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Hypernuclear Spectroscopy at JLab Hall C

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Abstract

Since the 1st generation experiment, E89-009, which was successfully carried out as a pilot experiment of (e,e'K+) hypernuclear spectroscopy at JLab Hall C in 2000, precision hypernuclear spectroscopy by the (e,e'K+) reactions made considerable progress. It has evolved to the 2nd generation experiment, E01-011, in which a newly constructed high resolution kaon spectrometer (HKS) was installed and the "Tilt method" was adopted in order to suppress large electromagnetic background and to run with high luminosity. Preliminary high-resolution spectra of ${}^{7}_{\Lambda}$He and ${}^{28}_{\Lambda}$Al together with that of ${}^{12}_{\Lambda}$B that achieved resolution better than 500 keV(FWHM) were obtained. The third generation experiment, E05-115, has completed data taking with an experimental setup combining a new splitter magnet, high resolution electron spectrometer (HES) and the HKS used in the 2nd generation experiment. The data were accumulated with targets of

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^{7}Li, ^{9}Be, ^{10}B, ^{12}C and ^{52}Cr as well as with those of CH_2 and H_2O for calibration. The analysis is under way with particular emphasis of determining precision absolute hypernuclear masses.

In this article, hypernuclear spectroscopy program in the wide mass range at JLab Hall C that has undergone three generation is described.

Key words: Λ Hypernuclei, Electron beam, Specroscopy, Biding energy

1. Introduction

Hypernuclear investigation at accelerator facilities using K^- beams began at CERN PS in the 1970's and later extensively developed at BNL AGS and KEK PS both with intense K^- and π beams. It is only very recent that hypernuclear experiments with electron beams are seriously explored even though the advantage of using high-quality electron beams for the investigation of Λ hypernuclei has been recognized for some time since CEBAF of JLab construction started.[1]

One of the advantages of the hypernuclear experiments by the electron beams is a potential for significantly high precision reaction spectroscopy that is expected to investigate Λ hypernuclei with mass resolution as good as a few 100 keV (FWHM). On the other hand, the best resolution by hadronic beams are 1.5 MeV (FWHM), which was achieved by the (π^+, K^+) reaction using the SKS spectrometer installed at KEK 12GeV PS. Only "good resolution spectroscopy" can be carried out with MeV resolution, which is basically limited by poor beam quality of secondary meson beams and also necessity of using thick targets. thanks to high quality primary electron beams, (e,e'K+) speectroscopy offer an opportunity that possibly realizes sub-MeV "high-resolution spectroscopy" down to a few 100 keV(FWHM). However, it had been an experimental challenge to successfully measure hypernuclear spectra by the (e,e'K+) reaction, since it requires two high resolution spectrometers, one for kaons and the other for scattered electrons, controlling high background from the electromagnetic processes. Very high accidental coincidence rates of the two arm spectrometer system prohibit to perform high-luminocity experiments that have reasonable hypernuclear yield rates with intense electron beams.

It is mentioned that spectroscopy of hypernuclei can be categorized into reaction spectroscopy and decay particle spectroscopy and "high-resolution reaction spectroscopy" by electron beams is a primary concern of this paper. Decay particle spectroscopy is expected to play unique roles, populating various hypernuclear states. Hypernuclear γ-ray spectroscopy with Ge detectors has been quite successful and achieved "ultra-high resolution spectroscopy" for states below nucleon emission thresholds, populating both spin flip and non-flip states. Magnitudes of spin-dependent ΛN interaction have been determined with a few keV resolution and characteristic hypernuclear structure in light Λ hypernuclei in the p-shell region were investigated.[1]. There are also efforts to develop other decay particle spectroscopy with decay pions andAuger neutrons, which could also be applied to states above nucleon thresholds when they are successfully established.

The Hall C program was originally proposed in 1989 even before JLab CEBAF delivered the first beam. [2, 3] Since then it could be said the program has undergone three stages. [2, 4, 5] As of September 2009, the 3rd generation experiment, which will be described in the latter part of this article, is under commissioning with careful tuning of beam and spectrometer conditions.

