Hypernuclear properties and hyperonic interactions

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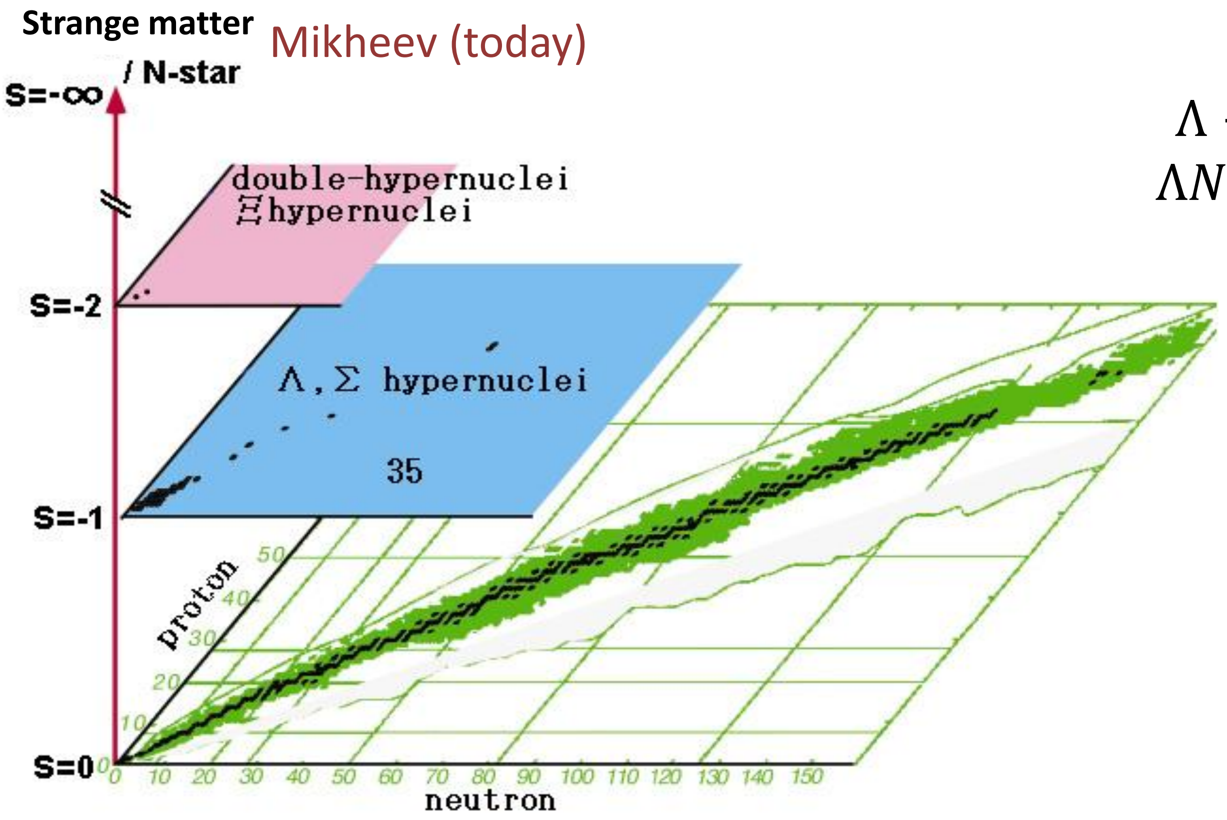
Hypernuclear systems

- Experiment vs theory – state of art
- Some hot points:
  - Drip lines
  - Hypertriton
  - Double-strange systems

Mikheev (today)



$$\Lambda \to \pi N \ (\sim 40\ \mathrm{MeV})$$
$$\Lambda N \to NN \ (176\ \mathrm{MeV})$$
$$\tau \sim 10^{-10}\ \mathrm{s}$$

$$\Sigma N \to \Lambda N$$
$$\Xi N \to \Lambda\Lambda$$
$$\tau \sim 10^{-23}\ \mathrm{s}$$

