Strange quarks in nuclear matter

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Outline

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

- Need of sub-MeV resolution apparatuses
  - γ-ray spectroscopy

- Ideas for PANDA apparatus
What is the strangeness nuclear physics?

Strangeness nuclear physics born exactly 50 years ago

60's

80's

90's

nuclei with a tracer

Today hypernuclear physics is a mature research field with a well defined “personality”

- Number of exp. physicists involved is growing
- Significative theoretical effort well tuned on exp. data
- Dedicated beams and apparatus
- Main item in several future physics program
Physics output

- Nuclear models
- Neutron rich Λ-hypernuclei
- 4B weak interaction
- Spectroscopy
- (Weak) decay
- Medium effect
- Quark substructures
- Low-energy N(Y)-Y interaction
1) **strangeness exchange** (both in flight and at rest):

\[ K^- + {}^A_Z \rightarrow {}_\Lambda^A Z + \pi^- \]

2) **associated production**:

\[ \pi^+ + {}^A_Z \rightarrow {}_\Lambda^A Z + K^+ \]

3) **electro-production**:

\[ e^- + {}^A_Z \rightarrow e^- + K^+ + {}_\Lambda^A (Z - 1) \]

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A hypernucleus is the outcome of a genetic engineering manipulation applied to the nuclear physics domain.
**Λ-hypernucleus spectroscopy**

The simple structure of light hypernuclear systems can be described in the frame of the shell model.

\[
V_{\Lambda-N}(r) = V_0(r) + V_\sigma(r) \vec{S}_N \cdot \vec{S}_\Lambda + V_\Lambda(r) \vec{I}_{NA} \cdot \vec{S}_\Lambda + V_N(r) \vec{I}_{NA} \cdot \vec{S}_N + V_T(r) [3(\vec{\sigma}_N \cdot \vec{r})(\vec{\sigma}_\Lambda \cdot \vec{r} - \vec{\sigma}_N \cdot \vec{\sigma}_\Lambda)]
\]

Each of the 5 terms (\(V, \Delta, S_\Lambda, S_N, T\)) correspond to a radial integral that can be phenomenologically determined from the low-lying level structure of \(p\)-shell hypernuclei.

The knowledge of the spin-dependent components of the \(\Lambda N\) interaction allows to improve baryon-baryon interaction models and to discriminate between the ones based on meson exchange picture and those including quark-gluon degree.
The energy spectrum of hypernuclei cannot be completely reproduced by a simplified 2-body effective interaction scheme.

Study of $\Lambda NN$ 3-body and of $\Lambda N$ 2-body forces is of great importance to understand the structure of hypernuclei.

- $\Delta m_{\Sigma-\Lambda} \ll \Delta m_{\Delta-N} \rightarrow \Lambda NN \rightarrow \Lambda NN$
- $\Lambda NN > \Lambda N$
Charge symmetry breaking

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

\[ \Lambda p = \Lambda n \]

if the charge symmetry holds exactly

\[ B_{\Lambda\left(\Lambda^4 H\right)} \neq B_{\Lambda\left(\Lambda^4 He\right)} \]

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

Possible explanations:
- \(\Lambda\Sigma^0\) mixing
- \(\Lambda N - \Sigma N\) coupling
Odd-state interaction

even-states $\Lambda N(s\text{-wave})$
odd-states $\Lambda N(p\text{-wave})$

$\begin{array}{c}
\Lambda \\
\Lambda^1 Z - 1 \\
\Lambda^1 Z
\end{array}$

Weak decay

$\begin{array}{c}
\Lambda \\
B_0 \\
B_n
\end{array}$

$\begin{array}{c}
\Lambda \\
Z
\end{array}$

- ND model: attractive odd-state force
- NSC97 model: repulsive odd-state force

Odd-states are usually particle unbound for light ($A < 50$) hypernuclei → best candidate hypernuclei $^{89}_{\Lambda}Y$ and $^{208}_{\Lambda}Pb$

In contrast with data on $^{13}_{\Lambda}C$!
The status of the art

\[ \Delta E \sim 1.65 \text{ MeV FWHM} \]

\[ \Delta E \sim 1.95 \text{ MeV FWHM} \]

\[ \Delta E \sim 1.45 \text{ MeV FWHM} \]

f-orbit splitting into two peaks observed?
$\Lambda$-hypernucleus decay

- **Free $\Lambda$ decay**
  - $p_N \sim 100 \text{ MeV}/c$
  - $\Lambda \rightarrow n + \pi^0 + 41 \text{ MeV} (36\%)$
  - $\Lambda \rightarrow p + \pi^- + 38 \text{ MeV} (64\%)$
  - $\tau_\Lambda = 263 \text{ ps}$

