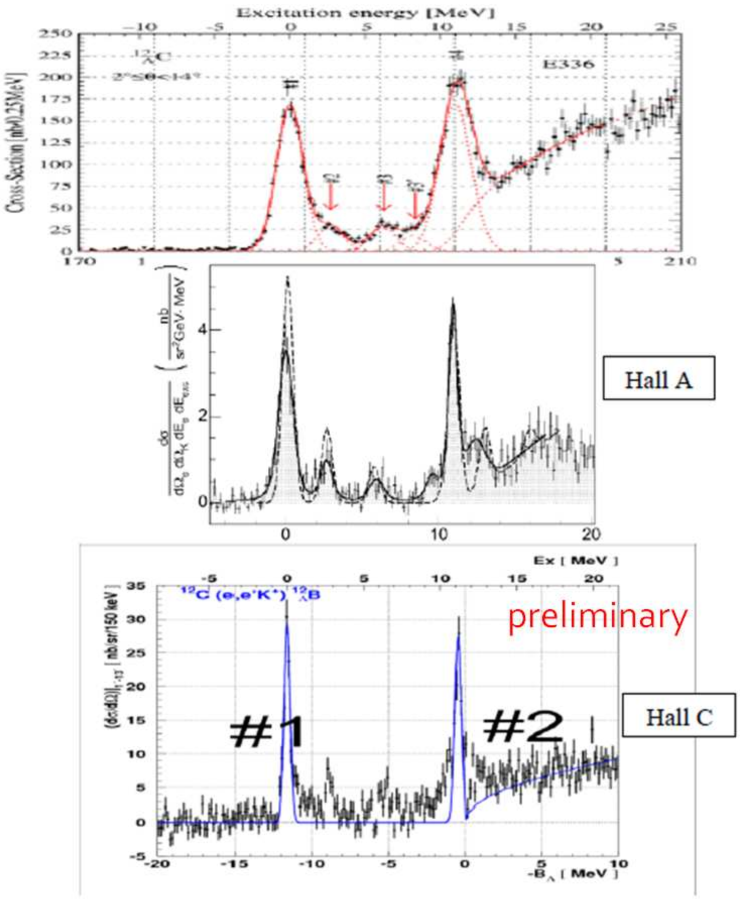

Fig. 6. Missing mass spectra of $^{12}_{\Lambda}C$ and $^{12}_{\Lambda}B$. Top spectrum is for $^{12}_{\Lambda}C$ obtained in the KEK-PS E336 experiment by the (π,K) reaction [13]. Center and Bottom ones are $^{12}_{\Lambda}B$ measured by E94-107 (JLab Hall A)[9] and E01-011 (preliminary, JLab Hall C)[10, 11, 12], respectively.

was obtained in the KEK-PS E336 experiment by the (π,K) reaction with an energy resolution of ~ 2 MeV [13]. The ${}^{12}_{\Lambda}$B spectra with an energy resolution of 0.65 MeV (center) and with 0.5 MeV resolution (bottom) were measured by E94-107 and E01-011, respectively. For the ${}^{12}_{\Lambda}$B spectra, sub-MeV resolution enabled us to see core excited states clearly in addition to two major peaks which correspond to the states with a Λ in s-shell and p-shell. Those two ${}^{12}_{\Lambda}$B spectra are more or less consistent. Binding energy of ${}^{12}_{\Lambda}$B ground state is $11.40 \pm 0.01(stat) \pm 0.14(sys)$ MeV (E01-011 preliminary) [10] and it is consistent to the emulsion result (11.45± 0.07 MeV) [15]. Emulsion and the (e,e'K$^+$) spectroscopy root in totally different experimental principles and it is quite important to confirm that they give consistent values.

^{9}Be (e,e'K$^+$) ${}^{9}_{\Lambda}$Li, ^{16}O (e,e'K$^+$) ${}^{16}_{\Lambda}$N in E94-107

E94-107 measured p-shell hypernuclei, ${}^{9}_{\Lambda}$Li and ${}^{16}_{\Lambda}$N hypernuclei, with ^{9}Be and ^{16}O targets (Figs. 7, 8) [16, 17].

