Study of Light Hypernuclei by Pionic Decay at JLAB

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Other spokespersons:
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Collaboration:
From both Hall C and A hypernuclear programs

NP08, Mito in Japan, March 5-7, 2008
The single and double hypernuclei are the main sources of the strange sector of baryon-baryon interaction.
Discovery of the first hypernucleus by pionic decay in emulsion produced by Cosmic Rays. Marian Danysz and Jerzy Pniewski, 1952

- $\Lambda \to p + \pi^-(64\%); \quad \Lambda \to n + \pi^0 (36\%)$
- Remain effective even at medium A
Access rich information about hypernuclear and nuclear physics

Used exclusively to determine the binding energy of light (A ≤ 15) hypernuclei in emulsion

- Precision: ~50 keV
- Resolution: ~0.5 – 1.0 MeV

Problems:
- Poor statistics
- Calibrations
- Cannot resolve pure 2-body decay

Was not interested in the past ~20 years – low energy and low yield

Λ → p + π⁻ (64%); Λ → n + π⁰ (36%)

Remain effective even at medium A
New Opportunity at JLAB

- Combination of the CEBAF beam and the HKS system → Spectrometer for $\pi^-$
- High precision and reasonable yield rate
- High mom. transfer → control background

Program features:

- Energy resolution: $\sigma \approx 55$ keV
- $B_\Lambda$ precision: $\delta B_\Lambda \approx \pm 10$ keV
- Simultaneous lifetime measurement (Timing resolution: $\sigma \leq 80$ps)

- Wide range of physics
Directly Produced Hypernuclei - Example

Ground state doublet of $^{12}_\Lambda B$

$B_\Lambda$ and $\tau$

- $2^- \sim 150$ keV
- $1^- = 0.0$

Mesonic two body decay
Indirectly Produced Hypernuclei – Example

Fragmentation Process

Access to variety of light and exotic hypernuclei, some of which cannot be produced or measured precisely by other means.

Fragmentation ($<10^{-16}$s)

Mesonic two body decay ($\sim10^{-10}$s)
Physics Objectives – YN Interactions

- Emulsion data of light hypernuclei (primarily the ground states) were used to check theoretical models on YN interaction in the past 40 some years.

<table>
<thead>
<tr>
<th>YN</th>
<th>$B_\Lambda(^3\Lambda H)$</th>
<th>$B_\Lambda(^4\Lambda H)$</th>
<th>$B_\Lambda(^4\Lambda H^*)$</th>
<th>$B_\Lambda(^4\Lambda He)$</th>
<th>$B_\Lambda(^4\Lambda He^*)$</th>
<th>$B_\Lambda(^5\Lambda He)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC97d(S)</td>
<td>0.01</td>
<td>1.67</td>
<td>1.2</td>
<td>1.62</td>
<td>1.17</td>
<td>3.17</td>
</tr>
<tr>
<td>SC97e(S)</td>
<td>0.10</td>
<td>2.06</td>
<td>0.92</td>
<td>2.02</td>
<td>0.90</td>
<td>2.75</td>
</tr>
<tr>
<td>SC97f(S)</td>
<td>0.18</td>
<td>2.16</td>
<td>0.63</td>
<td>2.11</td>
<td>0.62</td>
<td>2.10</td>
</tr>
<tr>
<td>SC89(S)</td>
<td>0.37</td>
<td>2.55</td>
<td>Unbound</td>
<td>2.47</td>
<td>Unbound</td>
<td>0.35</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.13 ± 0.05</td>
<td>2.04 ± 0.04</td>
<td>1.00 ± 0.04</td>
<td>2.39 ± 0.03</td>
<td>1.24 ± 0.04</td>
<td>3.12 ± 0.02</td>
</tr>
</tbody>
</table>

- Problem of inconsistency and model of choice exist

- Recent $\gamma$-spectroscopy program has been successful for spin dependent interactions but unable to measure $B_\Lambda$

- Recent successful mass spectroscopy programs cannot reach a precision on $B_\Lambda$ exceeding emulsion data
The wealth of information coming from this poor statistics emulsion experiment is solely attributable to the technique's inherent good energy resolution, \(~50\text{ keV}\) in this instance, and forcefully emphasizes the need to strive for comparable energy resolution in counter experiments.