Λ-hypernuclei

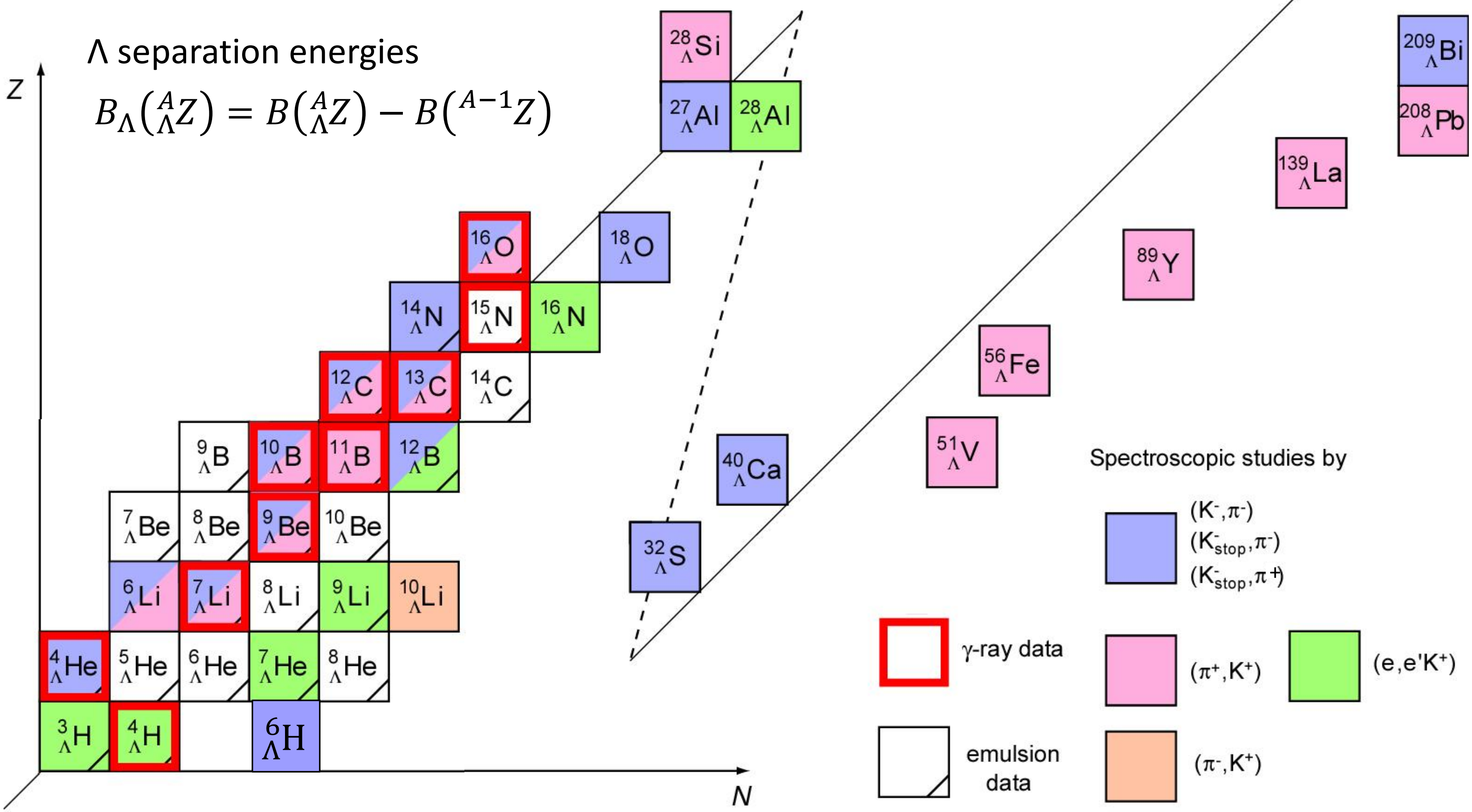
Tamura 2012

<= Few-body / Cluster models

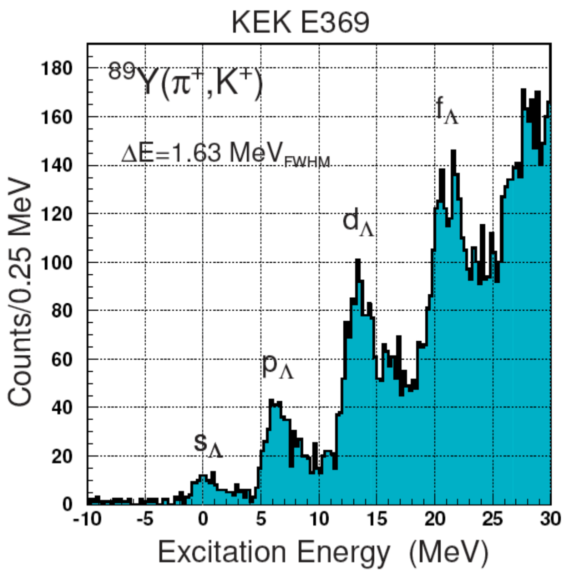
Mean-field models =>

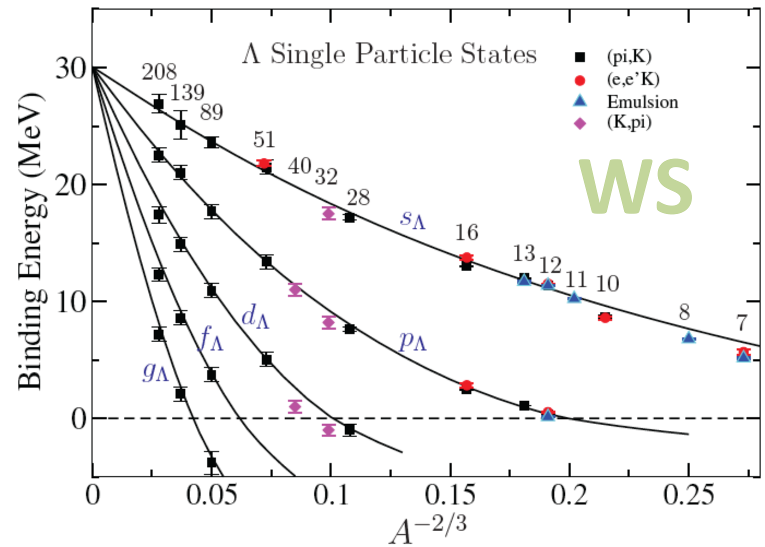
Λ separation energies

$$B_\Lambda({}^A_\Lambda Z) = B({}^A_\Lambda Z) - B({}^{A-1}Z)$$

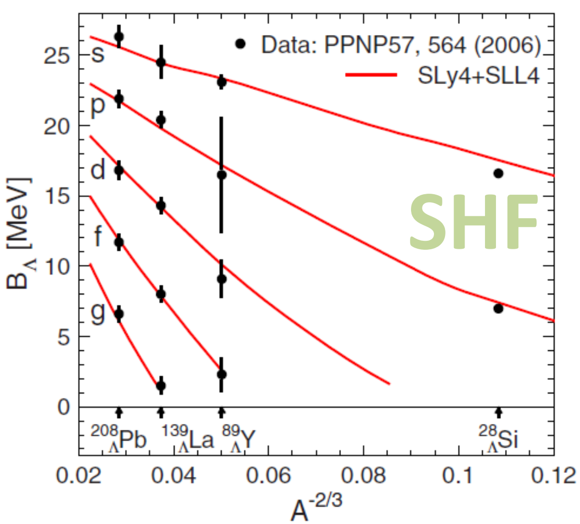


Λ-hypernuclei

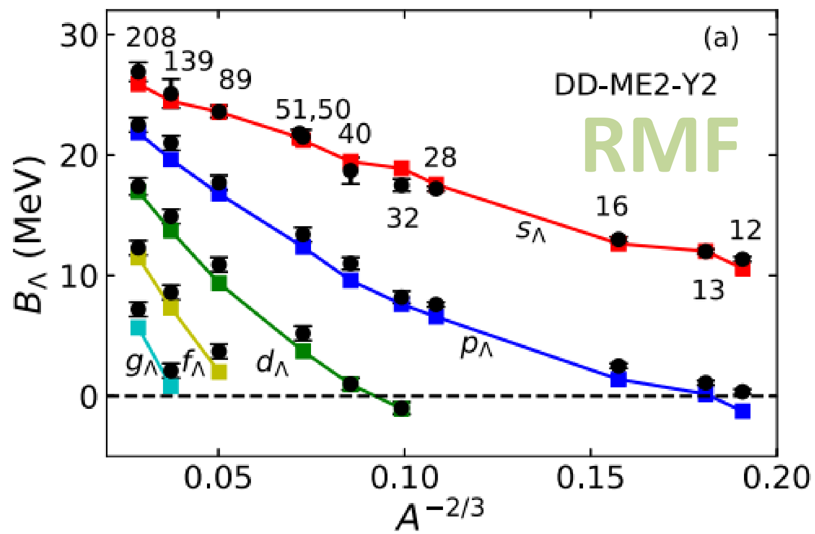




Gal, Hungerford, Millener RMP 88(2016)035004



Schulze, Hiyama PRC 90(2014)047301

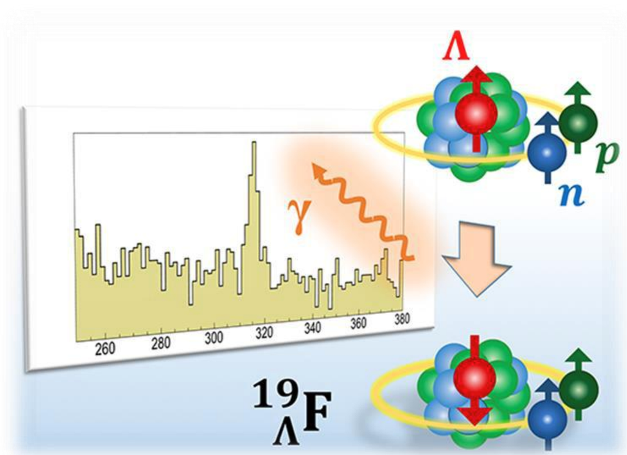


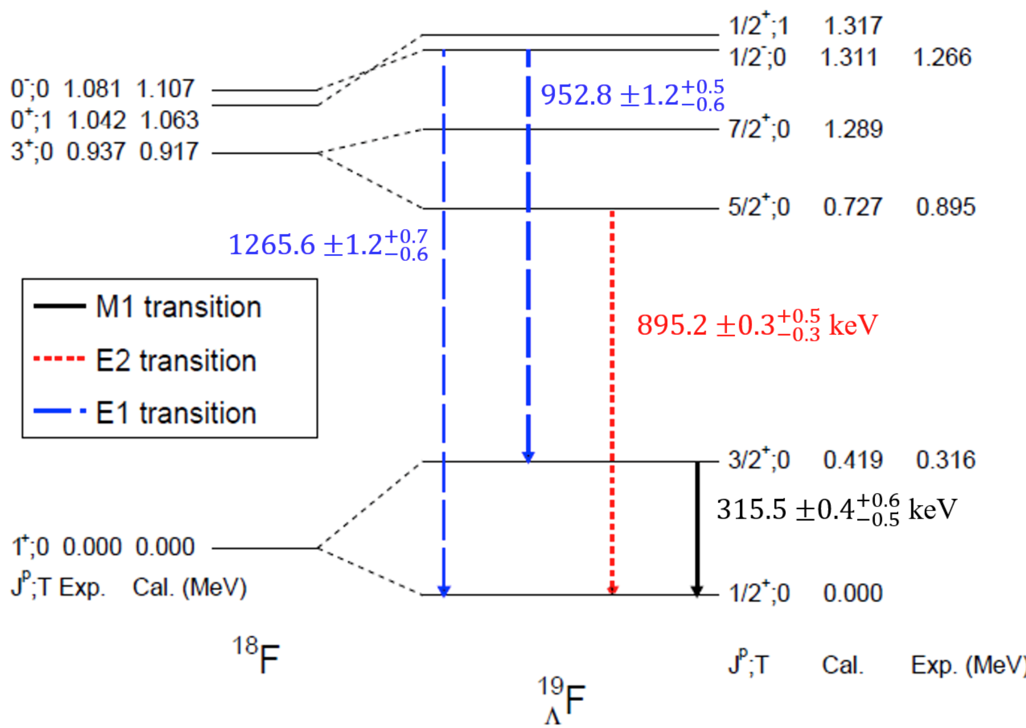
Rong, Tu, Zhou PRC 104(2021)054321

Λ-hypernuclei

Λ spin-orbit splitting (keV): 150 in ${}^{13}_{\Lambda}\mathrm{C}$ & related 43 in ${}^{9}_{\Lambda}\mathrm{Be}$

Precise structure *p*- hypernuclei ${}^{7}_{\Lambda}\mathrm{Li}$, ${}^{9}_{\Lambda}\mathrm{Be}$, ${}^{10,11}_{\Lambda}\mathrm{B}$, ${}^{12,13}_{\Lambda}\mathrm{C}$, ${}^{15}_{\Lambda}\mathrm{N}$, ${}^{16}_{\Lambda}\mathrm{O}$





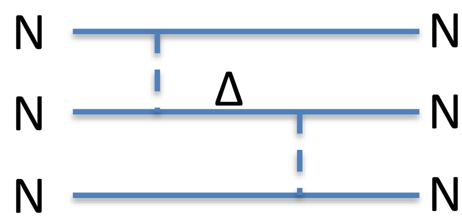
Yang et al., PhysRevLett 120 (2018) 132505

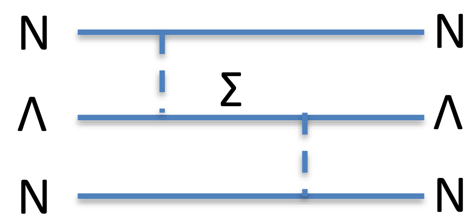
$$U_{\Lambda N} = U_0 + U_S(\boldsymbol{s}_N \boldsymbol{s}_\Lambda) + W_{LS}(\boldsymbol{l}_N \boldsymbol{s}_\Lambda) + W'_{LS}(\boldsymbol{l}_\Lambda \boldsymbol{s}_N) + TS_{12}$$
$$B_\Lambda(A \to \infty) = U_0 \approx -28 \text{ MeV}$$
$$U_S, W_{LS}, W'_{LS}, T - small$$

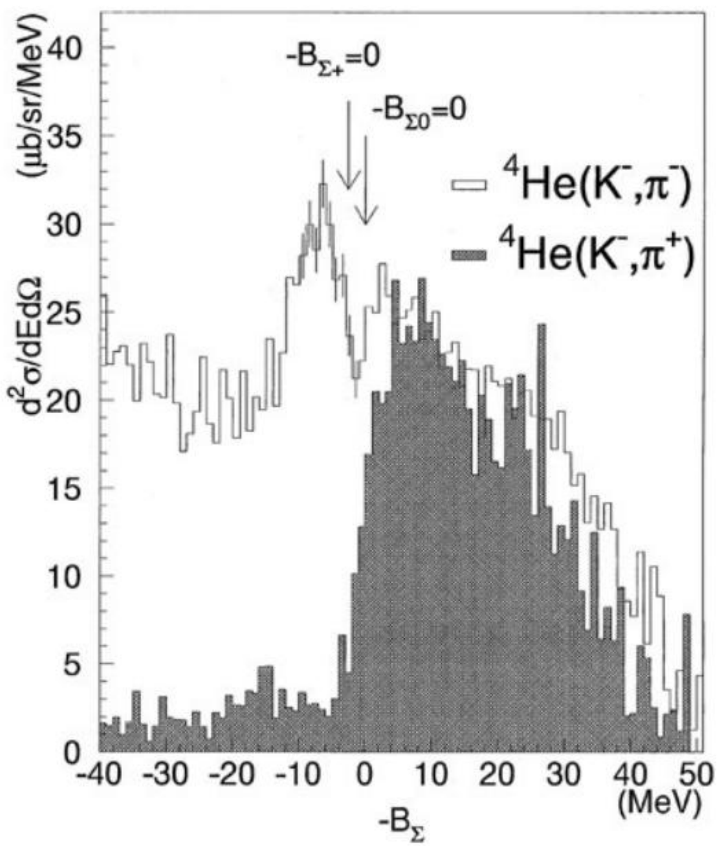
Σ-hypernuclei

$\Sigma^{\pm} \to N\pi$ (~113 MeV)
$\Sigma^{0} \to \Lambda\gamma$ (74 MeV)

$\Sigma N \to \Lambda N$ (~ 75 MeV)







$$B_{\Sigma^+}({}^{4}_{\Sigma}\mathrm{He}) = 4.4 \pm 0.3 \pm 1\ \mathrm{MeV}$$
$$\Gamma = 7.0 \pm 0.7^{+1.2}_{0.0}\ \mathrm{MeV}$$

$$U_{\Sigma}(r) = (U_0 + U_L(\boldsymbol{\tau}_{core}\boldsymbol{\tau}_{\Sigma})/A)\,\frac{\rho(r)}{\rho_0}$$