- **Mesonic decay**
  - $p_F \sim 270 \text{ MeV}/c$
  - $\Lambda \rightarrow n + \pi^- + 41 \text{ MeV} (36\%)$
  - $\Lambda \rightarrow p + \pi^- + 38 \text{ MeV} (64\%)$

- **Non-mesonic decay**
  - $p_N \sim 400 \text{ MeV}/c$
  - $\Lambda + n \rightarrow n + n + 176 \text{ MeV}$
  - $\Lambda + p \rightarrow n + p + 176 \text{ MeV}$

- Suppressed by Pauli blocking

- $\Delta I = \frac{1}{2}$ rule (not understood)

- Dominant in all but the lightest hypernuclei
The hypernucleus non-mesonic decay provides primary means of studying the baryon-baryon weak interaction.

- $\Delta S = 0$
  - $\Lambda + N \rightarrow N + N$
  - $S = 0$
  - $\pi^+, \rho, \omega$

- $\Delta S = 1$
  - $\Lambda + N \rightarrow N + N$
  - $S = 1$
  - $\pi, \rho, \eta, \omega, K, K^*$

- Only information on the parity violating part of weak interaction is accessible.
- Parity conserving part is masked by strong interaction.

- Both information on the parity violating and parity conserving parts of weak interaction can be extracted.
- $q \sim 400 \text{ MeV/c} \Rightarrow$ probes short distance.

- $\Delta = \frac{1}{2}$ rule applies also to non-mesonic weak decay?
- The role of explicit quark/gluon substructures can be put in evidence?
Medium effect

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

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

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

- Doppler-shift attenuation method
- \( \gamma \)-weak coincidence method

### Graphical Data

- \( \gamma \)-weak coincidence
- weak decay lifetime
- Doppler shift attenuation
- A=12
- A=208
- E1
- M1
- E2
- Coulomb excitation

### Life Time vs. \( E_\gamma \) (MeV)

- \( \tau \) (sec)
- \( E_\gamma \) (MeV)
Precise hypernuclear $\gamma$-spectroscopy has been established as new frontier in strangeness nuclear physics.
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 role

\[ B(\text{E2}; \Lambda^7\text{Li} : 5/2^+ \rightarrow 1/2^+) \]
\[ \frac{B(\text{E2}; \Lambda^7\text{Li} : 5/2^+ \rightarrow 1/2^+)}{B(\text{E2}; \text{Li}^6 : 3^+ \rightarrow 1^+)} = 3.6 \pm 0.5 \cdot 0.5 \quad \text{e}^2 \text{fm}^4 \]
\[ \approx \frac{1}{3} \]

\[ B(\text{E2}) \propto r^4 \implies \text{shrinkage of } \text{Li}^6 \text{ core by } \sim 20\% \]
Which model description?

BNL E930

experiment  OME  QM

$^9\Lambda\text{Be}(5/2^+ \rightarrow 3/2^+) \quad 31 \pm 2 \text{ keV} \quad 80 - 200 \text{ keV} \quad 35 - 40 \text{ keV}$

$^{13}\Lambda\text{C}(3/2^- \rightarrow 1/2^-) \quad 152 \pm 36 \text{ keV} \quad 390 - 960 \text{ keV} \quad 150 - 200 \text{ keV}$

BUT

quark based models have yet to provide an extensive and satisfactory description of $YN$ interaction
- **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
  - neutron star composition

- **challenges:**
  - (abundant) production of $\Lambda\Lambda$-hypernuclei is very difficult
  - identification of produced hypersystems is problematic
  - $\gamma$-ray measurement in coincidence
Observed $\Lambda\Lambda$-hypernuclei

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

After 40 years!
How to identify a $\Lambda$-hypernucleus

**Double-$\Lambda$ Compound states**

- 0.1 - 0.5
- Two $\Lambda$ Fragments

**Double-$\Lambda$ Fragment**

**sequential pionic decay**

$^{\Lambda}Z \rightarrow ^{\Lambda'}Z' \rightarrow ^{\Lambda''}Z''$

**limited target choice**
(at least for the pilot runs)

- $^6\text{Li}$, $^7\text{Li}$, $^8\text{Be}$, $^9\text{Be}$, $^{12}\text{C}$

**main background**

$\Xi^- \rightarrow \Lambda + \pi^-$

**critical!**

$\Lambda \rightarrow p + \pi^-$
Expected $\pi^-$ momentum spectrum
### Hypernucleus

