Perspectives on the physics of hypernuclei

from the point of view of an Italian experimentalist

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Outline

- BROOKHAVEN NATIONAL LABORATORY: completed
- Jefferson Lab: upgrading
- GSI FAIR: running
- INFN: stand-by
- HEPI: in preparation
- KEK: completed
Open questions

(low-energy) $YN$ interaction

- detailed knowledge of the hypernuclear fine structure
  - evaluation of the spin dependent terms of the $\Lambda N$ interaction
- measurement of angular distribution of $\gamma$-rays
  - determination of spin and parity of each observed level
The simple structure of light hypernuclear system can be described in the frame of the shell model.

Each of the 4 terms ($\Delta$, $S_\Lambda$, $S_N$, $T$) correspond to a radial integral that can be phenomenologically determined from the low-lying level structure of $p$-shell hypernuclei.

The knowledge of these characteristics of the $\Lambda N$ interaction allows to improve baryon-baryon interaction description.
Where do we stand?

Status of hypernuclear γ spectroscopy

=> “Table of Hyper-Isotopes”
Where do we stand?

\[
\begin{align*}
\Delta &= 0.48 \\
S_\Lambda &= -0.01 \\
S_N &= -0.40 \\
T &= 0.03
\end{align*}
\]

Where do we stand?

Status of hypernuclei.

$\Delta$, $S_A$, $T$: consistent

$S_A$: consistent

$S_N$: consistent

$T = 0.03$ MeV

$\Delta$: almost consistent

$\Delta$: consistent

$S_N$: consistent

$\Delta$: inconsistent

Spin-orbit force ($S_A$, $S_N$): consistent with not with mesons

$\Delta = 0.43$ MeV

Tensor force ($T$): consistent with mesons

$S_N = -0.4$ MeV

$S_A = -0.01$ MeV

Three-body force by $\Delta\Sigma$ coupling
-- Not well known but important in s-shell hypernuclei.
Essential role in n-stars

More data necessary to clarify the spin-dependent interactions and $\Sigma N-\Lambda N$ coupling force.
What do we learnt?

- the determined set of parameters is not universal
- γ-ray spectroscopy is the new frontier for hypernuclear physics
The crucial benchmark

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

$\Delta E \sim 1.9 \text{ MeV FWHM}$


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

$\Delta E \sim 1.3 \text{ MeV FWHM}$


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

$\Delta E \sim 0.67 \text{ MeV FWHM}$


Hall A
Charge symmetry breaking

\[ I = 0 \]
\[ q = 0 \]

if the charge symmetry holds exactly

\( B_\Lambda(4^4H) \not= B_\Lambda(4^4He) \)

\( \Lambda p \) more attractive than \( \Lambda n \)

possible explanations: • \( \Lambda\Sigma^0 \) mixing
• \( \Lambda N - \Sigma N \) coupling

Which role for magnetic spectrometer?

The region of high excitation energy in heavy $\Lambda$-hypernuclei cannot be explored with $\gamma$-spectroscopy.

Unambiguous identification of the $S = -2$ hypernuclei usually relies on the observation of the double sequential (pionic) weak decay.

The next generation apparatuses should be a smart combination of magnetic spectrometer and $\gamma$-ray detector arrays.
A paradigmatic example of collaboration
\[ e^- + e^+ \rightarrow \phi \rightarrow K^- K^+ \]

\[ K^- \text{stop} + A Z \rightarrow \Lambda Z + \pi^- \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>510 MeV</td>
</tr>
<tr>
<td>luminosity</td>
<td>$5 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma_x$ (rms)</td>
<td>2.11 mm</td>
</tr>
<tr>
<td>$\sigma_y$ (rms)</td>
<td>0.021 mm</td>
</tr>
<tr>
<td>$\sigma_z$ (rms)</td>
<td>35 mm</td>
</tr>
<tr>
<td>bunch length</td>
<td>30 mm</td>
</tr>
<tr>
<td>crossing angle</td>
<td>12.5 mrad</td>
</tr>
<tr>
<td>frequency (max)</td>
<td>368.25 MHz</td>
</tr>
<tr>
<td>bunch/ring</td>
<td>up to 120</td>
</tr>
<tr>
<td>part./bunch</td>
<td>$8.9 \times 10^{10}$</td>
</tr>
<tr>
<td>current/ring</td>
<td>5.2 A (max)</td>
</tr>
</tbody>
</table>
$^{12}\text{C}(K^-_{\text{stop}},\pi^-)^{12}\text{C}$

