Electron-Induced Hypernuclear Spectroscopy

Results in Hall A at Jefferson Lab

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- + Hypernuclei: A quick introduction
- + Electroproduction of hypernuclei
- + The experimental Program in Hall A at Jefferson Lab
 - ☀ The Hall A Experimental Setup
 - ☀ Results on ^{12}C and ^{16}O targets
 - ☀ Preliminary results on ^9Be and ^1H
- + Conclusions

HYPERNUCLEAR PHYSICS

- **H**ypernuclei are bound states of nucleons with a strange baryon (Lambda hyperon). A hypernucleus is a “laboratory” to study nucleon-hyperon interaction (**Λ -N interaction**).

- Extension of physics on N-N interaction to system with **$S \neq 0$**

- Internal nuclear shell are not Pauli-blocked for hyperons.

Hypernuclei - historical background - experimental techniques

1953 → 1970 : hypernuclear identification with visualizing techniques
emulsions, bubble chambers

1970 → Now : Spectrometers at accelerators:
CERN (up to 1980)
BNL : (K^- , π^-) and (π^+ , K^+) production methods
KEK : (K^- , π^-) and (π^+ , K^+) production methods

> 2000 : Stopped kaons at DAΦNE (FINUDA) : (K^-_{stop} , π^-)

> 2000 : **The new electromagnetic way :**
HYPERNUCLEAR production with
ELECTRON BEAM at JLAB

Elementary reaction
on neutron :

e.g.

Elementary reaction
on proton :

e.g.

Production of MIRROR hypernuclei

Λ : $I=0$, $q=0 \Rightarrow \Lambda n = \Lambda p$

Spectroscopy of mirror hypernuclei reveal $\Lambda n \neq \Lambda p \Rightarrow \Lambda\Sigma^0$ mixing and ΛN - ΣN coupling

What do we learn from hypernuclear spectroscopy

Hypernuclei and the Λ -N interaction

"weak coupling model"

$$J_{A-1} \quad + \quad \Lambda(s\text{-shell}) \quad \rightarrow \quad J_{Hyp} = J_{A-1} \pm \frac{1}{2}$$

(parent nucleus) (Λ hyperon) (doublet state)

$$V_{\Lambda N} = \underbrace{V_0(r)}_V + \underbrace{V_\sigma(r)}_\Delta \vec{s}_\Lambda \cdot \vec{s}_N + \underbrace{V_\Lambda(r)}_{S_\Lambda} \vec{\ell}_{\Lambda N} \cdot \vec{s}_\Lambda + \underbrace{V_N(r)}_{S_N} \vec{\ell}_{\Lambda N} \cdot \vec{s}_N + \underbrace{V_T(r)}_T S_{12}$$

Each of the 5 radial integral (V , Δ , S_Λ , S_N , T) can be phenomenologically determined from the low lying level structure of p-shell hypernuclei

Low-lying levels of Λ Hypernuclei

ELECTROproduction of Hypernuclei

The characteristics of the **Jefferson Lab electron beam (CEBAF)**, together with those of the experimental equipments, offer a unique opportunity to study hypernuclear spectroscopy via **electromagnetic induced reactions**. A new experimental approach: alternative to the hadronic induced reactions studied so far.

Experimental Challenge:

- **Low Cross sections** $\Rightarrow$ **Measurements at very forward angles**
- **High Pion contamination** $\Rightarrow$ **unambiguous Kaon identification**
- **High Kaon momenta** to enhance K survival probability

The CEBAF Accelerator

Continuous Electron Beam Accelerator Facility

- Energy 0.8 – 5.7 GeV
- 200 μA , polarization 75-85%
- 1499 MHz operation
- Simultaneous delivery to 3 halls

JLAB Hall A Experiment E94-107

E94107 COLLABORATION

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and Theorists: Petr Bydzovsky, John Millener, Miloslav Sotona

