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HIGH-PRECISION SPECTROSCOPY OF Λ-HYPERNUCLEI BEYOND P-SHELL USING ELECTROMAGNETIC PROBE AT JLAB

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The first experiment E89-009/HNSS has made the key demonstration and feasibility test on the electroproduction of hypernuclei. Based on the experiences learned, the newly approved experiment, E01-011, is under preparation with a new method in tagging the scattered electrons and a newly designed and built kaon spectrometer, that optimize the usage of electron beam for high precision hypernuclear spectroscopy. Comparing to HNSS, the hypernuclear yield and signal over background ratio will be increased by about 56 and 10 times, respectively. Most importantly, we expect to obtain an energy resolution of about 300 keV. This experimental setup will open a door for high yield, high quality, and high precision hypernuclear spectroscopic study in a wide mass range. The immediate goal of E01-011 is to study hypernuclei in the medium heavy region.

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1. Introduction

The introduction of a new degree of freedom, strangeness, into the nuclear medium stretches our conventional models of the nuclear many-body system to their limits. Many new features of the strong interaction between hyperons and the nuclear medium, and between hyperons and nucleons can be explored [1]. A ($S = -1$) hypernucleus is such a nuclear system that has one of the nucleons replaced by a hyperon, such as a Λ-particle. Due to the absence of Pauli blocking, it has been shown both theoretically and experimentally that the Λ can access almost all the orbital levels in the nuclear medium, even those filled with nucleons [2 − 6]. Therefore, Λ-hypernuclei have been used effectively as a rich laboratory to study fundamental issues such as ΛN interaction, nuclear structure deeply inside the nuclei, and structural features with new degree of freedom (for instance, a shrinkage of nuclear size [7]), as well as many others.

Significant amount of information has been obtained from the study of Λ-hypernuclei produced by the (K^-,π^-) or (π^+,K^+) reactions using secondary beams (K or π mesons). These reactions produce the Λ in the nucleus by a strong interaction with a nucleon. For the (K^-,π^-) reaction, the momentum transfer is small and the cross section is relatively large. The spectroscopy is characterized predominantly by the excitation of low-spin substitutional states [8,9] where the Λ replaces a neutron in the same shell model orbit. For the (π^+,K^+) reaction the momentum transfer is large and the cross section is relatively small [2]. This reaction preferentially populates high-spin stretched states [2,3] where a nucleon hole is coupled to a Λ. The large momentum transfer enables the Λ to change orbit, thus this reaction can produce deeply bound states such as the Λ in the s-shell. At forward angles, where the cross sections are reasonably large, neither of the two reactions has significant spin-flip amplitude, so that the spectra are dominated by the transitions to the states of natural parity.

However, energy resolution (≥ 1.5 MeV the best obtained from (π^+,K^+) reaction [10]) in the reactional spectroscopy has been a key limitation on extracting more detailed information needed for a major advance in this field, i.e. to model correctly the strongly interacting many-body system and associated interactions with the strangeness degree of freedom.

Recently, high-resolution (a few keV) gamma spectroscopy studies from level transitions of produced Λ-hypernuclei have provided exciting results [7,11] towards an understanding of the spin-dependent interactions between Λ and nucleus. However, the high precision reactional spectroscopy remains critically important for its power associated to directly study the single particle role of the Λ particle in nuclear medium from light to heavy hypernuclear systems. Sub-MeV energy resolution is critically needed.

2. *High precision hypernuclear spectroscopy*

The high-power and high-precision continuous wave (CW) electron beam at Thomas Jefferson National Accelerator Facility (JLab) has provided a new horizon to this field. The Λ-hypernuclei are produced by electromagnetic probe. Although the cross section is about two orders of magnitude smaller than of the (π^+,K^+) reaction, the usable intensity and 100% duty factor can compensates the small cross sections in the electroproduction. The key advantage is that this CW beam provides the unique chance to reach the needed sub-MeV resolution.

The spectroscopy using $(e,e'K^+)$ reaction has many new features. It converts a proton in the target nucleus into a Λ hyperon making a neutron-rich hypernucleus, in contrast to those produced by the (K^-,π^-) or (π^+, K^+) reactions. Thus it can produce many mirror hypernuclear systems to study charge symmetry breakings with strangeness degree of freedom. Momentum transfer ($q \approx 300$ MeV/c) is comparable to that of the (π^+,K^+) reaction. In addition, the reaction carries significant spin-flip amplitudes due to the absorption of the photon spin. These make it suitable to populate selectively the high spin stretched spin-flip states, complimentary to those produced by hadronic reactions. Thus, it produces an entirely new spectroscopy.

