Gamma spectroscopy of hypernuclei
--E13 and beyond--

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1. Introduction
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1. Introduction
Hyperball 1998~

Hypernuclear γ-ray data

$^7$Li ($\pi^+, K^+\gamma$) KEK E419

$^9$Be ($K^+, \pi^-\gamma$) BNL E930('98)

$^{10}$B ($K^+, \pi^-\gamma$) BNL E930('01)

$^{12}$C ($\pi^+, K^+\gamma$) KEK E566

$^{13}$C ($K^+, \pi^-\gamma$) BNL E929 (Nal)

$^{16}$O ($K^+, \pi^-\gamma$) BNL E930('01)

$^6$Li

$^{7}$Li

$^9$Be

$^{10}$B

$^{12}$C

$^{13}$C

$^{16}$O

References:

PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501
PRL 88 (2002) 082501
NPA 754 (2005) 58c

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EPJ A33 (2007) 243
PRL 66 (2001) 4255
PRC 65 (2002) 034607
PRC 77 (2008) 054315
PRL 93 (2004) 232501
EPJ A33 (2007) 247
\[ \Delta N \] spin-dependent interaction strengths determined:

- Spin-spin: \( \Delta = 0.33 \) MeV (\( A > 10 \)), 0.42 MeV (\( A < 10 \))
- \( \Lambda \) spin-orbit: \( S_\Lambda = -0.01 \) MeV
- \( N \) spin-orbit: \( S_N = -0.4 \) MeV
- Tensor: \( T = 0.03 \) MeV

- Almost all these p-shell levels are reproduced by this parameter set. (D.J. Millener)

- \( \Delta N - \Sigma N \) coupling force from NSC models looks good.

- Feedback to BB interaction models

\[ \text{NPA 754 (2005) 58c} \quad \text{EPJ A33 (2007) 243} \]
An example of $^{12}\text{C} (\pi^+, K^+\gamma)^{12}_\Lambda\text{C}$ at KEK

Reaction angle $\theta_{\pi K}$

Spin-flip production

$\Delta L = 1$

non-spin-flip production

Hosomi et al. To be published

Bound excited states w/o Doppler corr.

Bound excited states w/ Doppler corr.

Unbound region
Level scheme of $^{12}_\Lambda C$ (Updated Analysis)

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

$^{12}_C(e,e'K^+)^{12}_\Lambda C$ @ KEK-PS

$^{12}_C \left(\pi^+,K^+\right) ^{12}_\Lambda C$

$^{12}_C(p+p),K^+ \rightarrow ^{12}_\Lambda C$

$^{12}_C(p+p),K^+ \rightarrow ^{12}_\Lambda C$

This precise $^{12}_\Lambda C$ level scheme is useful for testing new reactions and apparatus.
2. E13: Purposes and Present Status
Ge cooled down to ~70K by pulse-tube refrigerator (c.f. 92K w/LN2)

Fast background suppressor made of PWO

Eff. ~ 6% @1 MeV with 32 Ge(re=60%)
Hyperball-J
installed in front of SKS magnet at K1.8
Hyperball-J performance in beam

Ge Adc (added for 16 detectors)

Measured range: 0.1 - 8 MeV

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>197.1 keV</td>
<td>19</td>
</tr>
<tr>
<td>718.4 keV</td>
<td>10</td>
</tr>
<tr>
<td>937 keV</td>
<td>18</td>
</tr>
<tr>
<td>870.7 keV</td>
<td>17</td>
</tr>
</tbody>
</table>

FWHM: 3.8 ± 0.3 keV
FWHM: 4.3 ± 0.5 keV

CF$_2$(20 g/cm$^2$) target
8 hours

Red: $\gamma$-rays from beam reaction on target nuclei

$^{19}$F(197.1 keV)
$^{10}$B(718.4 keV)
$^{18}$F(937 keV)
$^{17}$O(870.7 keV)