$^{16}\text{O}(e,e'K^+)^{16}_{\Lambda}\text{N}$

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

$^9\text{Be}(e,e'K^+)^9_{\Lambda}\text{Li}$

$\text{H}(e,e'K^+)\Lambda, \Sigma^0$

$E_{\text{beam}} = 4.016, 3.777, 3.656 \text{ GeV}$

$P_e = 1.80, 1.57, 1.44 \text{ GeV/c}$

$P_K = 1.96 \text{ GeV/c}$

$\theta_e = \theta_K = 6^\circ$

$W \sim 2.2 \text{ GeV} \quad Q^2 \sim 0.07 (\text{GeV/c})^2$

Beam current : $< 100 \mu\text{A}$ Target thickness : $\sim 100 \text{ mg/cm}^2$

Counting Rates $\sim 0.1 - 10 \text{ counts/peak/hour}$

JLAB Hall A Standard Experimental setup

The two High Resolution Spectrometer (HRS) in Hall A @ JLab

HRS – QDQ main characteristics:

Momentum range: 0.3, 4.0 GeV/c

$\Delta p/p$ (FWHM): 10^{-4}

Momentum accept.: $\pm 5\%$

Solid angle: 5 – 6 msr

Minimum Angle : 12.5°

E94-107 collaboration added:

- 2 superconduction septa
- Ring Imaging Cherenkov

Experimental requirements :

- Detection at very forward angle to obtain reasonable counting rate (increase photon flux) → **Septum magnets at 6°**
- Excellent **P**article**ID**entification system for unambiguous *kaon* selection over a large background of $\rho, \pi \rightarrow$ **RICH**
- Accurate **monitoring of many parameters** over a long period of data taking : Beam energy spread and absolute calibration, spectrometers settings and stability, ...
- **E**xcellent energy resolution → Best performance for beam and **HRS+Septa** with accurate optics calibrations

1. $\Delta E_{\text{beam}}/E : 2.5 \times 10^{-5}$

2. $\Delta P/P$ (HRS + septum) $\sim 10^{-4}$

3. Straggling, energy loss...

Excitation energy resolution $\leq$ **600 keV**

RICH detector – C₆F₁₄/CsI proximity focusing RICH

Performances:

$N_{p.e.}$ # of detected photons (p.e.)
and σ_θ (angular resolution)

Separation Power

$$\vartheta_2 - \vartheta_1 = n_\sigma \sigma_{\vartheta_c}$$

Cherenkov
angle resolution

$$\sigma_{\vartheta_c} = \frac{\sigma_{\vartheta}^{p.e.}}{\sqrt{N_{p.e.}}}$$

The **R**ICH detector

Results on ^{12}C target

Analysis of the reaction $^{12}\text{C}(e,e'\text{K})^{12}\text{B}_{\Lambda}$

Results published: M.Iodice et al., Phys. Rev. Lett. E052501, 99 (2007).

PHYSICAL REVIEW LETTERS

An experiment measuring electroproduction of hypernuclei has been performed in hall A at Jefferson Lab on a ^{12}C target. In order to increase counting rates and provide unambiguous kaon identification two superconducting septum magnets and a ring imaging Cherenkov detector were added to the hall A standard equipment. An unprecedented energy resolution of less than 700 keV FWHM has been achieved. Thus, the observed $^{12}\text{B}_{\Lambda}$ spectrum shows for the first time identifiable strength in the core-excited region between the ground-state s -wave Λ peak and the 11 MeV p -wave Λ peak.

DOI:

PACS numbers: 21.80.+a, 21.60.Cs, 25.30.Rw, 27.20.+n

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}\text{B}_{\Lambda}$

- BACKGROUND level is very low $\Rightarrow$ Signal/Noise Ratio is very high
- Clear evidence of **core excited peak levels** between the ground state and the strongly populated p-Lambda peak at 11 MeV
- Quasi free K-Lambda production dominate the spectrum above 13 MeV

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}\text{B}_{\Lambda}$

- Peak Search :

Identified 6 regions with excess counts above background

Position (MeV)	Width (FWHM, MeV)	SNR
0.0 ± 0.03	1.15 ± 0.18	19.7
2.65 ± 0.10	0.95 ± 0.43	7.0
5.92 ± 0.13	1.13 ± 0.29	5.3
9.54 ± 0.16	0.93 ± 0.46	4.4
10.93 ± 0.03	0.67 ± 0.15	20.0
12.36 ± 0.13	1.58 ± 0.29	7.3