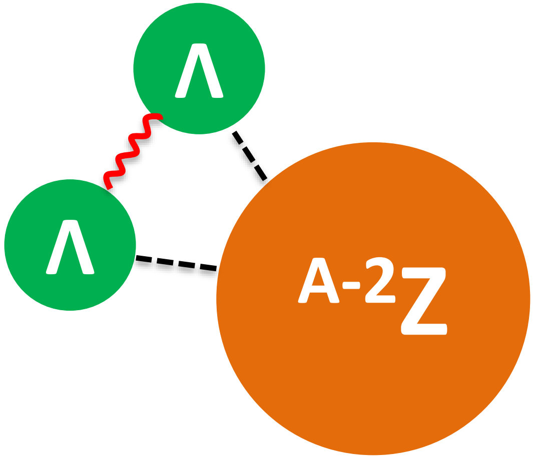
$$U_0 = +30 \pm 20\ \mathrm{MeV}$$
$$U_L \approx 80\ \mathrm{MeV}$$

Exitation energy spectra of ^{4}He(K^{-}, π^{-}) at 600 MeV/c K^{-} momentum (BNL AGS) [Nagae et al PhysRevLett 80 (1998)1605]

T. Nagae, in HandBook in Nuclear Physics. Springer 2023

Double-strangeness hypernuclei

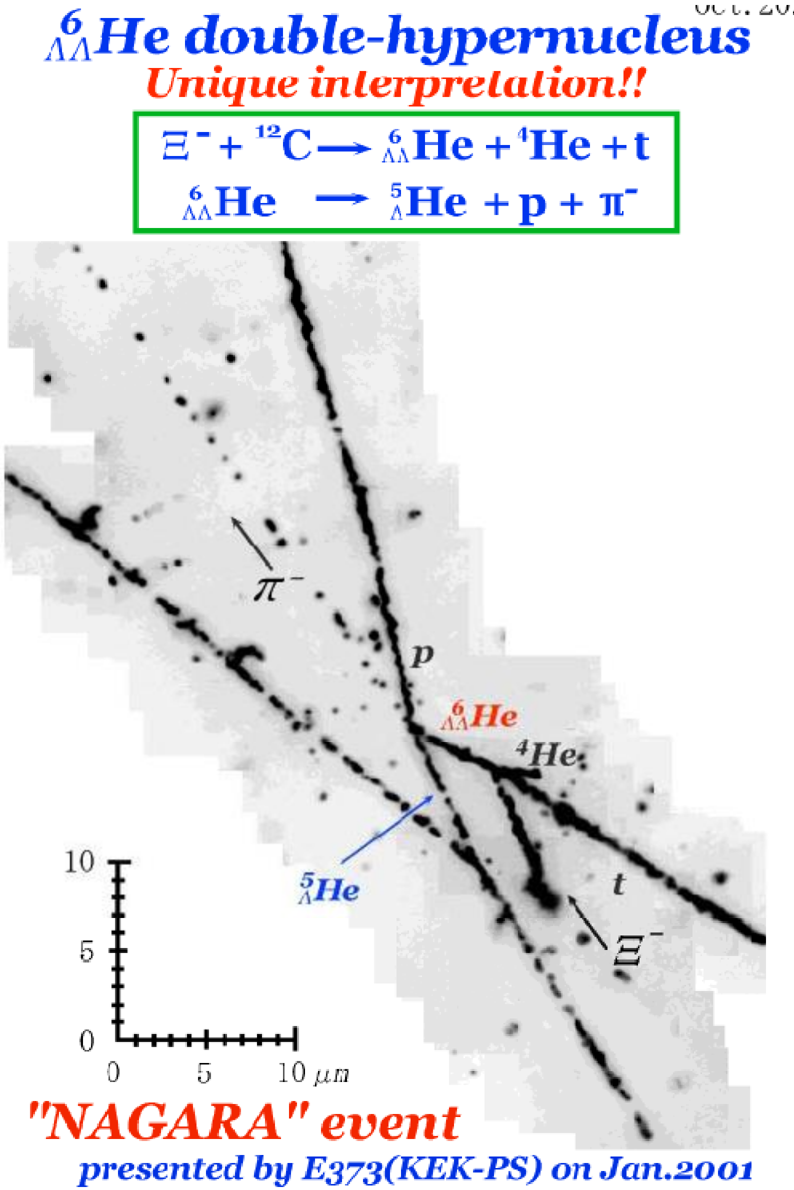
a unique source of information on baryon interactions
in the S=-2 sector



$$B_{\Lambda\Lambda}\left({}_{\Lambda\Lambda}^{A}Z\right) = B\left({}_{\Lambda\Lambda}^{A}Z\right) - B\left({}^{A-2}Z\right)$$

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}$$

Double-strangeness hypernuclei



- C(K^-,K^+) reaction to produce Ξ^- then stop it in emulsion (H. Takahashi et al., PRL87(2001)212502)

- Binding energy of $^{6}_{\Lambda\Lambda}$He is obtained to be

  $B_{\Lambda\Lambda} = 7.3 \pm 0.3$ MeV

  (from $\alpha + 2\Lambda$)

- In order to extract $\Lambda\Lambda$ interaction, we take

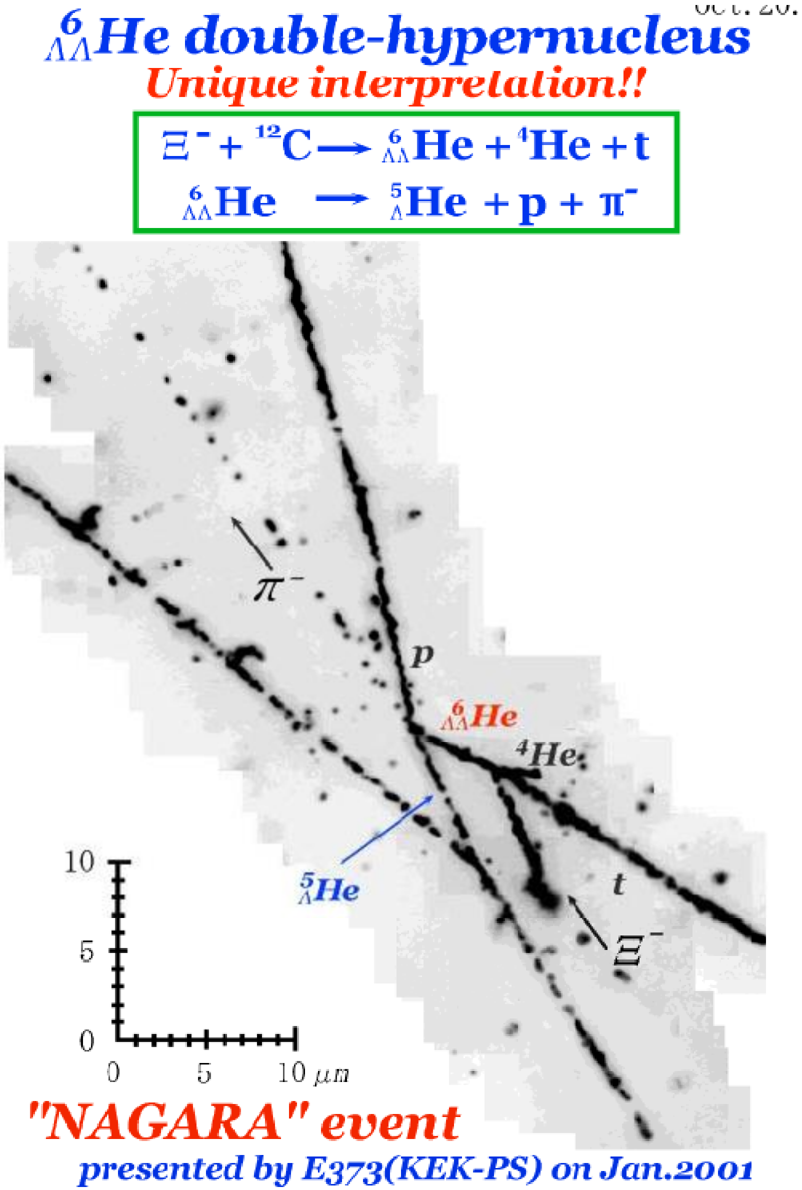
  $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}(^{5}_{\Lambda}He)$

  $= 1.0 \pm 0.3$ MeV

  → weakly attractive

Phys Rev Lett 87 (2001) 212502

Double-strangeness hypernuclei



- C(K$^-$,K$^+$) reaction to produce Ξ^- then stop it in emulsion
  (H. Takahashi et al., PRL87(2001)212502)

- Hyperon binding energy of $^{6}_{\Lambda\Lambda}$He is obtained to be
  $B_{\Lambda\Lambda}$ = 6.91 ± 0.16 MeV
  (from α+2Λ)

- In order to extract $\Lambda\Lambda$ interaction, we take
  $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}({}^{5}_{\Lambda}He)$
  =0.67 ± 0.17 MeV
  → weakly attractive