$^{74}$Ge
$^{27}$Al or $^{56}$Fe

$e^-(511$ keV)
**Purpose of E13 experiment**

Approved as DAY1, Second priority

**ΛN interaction**

1. **Charge symmetry breaking in ΛN interaction**
   
   $^4_\Lambda$He: Confirm (or deny) CSB effects suggested by old data
   
   1.5, 1.8 GeV/c ($K^-,\pi^-$) @K1.8

2. **Radial dependence of ΛN interaction**
   
   $^{19}_\Lambda$F: The first sd-shell hypernuclei
   
   1.8 GeV/c ($K^-,\pi^-$) @K1.8

3. **Study ΛN–ΣN coupling force**
   
   $^{10}_\Lambda$B and $^{11}_\Lambda$B: Inconsistency in p-shell data.
   
   1.1 GeV/c ($K^-,\pi^-$) @K1.1

4. **g-factor of Λ in nucleus**
   
   $^7_\Lambda$Li: $g_\Lambda$ measurement in ~3% accuracy
   
   1.1 GeV/c ($K^-,\pi^-$) @K1.1
Experimental approaches to Charge Symmetry Breaking puzzle in A=4

Origin: $\Delta N-\Sigma N$ coupling? But theoretically difficult

Will be measured via $(e,eK^+)$ at Jlab

Will be measured by Ge at J-PARC

Old NaI data

Experimental confirmation of CSB J-PARC E13 (+ more)

- $^4\text{He}(K^-,\pi^-)\ ^4\Lambda\text{He}(1^+\rightarrow0^+)$
- $^4\text{He}(K^-,\pi^0\gamma)\ ^4\Lambda\text{H}(1^+\rightarrow0^+)$
  with a few keV accuracy

$^4\Lambda\text{He}

$^4\Lambda\text{H}

$^3\text{H}

$^3\text{He}

Old emulsion data

Being measured at Maniz

Difficult by counter experiments
Experimental approaches to Charge Symmetry Breaking puzzle in A=4

**Old emulsion data**

Will be measured by Ge at J-PARC

4^He + p -> ... Being measured at Maniz

Will be measured via (e,eK^- + p) at Jlab

**Experimental confirmation of CSB**

J-PARC E13 (+ more)

- 4^He(K^-,π^-γ) 4^ΛHe(1^+-→0^+)
- 4^He (K^-,π^0γ) 4^ΛH(1^+-→0^+)

Data with a few keV accuracy

- E_γ[4^ΛHe] ≠ E_γ[4^ΛH]:
  - Clear evidence of CSB.
  - Spin dependence of CSB int.
- E_γ[4^ΛHe] = E_γ[4^ΛH]:
  - Strongly suggests CSB does not exist

**Bedjidian et al, PLB 83 (1979) 252**

- Origin: LN-SN coupling?
- But theoretically difficult
- Not a significant peak

\[ E_γ[4^ΛHe] = E_γ[4^ΛH] \]:
- Clear evidence of CSB.
- Spin dependence of CSB int.

\[ E_γ[4^ΛHe] ≠ E_γ[4^ΛH] \]:
- Strongly suggests CSB does not exist

**by counter experiments**
$^{19}_\Lambda F$ spectroscopy
The first study of sd-shell hypernuclei

(1) $\Delta N$ spin-spin interaction in sd shell
(2) spin-flip $B(M1) \rightarrow g_\Lambda$ (byproduct)
(3) shrinkage and N-spin-orbit force (byproduct)
$^{19}_\Lambda F$ spectroscopy
The first study of sd-shell hypernuclei

(1) $\Delta N$ spin-spin interaction in sd shell
(2) spin-flip $B(M1) \rightarrow g_\Lambda$ (byproduct)

(3) shrinkage and N-spin-orbit force (byproduct)

(4) Cross check of (1)

$^{18}_\Lambda O + p$

$^{16}O$ core

Calc. (Millener)
A-dependence of $\Lambda N$ spin-spin int. strength

$=>$ Information on wave functions and interaction range
$=>$ confirm short-range nature of $\Lambda N$ int.

\[ r(s_\Lambda - d_N) > r(s_\Lambda - p_N) > r(s_\Lambda - s_N) \]
Magnetic moment of a $\Lambda$ in a nucleus

Baryon magnetic moment in nucleus:
affected by partial restoration of chiral symmetry?
-> Origin of baryon spin and mass
$\Lambda$, free from Pauli effect, is a good probe.