- o Fit to the data: Fit 6 regions with 6 Voigt functions (convolution of Gaussian and Lorentzian) $\chi^2/\text{ndf} = 1.16$
- o Theoretical model superimposed curve based on :
 - Saclay-Lyon-A $p(e, e'K^+)\Lambda$ (elementary process)
 - ΛN interaction from $^7_{\Lambda}\text{Li}$ γ -ray spectra

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}\text{B}_{\Lambda}$

Position (MeV)	Experimental data		
	Width (FWHM, MeV)	SNR	Cross section (nb/sr ² /GeV)
0.0 ± 0.03	1.15 ± 0.18	19.7	$4.48 \pm 0.29(\text{stat}) \pm 0.63(\text{syst})$
2.65 ± 0.10	0.95 ± 0.43	7.0	$0.75 \pm 0.16(\text{stat}) \pm 0.15(\text{syst})$
5.92 ± 0.13	1.13 ± 0.29	5.3	$0.45 \pm 0.13(\text{stat}) \pm 0.09(\text{syst})$
9.54 ± 0.16	0.93 ± 0.46	4.4	$0.63 \pm 0.20(\text{stat}) \pm 0.13(\text{syst})$
10.93 ± 0.03	0.67 ± 0.15	20.0	$3.42 \pm 0.50(\text{stat}) \pm 0.55(\text{syst})$
12.36 ± 0.13	1.58 ± 0.29	7.3	$1.19 \pm 0.36(\text{stat}) \pm 0.35(\text{syst})$

- Measured cross sections in good agreement with theory
- Energy resolution ~ 670 keV
- First clear evidence of core excited states with high statistical significance
- Hint for a peak at 9.54 MeV (admixture states)

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}\text{B}_{\Lambda}$

Position (MeV)	Experimental data			E_x (MeV)	Theoretical prediction		
	Width (FWHM, MeV)	SNR	Cross section (nb/sr ² /GeV)		Main structure	J^{π}	Cross section (nb/sr ² /GeV)
0.0 ± 0.03	1.15 ± 0.18	19.7	$4.48 \pm 0.29(\text{stat}) \pm 0.63(\text{syst})$	0.0	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes s_{1/2\Lambda}$	1^{-}	1.02
				0.14	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes s_{1/2\Lambda}$	2^{-}	3.66
2.65 ± 0.10	0.95 ± 0.43	7.0	$0.75 \pm 0.16(\text{stat}) \pm 0.15(\text{syst})$	2.67	$^{11}\text{B}(\frac{1}{2}^{-}; 2.12) \otimes s_{1/2\Lambda}$	1^{-}	1.54
5.92 ± 0.13	1.13 ± 0.29	5.3	$0.45 \pm 0.13(\text{stat}) \pm 0.09(\text{syst})$	5.74	$^{11}\text{B}(\frac{3}{2}^{-}; 5.02) \otimes s_{1/2\Lambda}$	2^{-}	0.58
				5.85	$^{11}\text{B}(\frac{3}{2}^{-}; 5.02) \otimes s_{1/2\Lambda}$	1^{-}	0.18
9.54 ± 0.16	0.93 ± 0.46	4.4	$0.63 \pm 0.20(\text{stat}) \pm 0.13(\text{syst})$	...	...	...	...
10.93 ± 0.03	0.67 ± 0.15	20.0	$3.42 \pm 0.50(\text{stat}) \pm 0.55(\text{syst})$	10.48	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes p_{3/2\Lambda}$	2^{+}	0.24
				10.52	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes p_{\Lambda}$	1^{+}	0.12
				10.98	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes p_{1/2\Lambda}$	2^{+}	1.43
				11.05	$^{11}\text{B}(\frac{3}{2}^{-}; \text{g.s.}) \otimes p_{3/2\Lambda}$	3^{+}	2.19
12.36 ± 0.13	1.58 ± 0.29	7.3	$1.19 \pm 0.36(\text{stat}) \pm 0.35(\text{syst})$	12.95	$^{11}\text{B}(\frac{1}{2}^{-}; 2.12) \otimes p_{3/2\Lambda}$	2^{+}	0.91
				13.05	$^{11}\text{B}(\frac{1}{2}^{-}; 2.12) \otimes p_{\Lambda}$	1^{+}	0.27

Measured cross sections in good agreement with theory

Results on the **WATERFALL** target

Analysis of the reaction $^{16}\text{O}(e,e'K)^{16}\text{N}_{\Lambda}$
and $^1\text{H}(e,e'K)\Lambda$ (elementary reaction)