The (e,e'K+) hypernuclear spectroscopy is now an indispensable part of hypernuclear physics experiments. In this paper, recent developement of the (e,e'K+) hypernuclear spectroscopy program in JLab Hall C is described. Another hypernuclear program at JLab Hall A, which is described by Dr. Cuissino in this proceedings[6], focuses on the spectroscopy of Λ hypernuclei in the p-shell region.

2. Hall C hypernuclear program

In the Hall C hypernuclear spectroscopy program, Λ hypernuclei in the wide mass range are strategically investigated. Experimentally, we pursue high-resolution as good as 3-400 keV (FWHM) but at the same time hypernuclear yield rates comparable to that of the (π^+, K^+) reaction is also important to realize the intensive hypernuclear spectroscopy programs. We intend to firmly establish precision reaction spectroscopy of Λ hypernuclei using high-quality JLab electron beams in GeV region not only in the light mass region but also in the wide mass region including medium-heavy region.

For light hypernuclei in the *s*- and *p*-shell region, baryon-baryon interaction and characteristic structure of Λ hypernuclei with strangeness degree of freedom will be studied taking advantage of high-resolution spectroscopy for relatively neutron rich Λ hypernuclei. Comparing with the (π^+, K^+) reaction and (K^-, π^-) reaction excitation spectra, $\Lambda\Sigma$ coupling and charge symmetry breaking effect adn nuique structure of hypernuclei are investigated. Advanced few-body calculation based on cluster models and precision shell model have been in progress. [7, 8]

For hypernuclei beyond p-shell mass region, it is intended to precisely determine absolute masses and investigate single-particle states experimentally with mass resolution as good as a few 100 keV(FWHM). Although shell structure of Λ hypernuclei was systematically measured by the (π^+, K^+) reaction using the SKS spectrometer up to ${}^{208}_{\Lambda}$Pb, large experimental errors remain partly due to nuclear core excited states for the same Λ orbit were not clearly distinguished.[9, 10] Recent theoretical investigation based on advanced shell-model calculation and mean field theory stimulates us to study hypernuclear structure in the medium-heavy mass region with high resolution.

It is also noted progress of experimental study of bare YN and YY interaction and also elementary strangeness production by electromagnetic interaction forms basis of the hypernuclear program.

The elementary cross section starts to rise sharply at the threshold of $E_\gamma = 0.911$ GeV and stays almost constant from 1.1 GeV to 1.6 GeV. Total cross sections of K^+ production in the energy range from the threshold to 2 GeV is reasonably well explained by phenomenological models. Through the three generations of the hall C experiments, virtual photon energy around 1.5 GeV was selected and thus the kaon central momentum was set at 1.2 GeV/c. In the first generation experiment, E89-009, the SOS spectrometer which was a general short orbit spectrometer suitable for measuring short-lived kaons was used for kaon detection, while in the 2nd and 3rd generation experiments, E01-011 and E05-115, a high-resolution large-solid angle QQD spectrometer(HKS), which was newly constructed being optimized for hypernuclear spectroscopy, served as a kaon arm spectrometer.

On the other hand, for scattered electron arm, an ENGE spectrometer capable of measuring electrons in the central momentum of 0.3 GeV was used both for the 1st and 2nd generation experiments, E89-009 and E01-011. For the 3rd generation experiment, E05-115, however, a new scattered electron spectrometer (HES) was installed. Considering an optimum kinematics is expressed as $E_{beam} \approx E_{virtualphoton} + E_{scatteredelectron}$, beam energies of 1.7 and 1.8 GeV were adopted in the 1st and 2nd generation experiments but 2.34 GeV was used in the 3rd generation experiment. It is noted that electron beams in the wide energy region from 2.0 to 2.5 GeV can be accepted when we use the HKS-HES spectrometer system because the central momentum of HES can be set in the 1 GeV region felxibily.

