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. ${}^{6}_{\Lambda}$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”, μ^- and $\bar{p}$, was suggested.

The potential of Λ hypernuclear physics

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

Some recent **review:**

- O. Hashimoto and H. Tamura: *Spectroscopy of Λ hypernuclei* Progr. Part. Nuc. Physics, **57**, 564 (2006).
- Topics in Strangeness Nuclear Physics, (Eds. P. Bydžovský, A. Gal, J. Mareš) Lecture Notes in Physics, **724**, Springer, 2007.
- T. Bressani: *Hypernuclei: Perspectives of hypernuclear physics in this decade* Proceedings of the International School of Physics "Enrico Fermi", Course 153, Varenna, Italy, IOS Press 2003.
- Proceedings of the International School of Physics "Enrico Fermi", Course 158, Varenna, Italy, 2004, IOS Press 2005.

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

- Torino, Italy, 23 – 27 October, **2000** Nuclear Physics A **691** (2001) (Edited by E. Botta, T. Bressani and A. Feliciello).
- Newport News, VA, USA, 14 – 18 October, **2003** Nuclear Physics A **754** (2005) (Edited by A. Gal and E. Hungerford).
- Mainz, Germany, 10 – 14 October **2006** The European Physical Journal A (2007) *in press.*

Motto

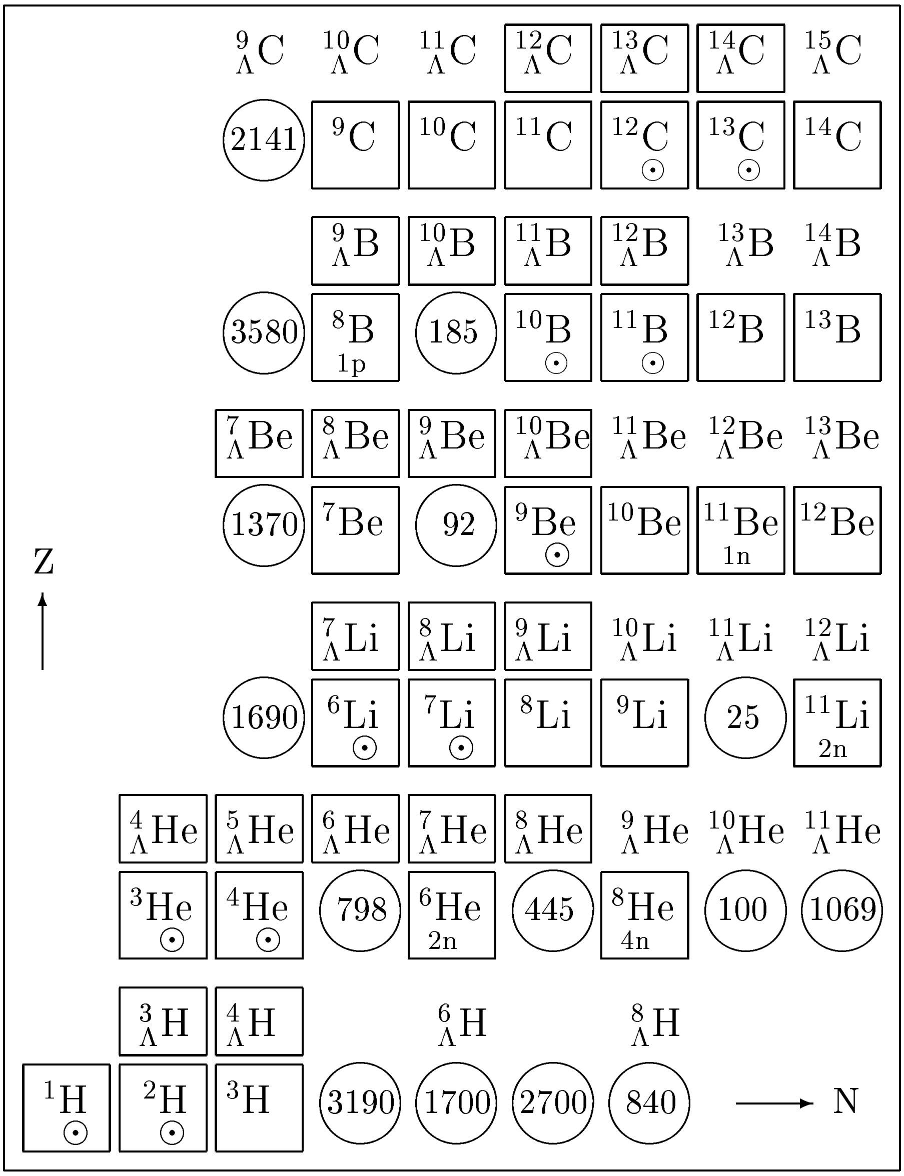
As our experimental and theoretical tools are sharpened, we proceed to build structure on top of foundations previously constructed.

Much of what we do was anticipated by our predecessors.

