NEUTRON-RICH HYPERNUCLEI ARE COMING.

WHAT THEY TELL US?

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OUTLINE

1. Nuclei with a Neutron Excess
2. Λ - Hypernuclei
3. Neutron - Rich Hypernuclei
4. $^6_Λ H$ could be identified - so what ?
5. Outlook
1. NUCLEI WITH A NEUTRON EXCESS

In the last twenty years a new main stream in nuclear physics, namely physics of nuclei in the vicinity of the neutron drip line has been constituted B. Jonson, Phys. Reports 389, 1 (2004).

A number of spectacular effects have been observed:
- a new type of clusterization, “neutron halo”,
- the N-Z dependence of NN interaction and shell occupancy, to mention a few.

The goals are clear:
- to identify the different phenomena,
- to develop and test proper models,
- to establish the foundation of these models.

Several generation facilities for the production and study of wide variety of exotic nuclei have been constructed around the world.

Recently, the exploration of “exotic probes”, $\mu^{-}$ and $\bar{p}$, was suggested.
The potential of $\Lambda$ hypernuclear physics

Hypernuclei are nuclei with a hyperon replacing nucleon. In some sense, $\Lambda$-hypernuclei are “radioactive” nuclei also - their lifetime $\tau \approx 2 \cdot 10^{-10}$ s is governed by weak processes.

Some recent review:


Proceedings of the Int. Conference on Hypernuclear & Strange Particle Physics:

**Motto**

As our experimental and theoretical tools are sharpened, we proceed to build structure on top of foundations previously constructed.

Much of what we do was anticipated by our predecessors.

Ed Hungerford,
Summary of HYP2006

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2. Λ - HYPERNUCLEI
Chart of light nuclei and hypernuclei

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$B_\Lambda$ values of light hypernuclei

$B_\Lambda$

\[ \begin{array}{cccccccccccc}
3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\
\hline
3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15
\end{array} \]

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Spectroscopy of \( \Lambda \) - hypernuclei

Systematic studies of hypernuclei began with the advent of separated kaon beams which permitted the use of counter technique. The level structure of primary hypernuclei is experimentally studied. There are two one-step direct reactions of such a type:

1: \( \text{neutron} \rightarrow \Lambda \)

\[ ^{AZ} (K^{-}, \pi^{-}) \quad ^{AZ}_\Lambda \]

Chrien, Dover, ARNPS 39, 113 '89, and

\[ ^{AZ} (\pi^{+}, K^{+}) \quad ^{AZ}_\Lambda \]

Hagesawa \textit{et al.}, PR C 53, 1210 '96.

2: \( \text{proton} \rightarrow \Lambda \)

\[ ^{AZ} (K^{-}, \pi^{0}) \quad ^{AZ}_\Lambda (Z-1) \]

Ahmed \textit{et al.}, PR C 68, 064004 '03, and

\[ ^{AZ} (e, e'K^{+}) \quad ^{AZ}_\Lambda (Z-1) \]

Miyoshi \textit{et al.}, PRL 90, 232502 '03,

Yuan \textit{et al.}, PR C 73, 044607 '06,

Iodice \textit{et al.}, PRL 99, 052501 '07.

Recently, Tamura constructed a large acceptance Ge detector array dedicated to \textit{hypernuclear gamma-ray spectroscopy}
A schematic representation of the decays of an excited hypernucleus showing the decay of highly excited states by Auger and $\gamma$ transitions.
Example

Hypernuclear mass spectrum of $^7\Lambda$Li obtained in ($\pi^+, K^+$).

Level scheme of the $^7\Lambda$Li bound states.
Doublet splitting

\[ \begin{align*}
\hline
\text{core} & \quad \text{doublet} & \quad \text{interaction} \\
\hline
2S_{1/2} & (3S_{1/2}, 1S_0) & 1 \\
5D_{3/2} & (5D_{3/2}, 5D_0) & -\frac{1}{16} & -\frac{21}{40} \\
3P_{1/2} & (3P_{1/2}, 3P_0) & \frac{7}{8} & \frac{3}{2} \\
\hline
\end{align*} \]

Contributions from the spin-dependent components of the effective $\Lambda N$ interaction to the $(1^+, 0^+)$ doublet splitting.
Phenomenological $\Lambda N$ interaction

\[ V_{\Lambda N}(r) = V_0(r) + V_\sigma(r) s_N s_\Lambda + V_A l_{\Lambda N} s_A + V_N(r) l_{\Lambda N} s_N + V_T(r) S_{12} \]

\[
\begin{array}{c}
\text{APPROACH} \\
\text{free NN} + \text{SU}_{\text{flavor}}(3) + \text{limited YN} \\
\Downarrow \\
\text{free YN model} \quad \text{Nijmegen} \\
\Downarrow \quad \Uparrow \\
\text{effective} \ \Lambda N \ \text{interaction} \quad \text{Millener} \\
\Leftarrow \quad \Rightarrow \\
\text{SHELL MODEL} \quad \text{EXPERIMENTAL DATA} \\
\text{Hypernuclear } \gamma \text{ transitions} \\
^7\Lambda\text{Li} : 5, \ ^9\Lambda\text{Be} : 2, \ ^{13}\Lambda\text{C} : 1, \ ^{16}\Lambda\text{O} : 2
\end{array}
\]
RESULT:

$V_{NA}$ radial integrals

<table>
<thead>
<tr>
<th>$V_{\text{eff}}$</th>
<th>$\Delta$</th>
<th>$S_\Lambda$</th>
<th>$S_N$</th>
<th>$T$</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSD</td>
<td>0.15</td>
<td>0.57</td>
<td>-0.21</td>
<td>0.00</td>
<td>1978</td>
</tr>
<tr>
<td>MGDD</td>
<td>0.50</td>
<td>-0.04</td>
<td>-0.08</td>
<td>0.04</td>
<td>1985</td>
</tr>
<tr>
<td>Millener</td>
<td>0.50</td>
<td>-0.04</td>
<td>-0.47</td>
<td>0.04</td>
<td>2001</td>
</tr>
<tr>
<td>$\Sigma N$</td>
<td>0.432</td>
<td>-0.010</td>
<td>-0.390</td>
<td>0.028</td>
<td>2005</td>
</tr>
</tbody>
</table>

$^7$Li

0.480 -0.010 -0.430 0.021 2001
0.430 -0.015 -0.390 0.030 2006

$^9$Be

0.619 -0.013 -0.549 0.029 2001
0.557 -0.013 -0.549 0.038 2003

$^{13}$C

0.550 -0.012 -0.508 0.025 2001

$^{16}$O

0.521 -0.011 -0.461 0.023 2001
0.468 -0.011 -0.354 0.030 2003

GSD: Gal, Soper and Dalitz, AP 113
MGDD: Millener, Gal, Dover and Dalitz, PR C 31
Millener: Millener, NP A 691
$\Sigma N$: Millener, NP A 754

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3. NEUTRON - RICH HYPERNUCLEI

The one problem is difficulty of making a neutron-rich hypernucleus, the other is to identify it from its decay modes.

3.1 DIRECT PRODUCTION

The strangeness and double charge exchange (S&DCX) reactions

\[
(K^-, \pi^+) : \quad (K^- + p) + p \rightarrow \Lambda + (\pi^0 + p) \\
\quad \rightarrow \Lambda + n + \pi^+
\]

or

\[
(\pi^-, K^+) : \quad (\pi^- + p) + p \rightarrow K^+ + (\Sigma^- + p) \\
\quad \rightarrow n + \Lambda + K^+
\]

open way to the production of neutron-rich hypernuclei.
The status of experimental efforts
Hypernuclei Production in S&DCX Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>year</th>
<th>$^6_\Lambda$H</th>
<th>$^7_\Lambda$H</th>
<th>$^9_\Lambda$He</th>
<th>$^{10}_\Lambda$Li</th>
<th>$^{12}_\Lambda$Be</th>
<th>$^{16}_\Lambda$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>($K^-_{st}, \pi^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Formation probability per stopped $K^-$, ($\times 10^5$)</td>
<td>&lt; 23</td>
<td>&lt; 6.1</td>
</tr>
<tr>
<td>KEK 1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FINUDA 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 2.5</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>($\pi^-, K^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cross section dσ/dΩ [ NANO barn / sr], ($p_\pi = 1.2$ GeV/c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KEK 2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.3±1.9</td>
<td>7</td>
</tr>
<tr>
<td>calculation 2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>2.5</td>
</tr>
</tbody>
</table>

calculation: Lanskoy, nucl-th/0411004

Cross sections of the two-steps ($\pi^-, K^+$) reaction are smaller by three orders of magnitude than those of one-step ($\pi^+, K^+$) reaction.
Published results

A. KEK
Missing mass spectrum of the ($\pi^-, K^+$) reaction on $^{10}$B target.
B. FINUDA Collaboration
Search for $^6\Lambda\mathrm{H}$ and $^7\Lambda\mathrm{H}$ with the $(K^-_{\text{stop}}, \pi^+)$ reaction
M. Agnello, ... T. Bressani, ... B. Dalone ... PL B 640 ('06) 145

So, we have not only upper limits for reactions with stopped kaons, but even first **positive results** for $(\pi^-, K^+)$ reaction.
3.2 NEUTRON - RICH HYPERFRAGMENTS

Tamura discussed formation of the neutron-rich hyperfragments from stopped $K^-\$ absorption.

But it is a problem how to identify hyperfragment species and enhance a signal to the background ratio.

There is one peculiar case where both problems are manageable: experiments with relativistic hypernuclei.

The new accelerator Nuclotron at Dubna together with a new “GIBS - NIS” spectrometer offer new possibilities of carrying out hypernuclear experiments.

The scheme of the experiment: $T$ is target; $M$ is magnet; $S$, $C_{1,2}$ are trigger counters; $V$ is vacuum decay volume; $PC_{1-4}$ are proportional chambers.
Identification

To DISCRIMINATE the MASS value of the isotopes of the hypernuclear daughter nuclei one should measure the corresponding momenta.