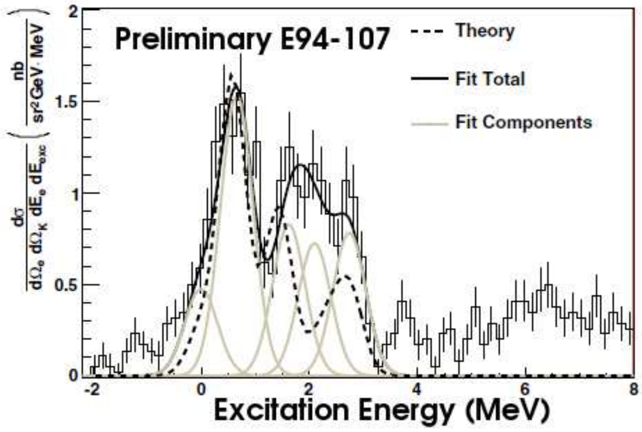

Fig. 7. Preliminary excitation energy spectrum of ${}^{9}_{\Lambda}$Li obtained in E94-107 [16].

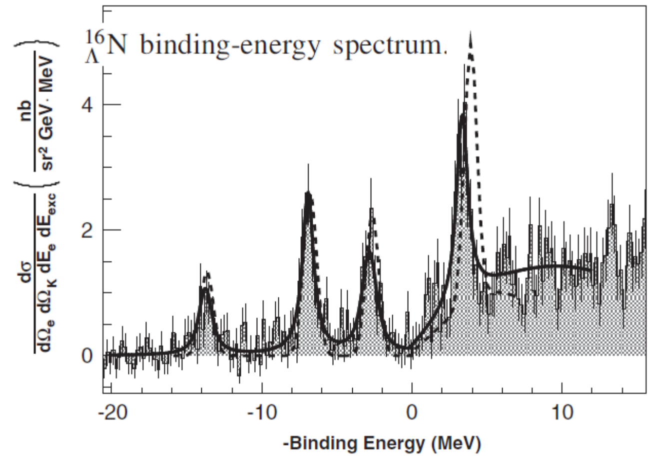

Fig. 8. Binding energy spectrum of ${}^{16}_{\Lambda}$N obtained in E94-107 [17].

The preliminary ${}^{9}_{\Lambda}$Li excitation spectrum shows overlapped peaks and deconvolution of the spectrum was tried with an assumed experimental resolution of 710 keV. Detailed analysis with theories and radiative corrections to the spectrum are in progress.

The ^{16}O target was prepared in a form of water fall target with a proton target for the absolute missing-mass calibration. Clear four peaks which correspond to $p^{-1}_{1/2} \otimes s_\Lambda, p^{-1}_{3/2} \otimes s_\Lambda, p^{-1}_{1/2} \otimes p_\Lambda$ and $p^{-1}_{3/2} \otimes p_\Lambda$ were observed. Preliminary result indicates that binding energies look understandable by theories except for $p^{-1}_{3/2} \otimes p_\Lambda$ (fourth peak) state. Detailed comparison between ${}^{16}_{\Lambda}$N and its mirror hypernucleus ${}^{16}_{\Lambda}$O studied by (π, K) reaction as well as analysis with theoretical calculations are in progress.

^{28}Si (e,e'K$^+$) ${}^{28}_{\Lambda}$Al and ^{7}Li (e,e'K$^+$)${}^{7}_{\Lambda}$He in E01-011

One of large advantages of the (e,e'K$^+$) hypernuclear study is that it can use a thin target because primary electron beam is much more intense than secondary meson beams. Thinner target makes smaller energy straggling in the target and thus it contributes to the better energy resolution. Furthermore, it makes easier to use precious isotopically enriched targets. Before the JLab E01-011 experiment in Hall C, the (e,e'K$^+$) hypernuclear study had been applied only to p-shell hypernuclei. E01-011 tried to measure beyond the p-shell hypernuclei by the ^{28}Si(e,e'K$^+$)${}^{28}_{\Lambda}$Al reaction with a 100 mg/cm^2-thick enriched ^{28}Si target which was prepared by the high energy vibrational powder plating method (HIVPP) [18].

