What can we learn from hypernucleus ${}^{6}_{\Lambda}$H ?

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Abstract. Inspired by the possibility of hyperhydrogen production at Nuclotron (JINR, Dubna), we pose a set of open questions which should be addressed in order to complement our knowledge of neutron rich hypernuclei.

PACS. 21.80.+a Hypernuclei – 21.45.+v Few-body systems

1 Introduction: neutron rich hypernuclei

Hyperfragments identified in photoemulsion [1] are given in Fig. 1. We can see many particle-stable hypernuclei with unstable cores: ${}^{6}_{\Lambda}$He, ${}^{7}_{\Lambda}$Be, ${}^{8}_{\Lambda}$He, ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B. There is also hypernucleus ${}^{7}_{\Lambda}$Be$=$${}^{5}_{\Lambda}$He $+p+p$, the proton-rich Borromean system. The orderly increase in binding energy B_{Λ} with A indicates that many other such species may exist. The hypernucleus ${}^{6}_{\Lambda}$H has attracted attention even at this early stage of hypernuclear physics: *"This hypernucleus could conveniently be formed in ^{6}Li- or ^{7}Li- loaded emulsion:* $K^{-}+{}^{6}\mathrm{Li}\rightarrow{}^{6}_{\Lambda}\mathrm{H}+\pi^{+}$, $K^{-}+{}^{7}\mathrm{Li}\rightarrow{}^{6}_{\Lambda}\mathrm{H}+p+\pi^{+}$. *The decay process* ${}^{6}_{\Lambda}\mathrm{H}\rightarrow\pi^{-}+{}^{6}He$ *has appearance similar as the two-body mode for ${}^{4}_{\Lambda}H$ except that there is a shorter ($\sim 5.4\ \mu m$), $\beta-$active recoil in the present case"* [2]. The three body decay mode ${}^{6}_{\Lambda}\mathrm{H}\rightarrow\pi^{-}+{}^{3}\mathrm{H}+{}^{3}\mathrm{H}$ was searched for in [3] but no decay at all was found.

In the last decades a new theme in nuclear physics, namely physics of nuclei in the vicinity of the neutron drip line has been constituted [4]. A number of spectacular effects were observed, e.g., a new type of clusters ("neutron halo") and the N-Z dependence of NN interaction (shell occupancy), to mention a few.

The recent progress of Λ hypernuclear spectroscopy [5,6], which provides information on spin-dependent ΛN interaction for species with a stable nucleon core could also be used in the study of the *neutron rich* nuclear systems.

In the next Section, the results for neutron rich hypernuclei production in strangeness and double charge exchange (S&DCX) reactions are presented. In Section 3, our special interest in the hypernucleus ${}^{6}_{\Lambda}$H is explained. A possibility to study baryon-baryon interaction in system with an extremely large value of N/Z = 6 (hypernucleus ${}^{8}_{\Lambda}$H) is mentioned.

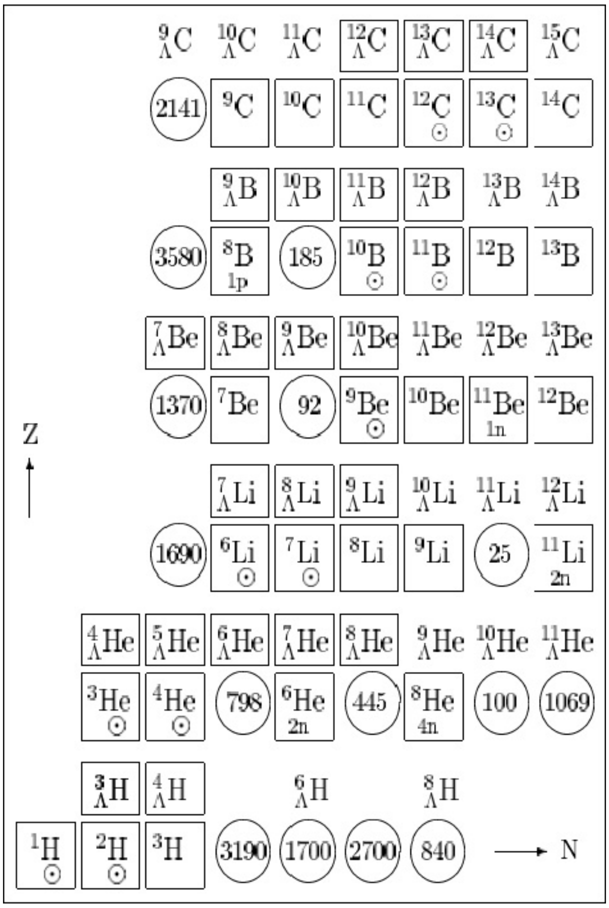

Fig. 1. Chart of light nuclei and hypernuclei (segment). Particle stable nuclei are in squares together with their halo structures. The stable isotopes are marked by ⊙. Resonance energy (in keV) is shown in a circle.