In the (e,e'K+) spectroscopy, both scattered electrons and kaons should be measured in the very forward angles. Angular distribution of Bremsstrahlung electrons peaks and electronpositron pairs are much more forward peaked compared with that of scattered electrons associated with hypernuclear production. In addition, Mϕller scattering electrons for a given momentum range also peak at very forward angles though it depends on the beam energy. The Hall C experimental configuration for the 2nd and 3rd generation experiments employed so called "tilt method", which was invented in order to considerably suppress background electrons due to such electromagnetic processes which are proportional to $\sim Z^2$. Because of such difficulty, there have been no experiments that clearly observed hypernuclear states in heavier system until recently. The 2nd generation experiment, E01-011, proved that the tilt method worked and thus reasonable hypernuclear yield rates became possible even with higher Z targets.

3. Experimental Precision of the (e,e'K+) reaction spectroscopy

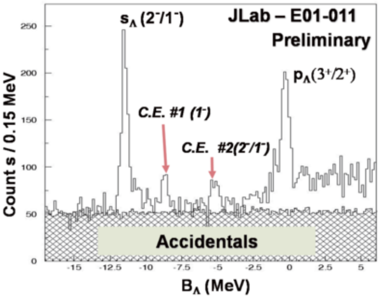

Figure 1: Preliminary hypernuclear mass spectrum of the ^{12}C(e,e'K$^+$)$^{12}_{\Lambda}$B reaction with the electron beam at 1.8 GeV.

In the analysis of the (e,e'K+) reaction spectroscopy, it is required to carefully examine the absolute mass scale of hypernuclear spectra. The (e,e'K+) reaction has an adavantage that can use a "proton" target for calibration of the mass scale. On the contrary, the (π^+, K^+) reaction and (K^-, π^-) reaction spectroscopy usually rely on hypernuclear masses known by the emulsion experiments bacause a neutron target cannot be obtained.

Momenta of kaons and scattered electrons are calculated by the backwoard transfer matrixes that convert focal plane observables of particle trajectories to initial momenta of scattered electrons and kaons. The matricis were tuned using proton target data (CH_2, H_2O) starting from a matrix obtained by a generated matix using MonteCarlo simulated data generated with a 3-dimentional field map. In the Hall C setup,both Λ and Σ peaks are simultaneously observed thanks to the large acceptances both for momentum of scattered electrons and kaons, and thus the large region for missing mass. The proton target data also serves to constraint absolute mass scale. Matrix coefficients depending on scattered angles were adjusted using sieve slit data, too. A preliminary spectrum for the ^{12}C(e,e'K+)$^{12}_{\Lambda}$B obtained in E01-011 is shown in Fig. 1. It is demonstrated that the resolution better than 0.5 MeV and hypernuclear yield rate of 8 countshour for the ground state of $^{12}_{\Lambda}$B are achieved with beam intensity of 30 μA and target thickness of 100 mg/cm^2.

The systematic errors due to Matrix tuning process were evaluated by analyzing full Monte Carlo data including background events using the same program for the real data. The data were analyzed as if they are real data with arbitrarily given hypernuclear masses and different signal-to-noise ratio. They were found to be < 100 keV for major peaks with SN ratio > 1, but < 400 keV for smaller peaks with SN ratio < 1. In addition, systematical errors due to uncertainty of kinematical variables such as absolute beam energy, central momenta of kaons and scattered electrons were also examined and its contribution to the systematical error was found up to 150 keV at present.

In E01-011, the overall errors of absolute binding energies were estimated taking into account the systematical and statistical errors to be less than 200 keV. Further examination of the errors is under way.

For hypernuclear cross sections, systematic errors in the E01-011 experiment were evaluated about 25 %, major contribution being due to estimate of virtual photon intensity which is calculated by convoluting acceptance of scattered electron spectrometer. The large error comes from strong dependence of virtual photon flux on the spectrometer angular acceptance at very forward angles.