The electron background becomes severer for heavier target since bremsstrahlung rate is roughly in proportional to Z^2. Newly introduced configuration of electron spectrometer (tilt method) effectively suppressed the background and enabled us to take data for the ^{28}Si target. Figure 9 shows preliminary missing-mass spectrum of ${}^{28}_{\Lambda}$Al taken by the ^{28}Si (e,e'K$^+$) ${}^{28}_{\Lambda}$Al reaction in JLab E01-011 and ${}^{28}_{\Lambda}$Si by ^{nat}Si (π,K)${}^{28}_{\Lambda}$Si in KEK-PS E104a [10, 11]. It should be noted that ${}^{28}_{\Lambda}$Si might be contaminated by its isotopes since the target was natural Si (natural abundance of ^{28}Si is 92.2%). Global structures of ${}^{28}_{\Lambda}$Al and ${}^{28}_{\Lambda}$Si look similar, but slight difference of binding energies of the ground states and level spacings are under discussion. Final check of systematic errors and distortion of energy scale by chance in terms of experimental analysis and theoretical efforts to understand the possible difference are in progress.

The E01-011 experiment observed the ground state of ${}^{7}_{\Lambda}$He clearly for the first time (Fig. 10). It was known that charge symmetry breaking (CSB) terms in ΛN potential are necessary to explain the mass difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He measured by emulsion. Recent progress of cluster calculation ($\alpha + N + N + \Lambda$) enabled us to apply this potential to calculate $A = 7,\ T = 1$ iso-triplet hypernuclei, ${}^{7}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li* and ${}^{7}_{\Lambda}$Be. The ground state masses of ${}^{7}_{\Lambda}$Li* and ${}^{7}_{\Lambda}$Be were already known, however old emulsion data of ${}^{7}_{\Lambda}$He was too poor to extract its binding energy reliably. The E01-011's new measurement of the ${}^{7}_{\Lambda}$He ground state makes it possible to study

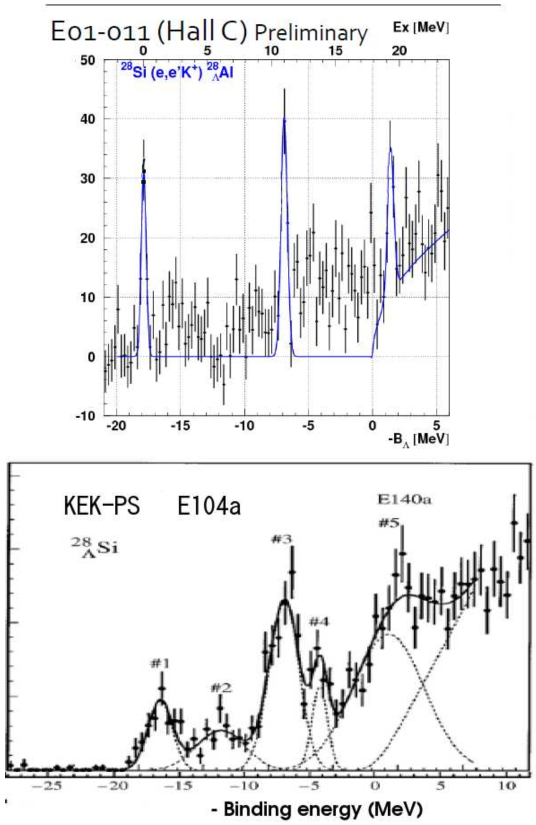

Fig. 9. Preliminary missing-mass spectrum of $^{28}_{\Lambda}$Al by E01-011 and $^{28}_{\Lambda}$Si by KEK-PS E140a [10, 11].

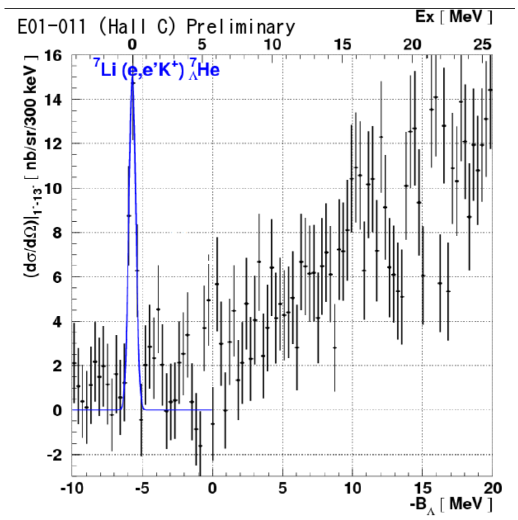

Fig. 10. Preliminary missing-mass spectrum of $^{7}_{\Lambda}$He by E01-011 [10, 11].