<table>
<thead>
<tr>
<th>Hypernucleus</th>
<th>( B_{\Lambda\Lambda} ) [MeV]</th>
<th>( \Delta B_{\Lambda\Lambda} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{10}_{\Lambda\Lambda} \text{Be} )</td>
<td>17.7 ± 0.4</td>
<td>4.3 ± 0.4</td>
</tr>
<tr>
<td>( ^{6}_{\Lambda\Lambda} \text{He} )</td>
<td>10.9 ± 0.5</td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>( ^{6}_{\Lambda\Lambda} \text{He} )</td>
<td>7.25 ± 0.19^{+0.18}_{-0.11}</td>
<td>1.01 ± 0.20^{+0.18}_{-0.11}</td>
</tr>
<tr>
<td>same event!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^{13}_{\Lambda\Lambda} \text{B} )</td>
<td>27.6 ± 0.7</td>
<td>4.8 ± 0.7</td>
</tr>
<tr>
<td>( ^{10}_{\Lambda\Lambda} \text{Be} )</td>
<td>8.5 ± 0.7</td>
<td>-4.9 ± 0.7</td>
</tr>
<tr>
<td>( ^{10}_{\Lambda\Lambda} \text{Be} )</td>
<td>12.33^{+0.35}_{-0.21}</td>
<td></td>
</tr>
</tbody>
</table>

One cannot interpret \( \Delta B_{\Lambda\Lambda} \) as \( \Lambda\Lambda \) binding energy because of:

- Dynamical change of the core nucleus
- \( \Lambda\Lambda \) spin-spin interaction for non-zero spin of core
- Possible excited states

If \( \Lambda\Lambda \)- or intermediate \( \Lambda \)-hypernuclei are produced in excited states:

- Q-value is difficult to extract (especially for heavy nuclei)
- Nuclear fragments are difficult to identify with usual emulsion technique

**New concept required!**

\[ \Delta B_{\Lambda\Lambda} \equiv -<V_{\Lambda\Lambda}> \]
Open questions

decay properties:

\[ \text{total decay rate} \]

\[ \text{lifetime measurements} \]

\[ \text{non-mesonic weak decay modes} \]

\[ \text{influence of the } H\text{-like structure} \]
$S = -2$ systems and H-dibaryon states

H-dibaryon in $^{10}\text{Be}$

$B_{\Lambda\Lambda} = 12.2$ MeV

H-particle formation can be revealed by a modification of the energy levels of $\Lambda\Lambda$-hypernuclei
General idea

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28 \text{ MeV}$$

(Kaidalov & Volkovitsky)

quark-gluon string model
Λ-hypernucleus production @ GSI

1. Hyperon-antihyperon production at threshold

2. Capture of $\Xi^-$ in secondary target nucleus

3. $\gamma$-spectroscopy with Ge-detectors

$\bar{p} \rightarrow \Xi^- + 28 \text{MeV}$

kaons

$3 \text{GeV}/c$

$\Xi^-$

trigger

$\gamma$

+23 MeV
**Expected rates**

\[
\sigma_{pp} (\Xi\Xi) = 2 \ \mu b \ \text{at} \ 3 \ \text{GeV/c}
\]

\[
\sigma_{pA} (\Xi\Xi) = A^{2/3} \cdot \sigma_{pp} (\Xi\Xi)
\]

by using, e.g., a $^{12}\text{C}$ wire target:

\[\mathcal{L} = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\] HESR will produce $\Xi\Xi$ pairs @ $\sim 7 \times 10^2 \text{ Hz}$

- joint $\Xi\Xi$ escape probability: $5 \times 10^{-4}$
  (trigger on $\Xi + p_\Xi = 100 - 500 \text{ MeV/c}$)
- $\Xi$ reconstruction efficiency: $\sim 50\%$
- $\Xi^-$ stopping and capture probability: $\sim 20\%$

- $\Xi^-p \rightarrow \Lambda\Lambda$ conversion probability: $5\%$

- $\gamma$-ray emission/event: $50\%$
- $\gamma$-ray Ge photopeak efficiency: $10\%$

- $K^+K^+$ trigger

\[\sim 3 \times 10^3 \text{ captured } \Xi^- / \text{d}\]
\[\sim 150 \Lambda\Lambda\text{-hypernuclei} / \text{d}\]
\[\sim 7 \text{ "golden events"} / \text{d}\]
\[\sim 700 \text{ events} / \text{d}\]
## Competition