Ed Hungerford,
Summary of HYP2006

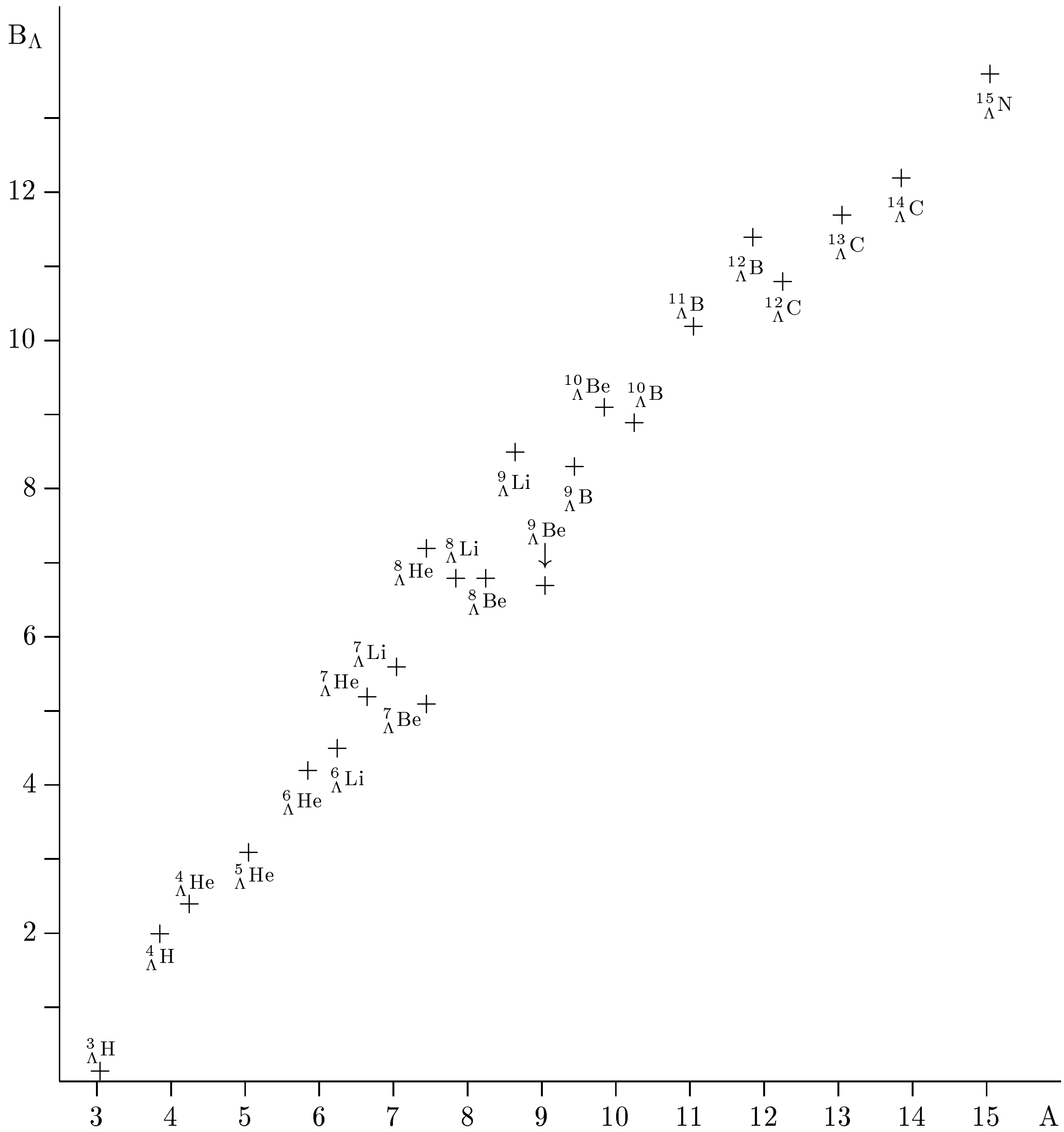
2. Λ - HYPERNUCLEI

Chart of light nuclei and hypernuclei



MSU 23 x. 2007

B_Λ values of light hypernuclei



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Spectroscopy of Λ - 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: **neutron → Λ**

$^{A}\mathrm{Z}\ (K^-, \pi^-)\ ^{A}_{\Lambda}\mathrm{Z}$ Chrien, Dover, ARNPS **39**, 113 '89, and

$^{A}\mathrm{Z}\ (\pi^+, K^+)\ ^{A}_{\Lambda}\mathrm{Z}$ Hagesawa *et al.*, PR C **53**, 1210 '96.