CSB effect systematically. A comparison between recent cluster calculation [19] and the ground state energies of the $A = 7$, $T = 1$ hypernuclear iso-triplet indicates that inclusion of the CSB term in the ΛN potential makes agreement worse between calculation and data, though the CSB term is necessary for the $A = 4$ system. This may be due to too naive treatment of the CSB term in YN potential or problem of the old $A = 4$ hypernuclear data. Comparison between the cluster calculation for $A = 10$ system $(\alpha + \alpha + \Lambda + N)$ and hypernuclear data will give more information. Experimental plans to re-examine the $A = 4$ system will be discussed later.

3.4. E05-115, the third generation JLab Hall-C experiment (HKS-HES)

During the beam time of the second generation experiment E01-011 in Hall C, a new proposal was submitted to JLab PAC28 and accepted as E05-115 [20]. The third generation experiment, E05-115 adopted a new high-resolution electron spectrometer (HES) with a new splitter magnet (SPL) in addition to the established spectrometer HKS and the tilt method used in the second generation experiment, E01-011.

Introduction of the new HES and SPL in addition to HKS allowed us to measure medium heavy ${}^{52}_{\Lambda}$V hypernucleus of which electron background is > 10 times more severe than the ${}^{12}_{\Lambda}$B measurement. The data taking of E05-115 with HKS and HES was successfully finished in 2009.

A schematic figure of the E05-115 setup is shown in Fig. 11. Both of HKS and HES were positioned at angles as forward as possible, but avoided the 0° electrons

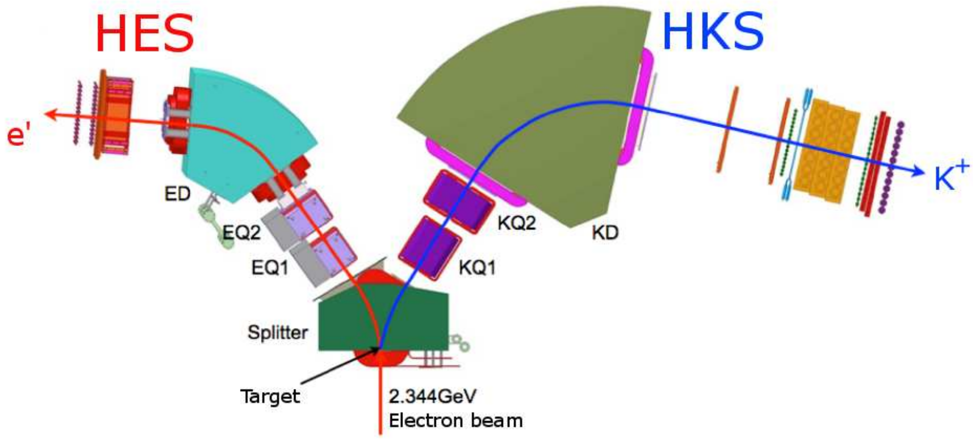

Fig. 11. Schematic drawing of the E05-115 setup. A new High-resolution Electron Spectrometer (HES) and a new SPLitter magnet (SPL) were introduced. All spectrometer components (HKS, HES, SPL) and a pre-chicane beamline were designed for the hypernuclear experiment.

and positrons. HKS for the kaon arm has a QQD configuration with a momentum resolution of 2×10^{-4} at 1.2 GeV/c and a solid angle acceptance of ~ 10 msr, when it is used with the newly designed SPL. The design principle of HES follows that of HKS, with a QQD configuration. The charge separation magnet, SPL, was also newly designed to make best matching between HKS and HES. The tilt method which worked successfully in E01-011 was adopted again for HES. The unused electron beam which was bent in SPL should be guided to the Hall's beam dump. The post beamline was used in E01-011 for this purpose but the beam was scattered in the target and post beam spatially diverged. It became one of serious background sources in E01-011. For E05-115, a pre-chicane beamline was newly constructed in Hall C. Beam transport can be done much more cleanly before the target, however, the photon dump had to be prepared separately from the Hall-C dump and special care to beam orbit tune was necessary to control directions of four output beams from the SPL magnet (scatter e', unused primary beam, bremsstrahlung photon and K^+) .

In E01-015, CH_2 and H_2O targets were prepared for mass calibration and physics data for ^{7}Li, ^{9}Be, ^{10}B, ^{12}C, and ^{52}Cr targets were acquired.