Ahn et al Phys Rev C 88 (2013) 014003

Double-strangeness hypernuclei

K. Nakazawa, in HandBook in Nuclear Physics. Springer 2023

Ev. name	Nuclide	Target	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)	Comments
Nagara	${}^{6}_{\Lambda\Lambda}$He	^{12}C	6.91 ± 0.16	0.67 ± 0.17	Uniquely identified
Danysz et al.	${}^{10}_{\Lambda\Lambda}$Be	^{12}C	14.7 ± 0.4	1.3 ± 0.4	${}^{10}_{\Lambda\Lambda}\mathrm{Be} \to {}^{9}_{\Lambda}\mathrm{Be}^*$ ($Ex. = 3.0$ MeV)
E176	${}^{13}_{\Lambda\Lambda}$B	^{14}N	23.3 ± 0.7	0.6 ± 0.8	${}^{13}_{\Lambda\Lambda}\mathrm{B} \to {}^{13}_{\Lambda}\mathrm{C}^*$ ($Ex. = 4.9$ MeV)
Demachi-Yanagi	${}^{10}_{\Lambda\Lambda}$Be*	^{12}C	11.90 ± 0.13	-1.52 ± 0.15	Most probable (topology) $Ex. \approx 2.8$ MeV for ${}^{10}_{\Lambda\Lambda}$Be*
Mikage	${}^{6}_{\Lambda\Lambda}$He	^{12}C	10.01 ± 1.71	3.77 ± 1.71	Most probable (mesonic decay)
	${}^{11}_{\Lambda\Lambda}$Be	^{12}C	22.15 ± 2.94	3.95 ± 3.00	
	${}^{11}_{\Lambda\Lambda}$Be	^{14}N	23.05 ± 2.59	4.85 ± 2.63	
Hida	${}^{11}_{\Lambda\Lambda}$Be	^{12}C	20.83 ± 1.27	2.61 ± 1.34	
	${}^{12}_{\Lambda\Lambda}$Be	^{14}N	20.48 ± 1.21	(2.00 ± 1.21)	Assumed 10.24 MeV for $B_{\Lambda}({}^{11}_{\Lambda}\mathrm{Be})$
Mino	${}^{10}_{\Lambda\Lambda}$Be	^{16}O	15.05 ± 0.11	1.63 ± 0.14	
	${}^{11}_{\Lambda\Lambda}$Be	^{16}O	19.07 ± 0.11	1.87 ± 0.37	Most probable (χ^2 minimum)
	${}^{12}_{\Lambda\Lambda}$Be	^{16}O	13.68 ± 0.11	-2.7 ± 1.0	
D001	${}^{8}_{\Lambda\Lambda}$Li	^{12}C	17.50 ± 1.46	6.34 ± 1.46	
	${}^{10}_{\Lambda\Lambda}$Be	^{14}N	15.05 ± 2.78	1.63 ± 2.78	Likely by $B_{\Lambda\Lambda}$

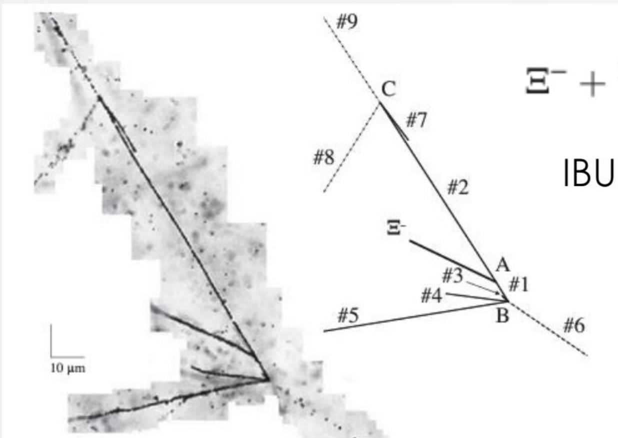
Double-strangeness hypernuclei

Ξ^-–Nuclear Bound States

KEK E373 and **J-PARC E07** experiments

Coulomb-Assisted Ξ^-–^{14}N $1p_{\Xi^-}$ nuclear bound state

Hayakawa (J-PARC E07), PRL (2021)



$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

IBUKI event

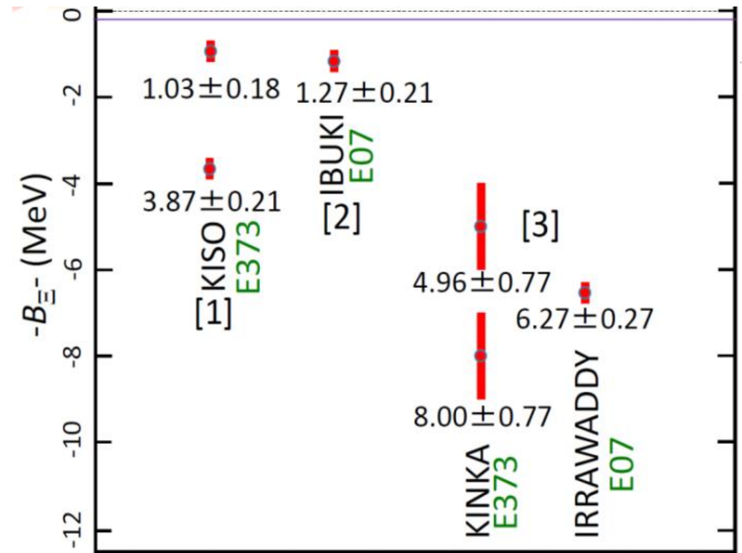
Yoshimoto, PTEP (2021)

KINKA (E373) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + n$

IRRAVADDY (E07) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + n$

→ $1s_{\Xi^-}$ nuclear state

Ξ hypernucleus ($^{15}_{\Xi}$C [Ξ^--^{14}N])



[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

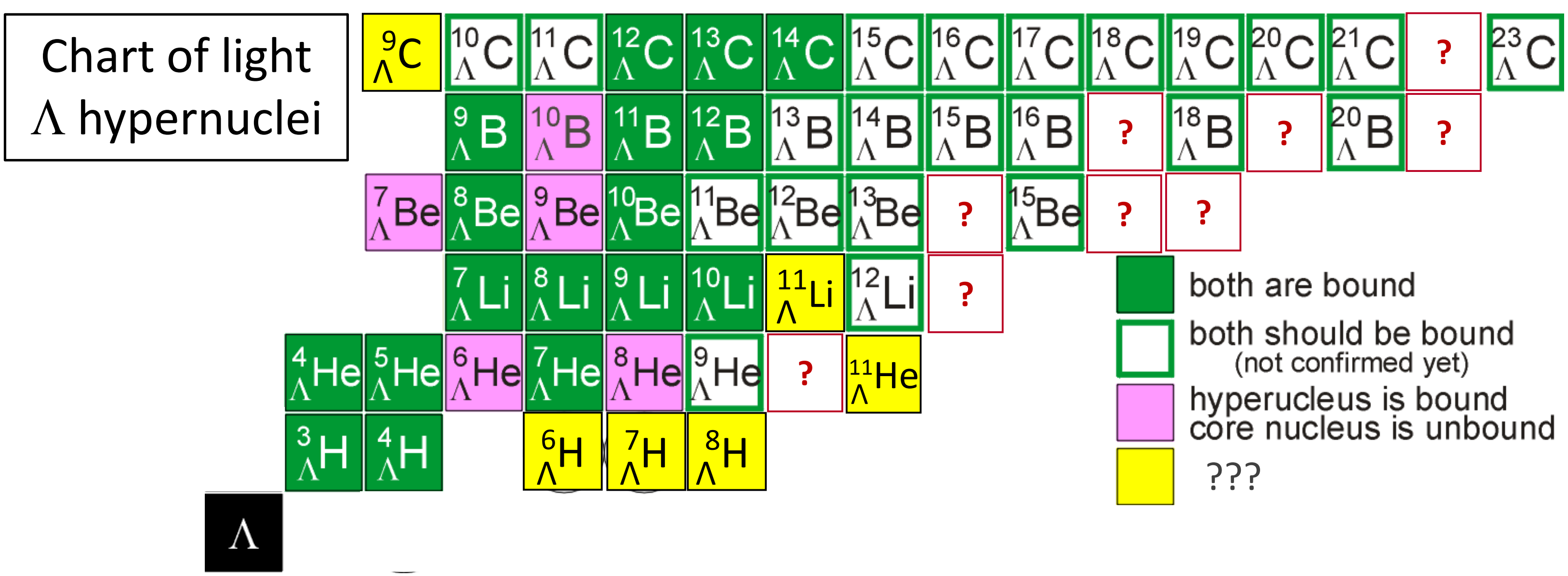
$U_{0\Xi}$ ~ 14 MeV

K. Nakazawa, in HandBook in Nuclear Physics. Springer 2023

Λ hypernuclei near drip-lines

- Chart of Λ hypernuclei
  - Particle-stable core nuclei guarantee stable Λ hypernuclei
    - Still there are many unobserved Λ hypernuclei
  - Λ-hyperon may reinforce the nuclear binding
    - Glue-like role of Λ-hyperon: also particle-unstable nuclei may form core of stable Λ hypernuclei

L. Majling, Nucl. Phys. A585 (1995) 211c



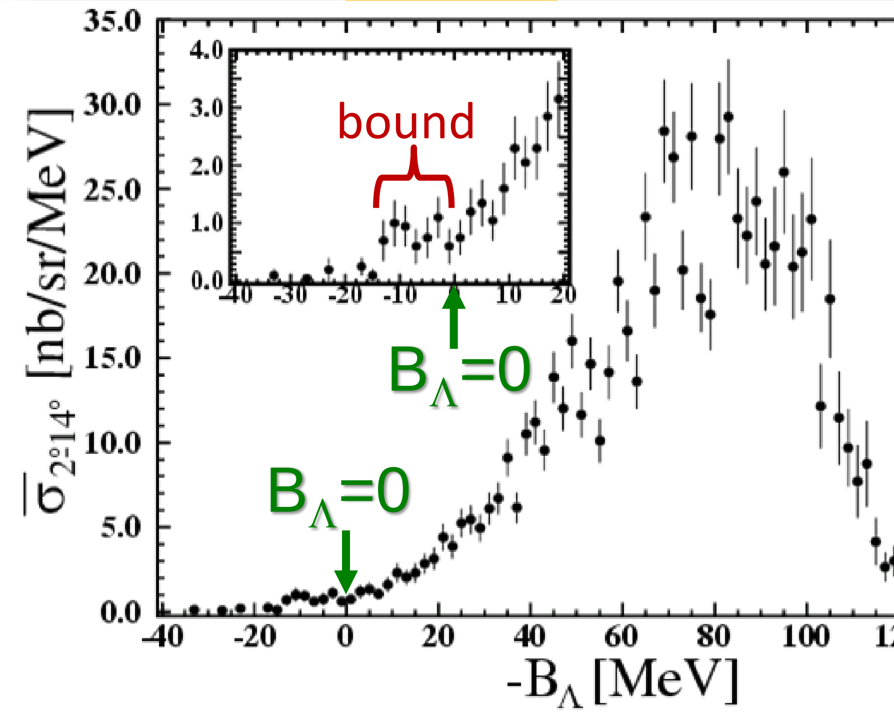
Neutron-rich hypernuclei

Study by using DCX reaction: $^{10}_{\Lambda}$Li

- **KEK E521:** P.K. Saha et al. PRL 94 (2005) 052501
  - Study of the $^{10}B(\pi^-,K^+)$ reaction
    - Successfully produced $^{10}_{\Lambda}$Li
    - Almost background free
  - Promising production method
  - Tiny production cross section