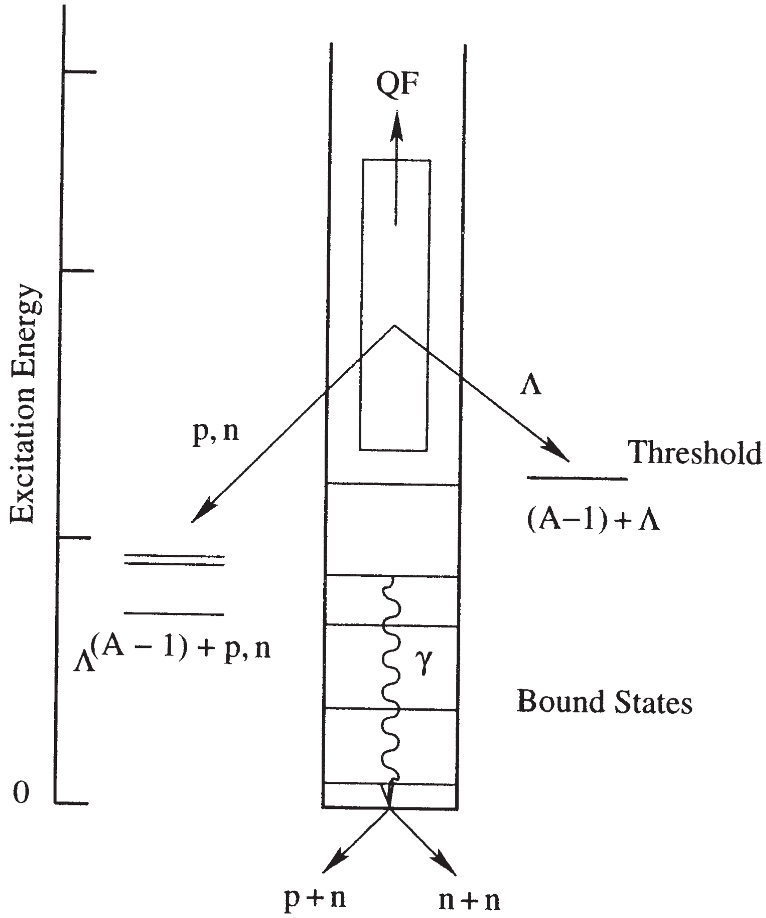
2: **proton → Λ**

$^{A}\mathrm{Z}\ (K^-, \pi^0)\ ^{A}_{\Lambda}(\mathrm{Z}\text{-}1)$ Ahmed *et al.*, PR C **68**, 064004 '03, and

$^{A}\mathrm{Z}\ (e, e'K^+)\ ^{A}_{\Lambda}(\mathrm{Z}\text{-}1)$ Miyoshi *et al.*, PRL **90**, 232502 '03,
Yuan *et al.*, PR C **73**, 044607 '06,
Iodice *et al.*, PRL **99**, 052501 '07.

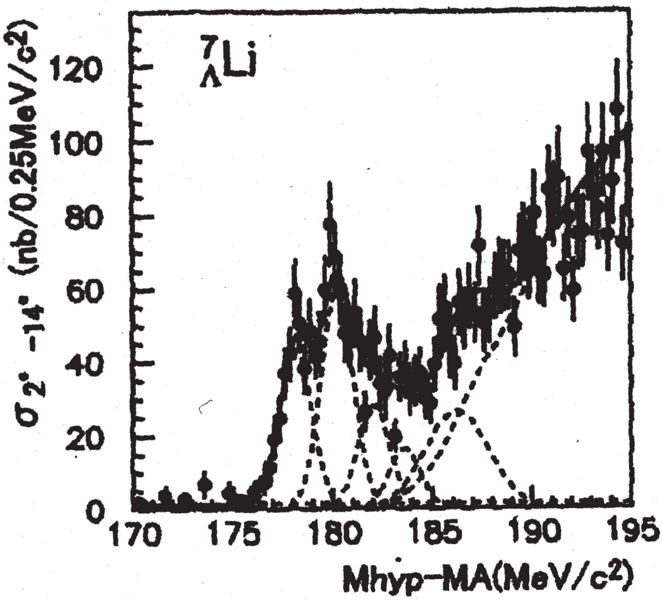
Recently, Tamura constructed a large acceptance Ge detector array dedicated to **hypernuclear gamma-ray spectroscopy**

Spectra of Λ - hypernuclei

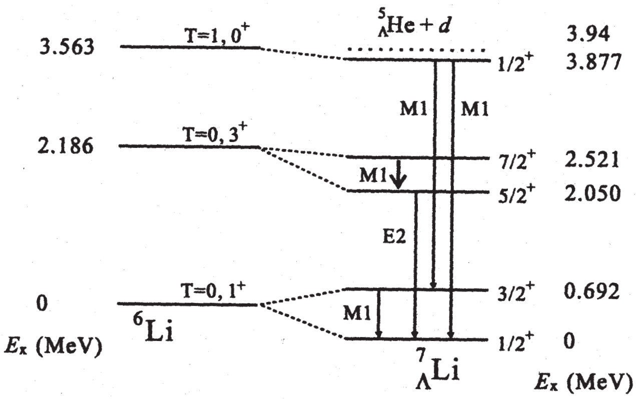


A **schematic** representation of the decays of en excited hypernucleus showing the decay of highly excited states by Auger and γ transitions.

Example

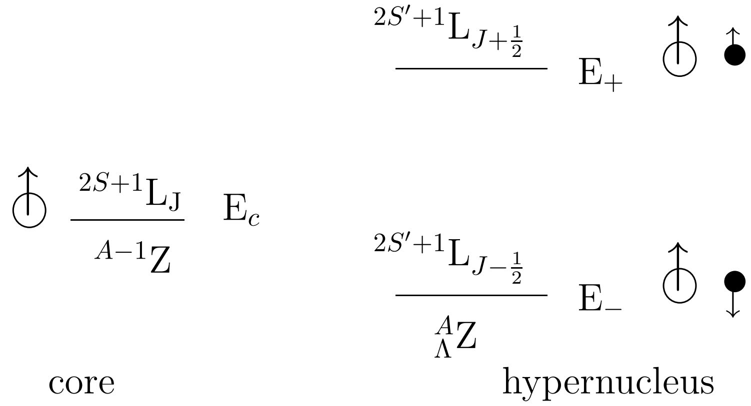


Hypernuclear mass spectrum of $^7_\Lambda$Li obtained in (π^+, K^+).