Direct measurement is difficult ($\tau \sim 0.1-0.2$ ns)

$\Lambda$-spin-flip M1 transition: $B(M1) \rightarrow g_\Lambda$

$B(M1) = (2J_{up} + 1)^{-1} |\langle \Psi_{low} \parallel \mu \parallel \Psi_{up} \rangle|^2$

$= (2J_{up} + 1)^{-1} |\langle \Psi_{\Lambda \downarrow} \psi_c \parallel \mu \parallel \Psi_{\Lambda \uparrow} \psi_c \rangle|^2$

$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$

$= \frac{3}{8\pi} \frac{2J_{low} + 1}{2J_c + 1} (g_\Lambda - g_c)^2 \left[ \mu_N^2 \right]$  

~100% Doppler Shift Attenuation Method

$\Gamma = BR / \tau = \frac{16\pi \cdot 3}{9} E_\gamma^3 B(M1)$
Preliminary data on $g_\Lambda$

**BNL E930 (M. Ukai)**

$g_\Lambda = -1.1 \pm 0.6 \mu_N$

$\tau$ from DSAM

$^{10}\text{B} (K^-, \pi^-) ^{10}_\Lambda \text{B}^* \rightarrow ^{7}_\Lambda \text{Li}^* + ^3\text{He}$

**KEK E566 (Y. Ma)**

$g_\Lambda > -1.76 \mu_N$

$\tau$ from DSAM

$g_\Lambda = -1.04 \pm 0.41 \mu_N$

$^{12}\text{C} (K^-, \pi^-) ^{12}_\Lambda \text{C}^* \rightarrow ^{11}_\Lambda \text{B}^* + p$

- Yield ratio for $[2^- \rightarrow 1^-] / [1^- \rightarrow 2^-]$ $\gamma$-rays
  -> $\text{Br}(2^- \rightarrow 1^-) = 0.19 \pm 0.12$ (80% of $2^-$ weakly decays)

- Weak decay rate of $2^-$ and $1^-$ are assumed to be the same, $\Gamma_{\text{weak}} = (\text{lifetime } 230.7 \pm 6.3 \text{ ps})^{-1}$

=> $\Gamma_{M1} = \text{Br} / (1 - \text{Br}) \Gamma_{\text{weak}}$

$\Leftrightarrow g_\Lambda(\text{free}) = -1.226 \mu_N$
Preliminary data on B(M1) in $^{7}_\Lambda$Li (BNL E930)

$^{10}$B ($K^-, \pi^-$) $^{10}_\Lambda B^*$, $^{10}_\Lambda B^*(3^+) \rightarrow ^7_\Lambda Li^*(3/2^+) + ^3$He indirect population

$g_L$ in nucleus - first data of $g_\Lambda = 1.1^{+0.4}_{-0.6}$ $\mu_N$

First data of $g_\Lambda$ in nucleus - precise (5%) B(M1) measurement of $^{7}_\Lambda$Li at J-PARC E13

Preliminary simulation

$\tau = 0.58^{+0.38}_{-0.20}$ ps

BR(M1) = 100%

$B(M1) = 0.30^{+0.12}_{-0.16}$ [$\mu_N^2$]

$\tau << 0.1$ ps

$\tau = 1.5$ ps

Stopping time ~ 2 ps

Counts/keV

$E_\gamma$ [keV]

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)

$^{10}$B(595)

$^{72}$Ge(683)

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)

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$^{72}$Ge(595)

$^{7}_\Lambda$Li(692)

$^{10}$B(718)

$^{72}$Ge(595)
Preliminary data on B(M1) in $^{7}_Λ$Li (BNL E930)

$^{10}$B ($K^-, \pi^-$) $^{10}_Λ B^*$, $^{10}_Λ B^*(3^+) \rightarrow ^7_Λ Li^*(3/2^+) + ^3$He indirect population