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX},{}^{10}_{\Lambda}\mathrm{Li}) \approx 10\,\mathrm{nb/sr}$$

$^{10}B(\pi^-,K^+)^{10}_{\Lambda}Li$



Reaction mechanisms

DCX: $\begin{cases}\pi^- p \to K^0 \Lambda \\ K^0 p \to K^+ n\end{cases}$ $\begin{cases}\pi^- p \to \pi^0 \Lambda \\ \pi^0 p \to K^+ n\end{cases}$

Σ-admixture doorway state:

$$\left|{}^{10}_{\Lambda}\mathrm{Li}\right\rangle = \alpha\left|\,{}^{9}\mathrm{Li}\otimes\Lambda\right\rangle + \beta\left|\,{}^{9}\mathrm{Be}\otimes\Sigma^-\right\rangle$$
$$\pi^- p \to K^+ \Sigma^-$$

Tretyakova, Lanskoy Phys. At. Nucl. 66 (2003) 1651

Neutron-rich hypernuclei

Study by using DCX reaction: $^{6}_{\Lambda}H$

- **FINUDA**: M. Agnello et al. PhysRevLett 108 (2012) 042501
  - Study of the $^{6}Li(K^{-}_{stop},\pi^{+})$ reaction

$$^{6}\mathrm{Li}(K^{-}_{\mathrm{stop}},\pi^{+})^{6}_{\Lambda}\mathrm{H} \qquad ^{6}_{\Lambda}\mathrm{H} \rightarrow {}^{6}\mathrm{He} + \pi^{-}$$

  - Reported 3 candidate events of $^{6}_{\Lambda}H$ production

$$B_{\Lambda}(^{6}_{\Lambda}\mathrm{H}) = (4.0 \pm 1.1)\mathrm{MeV}$$

$$\mathrm{BR}(\mathrm{DCX}, {}^{6}_{\Lambda}\mathrm{H}) / \mathrm{BR}(\mathrm{NCX}, {}^{12}_{\Lambda}\mathrm{C}) \approx 6 \times 10^{-3}$$

$$\mathrm{BR}(\mathrm{DCX}, {}^{6}_{\Lambda}\mathrm{H}) / \mathrm{BR}(\mathrm{NCX}, {}^{4}_{\Lambda}\mathrm{He}) \approx 3 \times 10^{-4}$$

- **J-PARC-E10**: H. Sugimura et al., PhysLettB 729 (2014) 39
  - Missing-mass spectrum of the $^{6}Li(\pi^{-},K^{+})$ reaction

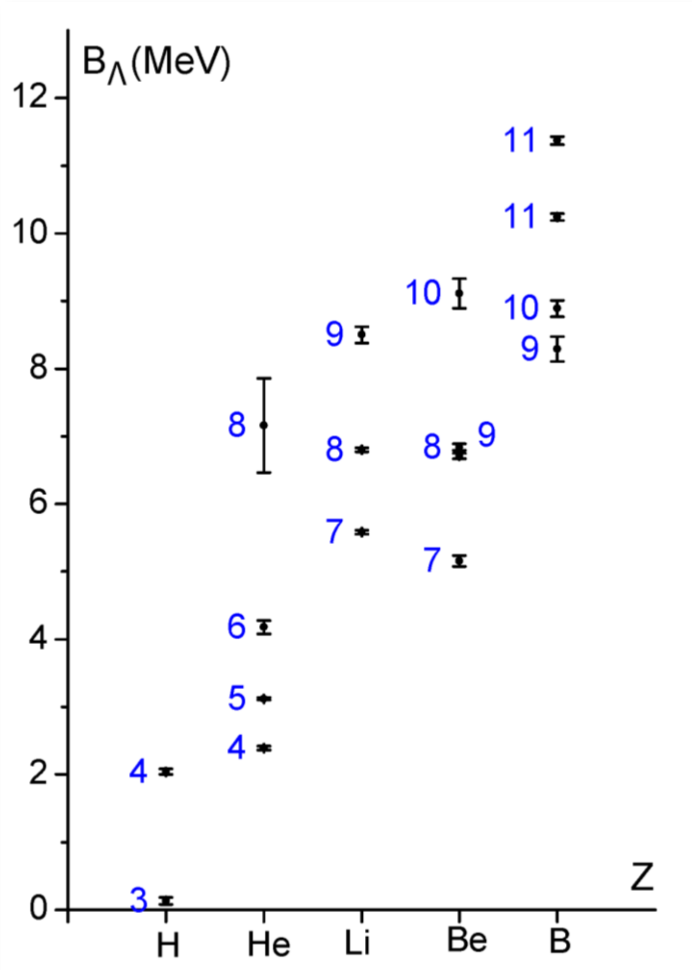
$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}) \Big/ \frac{d\sigma}{d\Omega}(\mathrm{NCX}) < 1.5 \times 10^{-4}$$

DCX: (π^{-},K^{+}) NCX: (π^{+},K^{+}) for $^{12}_{\Lambda}C$

No clear peak of $^{6}_{\Lambda}H$ production in threshold region

cross section is extremely smaller than it was expected

Neutron-rich Λ hypernuclei



Proposal $^{8}_{\Lambda}$H

L. Majling Nucl Phys A 585 (1995) 211c

$$^{6}_{\Lambda}\mathrm{H} \rightarrow {}^{4}_{\Lambda}\mathrm{H} + n + n$$

$$S_{2n}(^{6}_{\Lambda}\mathrm{H}) = S_{2n}(\,^{5}\mathrm{H}) + B_{\Lambda}(^{6}_{\Lambda}\mathrm{H}) - B_{\Lambda}(^{4}_{\Lambda}\mathrm{H})$$

~−2 (4.0)?? 2.1

$$^{8}_{\Lambda}\mathrm{H} \rightarrow {}^{4}_{\Lambda}\mathrm{H} + 4n$$

$$S_{4n}(^{8}_{\Lambda}\mathrm{H}) = S_{4n}(\,^{7}\mathrm{H}) + B_{\Lambda}(^{8}_{\Lambda}\mathrm{H}) - B_{\Lambda}(^{4}_{\Lambda}\mathrm{H})$$

−0,57 ?? 2.1

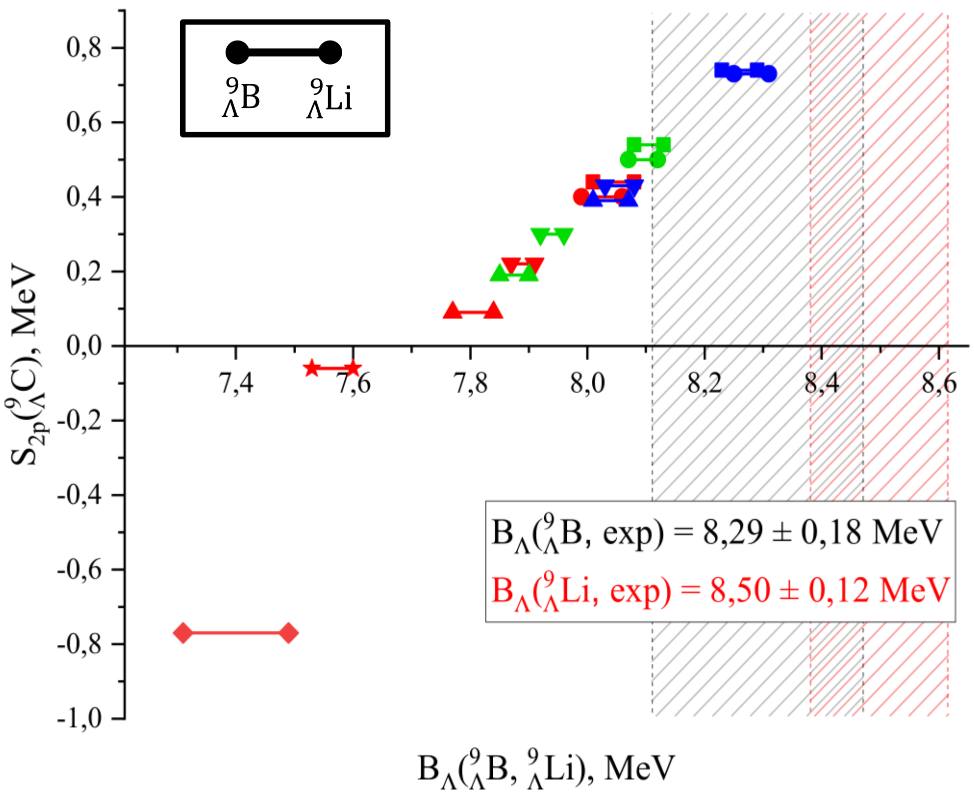
$B_{\Lambda}(^{8}_{\Lambda}\mathrm{H})$ ~ 7-8 MeV ?

Hydrogen isotopes

	^{4}H	^{5}H	^{6}H	^{7}H
Decay mode	*n*	2*n*	3*n*	4*n*
E_{res} [MeV]	3.2	1.7÷2.4	2.3±0.5	0.57^{+42}_{-21}

Proton-rich Λ hypernuclei

2p separation energy in ${}^{9}_{\Lambda}C$



$$ {}^{8}C \rightarrow {}^{4}He + 4p $$
$$ {}^{9}_{\Lambda}C \rightarrow {}^{7}_{\Lambda}Be + 2p $$

calc

$$ S_{2p}({}^{9}_{\Lambda}C) = S_{2p}({}^{8}C) + B_\Lambda({}^{9}_{\Lambda}C) - B_\Lambda({}^{7}_{\Lambda}Be) $$

exp: -2,14 МэВ   exp: 5,16 МэВ

Different NN and ΛN interactions

The better the description of $B_\Lambda({}^{9}_{\Lambda}B)$ and $B_\Lambda({}^{9}_{\Lambda}Li)$, the greater 2p separation energy in ${}^{9}_{\Lambda}C$.