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

Doublet splitting



Contributions from the spin-dependent components of the effective ΛN interaction to the (1^+, 0^+) doublet splitting

core	doublet	interaction Δ	S_Λ	T
$^2S_{\frac{1}{2}}$	$(^3S_1, ^1S_0)$	1		
$^5D_{\frac{1}{2}}$	$(^5D_1, ^5D_0)$		$-\frac{1}{16}$	$-\frac{21}{40}$
$^3P_{\frac{1}{2}}$	$(^3P_1, ^3P_0)$		$-\frac{7}{8}$	$\frac{3}{2}$

Phenomenological ΛN interaction

$$\begin{array}{llllll} V_{\Lambda N}(r) = & V_0(r) + & V_\sigma(r)\, \mathbf{s}_N\, \mathbf{s}_\Lambda + & V_\Lambda\, \mathbf{l}_{\Lambda N}\, \mathbf{s}_\Lambda + & V_N(r)\, \mathbf{l}_{\Lambda N}\, \mathbf{s}_N + & V_T(r)\, S_{12} \\ & & \Delta & S_\Lambda & S_N & T \end{array}$$

APPROACH

free NN + $SU_{\text{flavor}}(3)$ + limited YN

$\Downarrow$

free YN model *Nijmegen*

$\Downarrow$ $\Uparrow$

effective ΛN interaction *Millener*

$\swarrow$ $\nearrow$

SHELL MODEL $\Longleftrightarrow$ EXPERIMENTAL DATA

Hypernuclear γ transitions

${}^{7}_{\Lambda}$Li :5, ${}^{9}_{\Lambda}$Be :2, ${}^{13}_{\Lambda}$C :1, ${}^{16}_{\Lambda}$O :2

RESULT:

$V_{N\Lambda}$ radial integrals

V_{eff}	Δ	S_Λ	S_N	T	year
GSD	0.15	0.57	-0.21	0.00	1978
MGDD	0.50	-0.04	-0.08	0.04	1985
Millener	0.50	-0.04	-0.47	0.04	2001
$+ \Sigma N$	0.432	-0.010	-0.390	0.028	2005
${}^{7}_{\Lambda}$Li	0.480	-0.010	-0.430	0.021	2001
	0.430	-0.015	-0.390	0.030	2006
${}^{9}_{\Lambda}$Be	0.619	-0.013	-0.549	0.029	2001
	0.557	-0.013	-0.549	0.038	2003
${}^{13}_{\Lambda}$C	0.550	-0.012	-0.508	0.025	2001
${}^{16}_{\Lambda}$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**

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

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

or

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

open way to the production of **neutron-rich hypernuclei.**

The status of experimental efforts

Hypernuclei Production in S&DCX Reactions

Reaction	year	${}^{6}_{\Lambda}$H	${}^{7}_{\Lambda}$H	${}^{9}_{\Lambda}$He	${}^{10}_{\Lambda}$Li	${}^{12}_{\Lambda}$Be	${}^{16}_{\Lambda}$C
(K^-_{st}, π^+)		Formation probability per stopped K^-, $(\times 10^5)$					
KEK	1996			< 23		< 6.1	< 6.2
FINUDA	2006	< 2.5	< 4.5			< 2.1	
(π^-, K^+)		Cross section dσ/dΩ [NANO barn / sr], $(p_\pi = 1.2$ GeV/c)					
KEK	2005				**11.3±1.9**	**7**	
calculation	2004				22	2.5	

calculation: Lanskoy, `nucl-th/0411004`

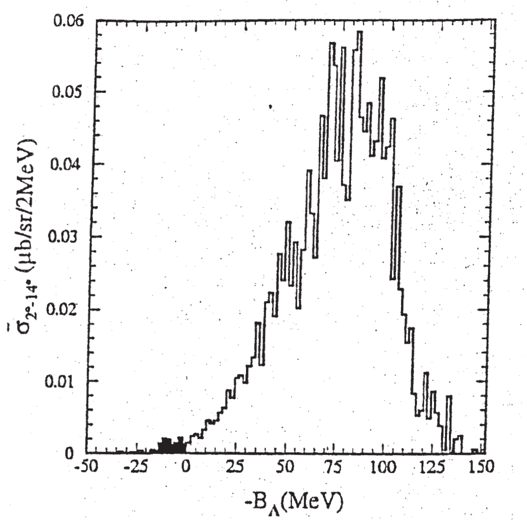
Cross sections of the two-steps (π^-, K^+) reaction are **smaller by three orders** of magnitude than those of one-step (π^+, K^+) reaction.

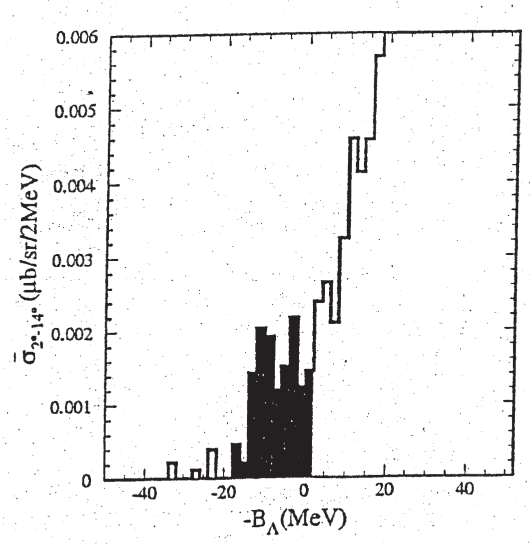
Published results

A. **KEK**

Missing mass spectrum of the (π^-, K^+) reaction on ^{10}B target.