The **WATERFALL** target: reactions on ^{16}O and ^1H nuclei

Preliminary Results on the WATERFALL target - ^{16}O and ^1H

$^1\text{H}(e,e'K)\Lambda,\Sigma$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Energy Calibration Run

Σ

- Water thickness from elastic cross section on H
- Precise determination of the particle momenta and beam energy using the Lambda and Sigma peak reconstruction (energy scale calibration)

Results on ^{16}O target – Hypernuclear Spectrum of $^{16}\text{N}_\Lambda$

Binding Energy $B_\Lambda = 13.76 \pm 0.16$ MeV
Measured for the first time with this level of accuracy

(ambiguous interpretation from emulsion data; interaction involving Λ production on n more difficult to normalize)

Within errors, the binding energy and the excited levels of the mirror hypernuclei $^{16}\text{O}_\Lambda$ and $^{16}\text{N}_\Lambda$ (this experiment) are in agreement, giving no strong evidence of charge-dependent effects

E_x (MeV)	Width (FWHM, MeV)	Cross section (nb/sr ² /GeV)	E_x (MeV)	Wave function	J^π	Cross section (nb/sr ² /GeV)
0.0/13.76±0.16	1.71	1.45 ± 0.26	0.00	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	0 ⁻	0.002
			0.03	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	1 ⁻	1.45
6.83 ± 0.06	0.88	3.16 ± 0.35	6.71	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	1 ⁻	0.80
			6.93	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	2 ⁻	2.11
10.92 ± 0.07	0.99	2.11 ± 0.37	11.00	$p_{1/2}^{-1} \otimes p_{3/2\Lambda}$	2 ⁺	1.82
			11.07	$p_{1/2}^{-1} \otimes p_{1/2\Lambda}$	1 ⁺	0.62
17.10 ± 0.07	1.00	3.44 ± 0.52	17.56	$p_{3/2}^{-1} \otimes p_{1/2\Lambda}$	2 ⁺	2.10
			17.57	$p_{3/2}^{-1} \otimes p_{3/2\Lambda}$	3 ⁺	2.26

Results on ^{16}O target – Hypernuclear Spectrum of $^{16}\text{N}_\Lambda$

Theoretical model based on :

SLA $p(e,e'K^+)\Lambda$ (elementary process)

ΛN interaction fixed parameters from KEK and BNL $^{16}_\Lambda\text{O}$ spectra

- Four peaks reproduced by theory
- The fourth peak (Λ in p state) position disagrees with theory. **This might be an indication of a large spin-orbit term S_Λ (under investigation)**

E_x (MeV)	Width (FWHM, MeV)	Cross section (nb/sr ² /GeV)	E_x (MeV)	Wave function	J^π	Cross section (nb/sr ² /GeV)
0.0/13.76±0.16	1.71	1.45 ± 0.26	0.00	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	0 ⁻	0.002
			0.03	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	1 ⁻	1.45
6.83 ± 0.06	0.88	3.16 ± 0.35	6.71	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	1 ⁻	0.80
			6.93	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	2 ⁻	2.11
10.92 ± 0.07	0.99	2.11 ± 0.37	11.00	$p_{1/2}^{-1} \otimes p_{3/2\Lambda}$	2 ⁺	1.82
			11.07	$p_{1/2}^{-1} \otimes p_{1/2\Lambda}$	1 ⁺	0.62
17.10 ± 0.07	1.00	3.44 ± 0.52	17.56	$p_{3/2}^{-1} \otimes p_{1/2\Lambda}$	2 ⁺	2.10
			17.57	$p_{3/2}^{-1} \otimes p_{3/2\Lambda}$	3 ⁺	2.26

Results on ^{16}O target – Hypernuclear Spectrum of $^{16}\text{N}_\Lambda$

Evidences of a fifth peak in the quasi-free regions (already observed in KEK data) is now investigated. Results from new fits are VERY PRELIMINARY.
Theoretical effort is ongoing to investigate $s_{1/2}\Lambda$ coupling to core excited states

CoreExcitedStates $\otimes$ $s_{1/2}\Lambda$

Results on **H** target – The elementary process $^1\text{H}(e,e'\text{K})\Lambda$

In all Jlab hypernuclear electroproduction experiments the K^+ mesons are detected at very small (few degrees) laboratory scattering angles, at very low Q^2 (**close to the photon-point**).