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2 S & DCX reactions

The announcement of the plan for the hypernuclear facility FINUDA by T. Bressani [7] initiated great expectations [8]. The two-step strangeness and double charge exchange reaction

$$\begin{aligned} K^- + p_1 &\to \Lambda + \pi^0 \\ &\qquad \pi^0 + p_2 \to n + \pi^+ \end{aligned} \tag{1}$$

opens a way for production of some neutron rich hypernuclei ${}^{A}Z\ (K^-,\pi^+){}^{A}_{\Lambda}(Z-2)$. The observation of such neutron-rich hypernuclei is on the list of important items for FINUDA [9–11]. A recent paper [12] shows their first results (see also [13]). In 1986 - 1987 the experiment was performed in a series of Σ- and Λ-hypernuclear studies using $(K^-_{\rm st},\pi^+)$ reactions at the K3 beam line at KEK [14]. They searched for discrete peaks in the region of Λ-hypernucleus production, only upper limits were given.

Tretyakova and Lanskoy have considered another mechanism: production of Λ hypernuclei in the *one-step* process

$$K^- p \to \pi^+ \Sigma^- \tag{2}$$

via a small admixture of the *virtual* Σ^- state appearing due to the $\Sigma^- p \leftrightarrow \Lambda n$ coupling [15].

In KEK 521 experiment [16], the *in-flight reaction*

$$\begin{aligned} \pi^- + p_1 &\to K^+ + \Sigma^- \\ &\qquad \Sigma^- + p_2 \to \Lambda + n \end{aligned} \tag{3}$$

on a ^{10}B target was used in order to produce the ${}^{10}_{\Lambda}$Li hypernucleus with much less background.

The current status of experimental efforts to produce neutron-rich Λ hypernuclei is given in Table 1.

Now we have not only the upper limits for reactions with stopped kaons but even first positive results for the (π^-,K^+) reaction. Cross sections of the two-step (π^-,K^+) reaction are smaller by three orders of magnitude than those of the one-step (π^+,K^+) reaction [17].

Table 1. Hypernuclei production in S&DCX reactions.

${}^{A}_{\Lambda}$Z	(K^-_{st},π^+) [a] KEK 166 [14]	FINUDA [12]	(π^-,K^+) [b] KEK 521 [16]
${}^{6}_{\Lambda}$H		< 2.5	
${}^{7}_{\Lambda}$H		< 4.5	
${}^{9}_{\Lambda}$He	< 23		
${}^{10}_{\Lambda}$Li			11.3
${}^{12}_{\Lambda}$Be	< 6.1	< 2.1	
${}^{16}_{\Lambda}$C	< 6.2		

[a] Formation probability per stopped K^-, $(\times 10^5)$.

[b] Cross section $d\sigma/d\Omega$ [nano barn/sr].

Table 2. Hypernuclear lifetimes.

${}^{A}_{\Lambda}$Z	Dubna [20]	other methods		
${}^{3}_{\Lambda}$H	240^{+170}_{-100} ps	246^{+62}_{-41} ps	bubble ch.	[21]
${}^{4}_{\Lambda}$H	220^{+50}_{-40} ps	194^{+24}_{-26} ps	(K^-,π^-)	[22]

Table 3. The number of hypernuclear decays.

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

2.1 ${}^{6}_{\Lambda}$H as a hyperfragment

Tamura discussed formation of the neutron-rich hypernuclei as *hyperfragments* from stopped K^- absorption [18]. But it is a problem how to identify hyperfragment species and enhance a signal to the background ratio.

In what follows we will discuss one peculiar case where both problems are manageable.

The experiments with *relativistic hypernuclei* on the Dubna synchrophasotron ion beams (^{3}He, ^{4}He and ^{6}Li) demonstrated their advantage: low background (no process can produce a vertex in the vacuum) and unambiguous identification of the ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H isotopes [19,5]. The lifetimes measured there agree nicely with the results obtained by other methods, see Table 2.

The extended hypernuclear program was offered for the new accelerator Nuclotron and new "GIBS-NIS" spectrometer, see [23] for details.