P.K. Saha, T. Fukuda *et al.* PRL **94** ('05) 052502

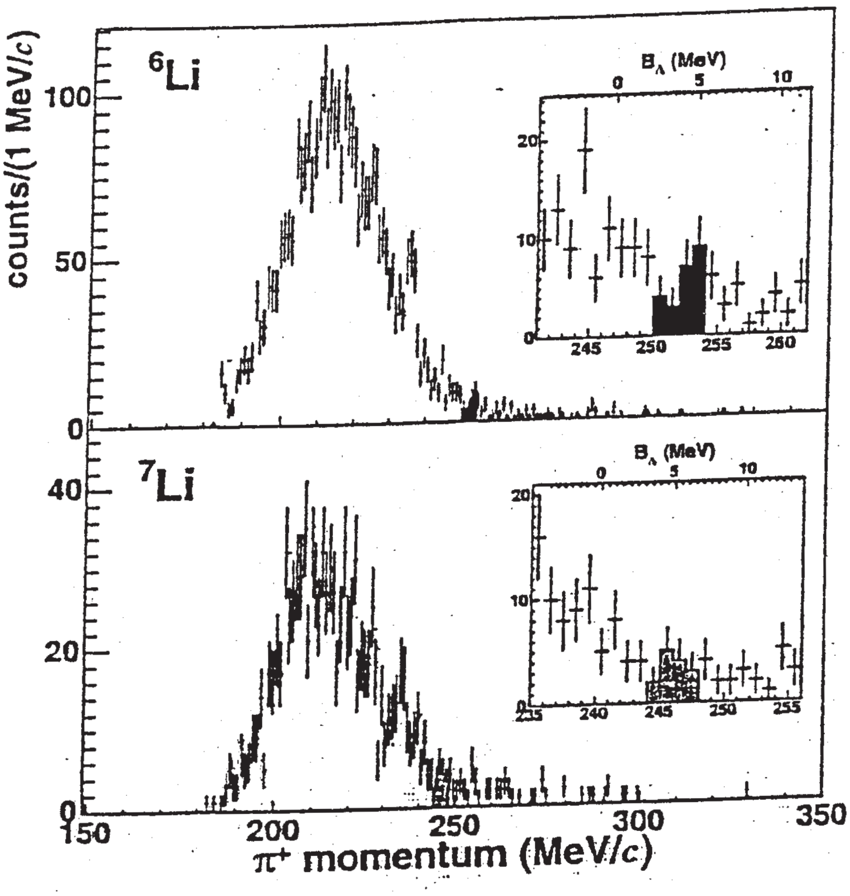




B. **FINUDA Collaboration**

Search for ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H with the $(K^-_{\rm stop}, \pi^+)$ reaction

M. Agnello, ... T. Bressani, ... B. Dalone ... PL B **640** ('06) 145



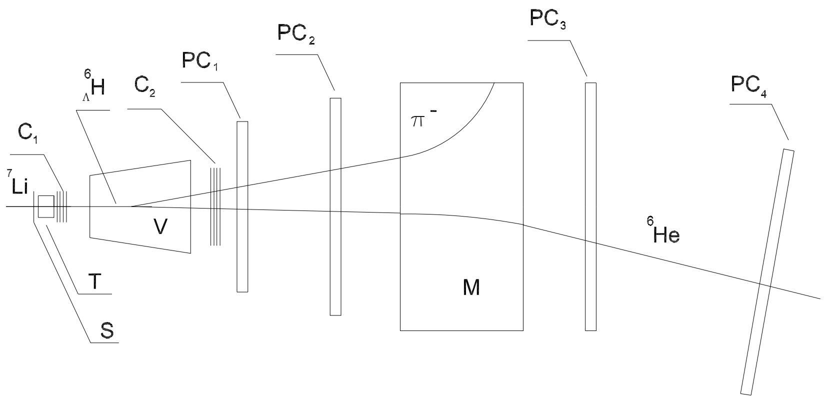
So, we have not only upper limits for reactions with stopped kaons, but even first **positive results** for (π^-, K^+) reaction.

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.