4. A=7 hypernuclear system

The A=7 hypernuclear system forms T=1 iso-triplet and $^{7}_{\Lambda}$He is one of the multiplet members. Although there is some information on the hypernuclear mass of the other two members, $^{7}_{\Lambda}$Li and $^{7}_{\Lambda}$Be, the only known mass spcetrum of $^{7}_{\Lambda}$He is very poor. Determining the precision mass of $^{7}_{\Lambda}$He taking advantage of the (e,e'K+) reaction, we can have a set of hypernuclear masses for the T=1 multiplets. Hiyama et al recently calculated masses of A=7 Λ hypernuclei based on an α+N+N+Λ four body cluster model, renormalizing three body ΛNN force.[7] They made comparison of the T=1 ground states for $^{7}_{\Lambda}$He,$^{7}_{\Lambda}$Li and $^{7}_{\Lambda}$Be and discussed hypernuclear mass changes due to charge symmetry breaking effect, which was concluded to be around 200 keV.

The experimental data for the A=7 hypernuclear system were obtained by the emulsion measurements for $^{7}_{\Lambda}$Li and $^{7}_{\Lambda}$Be. Because the T=1 $^{7}_{\Lambda}$Li ground state is in an excited state, its binding energy was derived by γ-ray transition energy from the T=1 $1/2^+$ state to T=0 $1/2^+$ ground state and the T=0 ground state mass which was obtained by an emulsion experiment. The mass of the $^{7}_{\Lambda}$Be ground state was determined by measuring 5-body decay particles associated with a pionic decay in emulsion. On the other hand, the ground state mass of the $^{7}_{\Lambda}$He is not reliably determined due to very poor emulsion spectrum.[11]

The spectrum measured in E01-011 experiment is shown in Fig. 2 together with that of the ^{7}Li(π^+,K$^+$) reaction measured using the SKS spectrometer at KEK PS. It was mentioned that the core state of $^{7}_{\Lambda}$Be hypernucleus, that is ^{6}Be, is known unbound and the calculation suffers some ambiguity for nuclear structure. On the other hand, it is believed the calculation for $^{7}_{\Lambda}$He is more reliable and precision binding energy by the (e,e'K+) reaction gives much clearer information on possible charge symmtry breaking.

The present preliminary result for $^{7}_{\Lambda}$He, which is neutron rich Λ hypernucleus, was obtained for its absolute mass with an error of 200 keV, although the systematic error is under careful examination before we finalize the value. Present preliminary spectrum does not agree with that of the E89-009 experiment previously given by us but it had poorer statistics.[12]

5. $^{28}_{\Lambda}$Al

Since one of the goals of JLab hall C hypernuclear program is to perform precision measurements of medium-heavy Λ hypernuclear spectra, spectroscopy of the ^{28}Si(e,e'K+)$^{28}_{\Lambda}$Al was carried out as a gateway toward high-Z taget experiments. The ^{28}Si target was also selected because we have already carried out (π^+,K$^+$)) reaction spectroscopy on a 2.4 g/cm^2 thick natural Si target(^{28}Si:92%) using the SKS spectrometer at KEK 12 GeV PS.[9, 1] In the case of the (e,e'K+) reaction, however, we could use an enriched target of ^{28}Si with thickness of 100 mg/cm^2 thanks to a small beam size of 100 μm at the target position.

In fig. 2 is also shown a preliminary spectrum by the (e,e'K+) reaction on the ^{28}Si target and compared that of the (π^+,K$^+$)) spectrum shown benieth it. The resolution is far better than that for the (π^+,K$^+$)) spectrum and peaks corresponding to the major shell structure are observed. The