$$ S_{2p}({}^{9}_{\Lambda}C) > 0. $$

${}^{9}_{\Lambda}C$ should be bound

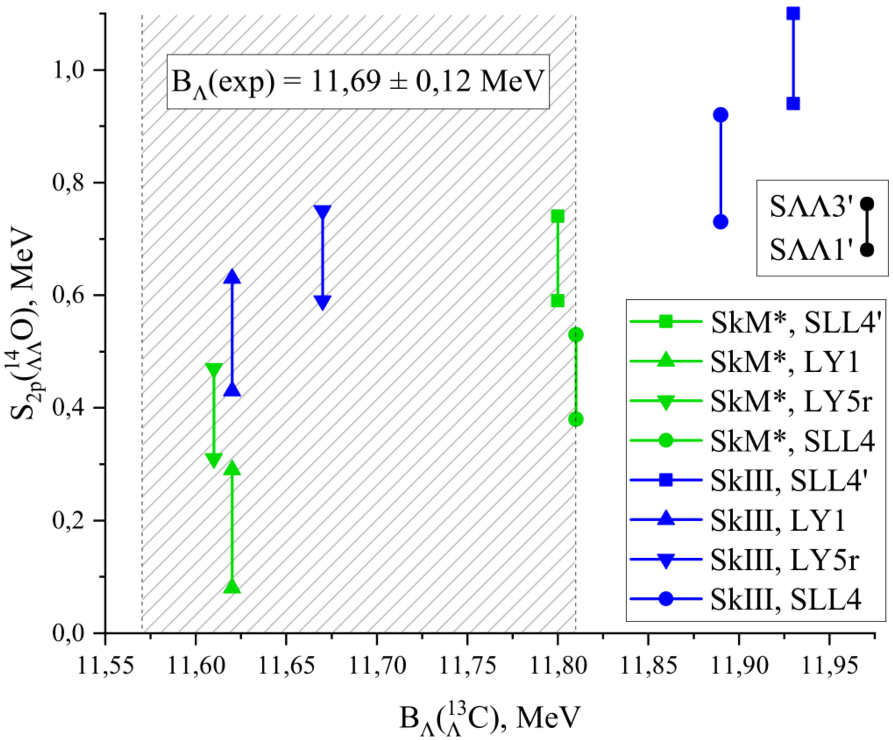
Isotope	S_p or S_{2p}, MeV	δB_Λ, MeV
${}^{16}F$	$S_p = -0.531 \pm 0.005$	$\delta B^p_\Lambda = 0.37 \div 1.17$
${}^{19}Na$	$S_p = -0.323 \pm 0.011$	$\delta B^p_\Lambda = 0.30 \div 0.36$
${}^{19}Mg$	$S_{2p} = -0.76 \pm 0.06$	$\delta B^{2p}_\Lambda = 0.48 \div 0.72$

Whether ${}^{17}_{\Lambda}F$, ${}^{20}_{\Lambda}N$ and ${}^{20}_{\Lambda}Mg$ hypernuclei are bound remains questionable.

Lanskoy, Sidorov, Tretyakova EPJ A. 2022

Proton-rich Λ hypernuclei

Double-strangeness hypernuclei. 2p separation energy in ${}^{14}_{\Lambda\Lambda}\mathrm{O}$



exp

$$S_{2p}\left({}^{14}_{\Lambda\Lambda}\mathrm{O}\right) = S_{2p}\left({}^{12}\mathrm{O}\right)$$
$$+B_{\Lambda\Lambda}\left({}^{14}_{\Lambda\Lambda}\mathrm{O}\right) - B_{\Lambda\Lambda}\left({}^{12}_{\Lambda\Lambda}\mathrm{C}\right)$$

calc

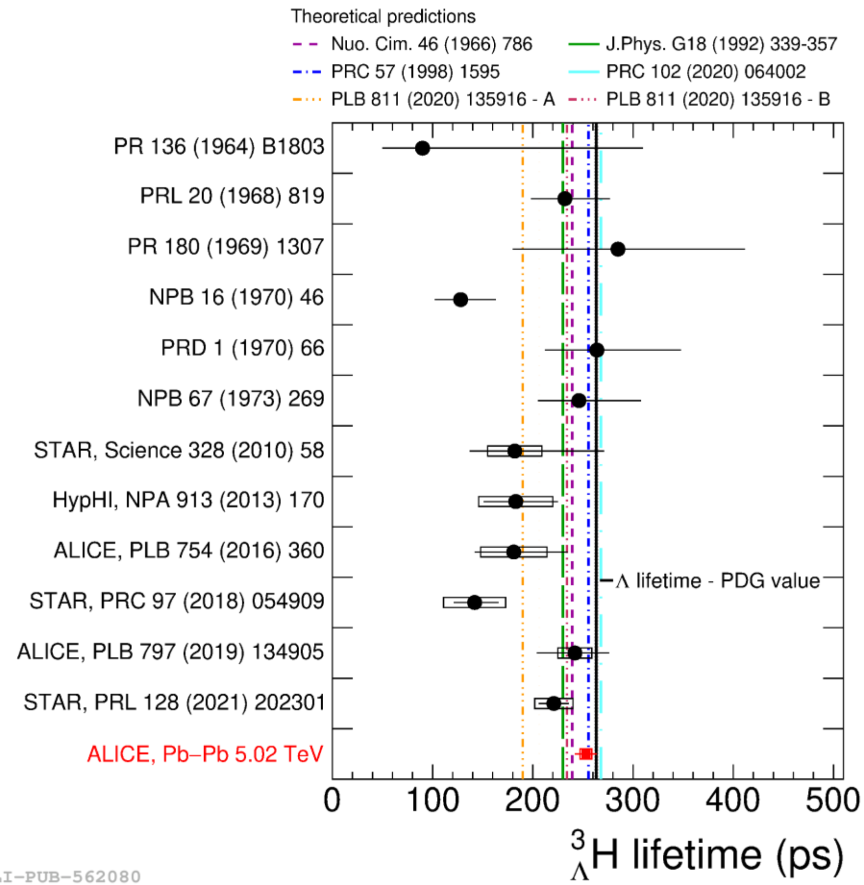
as function $B_\Lambda\left({}^{13}_{\Lambda}\mathrm{C}\right)$ for different NN and ΛN Skyrme parameter sets. Hypernucleus ${}^{13}_{\Lambda}\mathrm{O}$ is unbound; a second hyperon addition completes the binding of the hypernucleus.

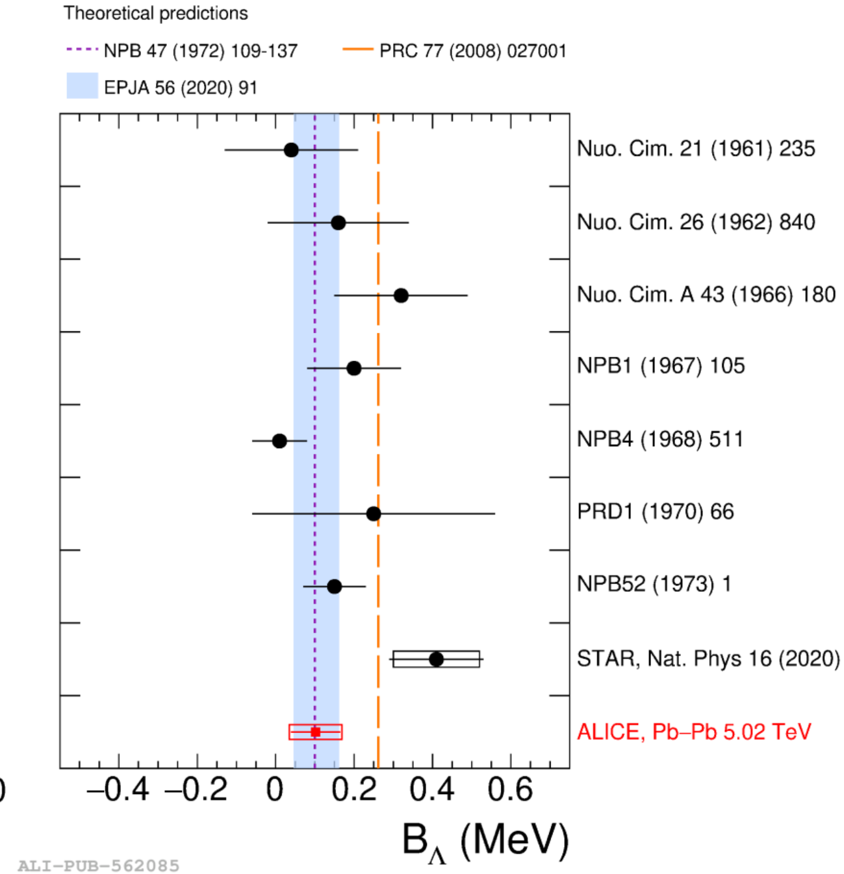
${}^{14}_{\Lambda\Lambda}\mathrm{O}$ should be bound

Lanskoy, Sidorov, Tretyakova EPJ A 58 (2022) 203

Lightest hypernuclei
Hyperhydrogen and hyperhelium

Hypertriton $^{3}_{\Lambda}H$





$$\tau = [253 \pm 11(stat) \pm 6(syst)]\ \text{ps}$$

$$B_{\Lambda} = [102 \pm 63(stat) \pm 67(syst)]\ \text{keV}$$

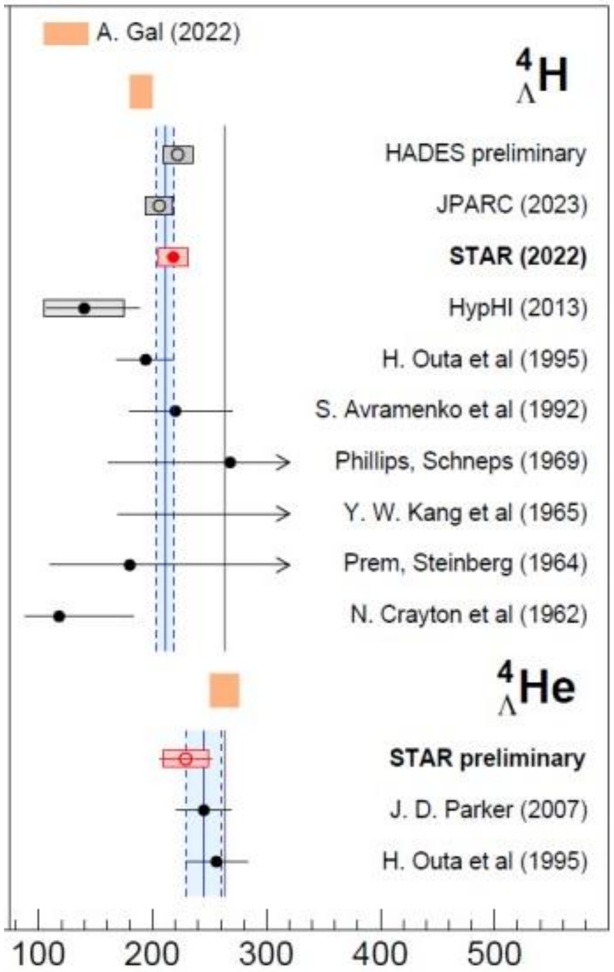
$$\frac{\tau\left({}^{3}_{\Lambda}\text{H}\right) - \tau\left({}^{3}_{\Lambda}\overline{\text{H}}\right)}{\tau\left({}^{3}_{\Lambda}\text{H}\right)} = [3 \pm 7(stat) \pm 4(sys)] \times 10^{-2}$$