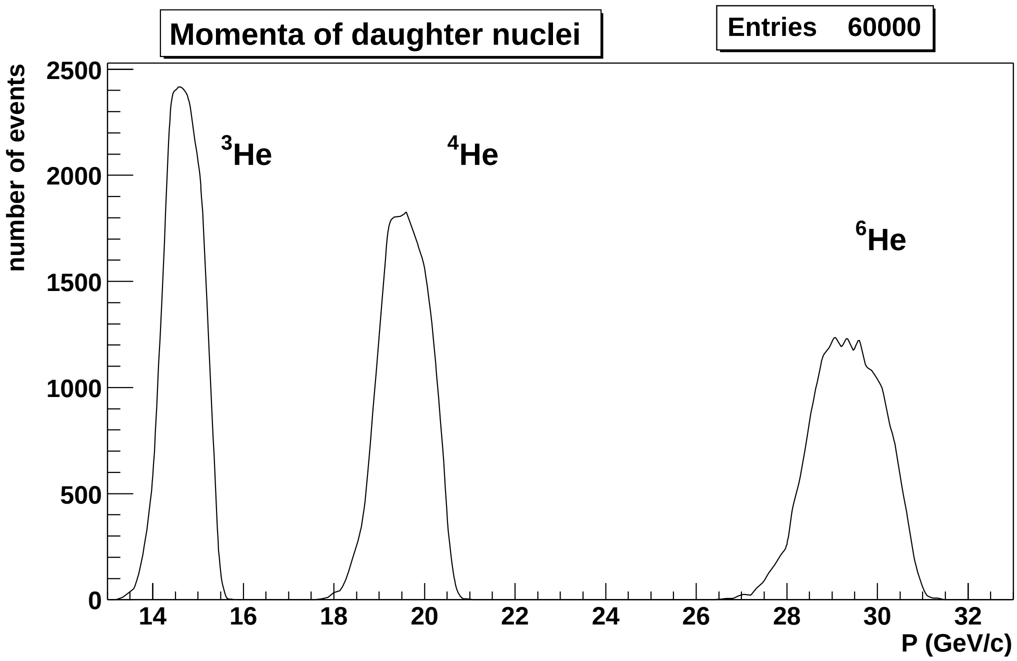
The scheme of the experiment: T is target; M is magnet; S, $C_{1,2}$ are trigger counters; V is vacuum decay volume; PC_{1-4} are proportional chambers.

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:



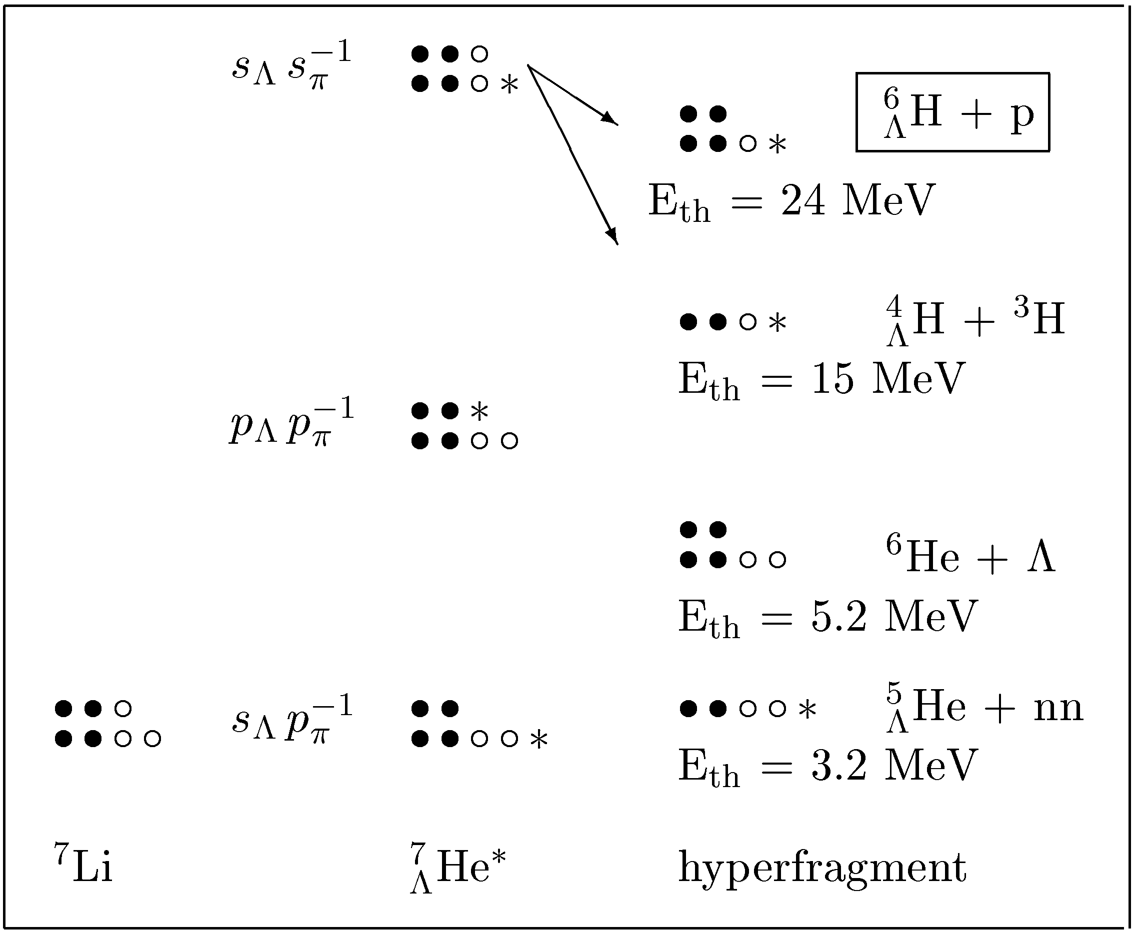
Expected yields

beam		target		production		decay	N
^{3}He	+	^{12}C	$\rightarrow$	$^3_\Lambda$H + $\cdots$	$\rightarrow$	^{3}He + π^-	100
^{4}He	+	^{12}C	$\rightarrow$	$^4_\Lambda$H + $\cdots$	$\rightarrow$	^{4}He + π^-	600
			$\rightarrow$	$^3_\Lambda$H + $\cdots$	$\rightarrow$	^{3}He + π^-	
^{7}Li	+	^{12}C	$\rightarrow$	$\boldsymbol{^6_\Lambda}$**H** + $\cdots$	$\rightarrow$	^{6}He + π^-	**400**
			$\rightarrow$	$^4_\Lambda$H + $\cdots$	$\rightarrow$	^{4}He + π^-	
			$\rightarrow$	$^3_\Lambda$H + $\cdots$	$\rightarrow$	^{3}He + π^-	