$\Delta E \sim 1.3 \text{ MeV FWHM}$

![Graph showing capture rate distribution with peaks labeled #1 to #7]

<table>
<thead>
<tr>
<th>Peak number</th>
<th>$-B_\Lambda$ (MeV)</th>
<th>Capture rate/(stopped $K^-$)$\times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-10.94 \pm 0.06$</td>
<td>$1.01 \pm 0.11_{\text{stat}} \pm 0.10_{\text{sys}}$</td>
</tr>
<tr>
<td>2</td>
<td>$-8.4 \pm 0.2$</td>
<td>$0.21 \pm 0.05$</td>
</tr>
<tr>
<td>3</td>
<td>$-5.9 \pm 0.1$</td>
<td>$0.44 \pm 0.07$</td>
</tr>
<tr>
<td>4</td>
<td>$-3.8 \pm 0.1$</td>
<td>$0.56 \pm 0.08$</td>
</tr>
<tr>
<td>5</td>
<td>$-1.6 \pm 0.2$</td>
<td>$0.50 \pm 0.08$</td>
</tr>
<tr>
<td>6</td>
<td>$0.27 \pm 0.06$</td>
<td>$2.01 \pm 0.17$</td>
</tr>
<tr>
<td>7</td>
<td>$2.1 \pm 0.2$</td>
<td>$0.58 \pm 0.18$</td>
</tr>
</tbody>
</table>

**FINUDA @ DAΦNE**

$^7\text{Li}(K^-\text{stop},\pi^-)^{\Lambda}\text{Li}$

$\Delta E \sim 1.1$ MeV FWHM


$K^- n \rightarrow \Lambda\pi$

$K^- \rightarrow \mu^-\nu_\mu$ in flight

**background process giving $\pi^-$ following $K^-$ absorption on $^7\text{Li}$**

$K^- (\Sigma^- N) \rightarrow \Sigma^- N$

$\Sigma^- \rightarrow n\pi^-$

$K^- n \rightarrow \Lambda\pi$

$K^- \rightarrow \mu^-\nu_\mu$

$B_{\Lambda}^{g.s.} = 5.58 \pm 0.03$ MeV

M. Jurić et al., Nucl. Phys. Rev. B 52 (1973) 1

<table>
<thead>
<tr>
<th>$-B_{\Lambda}$</th>
<th>Yield</th>
<th>Production rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-5.33 \pm 0.13 \pm 0.18$</td>
<td>52 ± 11</td>
<td>$0.47 \pm 0.12 \pm 0.11%$</td>
</tr>
<tr>
<td>$-3.68 \pm 0.15 \pm 0.18$</td>
<td>44 ± 10</td>
<td>$0.39 \pm 0.11 \pm 0.11%$</td>
</tr>
</tbody>
</table>

spin-flip amplitude ≈ 0

spin-flip amplitude $\approx 0$

1. $\equiv 1/2^+$

2. $\equiv 5/2^+$
Λ-hypernucleus decay

\(\Lambda\)-hypernucleus non-mesonic decay

- very thin targets: 0.2-0.3 g/cm\(^2\)
- detector “transparency”
Λ-hypernucleus non-mesonic decay

SKS data

FINUDA data

Open questions

- (low-energy) $YN$ interaction
  - detailed knowledge of the hypernuclear fine structure
    $\rightarrow$ evaluation of the spin dependent terms of the $ΛN$ interaction
  - measurement of angular distribution of $γ$-rays
    $\rightarrow$ determination of spin and parity of each observed level

- Impurity nuclear physics
  - measurement of transition probability $B(E2)$
    $\rightarrow$ information on the size and deformation of hypernuclei
  - measurement of nucleus core shrinking $\rightarrow$ glue-like role of $Λ$
Open questions