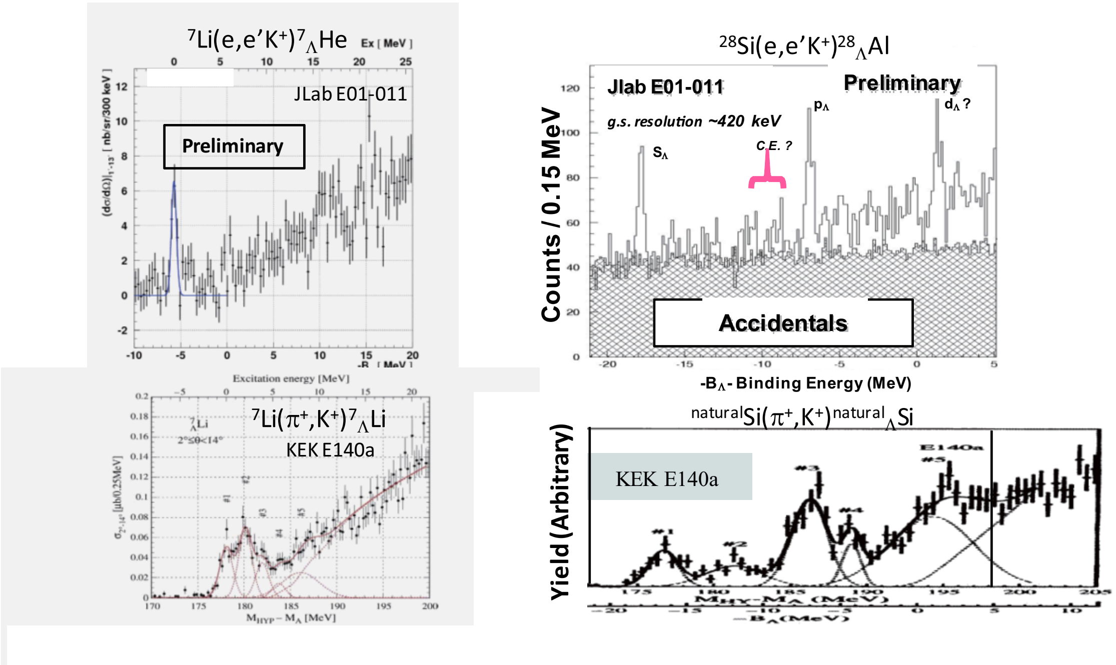

Figure 2: Preliminary hypernuclear mass spectra of the ^{7}Li(e,e'K^{+})$^{7}_{\Lambda}$He and ^{28}Si(e,e'K^{+})$^{28}_{\Lambda}$Al reactions with the electron beam at 1.8 GeV. Those of the (π^{+}, K^{+}) reaction are also shown below the corresponding spectra.

bump structure which appears in the (π^{+},K^{+})) spectrum between the s and p orbit peaks, which was a puzzle, is not clearly seen. It may suggest the structure is originated due to about 8% Si isotopes other than ^{28}Si because a natural target was used in the (π^{+}, K^{+}) reaction.

The successful observation of the $^{28}_{\Lambda}$ spectrum by the (e,e'K+) reaction has opened the door to the spectroscopy of medium-heavy Λ hypernuclei, which is well saturated as nuclei and can be well treated baseed on various mean field approaches, too. The 3rd generation experiment was designed based on this achievement of the 2nd generation experiment, E01-011.

6. The 3rd generation hypernuclear spectroscopy in JLab Hall C

The 3rd generation experiment at JLab Hall C was carried out in the fall of 2009. It aims to conduct hypernuclear spectroscopy in the wide mass range of Λ hypernuclei from light up to the A=50 region, newly introducing a high-resolution electron spectrometer (HES) and a new splitter magnet together with the HKS contructed for the 2nd generation experpiment. The HES spectrometer accepts scattered electrons in the momentum range from 0.55 to 1.0 GeV/c in contrast to the range from 0.2 to 0.4 MeV/c for the ENGE spectrometer used in E01-011. Higher momentum being accepted in the scattered electronarm and kaon momentum acceptance being the same as from 1.05 to 1.35 GeV/c with HKS, we can receive higher-energy electron beams up to 2.5 GeV/c keeping the virtual photon energy of 1.5 GeV. As a result, the Bremsstrahlung and Mϕller scattering electron backgrounds can be more efficiently reduced because these backgrounds are even more forwardly peaked. These backgrounds are rejected by tilting the HES QDD spectrometer system, which was tilted by 6.5 degrees similarly to the E01-011 experiment.