Figure 12 shows a preliminary missing-mass spectrum for the CH_2 target. Though, serious optics tunings of spectrometers were not yet applied, the Λ and Σ^0 peaks were clearly seen with a resolution of 1.5 MeV (rms). This spectrum proves that all detectors and spectrometer systems are basically working as we expected, even though further detailed analyses are necessary to achieve designed resolution (< 500 keV, FWHM) for the hypernuclear masses.

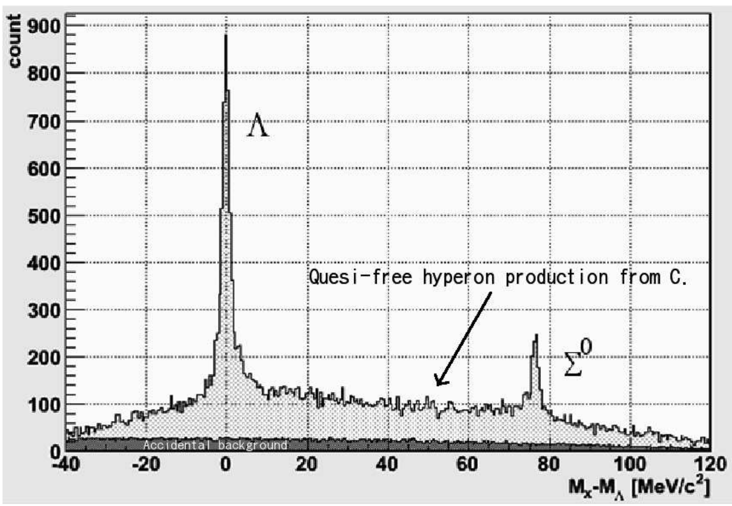

Fig. 12. Missing mass spectrum for the CH_2 target with a subtraction of Λ's mass. Hatched region refers to the accidental background. Remaining events under the hyperon peaks are originating from the quasi-free hyperon production from carbon.

3.5. Future plans for hypernuclear study with electron beams

At JLab, Hall-A and Hall-C hypernuclear collaborations have started to form a new collaboration. A new measurement of an angular dependence of ^{16}O (e,e'K$^+$) $^{16}_{\Lambda}$N and elementary strangeness production process p (e,e'K$^+$) Λ was proposed and approved [21]. Angular dependence and momentum transfer q^2 dependence of hypernuclear production by the (e,e'K$^+$) reaction are affected by 1) the transition operator which describes the elementary process and 2) the structure of the target nucleus and hypernuclear states. Careful comparison between electro-production of a hypernucleus and the elementary process will shed light on separation of the above effects. This experiment aims to measure the above processes simultaneously with the water fall target developed in Hall A.

Another interesting future plan is the decay pion spectroscopy of electro-produced hypernucleus.

So far, the (e,e'K$^+$) reaction has been used only for reaction spectroscopy. As a next step, measurement of decay products from the hypernuclei was proposed [22]. Figure 13 shows the experimental principle of spectroscopy of the decay pion. By adjusting target thickness, the hypernuclei produced by the (e,e'K$^+$) reaction directly or indirectly after nuclear fragmentation can be stopped in the target. A fraction of them undergo two-body decay by the weak interaction to a normal nucleus and a pion. Knowing the normal nucleus and pion masses, only pion momentum is necessary to obtain the hypernuclear mass. This method can be applied to hypernuclei produced by any reaction, but the (e,e'K$^+$) reaction enables us to use a very thin target and thus better energy resolution can be achieved.

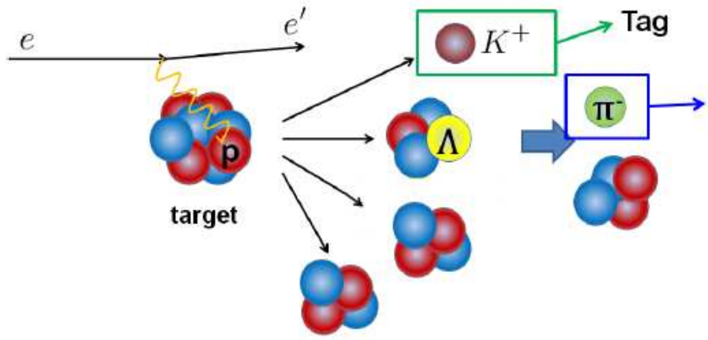

Fig. 13. Principle of measurement of the decay pion spectroscopy.