The momentum values of $^3$He, $^4$He and $^6$He are concentrated in the $\approx 14$ GeV/c, $\approx 19$ GeV/c and $\approx 29$ GeV/c bands.

Such difference can be measured easily to separate three possible reactions of the hydrogen hypernuclei production and decay in the $^7$Li beam:
Expected yields

<table>
<thead>
<tr>
<th>beam</th>
<th>target</th>
<th>production</th>
<th>decay</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>$^{12}\text{C}$</td>
<td>$\rightarrow \ ^3\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^3\text{He} + \pi^-$</td>
<td>100</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>$^{12}\text{C}$</td>
<td>$\rightarrow \ ^4\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^4\text{He} + \pi^-$</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow \ ^3\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^3\text{He} + \pi^-$</td>
<td></td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>$^{12}\text{C}$</td>
<td>$\rightarrow \ ^6\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^6\text{He} + \pi^-$</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow \ ^4\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^4\text{He} + \pi^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow \ ^3\Lambda\text{H} + \cdots$</td>
<td>$\rightarrow \ ^3\text{He} + \pi^-$</td>
<td></td>
</tr>
</tbody>
</table>

**HYDROGEN HYPERNUCLEI CAN BE UNAMBIGUOUSLY IDENTIFIED**

We note that **ALL** Hydrogen hypernuclei are produced. The $^3\Lambda\text{H}$ and $^4\Lambda\text{H}$ can be used as a **reference sample** to confirm production of $^6\Lambda\text{H}$.
Decay channels of the $^7\Lambda\text{He}$ hypernucleus.
The neutron, proton and $\Lambda$ are marked by $\bullet$, $\circ$, and $\ast$, respectively.

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4. \( ^6_{\Lambda}H \) COULD BE IDENTIFIED - SO WHAT?

CHAIN of four (hyper) nuclei with two neutron “halo”

ENERGY SPECTRA

<table>
<thead>
<tr>
<th>E, [MeV]</th>
<th>( \frac{5}{2}^+ )</th>
<th>( \frac{1}{2}^+ )</th>
<th>( \frac{1}{2}^+ )</th>
<th>( 0^+ )</th>
<th>( \frac{5}{2}^+ )</th>
<th>( \frac{1}{2}^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>3H + ( \Lambda + n^2 )</td>
<td>( \frac{4}{2}^+ )</td>
<td>( \frac{4}{2}^+ )</td>
<td>( 3H + n^2 )</td>
<td>( \Lambda + n^2 )</td>
<td>( 5_{\Lambda}H + n^2 )</td>
</tr>
<tr>
<td>-4</td>
<td>- 4.1</td>
<td>0^+</td>
<td>0^+</td>
<td>0^+</td>
<td>0^+</td>
<td>0^+</td>
</tr>
<tr>
<td>( ^5H )</td>
<td>( ^6_{\Lambda}H )</td>
<td>( ^6_{\Lambda}He )</td>
<td>( ^7_{\Lambda}He )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Model description

Such a unique comparison could shed light on a limit of three-body model \((\text{core} + n + n)\) as well as on the role of continuum.

A proper shell model description of loosely bound nuclei should take into account the coupling of the discrete bound states with the continuum of scattering states.

The tool of choice is **Gamow shell model**: N. Michel, W. Nazarewicz, M. Ploszajczak and J. Okołowicz: *Gamow shell model description of weakly bound nuclei and unbound nuclear states*  

and / or the **continuum shell model**: 
A. Volya, V. Zelevinsky: *Continuum Shell Model* 

in which both continuum effects and correlations between nucleons are taken into account simultaneously.

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Neutron rich Hydrogen

What does it happen if one proton is added in the six neutron system?

S. Aoyama, FINUSTAR 2
5. OUTLOOK

The setup at JINR Dubna could identify $^8_\Lambda H$ also – if it exists. It is a great challenge to produce such a neutron-rich hypernucleus.

\[
\begin{array}{ccc}
\text{4He} & \text{6He} & \text{8He} \\
0^+ & 0^+ & 0^+ \\
[\Lambda s^{-1}] \times \text{4He} : & [\Lambda s^{-1}] \times \text{6He} : & [\Lambda s^{-1}] \times \text{8He} : \\
\Delta_4 & \Delta_6 & \Delta_8 \\
0^+ & 0^+ & 0^+ \\
\frac{N}{Z} = 2 & \frac{N}{Z} = 4 & \frac{N}{Z} = 6 \\
\end{array}
\]

\textit{Spectra of the low lying levels in 4He, 6He and 8He nuclei and doublet splitting in 4}_\Lambda H, 6}_\Lambda H and 8}_\Lambda H hypernuclei.}

So, we obtain chain of three hypernuclei with a similar (and very simple !) ground state doublet.
GIBS - NIS Collaboration:
D. Chren, T. Horaždovský, Z. Kohout, O. Majlingová, M. Solar, B. Sopko, FME CTU, Prague,
C. Granja, S. Pospíšil, V. Sopko, IAEP CTU, Prague,
L. Majling,
INP CAS, Řež

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