It is also mentioned that pre-chicane beam transport is employed in the E05-115, while the post-chicane system was used in the previous experiment as shown in Fig. 3. It also greatly contribute to reduce backgrounds from downstream of the target.

Table 1 summarizes the parameters of the 3rd generation experiments.

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 1: Parameters of the E05-115 experiment

It was planned to take physics data for the 6 targets, ^{7}Li, ^{9}Be, ^{10}B, ^{12}C,^{52}Cr and the two targets, H_2O and CH_2,for calibration. All the data taking has been completed at the beginning of November, 2009 and the data analysis is under way. New data for $^{52}_{\Lambda}$V are expected to provide information on behaviour of a Λ hyperon in a nucleus and on-characteristic structure of a medium-heavy hypernucleus. The target was chosen considering expected clean spectrum that demonstrates major shell structure.[13] In addition, p-shell Λ hypernucler spectra will offer basis for the invastigation of $\Lambda\Sigma$ coupling, Charge Symmetry Breaking effect and structure of light nuclei. It is expeced to open a new era of high-resolution reaction spectroscopy of Λ hypernuclei for the wide mass range by the (e,e'K+) reactions.

7. Summary

JLab Hall C hypernuclear spectroscopy program has steadily evolved since the 1stpioneering experiment, E89-009. The 2nd generation hypernuclear spectroscopy was successfully carried out and achieved the highest resolution of better than 0.5 MeV for the ground state of $^{12}_{\Lambda}$B. The analysis under way is close to the goal. High precision $^{7}_{\Lambda}$He spectrum was measured and its

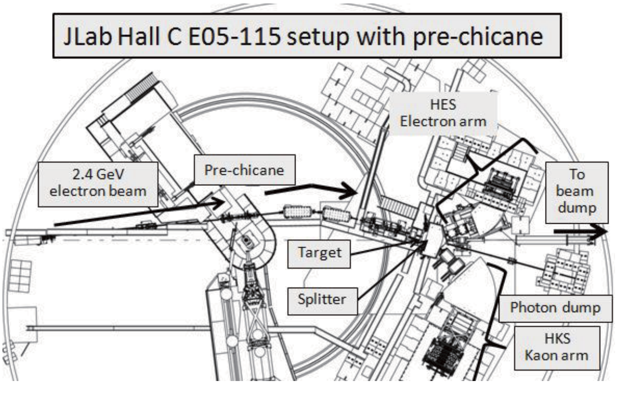

Figure 3: Hypernuclear Spectrometer system in JLab Hall C for E05-115 and the pre-chicane system.

absolute mass was derived with resolution better than 200 keV including both statistical and systematical errors. The Λ binding energies of the T=1 iso-triplet Λ hypernuclei with A=7 is expected to provide us with information on charge symmetry breaking. A $^{28}_{\Lambda}$Al spectrum was also measured in the ^{28}Si(e,e'K+) reaction. The spectrum clearly demonstrates major shall structure with better than 500 keV (FWHM) resolution.

Extending the Hall C hypernuclear program, the 3rd generation hypernuclear spectroscopy experiment, JLab E05-115, started with a new high-resolution electron spectrometer (HES) and the high-resolution kaon spectrometer (HKS) which was used in the previous E01-011 experiment. The data taking was done for $^{52}_{\Lambda}$V with a ^{52}Cr target and for p-shell hypernuclei. The data taking was carried out at the beam intensity as high as 40 μA and was completed at the beginning of November, 2009.

For (e,e'K+) spectroscopy, JLab Hall A also made significant progress for the spectroscopy of p-shell Λ hypernuclei with resolution around 700 keV(FWHM)and MAMI-C is now preparing experiments for new hypernuclear programs after its successful energy upgrade to 1.5 GeV. [14]. Hypernuclear investigation by the electron beams is now an indispensable part of strangeness nuclear physics and we expect global cooperation will further stimulate exploring the field at the currently operating electron facilities, JLab and MAMI-C and at the facilities soon receiving hadronic beams such as J-PARC[15] and PANDA[16] for strangeness nuclear physics.

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