Spectroscopy of hypernuclei

Gamma-Ray Spectroscopy in Europe
Present and Future Challenges
ECT*, 8-12 May, 2006

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Outline

- Discovery potential of the strangeness nuclear physics
  - recent experimental results
  - unexpected effects

- Need of sub-MeV resolution apparatuses
  - $\gamma$-ray spectroscopy

- Proposal for new experiments
Physics output (S=-1)

- Nuclear models
- Neutron rich Λ-hypernuclei
- 4B weak interaction
- Spectroscopy
- (Weak) decay
- Medium effect
- Quark substructures
- Low-energy N-Y interaction
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
**Spin-dependent forces**

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 phenomelogically 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?

\[ \Delta = 0.43 \]
\[ S_\Lambda = -0.01 \]
\[ S_N = -0.40 \]
\[ T = 0.03 \]

HYPERBALL
KEK E419: \((\pi^+, K^+)_{^7\text{Li}}\)
BNL E930: \((K^-, \pi^-)_{^7\text{Li}}\)
KEK E509: \((K^-, \pi^-)_{^7\text{Li}}\)

**Charge symmetry breaking**

\[ \Lambda \begin{cases} I = 0 \\ q = 0 \end{cases} \]

\[ \Lambda p = \Lambda n \]

If the charge symmetry holds exactly

\[ B_\Lambda(4^4H) \neq B_\Lambda(4^4He) \]

\[ \Lambda p \text{ more attractive than } \Lambda n \]

Possible explanations:

- \( \Lambda \Sigma^0 \) mixing
- \( \Lambda N - \Sigma N \) coupling

Open questions

(low-energy) $YN$ interaction

- detailed knowledge of the hypernuclear fine structure
  - evaluation of the spin dependent terms of the $ΛN$ interaction
- measurement of angular distribution of $γ$-rays
  - determination of spin and parity of each observed level

Impurity nuclear physics

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

A hypernucleus can be considered the outcome of a genetic engineering manipulation applied to the nuclear physics domain.

The introduction of 1 (or 2) hyperons in a nucleus may give rise to various changes of the nuclear structure:

- changes of the size and of the shape
- changes of the cluster structure
- manifestation of new symmetries
- change of collective motions
- ...

study of hypernucleus level schemes and B(E2)

Doppler-shift attenuation method
The $\Lambda$ glue-like role

**KEK E419**

$B(E2, {}^7\Lambda Li: 5/2^+ \rightarrow 1/2^+) = \frac{3.6 \pm 0.5^{+0.5}_{-0.4}}{10.9 \pm 0.9} \frac{e^2 fm^4}{e^2 fm^4} \approx \frac{1}{3}$

$B(E2, {}^6Li: 3^+ \rightarrow 1^+)$

$B(E2) \propto r^4 \Rightarrow \text{shrinkage of } {}^6Li \text{ core by } \sim 20\%$

Open questions

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

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

- Properties of hyperons in nuclear matter (medium effect)
  - measurement of transition probability $B(M1)$
    - $g$-factor value for $\Lambda$ in nuclear matter
Medium effect

If the mass or the size of a hyperon is modified in a nucleus, its magnetic moment may be changed.

\[ B(M1) \propto \left| \langle \phi_{lo} | \mu^z | \phi_{up} \rangle \right|^2 = \left| \langle \phi_{lo} | g_N J_N^z + g_\Lambda J_\Lambda^z | \phi_{up} \rangle \right|^2 \]

\[ \propto (g_N - g_\Lambda)^2 \]

B(M1) can be derived from excited states lifetimes.

- Doppler-shift attenuation method
- γ-weak coincidence method
Physics output ($S=-2$)

- Nuclear models
- Strangelets
- $H$ dibaryon existence
- Spectroscopy
- (Weak) decay
- Astrophysics
- $S=-2$ system g.s.
- Low-energy $Y-Y$ interaction
- $H$ particle mass
Observed $\Lambda\Lambda$-hypernuclei