This region of kaon scattering angles is not covered, unfortunately, even by recent very precise photo- and electroproduction data on the elementary production process from CLAS, SAPHIR, and LEPS Collaborations.

In this kinematic region different models for the $\text{K}^+-\Lambda$ electromagnetic production on protons differ drastically.

This lack of relevant information about the elementary process makes an interpretation of obtained hypernuclear spectra difficult.

Lack of data at forward angle

Results on **H** target – The $p(e,e'K)\Lambda$ Cross Section

Work on normalizations,
acceptances, efficiencies still
underway

Results on **H** target – The $p(e,e'K)\Lambda$ Cross Section

Work on normalizations,
acceptances, efficiencies still
underway

Preliminary results on the $p(e,e'K)\Lambda$
cross section (consistent between LH_2
and Waterfall target) agree with the
Saclay Lyon A Model

Results on **H** target – The $p(e,e'K)\Lambda$ Cross Section

Work on normalizations,
acceptances, efficiencies still
underway

**Expected data from the
Proposal E07-012 to study the
angular dependence of $p(e,e'K)\Lambda$ and
 $^{16}\text{O}(e,e'K)^{16}\text{N}_\Lambda$ at Low Q^2
approved January, 2007**

Results from the ^9Be target

Analysis of the reaction $^9\text{Be}(e,e'\text{K})^9\text{Li}_\Lambda$ (preliminary)

Theoretical cross sections based on Saclay-Lyon A model.

Core nucleus ^8Li has 3 low lying states to which lambda in s-state can couple generating 3 doublets of hypernuclear states

Hypernuclear Investigation in **wide mass range** at **JLab Hall C**

Conclusions:

- ☀ High resolution hypernuclear spectroscopy is a reality
- ☀ New experimental equipments showed excellent performance.
- ☀ **High quality data on ^{12}C , ^9Be and ^{16}O targets ($^{12}\text{B}_\Lambda$, $^9\text{Li}_\Lambda$ and $^{16}\text{N}_\Lambda$ hypernuclei) have been taken in Hall A.** ^{12}C results published. ^{16}O paper in preparation. Analysis in progress also for the important data on the elementary process $p(e,e'K)\Lambda$
- ☀ Complementary data comes from **Hall C** (extending range in A)
- ☀ VERY Promising physics is coming out from Jlab hypernuclear Program
 - ✓ From present data
 - ✓ From APPROVED Experiments

BACKUP SLIDES

HYPERNUCLEI and ASTROPHYSICS

- Strange baryons may appear in neutral β -stable matter through process like:

- The presence of strange baryons in neutron stars strongly affect their properties. **Example:** mass-central density relation for a non-rotating (left) and a rotating (right) star

- The effect strongly depends upon the poorly known interactions of strange baryons

More data needed to constrain theoretical models.

E94-107 Hall A Experiment Vs. KEK-E369

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

$$^{12}\text{C}(\pi^+, \text{K}^+)^{12}\text{C}_{\Lambda}$$

Statistical significance of core excited states:

$$\frac{\text{Signal}}{\sqrt{\text{Bckgnd}}} > 5$$

E94-107 Hall A Experiment Vs. FINUDA (at DaΦne)

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

$$^{12}\text{C}(\text{K}^-, \pi^-)^{12}\text{C}_{\Lambda}$$

Statistical significance of core excited states:

$$\frac{\text{Signal}}{\sqrt{\text{Bckgnd}}} > 5$$

E94-107 Hall A Experiment Vs. HallC E89-009

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

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

Miyoshi et al., PRL 90 (2003) 232502.

Statistical significance of core excited states:

$$\frac{\text{Signal}}{\sqrt{\text{Bckgnd}}} > 5$$

E94-107 Hall A Experiment Vs. HallC E01-011

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

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

$$^{12}\text{C}(e,e'\text{K}^+)^{12}_{\Lambda}\text{B JLAB E01-011}$$

Statistical significance of core excited states:

$$\frac{\text{Signal}}{\sqrt{\text{Bckgnd}}} > 5$$