- (low-energy) $YN$ interaction
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- Impurity nuclear physics
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    - measurement of nucleus core shrinking → glue role of $Λ$

- Properties of hyperons in nuclear matter (medium effect)
  - measurement of transition probability $B(M1)$
    - $g$-factor value for $Λ$ in nuclear matter
Phase 1: Total 1500 Oku-Yen (56% JAEA, 44% KEK)

3 GeV Synchrotron
25 Hz (350m)

LINAC (330m)

Neutrino Beam line

50 GeV Synchrotron
0.3 Hz (1600m)

Materials and Life Science Facility

Hadron Exp. Facility
Strangeness Nuclear Physics approved experiments

- **E05**: Ξ hypernuclei spectroscopy  \((1^{\text{st}} \text{ priority})\)
- **E13**: hypernuclear γ-ray spectroscopy  \((2^{\text{nd}} \text{ priority})\)
- **E15**: search for \(K\)-pp bound state
- **E17**: kaonic \(^3\text{He} \rightarrow 2p\) \(X\)-ray
- **E19**: search for penta-quark in \(\pi^-p \rightarrow K^-X\) reaction
- **E07**: hybrid emulsion for double Λ hypernuclei
- **E03**: Ξ-atom \(X\)-rays
- **...**
γ-ray spectroscopy of hypernuclei

- further study of ΛN interaction: \(^4\)He, \(^{10}\)B, \(^{11}\)B, \(^{19}\)F
  - ΛN-ΣN coupling and 3-body force
  - charge symmetry breaking (Λn \(\neq\) Λp?)
  - radial dependence (interaction range)

- \(g_\Lambda\) in a nucleus from spin-flip B(M1): \(^7\)Li
angular distributions:

\[ ^{16}O(e,e'K^+)_{^A}N \]
new physics items:

- a detailed and consistent understanding of the quark aspect of the baryon-baryon forces in the SU(3) space will not be possible as long as experimental information on the $YY$ channel is not available
- search for $H$ particle
- existence of $S = -2$ (deeply) bound $\bar{K}$ states

experimental challenges:

- (abundant) production of $\Lambda\Lambda$- and $\Xi$-hypernuclei is really difficult
- identification of produced hyperfragments is problematic
- $\gamma$-ray measurement in coincidence
### The status of the art

<table>
<thead>
<tr>
<th>reference (year)</th>
<th>hyper nucleus</th>
<th>$B_{\Lambda\Lambda}$ [MeV]</th>
<th>$\Delta B_{\Lambda\Lambda}$ [MeV]</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Danysz et al., Nucl. Phys. 49 (1963) 121</td>
<td>$^{10}_{\Lambda\Lambda}\Lambda Be$</td>
<td>17.7 ± 0.4</td>
<td>4.3 ± 0.4</td>
<td>emulsion exp.; Dalitz’ reanalysis</td>
</tr>
<tr>
<td>D. Prowse et al., Phys. Rev. Lett. 17 (1966) 782</td>
<td>$^{6}_{\Lambda\Lambda}\Lambda He$</td>
<td>10.9 ± 0.5</td>
<td>4.6 ± 0.5</td>
<td>emulsion exp.; Dalitz’ criticism</td>
</tr>
<tr>
<td>S. Aoki et al., Prog. Theor. Phys. 85 (1991) 951</td>
<td>$^{13}_{\Lambda\Lambda}\Lambda B$</td>
<td>27.6 ± 0.7</td>
<td>4.8 ± 0.7</td>
<td>KEK-E176 emulsion-counter hybrid exp. (*)</td>
</tr>
<tr>
<td>S. Aoki et al., Prog. Theor. Phys. 85 (1991) 1287</td>
<td>$^{10}_{\Lambda\Lambda}\Lambda Be$</td>
<td>8.5 ± 0.7</td>
<td>-4.9 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>H. Takahashi et al., Phys. Rev. Lett. 87 (2001) 212501</td>
<td>$^{6}_{\Lambda\Lambda}\Lambda He$</td>
<td>7.25 ± 0.19 $^{+0.18}_{-0.11}$</td>
<td>1.01 ± 0.20 $^{+0.18}_{-0.11}$</td>
<td>KEK-E373 emulsion-counter hybrid exp. (***)</td>
</tr>
<tr>
<td>H. Takahashi et al., Nucl. Phys. A 721 (2003) 951c</td>
<td>$^{10}_{\Lambda\Lambda}\Lambda Be$</td>
<td>12.33 $^{+0.35}_{-0.21}$</td>
<td>---</td>
<td>KEK-E373 emulsion-counter hybrid exp. (***)</td>
</tr>
</tbody>
</table>