HYDROGEN HYPERNUCLEI
CAN BE UNAMBIGUOUSLY IDENTIFIED

We note that **ALL** Hydrogen hypernuclei are produced.
The $^3_\Lambda$H and $^4_\Lambda$H can be used as a **reference sample** to confirm production of $^6_\Lambda$H.

Source of hyperfragments



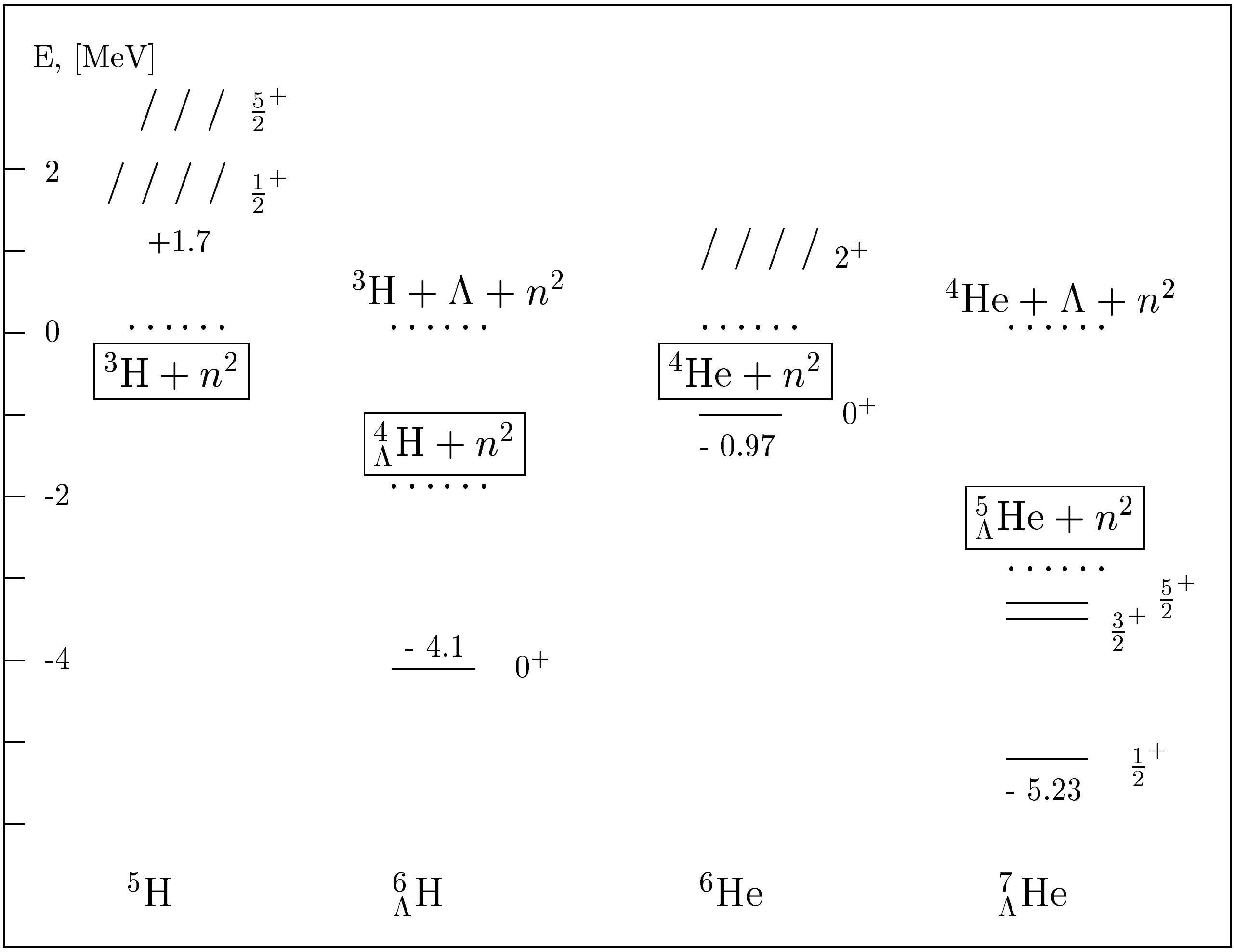
Decay channels of the $^{7}_{\Lambda}$He hypernucleus.

The neutron, proton and Λ are marked by •, ∘, and ∗, respectively.