This method has a potential to study light hypernuclei very precisely. As already mentioned, $A = 4$ hypernuclear masses are important parameters to discuss the CSB term in ΛN potential, however, the masses measured by emulsion technique are not very reliable. For example, $^{4}_{\Lambda}$H mass was measured in $\pi^- pt$ and $\pi^- dd$ modes, however, the Λ binding energies measured by these channels are not consistent within statistical errors. Therefore, it is meaningful to achieve the ∼10 keV accuracy by a different experimental technique. The ${}^4_\Lambda$H hypernucleus is expected to be produced dominantly as a hyperfragment from light hypernuclei and thus it is a good candidate for the first target of the pilot experiment.

A pilot experiment of the decay pion spectroscopy is planned to run concurrently with the next (e,e'K$^+$) experiment at JLab since an additional pion spectrometer can co-exist with the (e,e'K$^+$) setup, and data taking can be performed simultaneously.

Another important progress of the electro-production of hypernuclei is the upgrade of MAMI-C accelerator at the Institut für Kernphysik, Mainz University. Now, MAMI-C provides upto 1.5-GeV electron beam and the electro-production of strangeness can be studied there. KaoS spectrometer (Fig. 14) was set up to be a double-arm single-dipole spectrometer by the A1 hypernuclear collaboration [23].

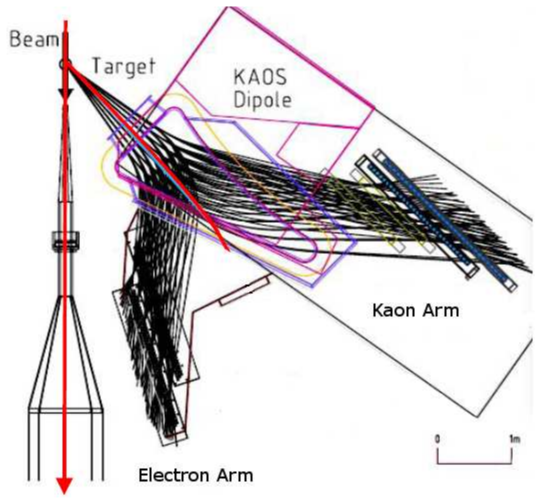

Fig. 14. KaoS spectrometer installed at MAMI-C, Mainz University.

Performance of the kaon arm of KaoS was already studied with the well-established Spek-B spectrometer as an electron spectrometer by the p(e,e'K$^+$) reaction. The Λ, Σ^0 missing mass spectrum was already obtained [23]. Electron arm with a newly developed scintillation fiber detector is now under commission. Combined with the upgraded MAMI-C accelerator and KaoS spectrometer, elementary process of the strangeness electro-production, the (e,e'K$^+$) spectroscopy of light hypernuclei and the decay pion spectroscopy will be studied. KaoS at MAMI-C will provide precious opportunity to study the electro-production of hypernuclei with its relatively flexible beam time allocation.

4. *Summary*

Hypernuclear study with electron beams was initiated at JLab and many experimental techniques have been developed after the first (e,e'K$^+$) hypernuclear spectroscopy experiment in 2000. J-PARC at Tokai has recently started to provide slow extracted beam and new results on hypernuclear physics with high-intensity meson beams will be obtained soon. It is very important to make hypernuclear study with electron beams also active to provide new results. These results will be complementary and will advance the hypernuclear study. In the next decade, JLab and MAMI-C will play key roles in this research area.

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HIPERNUKLEARNA SPEKTROSKOPIJA S ELEKTRONSKIM SNOPOM I OČEKIVANJA

U 2000. započela je hipernuklearna spektroskopija s elektronskim snopom programom E89-009 u hali C Th. Jefferson Laboratorija (JLab-a). Nakon uspješnog početnog mjerenja slijedila su poboljšanja uvođenjem novih eksperimentalnih metoda, kao RICH, novih spektrometara (HKS, HES) i boljim položajem elektronskog spektrometra u halama A i C u JLab-u. U ovom se članku daje pregled napretka hipernuklearne spektroskopije s elektronskim snopom u proteklom desetljeću i raspravljaju očekivanja tih istraživanja u JLab-u i u MAMI-C.