-$\Delta \tau/\tau = 5.6\%$

Stat. error $\frac{|g_Λ-g_c|}{|g_Λ-g_c|} \sim 3\%$

$\tau = 0.5$ ps

$\tau = 1.5$ ps

$|g_Λ-g_c|/|g_Λ-g_c| \sim 3\%$

$\Delta |g_Λ-g_c|/|g_Λ-g_c| = 5.6\%$

$E13 \ (2^{nd}): \ Simulation$

$Nucl.Phys. \ A881 \ (2012) \ 310$

$\tau = 0.5$ ps

$\tau = 1.5$ ps

$|g_Λ-g_c|/|g_Λ-g_c| \sim 3\%$

$\Delta |g_Λ-g_c|/|g_Λ-g_c| = 5.6\%$

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$E13 \ (2^{nd}): \ Simulation$

$Nucl.Phys. \ A881 \ (2012) \ 310$
3. Beyond E13
Future Plans

- Systematic study of $g_\Lambda (^{7}_\Lambda Li, ^{12}_\Lambda C, ^{19}_\Lambda F, \ldots)$
  - $\rho$ dependence -> chiral symmetry restoration
  - Isospin dependence -> effect of $\Sigma$ mixing

Doppler shift attenuation method
  + Weak-gamma coincidence method

- Impurity effects in $p$ and $sd$ shell hypernuclei
  - Shrinkage/ deformation change ($^{9}_\Lambda Be, ^{13}_\Lambda C, ^{20}_\Lambda Ne, \ldots$)
  - Disappearance of neutron halo ($^{7}_\Lambda He$)
  - Study structure of normal nuclei using a $\Lambda$
    Triaxial deformation ($^{25}_\Lambda Mg$), $\alpha$-cluster gas ($^{12}_\Lambda C(0^+)_2 + \Lambda$)

- $\Lambda$’s single particle energies for a wide range of $A$
  - $1\hbar\omega$ energy
  - LS splitting
    from $E1$: ($p_{1/2}^\Lambda \rightarrow s^\Lambda$, $p_{3/2}^\Lambda \rightarrow s^\Lambda$) for a wide mass range
$\Lambda$'s single particle energy

$B_\Lambda$ (MeV)

$A$ Binding Energy

$A$ Binding Energy

(E1 $\gamma$-ray error $\sim 1$ keV

LS splitting

Density dependence of $\Lambda N$ interaction

$\rightarrow$ EOS and hyperon puzzle

(Y.Yamamoto's talk)

Origin of LS splitting

(2B-LS force, tensor force, many body effects)

$(K^-,\pi^-), (\pi^+,K^+) \rightarrow \Delta E \sim 200$ keV @J-PARC Ext-HH

$(e,e'K^+) \Delta E \sim 500$ keV, syst.err. $\sim 100$ keV @Jlab Hall-A (HKS+HRS)
E1 measurement for heavy hypernuclei

\( \gamma \)-spectroscopy of \(^{208}_\Lambda \text{Pb} \)

H. Tamura et al., J-PARC LOI

(K\(^-\),\(\pi^-\)) at 1.8 GeV/c
10 g target
3\times10^6 K^-/4s (~270 kW)

500 h
\( p3/2(5^-) \) ~500 events
\( p1/2(7^-) \) ~200 events
\( p3/2(7^-) \) ~130 events

Higher intensity is necessary!
4. Summary

- E13-1\textsuperscript{st} will study $^4_\Lambda\text{He}$ and $^{19}_\Lambda\text{F}$ for CSB and $\Lambda N$ interaction in sd-shell hypernucleus.

- Hyperball-J is ready and commissioning has been done.

- E13-2\textsuperscript{nd} will study $g_\Lambda$ in nucleus from B(M1) measurement.

- Beyond E13, we plan E1 ($p_\Lambda \rightarrow s_\Lambda$) measurement for heavy hypernuclei, as well as systematic study of $g_\Lambda$ and impurity effects.