The first pioneering high precision Λ-hypernuclear spectroscopy experiment (E89-009/HNSS) was successfully performed using the CW electron beams at JLab. It proved the feasibility of using electron beam in terms of technique, yield rate (cross section) and reachable resolution. The experiment obtained a ${}^{12}_{\Lambda}$B spectrum with an energy resolution of about 900 keV, reached sub-MeV for the first time, although the yield and quality are affected by a high accidental background rate [12]. It is understood that this resolution is dominated by the contribution of the short orbit spectrometer (SOS) that is not designed for high-resolution study.

The success of the HNSS experiment spirited a funding contributed from Japan for a new dedicated high resolution spectrometer, and the new extension experiment, E01-011, was approved with high priority. The design of this new experiment aims to fully optimize the technique of using the high-power and high-precision electron beam for high-resolution, high-yield, and high-quality measurements, based on the experience and parameters from the HNSS experiment. The upgrade and optimization are expected to improve the energy resolution to a level of 300 − 400 keV (see details later).

Under the optimized condition, the immediate goal of this experiment is to measure the bound hypernuclear level structures in the medium-heavy systems in which the Λ particle is inserted to various shell orbits (s, p, d, . . . depending on the mass of the measured system) with respect to the residual nuclear core. Such resolution allows a precise determination of the binding energies and level spacing of a variety of excitation states, including possibly those with the Λ particle at certain orbit coupled to the low-lying excited core states. Such resolution permits the Λ particle being treated as an "impurity" to probe the interior of the nucleus and study the nuclear structure with new degree of freedom. In addition, it is expected that the spin-orbital force is proportional to the orbital angular momentum, thus the spin-orbital splitting at higher orbits than s and p may be large enough to be observed directly from the spectroscopy.

3. *Required experimental setup upgrade*

To obtain the required resolution a major upgrade is planned to improve the energy resolution by replacing the SOS spectrometer with a newly designed dedicated high-resolution short-orbit large-solid-angle-acceptance kaon spectrometer (HKS). It has the similar path length as SOS, thus maintaining the same good kaon survival rate. The momentum dispersion will increase from 0.9 cm/% (SOS) to 4.7 cm/% (HKS). The solid angle acceptance will increase from 5 msr (SOS) to 15 msr (HKS), thus increasing the yield by a factor of three. Table 1 lists the sources of contributions to the energy resolution. Due to the improvement of the kaon momentum resolution by a factor od three, an energy resolution of 300 – 400 keV should be reached.

TABLE 1. Expected energy resolution of the JLab experiment E01-011.

Item	Contribution to the resolution (keV, FWHM)			
Target	C	Si	V	Y
Beam energy (1.8 GeV)	< 180			
HKS (K^+) momentum (1.2 GeV/c)	170			
Enge (e') momentum (0.3 GeV/c)	120			
K^+ angle (ranged 1–14 degrees)	152	64	36	20
Target thickness	< 180	< 171	< 148	< 138
Overall	< 360	< 330	< 315	< 310

The top view of the experimental layout is illustrated in Fig. 1. The selected kinematics and general layout are almost identical to that of the HNSS experiment.

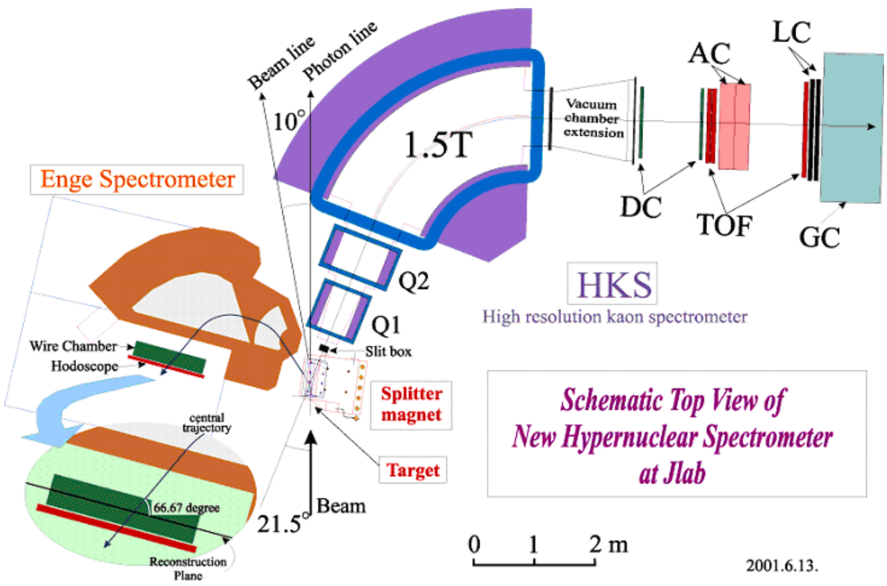

Fig. 1. Schematic top view of the experimental layout of E01-011 with the new HKS.