- 1963: Danysz et al. $^{10}\Lambda\Lambda Be$ (emulsion)
- 1966: Prowse $^{6}\Lambda\Lambda He$ (emulsion, Dalitz criticises the interpretation)
- 1991: KEK-E176 $^{13}\Lambda\Lambda B$ (or $^{10}\Lambda\Lambda Be$, emulsion counter hybrid experiment)
- 2001: BNL-E906 $^{4}\Lambda\Lambda H$
- 2001: KEK-E373 $^{6}\Lambda\Lambda He$
- 2001: KEK-E373 $^{10}\Lambda\Lambda Be$

$$\Xi^- + ^{12}C \rightarrow ^{6}\Lambda\Lambda He + ^4He + t$$

$$^6\Lambda\Lambda He \rightarrow ^5\Lambda\Lambda He + p + \pi^-$$
### Energy and Luminosity

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>510 MeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$</td>
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</table>

### Other Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\sigma_x$ (rms)</td>
<td>2.11 mm</td>
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<tr>
<td>$\sigma_y$ (rms)</td>
<td>0.021 mm</td>
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<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>

### Reaction Equations

- $e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$
- $K^-_{\text{stop}} + {}^A Z \rightarrow {}^A \Lambda Z + \pi^-$
Is the integration possible?

Hyperball

FINUDA
Experimental challenges

Do HPGe crystals work in (strong) magnetic field?

[Graph showing energy resolution vs. magnetic field.]

Euroball @ GSI
FINUDA2

X-COOLER II, AMETEK, ORTEC

Geometrical acceptance reduced to 82%
Interested community

HadronPhysics I3
Study of Strongly Interacting Matter

JRA6

INFN
Istituto Nazionale di Fisica Nucleare

KEK

Riken

University of Tokyo

GSI

Technische Universität Mainz

Kungl Tekniska högskolan

HyperGamma
Strategy

Total synergy with the I3HP JRA6 project
- study of HPGe crystal performance in strong magnetic field

Close collaboration with TORTOLISO experiment, approved by INFN CSN 5
- Cagliari-Torino Collaboration
- production of LYSO crystals by an Italian firm

Contacts with INFN Groups, with solid experience on HPGe
- exploitation of previous INFN investment

PRIN dedicated to an operative test of final HPGe configuration in magnetic field
- last step before to go
\[
\bar{p}p \rightarrow \Xi^+ \Xi^-
\Xi^- + A Z \rightarrow A + 1 \Lambda \Lambda (Z - 1)
\]
PANDA Collaboration

Universität Basel, IHEP Beijing, Ruhr-Universität Bochum, Universität Bonn, Università di Brescia + INFN, Università di Catania, University of Silesia, University Cracow, GSI Darmstadt, TU Dresden, JINR Dubna, JINR Dubna, University Edinburgh, Universität Erlangen, Northwestern University, INFN Sezione di Ferrara, Universität Frankfurt, LNF-INFN Frascati, INFN Sezione di Genova, Università di Genova, Universität Gießen, University of Glasgow, KVI Groningen, Institute of Physics Helsinki, FZ Jülich - IKP I, FZ Jülich - IKP II, IMP Lanzhou, Universität Mainz, Universität di Milano, TU München, Universität Münster, BINP Novosibirsk, IPN Orsay, Università di Pavia, PNPI Gatchina St. Petersburg, IHEP Protvino, Stockholm University, Universität di Torino, Universität de Piemonte, Università di Trieste + INFN, Universität Tübingen, Uppsala Universitet, TSL Uppsala, Universidad de Valencia, Stefan Meyer Institut für subatomare Physik, Vienna, SINS Warschau

15 countries – 47 institutes – 370 scientists
possible Joint Research Project in the Seventh Framework Programme (FP7)

- further study of HPGe crystal performance with the electromechanical cooling system
- design of a 3-crystal cluster, equipped with new readout electronics

strict collaboration with INFN Groups, with solid experience on HPGe

- exploitation of previous INFN investment

PRIN dedicated to an operative test of chosen HPGe configuration in magnetic field

- last step before to go
Summary

- Strangeness nuclear physics still has a great discovery potential.

- Spectroscopy of hypernuclei offers a couple of interesting opportunity to successfully employ the existing HPGe detectors:
  - FINUDA at DAΦNE (LNF/INFN)
  - PANDA at HESR (FAIR/GSI)

- A. Bracco, F. Camera and S. Lenzi
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