<table>
<thead>
<tr>
<th>experiment</th>
<th>reaction</th>
<th>device</th>
<th>beam / target</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL-AGS E885</td>
<td>((\Xi^-,^{12}\text{C}) \rightarrow \Lambda^{12}\text{B} + n)</td>
<td>neutron detector arrays</td>
<td>(K^\pm) beam, diamond target</td>
<td>20000 stopped (\Xi^-)</td>
</tr>
<tr>
<td>BNL-AGS E906</td>
<td>2(\pi) decays</td>
<td>Cylindrical Detector System</td>
<td>(K^\pm) beam line</td>
<td>few tens 2(\pi) decays of (\Lambda^4\text{H})</td>
</tr>
<tr>
<td>KEK-PS E373</td>
<td>((K,K^*)\ \Xi)</td>
<td>emulsion</td>
<td>((K,K^*))</td>
<td>several hundreds stopped (\Xi^-)</td>
</tr>
</tbody>
</table>

### facility

<table>
<thead>
<tr>
<th>reaction</th>
<th>device</th>
<th>beam / target</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>((K,K^*)\ \Xi)</td>
<td>spectrometer, (\Delta\Omega = 30) mrs</td>
<td>8(\cdot10^6)/s, 5 cm (^{12}\text{C})</td>
<td>(&lt; 7000)</td>
</tr>
<tr>
<td>(p\bar{p} \rightarrow K\bar{K})</td>
<td>vertex detector</td>
<td>(10^6) stopped (\bar{p}/s)</td>
<td>2000</td>
</tr>
<tr>
<td>(K\bar{N} \rightarrow \Xi K)</td>
<td>vertex detector + (\gamma)-spectrometer</td>
<td>(\mathcal{L} = 2\cdot10^{32}), thin target, production vertex (\neq) decay vertex</td>
<td>(\sim 3000) (\sim 300000) KK trigger (incl. trigger)</td>
</tr>
<tr>
<td>(p\bar{p} \rightarrow \Xi\Xi)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ω-atoms production @ GSI

1. Hyperon-antihyperon production at threshold

2. Slow down and capture of Ω⁻ in secondary target nucleus

3. γ-spectroscopy with Ge-detectors

\[
\frac{\sigma(\Xi + \Xi)}{\sigma(\Omega + \Omega)} \sim \frac{1}{20}
\]
The PANDA detector
Ge array for hypernuclei detection

- **solid state micro-tracker (diamond or silicon)**
  - compact: thickness ~ 3 cm
  - high rate capability
  - high resolution
- **capillar (2D) or pixel (3D) detector**
- **position sensitive Ge detector (VEGA or AGATA like)**
  - high rate capability
VEGA (Versatile and Efficient GAmma detector)

The Segmented Clover Detector

- BGO Compton suppression shield
- Ge crystals
- active collimator (scintillator)
AGATA (Advanced Gamma-ray Tracking Array)

- 180 hexagonal crystals in 3 different, asymmetric shapes grouped in 60 triple-cluster cryostats
- 10 pentagonal crystals individually canned
- 230 kg of germanium crystals of Ø 8 cm; L : 9 cm
- full sphere with solid angle coverage ~78 % inner-outer radius of 17-26 cm total of 6780 segments

- immersed in magnetic field
- exposed to huge hadronic background

(1) three 36-fold segmented Ge detectors
(2) 111 preamplifiers
(3) frame support
(4) digital electronics
(5) fiber-optics read-out
(6) LN₂ dewar
(7) target position
Summary

- textbook evidence for the validity of the shell model
- spin-orbit terms in the optical potential
- glue-role of the $\Lambda$ (nuclear medium effect)

hypernucleus spectroscopy and decay

- 4 baryon weak interaction $\Lambda N \rightarrow NN$ (validity of $\Delta I = \frac{1}{2}$ rule)
- low energy $\Lambda N$ scattering (short range aspects of the nuclear force)

- $\Lambda\Lambda$ interaction
- search for $H$ particle

very clean nuclear physics!

unique particle physics!
Conclusions

✓ The fifty-year-old field of strangeness nuclear physics is still alive and has a great discovery potential
  
  - number of exp. physicist involved is growing
  - significative theoretical effort well tuned on exp. data
  - dedicated beams and apparatus
  - main item in several future physics program at new facilities

- By exploiting the potentialities of the new HESR machine a large number of ΛΛ-hypernuclei will be produced, allowing a significative step forward in multi-strange system knowledge

רות 2013 will be the 50th anniversary of ΛΛ-hypernucleus discovery: GSI could successfully celebrate it with a long series of fundamental questions solved