The beam energy of 1.8 GeV has been chosen, sufficiently high to optimize the virtual photo flux and control the momentum transfer to be at about the 300 MeV/c level, but low enough to avoid opening of other channels for K^+ production. The central momentum of the scattered electron is 0.3 GeV/c, low enough to obtain minimized contribution for resolution and suitable to use the existing Enge split-pole spectrometer (Enge) as the electron arm. The photon energy is 1.5 GeV in order to maintain the highest elementary photoproduction cross section of K^+s.

The same splitter magnet at the target is used to separate the forward scattered electrons and kaons in order to keep the highest possible virtual photon flux and hypernuclear production cross sections. The central momentum of K^+ is 1.2 GeV/c, optimized for good survival rate and momentum resolution.

The key upgrade of this experiment in terms of improving yield and quality (signal over accidental ratio) comes from an application of the so called "tilt method". For E01-011, Enge is vertically tilted up with respect to the horizontal splitter bending plane at the virtual target point. The tilt makes the central scattering angle of electrons at 4.7 degrees, instead of zero degrees without such a tilt in HNSS. In such case, the extremely high flux of electrons from bremsstrahlung and Møller scattering processes completely misses the Enge acceptance while the virtual photon flux is maintained as high as possible. This allows an increase of target thickness to 100 mg/cm^2 and a beam current to 30 μA in comparison to 22 mg/cm^2 and 0.66 μA used in HNSS, corresponding to the increase by a factor of 207 in luminosity. However, the tilt lowers the electron single rate from 200 MHz to a few MHz.

In addition, the new HKS has a larger solid angle acceptance, 15 msr in comparison to 5 msr in HNSS. Thus, there is a factor of 3 increase of the experimental yield. By trading off the reduction of the virtual photon flux and other reduction factors, the overall yield increase is by a factor of 56. This means that the production yield of the ground state of $^{12}_{\Lambda}$B hypernuclei will be at a level of 50 counts per hour, equal or even better than the production yield using the (π^+,K^+) reaction for high resolution spectroscopy. This ensures that an efficient spectroscopy in a wide mass range up to ^{89}Y will be possible. Table 2 shows a detailed list of the improvements of the new setup.

TABLE 2. Gain factors of the E01-011 experiment relative to the E89-009.

Item	E01-011	E89-009	Gain factor
Virtual photon flux/e (10^{-4})	0.35	4	0.0875
Target thickness (mg/cm^2)	100	22	4.5
e′ momentum acceptance (MeV/c)	150	120	1.2
K^+ survival rate	0.35	0.4	0.88
Solid angle acceptance of K^+ arm	15	5	3
Beam current (μA)	30	0.66	45
Overall yield ($^{12}_{\Lambda}B_{gs}$: counts/h)	50	0.9 (measured)	56

By avoiding the high flux of background of scattered electrons, the ratio of the real coincidences over accidentals will be improved by about an order of magnitude. The quality of the spectrum will be greatly improved.

In addition, since the HKS covers a kaon scattering angle from 1 to 14 degrees in the laboratory system with respect to the photon direction, it covers almost the full range of the angular distribution of interest for all predicted hypernuclear states. Thus, given the obtainable statistics, it is possible to measure the angular variation of the differential cross sections for those separable states without movement of the HKS spectrometer.

The design and construction of the HKS magnets is completed. Fig. 2 shows the photos of the two quadrupoles and the dipole in Mitsubishi Electric Co. in Japan. High precision field mapping will be completed in the summer of 2003 and the magnets will be shipped to JLab after the mapping is done.