$$\tau\left({}^{3}_{\Lambda}\text{H}\right) \approx 0.96\tau_{\Lambda}$$

$${}^{3}_{\Lambda}\text{H} \rightarrow {}^{3}\text{He} + \pi^{-}$$

ALICE PhysRevLett 131 (2023) 102302

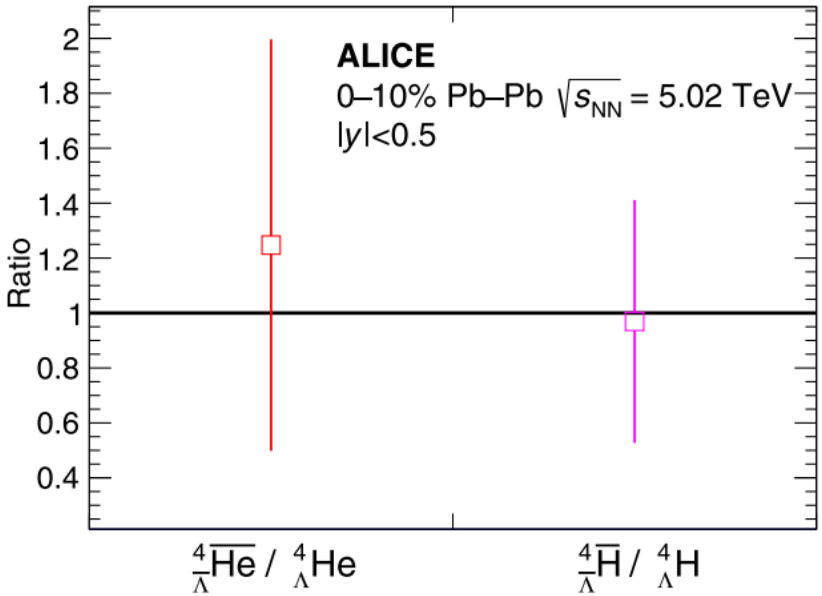
Λ hypernuclei A=4



Lifetime [ps]

Masses (keV)

STAR 2022	$^4_\Lambda\mathrm{H}$	3922.38±0.06	$^4_\Lambda\mathrm{He}$	3921.69 ± 0.13
ALICE 2025	$^4_{\Lambda}\overline{\mathrm{H}}$	3922.5± 0.5	$^4_{\Lambda}\overline{\mathrm{He}}$	3922.4± 0.6



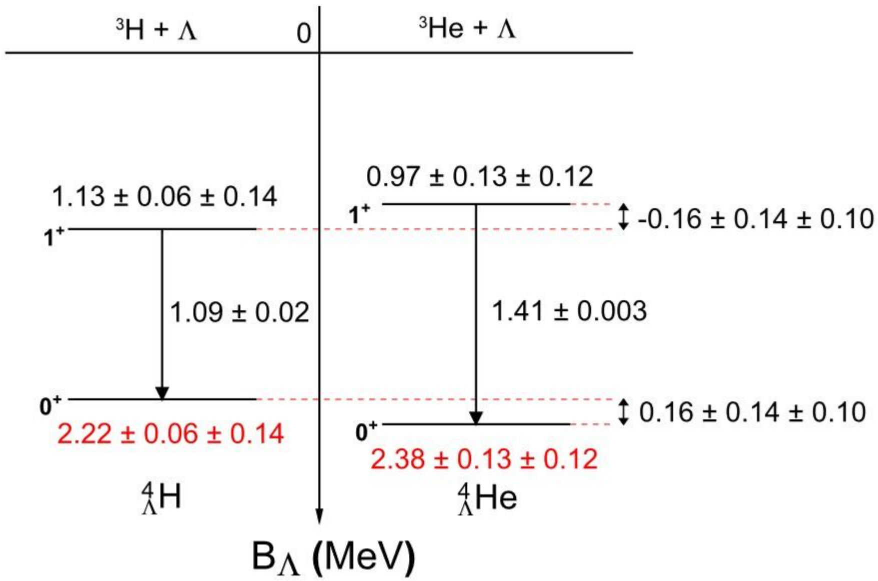
ALICE PhysRevLett 134 (2025) 162301

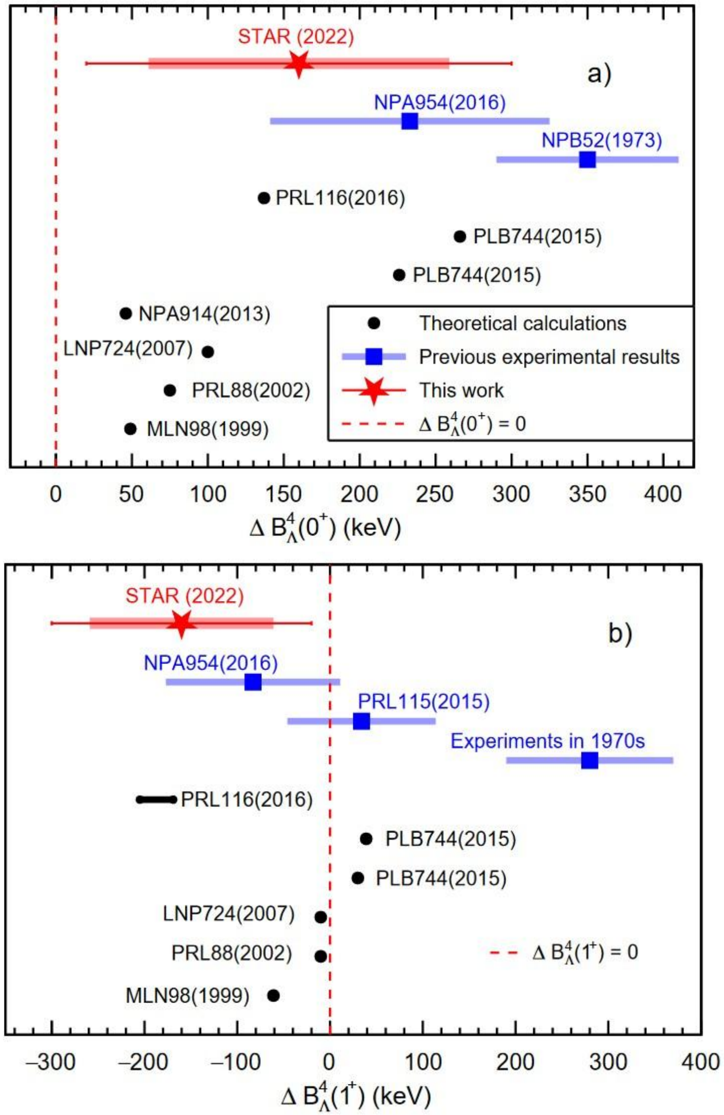
Λ hypernuclei A=4

$$\Delta B_\Lambda^4(J^\pi) = B_\Lambda({}^4_\Lambda\mathrm{He}) - B_\Lambda({}^4_\Lambda\mathrm{H})$$

Charge Symmetry Breaking (CSB) in ΛN-interaction

- The difference between *pp*- and *nn*-interaction, between Λp- and Λn-interaction
- Different character of CSB in the singlet and triplet ΛN-pair states





STAR, PhysLettB 834 (2022) 137449

Double-strangeness hypernuclei

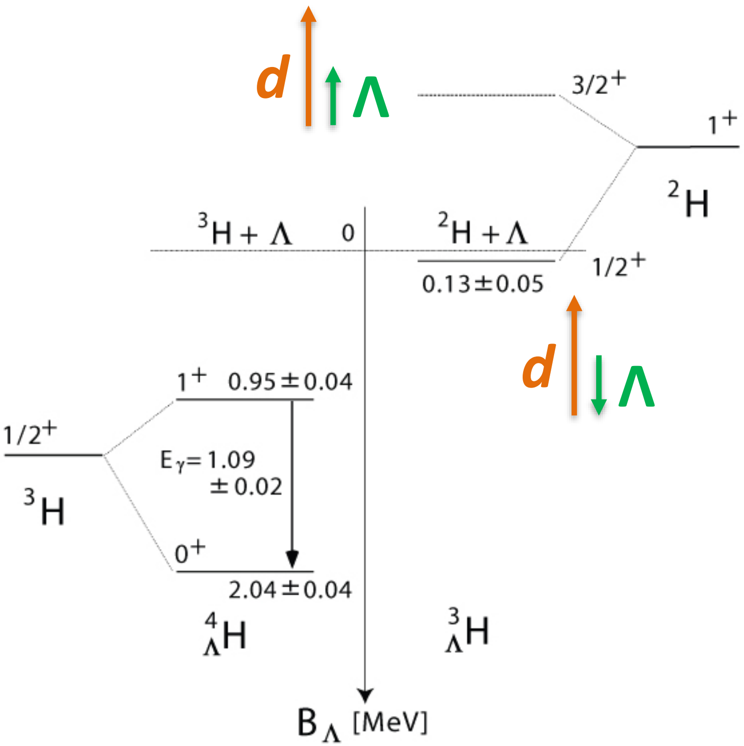
$^{4}_{\Lambda\Lambda}H$

BNL-AGS E906 ^{9}**Be (K⁻, K⁺)** (Ahn et al, PRL 87 (2001) 132504) — evidence

Reevaluation of the reported observation of the $^{4}_{\Lambda\Lambda}H$ hypernucleus (Randeniya and Hungerford PRC **76**, 064308 (2007)) — serious doubt