- *D. Davis, 1992*

As it turns out, binding energies of light hypernuclei are highly correlated from calibrations to $^{12}_\Lambda C$ for example, and most likely incorrect.

- *D. Davis, HYP2006*
YN Interactions – cont.

- Replace emulsion data with a new set of data that has a factor of 2-5 times better precision on $B_\Lambda$ to check current and future theories with stringent limits.

- Separate small ground state doublets.

- Study charge symmetry breaking in YN interaction, such as $B_\Lambda(^4\Lambda H_{g.s.}) - B_\Lambda(^4\Lambda He_{g.s.})$. 
Search for Highly Exotic Hypernuclei

- Search for and measure precisely the $B_\Lambda$ of the exotic hypernuclei is another effective way for exotic nuclear physics.

- Many hypernuclei with unstable nuclear core exist, e.g. $^6_\Lambda He$, $^7_\Lambda Be$, $^8_\Lambda He$, $^9_\Lambda Be$. Other exotic hypernuclei may exist, e.g. $^6_\Lambda H$, $^7_\Lambda H$, $^8_\Lambda H$, $^{10}_\Lambda He$, and $^{11}_\Lambda Li$ through fragmentation process.
Search for Highly Exotic Hypernuclei

- Search for light hypernuclei toward nucleon drip-lines: hypernuclei with extreme isospins

Hypernuclei at:
- $\beta$-stability line
- Neutron rich
- Nucleon drip-lines

Other programs:
- Heavy ion collision
- JINR, HypHI

This program – high precision on $B_\Lambda$
Impurity Nuclear Physics

*Hypernuclear and nuclear structure*

- Pion decays offer insights into the hypernuclear and nuclear structure, and the momentum dependence of the single particle wave functions.
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Example: $^7\Lambda Li$ w/ g.s. doublet $1/2^+$ & $3/2^+$
Impurity Nuclear Physics – cont.

Probing nuclear structure with Λ

- Example: $^{10}_ΛB$ w/ g.s. doublet $1^-$ & $2^-$
Example: $^{10}_\Lambda B$ w/ g.s. doublet $1^{-}$ & $2^{-}$
- Spin order is not known
- $\gamma$ transition ($2^{-} \rightarrow 1^{-}$) was not found
- Success competition by weak mesonic decay
- Assumed order could be wrong
- Decay pion may provide clarification
- $^{10}_\Lambda Be$ may be the candidate at JLAB
Impurity Nuclear Physics

Role and effect of $\Lambda$ in Nucleus Medium

- Precise $B_A$ allows separation of those low lying states which have sufficient long lifetime (i.e. $\gamma$ decay competes with weak decay)

- Lifetime of these separable states allows to extract transition probabilities $B(E2)$ and $B(M1)$ which provide information about the medium effect to baryon or $\Lambda$ to the core medium
Impurity Nuclear Physics

Role and effect of $\Lambda$ in Nuclear Medium

$\Lambda^7$He

$\Lambda^7$Li

$\pi^-$

$\Lambda^{11}$B

$\Lambda^{11}$C

$\pi^-$

5/2$^+$ and 3/2$^+$ states are from unbound 2$^+$ state of $^6$He core
Tagged-Weak Pi-Method of B(E2) and B(M1) Measurement

If states can be separated and statistics is sufficient to measure lifetimes, then

By measuring both of $P^{B\rightarrow weak}(t)$ and $P^{A\rightarrow weak}(t)$ and fitting them together to the equations above, $\lambda^A_W$, $\lambda^B_W$, and $m$ can be determined.
Technique & Exp. Layout

- Standard Splitter and HKS for K⁺
- Enge & target moved upstream for decay pions
- Tilted TGT (25mg/cm²) Eff. TGT (50mg/cm²)
- Standard pre-chicane beam line (E05-115)
- Local dump for photons
- Similar luminosity as E05-115 (HKS/HES)