To discriminate the mass value of the isotopes of the daughter nuclei, one should measure the corresponding momenta. The momentum values of ^{3}He, ^{4}He and ^{6}He are concentrated in the $\approx$ 9 GeV/c, $\approx$ 14 GeV/c and $\approx$ 22 GeV/c bands, respectively [24]. Such a difference can be measured easily to separate three possible reactions of the hydrogen hypernuclei production and decay in the ^{7}Li beam. The number of hypernuclear decays, N, expected for 24 hours is given in Table 3.

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.

The first hypernuclear experiment at the Dubna Nuclotron is scheduled for next few months.

3 ${}^{6}_{\Lambda}$H Could be identified —so what ?

If the experiment at the Dubna Nuclotron confirms the *very existence* of the ${}^{6}_{\Lambda}$H hypernucleus, it will be a strong motivation to search for *spectra* of other neutron-rich hypernuclei produced by S&DCX reactions at **DAΦNE2** [11] and at J-PARC [25].

In such experiments it will be possible to determine the value of B_Λ for ${}^{6}_{\Lambda}$H and verify an interesting suggestion that this value in neutron-rich hypernuclei should be increased due to a specific "coherent $\Lambda - \Sigma$ mixing mechanism" [26,27].

On the other hand, by the Dubna set-up one could measure *two different values* of τ for ${}^{6}_{\Lambda}$H. The possibility of the existence of a long-lived isomeric state in another neutron-rich hypernucleus, ${}^{7}_{\Lambda}$He, was discussed already [28].

3.1 Source of hyperfragments

The nuclei of beam ^{7}Li interacting with a target are also fragmented (^{6}Li+n, ^{6}He+p, ^{4}He+^{3}H), so the outgoing beam is rather a complicated mixture of primary and secondary hypernuclei. We recall that all Hydrogen hypernuclei: ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{6}_{\Lambda}$H will be registered.

Figure 2 clearly shows why the highly excited states of ${}^{7}_{\Lambda}$He, in which the *'inner'* proton is substituted by Λ ($s_\pi \to s_\Lambda$ transition), are the source of hyperfragments ${}^{4}_{\Lambda}$H and ${}^{6}_{\Lambda}$H. The thresholds for these decay channels are rather high, but large changes in the *structure* of these states prevent the neutrons or Λ from emission.

The states of this type ($s_\Lambda s^{-1}$) have been recognized in the 'in-flight' (K^-, π^-) reactions [29]. The γ-rays have been observed recently from ${}^{7}_{\Lambda}$Li produced as hyperfragments from highly excited $s_\Lambda s^{-1}$ states of ${}^{10}_{\Lambda}$B decaying into ^{3}He + ${}^{7}_{\Lambda}$Li ($\frac{7}{2}^+$) [30,31].

The experiment will shed light on the mechanism of hyperfragment production. Until now only formation of ${}^{4}_{\Lambda}$H from K^- absorption at rest was studied [32]. The main mechanism varied from a statistical decay to a direct formation. New project, HypHI at GSI is proposed [33].

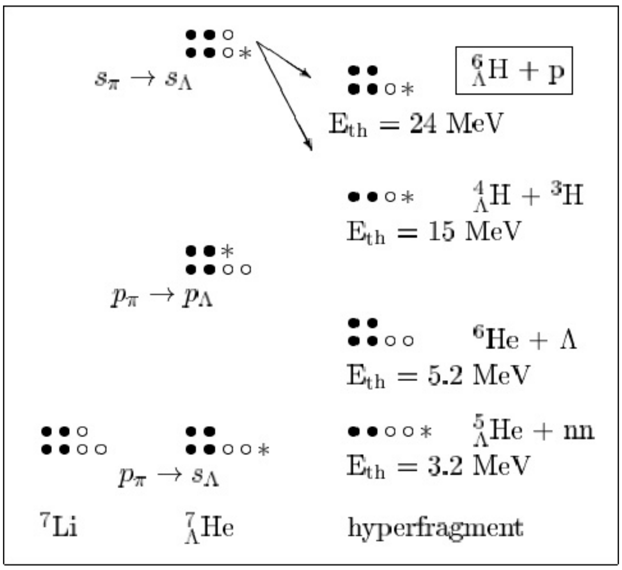

Fig. 2. Decay channels of the ${}^{7}_{\Lambda}$He hypernucleus. The neutron, proton and Λ are marked by •, ∘ and ∗, respectively.