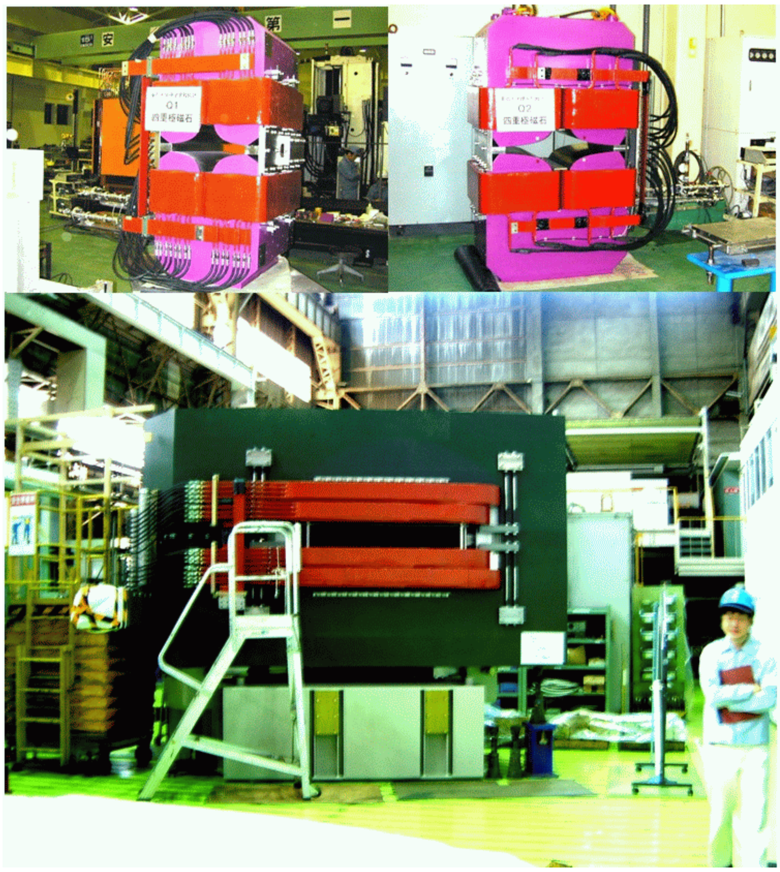

Fig. 2. The HKS magnets in Mitsubishi Electric Co. in Japan.

Single rate in the electron arm is significantly reduced due to the "tilt method" as mentioned above. The rate is low enough to apply conventional wire chamber to measure the positions and orientations of the scattered electrons at the focal plane. Segmented scintillation hodoscopes will provide timing for the chamber and the coincidence to the kaon arm.

However, the single rates in the kaon arm (HKS) will increase significantly. Table 3 shows the list of the expected single rates in both arms after the upgrade. Without a more sophisticated kaon-identification (KID) system, the online (real and accidental) coincidence trigger rate will be too high to handle, although the offline KID can clean the background particles using coincidence time versus the time of flight (TOF) almost cleanly.

TABLE 3. Expected single rates of the experiment E01-011 after the upgrade.

Target	HKS				ENGE	
	e^+ (Hz)	π^+ (kHz)	K^+ (Hz)	p (kHz)	e^- (MHz)	π^- (kHz)
^{12}C	-	420	380	150	2.6	2.8
^{28}Si	-	420	320	130	5.1	2.8
^{51}V	-	410	290	120	6.9	3.0

Therefore, new KID detectors were developed. Three layers of segmented aerogel Čerenkov detectors with the optimized index of refraction ($n = 1.05$) for HKS momentum range will be used to achieve a 10^{-4} rejection ratio of positively charged pions. Two layers of segmented water Čerenkov detectors will achieve proton rejection at a level of 3×10^{-4}. The combined KID detectors will ensure a reasonable low trigger rate from background and accidentals that will be further cleaned by the offline KID and coincidence analysis. TOF is also critical for KID and coincident timing. Design optimization and prototypes of these KID and timing detectors were done and tested in three separated beam runs at KEK in Japan. Excellent results were achieved and detailed description of these detectors and test results will be submitted for publication. All detectors, including new tracking chambers in both arms, will be fully prepared and bench tested at JLab in the fall of 2003.

The overall preparation of this experiment will be completed in the spring of 2004, including beam line and dump lines. The targeted installation time of this experiment is summer of 2004. It is believed that this experiment is the best optimized one using the CW electron beam to obtain the best reactional spectroscopy of Λ-hypernuclei.

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VRLO PRECIZNA SPEKTROSKOPIJA Λ-HIPERJEZGRI IZA P-LJUSKE POMOĆU ELEKTROMAGNETSKE PROBE U JLABU

Prvotno mjerenje E89-009/HNSS predstavlja ključan korak i provjeru izvedivosti elektrotvorbe hiperjezgri. Na osnovi postignutog iskustva, u pripremi je nov odobren eksperiment, E01-011, s novom metodom obilježavanja raspršenih elektrona i novo konstruiran i sagrađen kaonski spektrometar, koji optimiziraju upotrebu elektronskog snopa radi hipernuklearne spaktroskopije visokog razlučivanja. U usporedbi s HNSS, prinos hiperjezgri i omjer signal/šum povećat će se 56 odn. 10 puta. Najvažnije je očekivano poboljšanje energijskog razlučivanja na oko 300 keV. Ovaj eksperimentalni postav otvara mogućnosti za vrlo precizna istraživanja hipernuklearne spektroskopije u širokom području masa, s visokim prinosima i visoke kvalitete. Neposredan cilj E01-011 je proučavanje hiperjezgri u području srednjih masa.