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

CHAIN of four (hyper) nuclei with two neutron "halo"

ENERGY SPECTRA



Model description

Such a unique comparison could shed light
on a limit of *three-body model* (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 :**

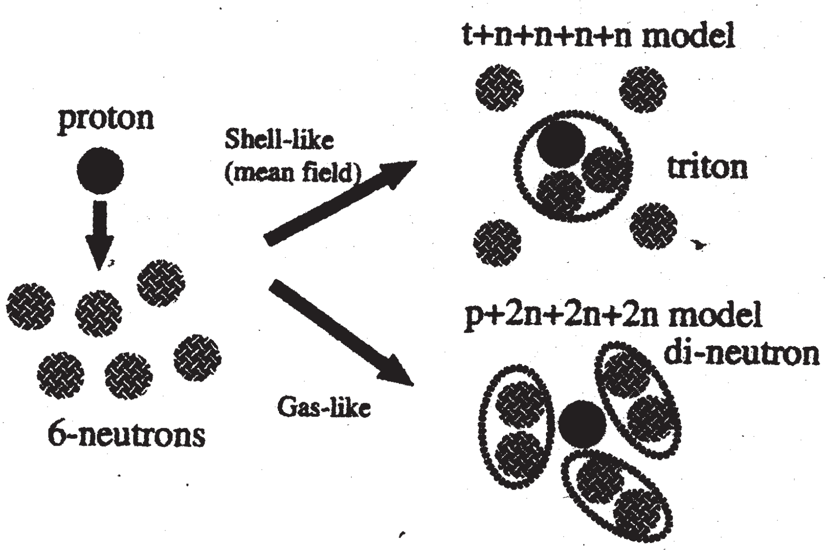
N.Michel, W.Nazarewicz, M.Płoszajczak and J.Okołowicz:
Gamow shell model description of weakly bound nuclei and unbound nuclear states Phys. Rev. C **67** (2003) 054311

and / or the **continuum shell model :**

A. Volya, V. Zelevinsky: *Continuum Shell Model*
Phys. Rev. C **74** (2006) 064314

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

Neutron rich Hydrogen

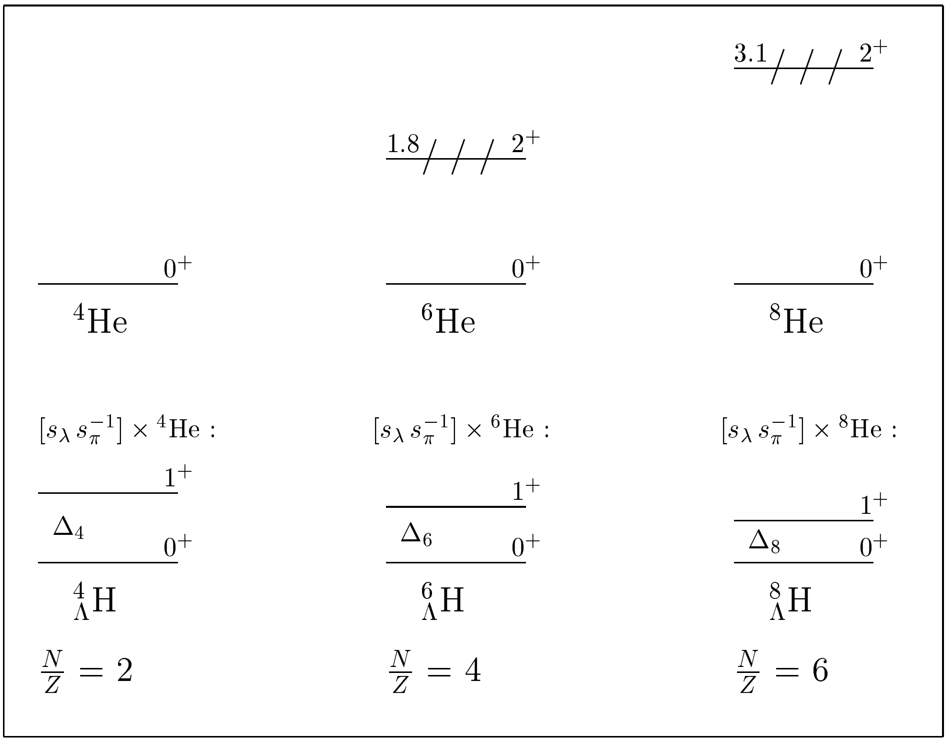


What does it happen if one proton is added in the six neutron system?

S. Aoyama, FINUSTAR 2

5. OUTLOOK

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



Spectra of the low lying levels in ^{4}He, ^{6}He and ^{8}He 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 :

S. Afanasiev, V. Aksinenko, Yu. Anisimov, S. Avramenko, V. Balandin, Yu. Batusov, S. Bazylev, Yu. Belikov, Yu. Borzunov, Yu. Chencov, L. Golovanov, A. Golokhvastov, A. Isupov, A. Ivanov, Yu. Ivanov, A. Kovalenko, A.Litvinenko, **J.Lukstins**, V.Lysyakov, A.Malakhov, P.Manyakov, E.Matyushevskiy, V.Matyushin, I.Migulina, G.Nikoloyevskiy, O. Okhrimenko, A. Parfenov, N. Parfenova, V. Peresedov, S. Plyaskevich, A. Povtoreiko, P. Rukoyatkin, R. Salmin, V. Tereschenko, I. Yudin,
JINR, Dubna,

D. Chren, T. Horaždovský, Z. Kohout, O. Majlingová, M. Solar, B. Sopko,
FME CTU, Prague,

C. Granja, S. Pospíšil, V. Sopko,
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