3.2 Chain of four (hyper) nuclei with 2n "halo"

It is interesting to ask how the halo structure is modified by addition of Λ. The ${}^{6}_{\Lambda}$H completes a chain of the four (hyper) nuclei ^{5}H, ^{6}He and ${}^{7}_{\Lambda}$He with two neutrons in p-shell and a different composition of the s-shell core. (The reaction ^{7}Li $(e, e'K^+)$ ${}^{7}_{\Lambda}$He is prepared in JLab [34].) Their spectra are changed dramatically, see Fig. 3. Such a unique comparison could shed light on a limit of the *three-body model* (core + n + n) too.

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 the continuum shell model [35] and, most recently, the Gamow shell model [36,37] in which both the continuum effects and correlations between nucleons are taken into account simultaneously.

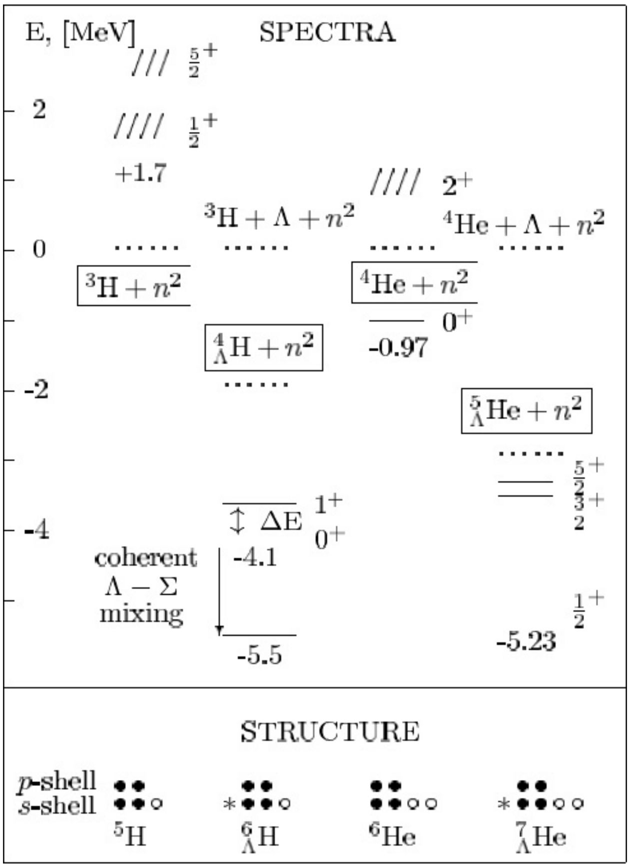

Fig. 3. Chain of four (hyper)nuclei with different s-shell core. The n, p, Λ are marked by •, ∘ and ∗, respectively.

3.3 Outlook: ${}^{8}_{\Lambda}$H

The result of recent experiment [38]: nucleus ^{7}H is unbound only by 840 keV suggests that hypernucleus ${}^{8}_{\Lambda}$H might be stable [39], see Fig. 1. The setup at JINR Dubna could identify ${}^{8}_{\Lambda}$H as well – if it exists. It is a great challenge to produce such a neutron-rich (N/Z = 6) hypernucleus. We expect that in ${}^{6}_{\Lambda}$H and ${}^{8}_{\Lambda}$H there is a low-lying state 1^+. So we obtain a chain of three hypernuclei - ${}^{4}_{\Lambda}$H, ${}^{6}_{\Lambda}$H and ${}^{8}_{\Lambda}$H - with a similar (and very simple!) ground state doublet.

There is accumulated experience in hypernuclear community how to extract the spin-dependent part of YN interaction from doublet splitting [40]. The understanding of the structure of neutron-rich hypernuclei plays an important role also in description of neutron stars [41, 42].

4 Summary

The production of neutron-rich hyper Hydrogen isotopes ${}^{6}_{\Lambda}$H and ${}^{8}_{\Lambda}$H is not only instructive for understanding the mechanism of their production but could answer very intersting questions on the role of $\Lambda - \Sigma$ mixing in such systems and on the existence of long-lived isomeric state.

Comment. This 45-year story of hunting for neutron rich hypernuclei is a nice illustration of Ed Hungerford's final sentence in his Summary of HYP2006 [43]: *"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."*

The experiment is prepared by 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.Lit-vinenko, **J. Lukstins**, V. Lysyakov, A. Malakhov, P. Manya-kov, E. Matyushevskiy, V. Matyushin, I. Migulina, G. Niko-loyevskiy, 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, *IAEP CTU, Prague*, L. Majling, *NPI AS CR, Řež.* This work was supported by grant 202/05/2142 of the Grant Agency of the Czech Republic.

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