\[ B_{\Lambda\Lambda}(A\Lambda Z) = B_{\Lambda}(A\Lambda Z) + B_{\Lambda}(A-z) \]

\[ \Delta B_{\Lambda\Lambda}(A\Lambda Z) = B_{\Lambda}(A\Lambda Z) - B_{\Lambda}(A-z) \]

**ΛΛ- and Ξ-hypernucleus production**

**Ξ- atomic capture reaction at rest**
is one of the **most effective way** to look for **double Λ-hypernuclei**

- **compound double Λ state:**
  \[ \Xi^- + A Z \rightarrow (A-1)(Z-1) + \Lambda + \Lambda \]
  \[ \Xi^- + p \rightarrow \Lambda + \Lambda + 28 \text{ MeV} \]

- **quasi deuteron model:**
  \[ \Xi^- + A Z \rightarrow A(Z-1) + n \]

**K- beams:**
- @ BNL 1.88 GeV/c
- @ KEK 1.66 GeV/c
- @ J-PARC 1.80 GeV/c
E05 experimental layout

- first spectroscopic study of $S = -2$ systems in $(K^-,K^+)$ reaction

- $\Xi N$ interaction
  - attractive or repulsive
  - depth of $\Xi$-nuclear potential
  - isospin dependence
  - $\Xi N$-$\Lambda\Lambda$ coupling force

Spectroscopic study of $\Xi$-hypernucleus, $^{12}\text{Be}_\Xi$, via the $^{12}\text{C}(K^-,K^+)$ reaction
primary beams
- $^{238}\text{U}^{28+} 10^{12}/s @ 2.7 \text{ AGeV}$
- $^{238}\text{U}^{92+} 10^{10}/s @ 35 \text{ AGeV}$
- protons $2 \times 10^{13}/s$ @ 30 GeV

secondary beams
- radioactive ion beams @ 2 AGeV
- antiprotons $0 \rightarrow 15 \text{ GeV/c}$

storage and cooler rings
- rare isotope and stable ion beams
- $e^-\text{-A or } \bar{p}-\text{A collider}$
- $10^{11}$ stored and cooled $\bar{p} 0.8 \rightarrow 15 \text{ GeV/c}$
- future options:
  - low energy $\bar{p}$ for $\bar{H}$ beyond 2015
  - polarized $\bar{p}$ (?)

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-existing facility
-new facility

FaA:
- FRS
- ESR
- SIS18
- UNILAC
- SIS 100/300
- HESR
- PANDA
- HADES & CBM
- Super FRS
- NUSTAR
- FLAIR
- RESR
- NESR
- CR

cost: 1.2 G€
commissioning: 2015
A look to the future

\[ \bar{p} + p \rightarrow \Xi^- + \Xi^+ \quad (\@ \sim 3 \text{ GeV/c}) \]

\[ \Xi^- + {}^A Z \rightarrow (A-1)(Z-1) \oplus \Lambda \oplus \Lambda \]
Summary

✓ Hypernuclear physics is a challenging research field and has a great discovery potential
  ✡ number of exp. physicist involved is growing
  ✡ main item in several future physics program at new facilities
  ✡ dedicated beams and apparatus
  ✡ significant theoretical effort well tuned on exp. data

ิน The synergic exploitation of the progress in detection techniques and of the improvement of the quality of the available beams is the premise for a significant step forward in our understanding of the baryon-baryon interaction.
Thank you!

どうも ありがとう