Need calibration for the absolute \( \bar{H}πS \) central momentum
### Parameters of the $H\pi S$ spectrometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration</strong></td>
<td>Enge Split-Pole (or HES) spectrometer and detector package</td>
</tr>
<tr>
<td>Central momentum</td>
<td>115 MeV/c</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>± 40%</td>
</tr>
<tr>
<td>Momentum resolution (r.m.s.)</td>
<td>$10^{-4}$ without multiple scattering</td>
</tr>
<tr>
<td>Momentum resolution (r.m.s.)</td>
<td>$4.9 \times 10^{-4}$ with multiple scattering</td>
</tr>
<tr>
<td>Dispersion</td>
<td>1.28 cm/%</td>
</tr>
<tr>
<td>Time-zero precision</td>
<td>&lt; 100 ps (~80 ps)</td>
</tr>
<tr>
<td>Pion detection angle</td>
<td>~60 degree relative to the incident beam</td>
</tr>
<tr>
<td>Flight path length</td>
<td>309 cm</td>
</tr>
<tr>
<td>- survival rate</td>
<td>~ 60%</td>
</tr>
<tr>
<td>Solid angle</td>
<td>~20 msr</td>
</tr>
<tr>
<td>Total efficiency of the detector package</td>
<td>~80%</td>
</tr>
</tbody>
</table>
Example of Possible G.S. of Light Hypernuclei from $^{12}$C Target

- G.S. only (doublet structures are not shown)
- Estimated based on emulsion data thus may under-estimated for some of the hypernuclei
- Additional hypernuclei may appear
Example of Possible G.S. of Light Hypernuclei from $^{12}\text{C}$ Target

Background:
- $\sim 97.5\%$ QF $\Lambda$ decay
- $\sim 2.5\%$ ($K^+$ & $\pi^-$) accidentals
Beam Parameters and Beam Time

- **Targets:** $^{12}\text{C}$ and $^{7}\text{Li}$ (Optimized combination)
  - $^{12}\text{C}$ – Heaviest in p-shell; reliable yield rates on variety of light hypernuclei but not too crowded
  - $^{7}\text{Li}$ – Best chance for the lightest and highly exotic hypernuclei, such as $^6\Lambda\text{H}$

- **Beam energy:** 1.8 – 2.2 GeV

- **Beam current and acq. time**
  - $^{12}\text{C}$, 60$\mu$A (100 Max.), 20 days
  - ~1000 counts for $^4\Lambda\text{H}$ (physics w/ moderate yield)
  - ~6000 counts for $^5\Lambda\text{He}$ (physics and calibration)
  - $^{7}\text{Li}$, 30$\mu$A (50 Max.), 20 days
    Primary: $^7\Lambda\text{He}$, $^6\Lambda\text{He}$, $^5\Lambda\text{He}$; Questionable: $^4\Lambda\text{He}$, $^6\Lambda\text{H}$, $^5\Lambda\text{H}$, $^4\Lambda\text{H}$

- **Trigger rate:** ~ few hundred Hz
CEBAF beam and HKS provide unique opportunity for a new counter type high precision decay pion program – *Producing data that replaces emulsion data in the role of checking theories*

- It can study a wide range of physics that either not accessible by other means or complementary to other programs
International Hypernuclear Network

PANDA at FAIR
- 2012~
- Anti-proton beam
- Double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy

MAMI C
- 2007~
- Electro-production
- Single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

SPHERE at JINR
- Heavy ion beams
- Single $\Lambda$-hypernuclei

HypHI at GSI/FAIR
- Heavy ion beams
- Single $\Lambda$-hypernuclei at extreme isospins
- Magnetic moments

FINUDA at DAΦNE
- $e^+e^-$ collider
- Stopped-$K$ reaction
- Single $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy (2012~)

JLab, HπS
- Electro-production
- Single $\Lambda$-hypernuclei at normal and extreme isospins
- Binding energies
- $\pi^-\pi^+$ decay spectroscopy
- Impurity nuclear physics

JLab
- 2000~
- Electro-production
- Single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

J-PARC
- 2009~
- Intense $K^-$ beam
- Single and double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy for single

Basic map from Saito, HYP06