Few-body calculations: Filikhin, Gal 2002 - No 4H-LL bound state

Nemura et al, 2005 - stable bound state of 4H-LL



Without $\Lambda\Lambda$-interaction:

$$B^{0}_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{4}H) = \frac{2}{3}B_{\Lambda}\left({}_{\Lambda}^{3}H_{gs}\right) + \frac{4}{3}B_{\Lambda}\left({}_{\Lambda}^{3}H^{*}\right)$$

$${}_{\Lambda\Lambda}^{4}\mathrm{H} \quad \text{bound} \quad \text{if} \quad B_{\Lambda\Lambda} > B_{\Lambda}$$

$$4B^{*}_{\Lambda} > B_{\Lambda}$$

$\Lambda\Lambda$-attraction:

$$B^{0}_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{4}H) = \frac{2}{3}B_{\Lambda}\left({}_{\Lambda}^{3}H_{gs}\right) + \frac{4}{3}B_{\Lambda}\left({}_{\Lambda}^{3}H^{*}\right) + \delta B$$

$$4B^{*}_{\Lambda} > B_{\Lambda} - 3\delta B$$

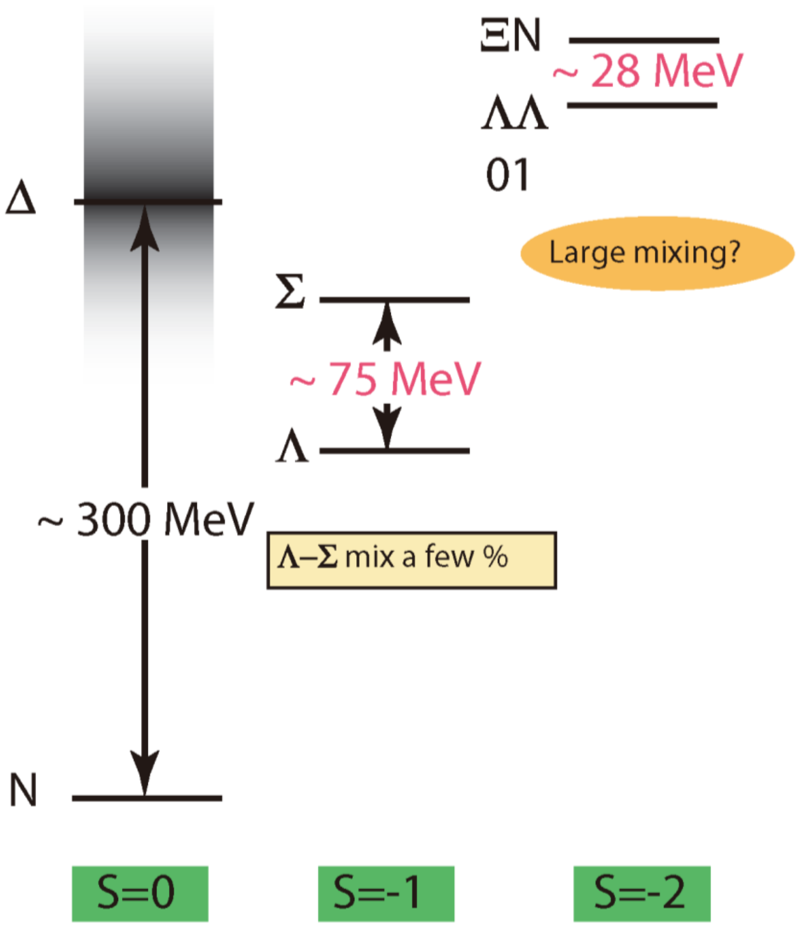
$\delta B = 0.2$ MeV (compatible with Nagara event)

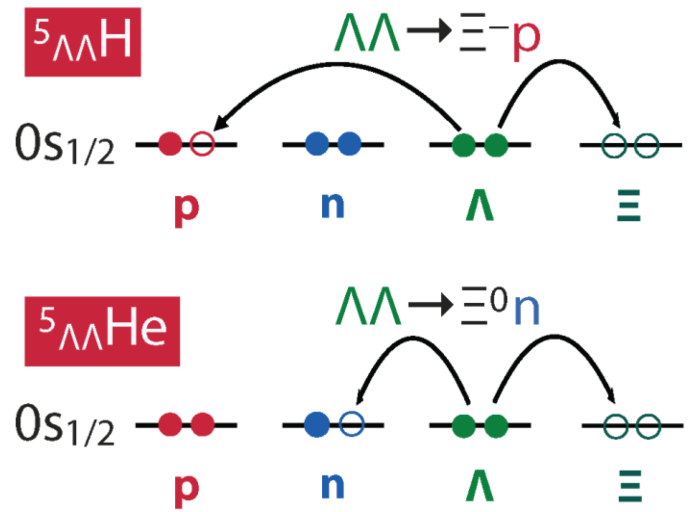
$B^{*}_{\Lambda} > -0{,}1$ MeV — 4H-LL is bound

Predictions: Au+Au, $\sqrt{s_{NN}}$ = 3 GeV – yield per event ~ 10^{-5}–10^{-4} [Buyukcizmeci EPJ A61(2025) 23]

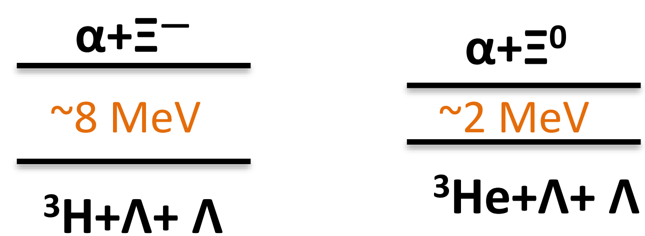
Double-strangeness hypernuclei

ΛΛ – Ξ N mixing





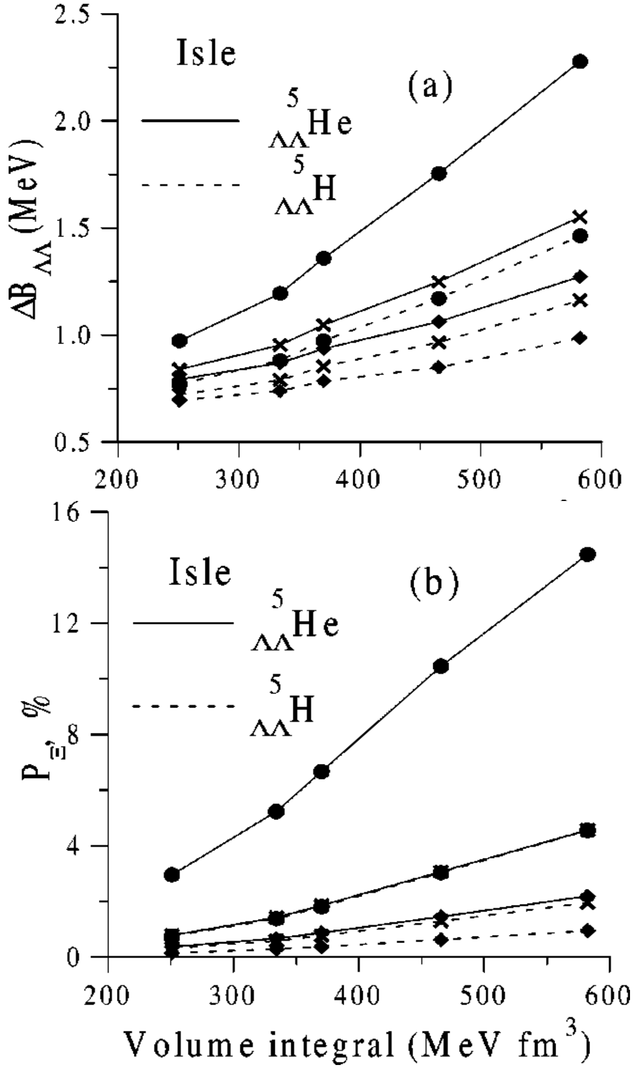
$$\Delta B_{\Lambda\Lambda}\left({}^{5}_{\Lambda\Lambda}\mathrm{H}\right) < \Delta B_{\Lambda\Lambda}\left({}^{5}_{\Lambda\Lambda}\mathrm{He}\right)$$

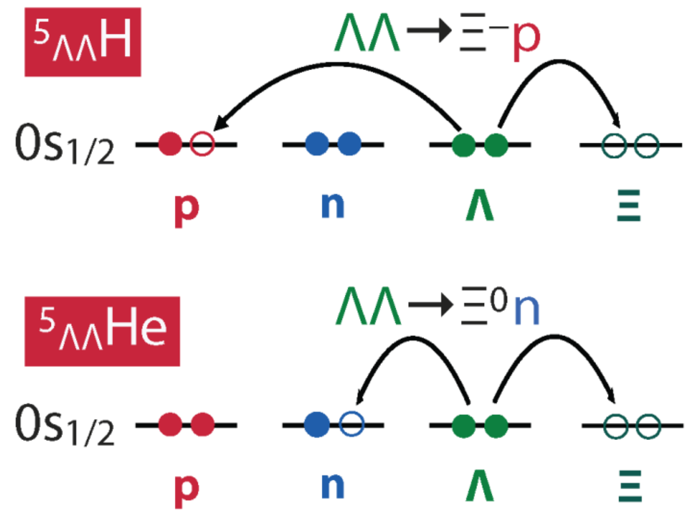


$m_{\Xi^-} - m_{\Xi^0}$ = 6,85 ± 0,21 MeV (PDG 2024)

Double-strangeness hypernuclei

D. E. LANSKOY AND Y. YAMAMOTO PRC **69**, 014303 (2004)





$m_{\Xi^-} - m_{\Xi^0}$ = 6,85 ± 0,21 MeV (PDG 2024)

Five-baryons wave function:

$$\left|{}^{5}_{\Lambda\Lambda}\mathrm{H}\right\rangle = \alpha_1\left|\,{}^{3}\mathrm{H}\otimes\Lambda\Lambda\right\rangle + \beta_1\left|\,{}^{4}\mathrm{He}\otimes\Xi^{-}p\right\rangle$$

$$\left|{}^{5}_{\Lambda\Lambda}\mathrm{He}\right\rangle = \alpha_2\left|\,{}^{3}\mathrm{He}\otimes\Lambda\Lambda\right\rangle + \beta_2\left|\,{}^{4}\mathrm{He}\otimes\Xi^{0}n\right\rangle$$

$$P_{\Xi} = \beta^2$$

FIG. 1. $\Delta B_{\Lambda\Lambda}$ (a) and Ξ admixture probabilities p_{Ξ} (b) as functions of volume integral $\int V_{\Lambda\Lambda,\,\Xi\alpha}\, d^3r$ in $_{\Lambda\Lambda}{}^{5}$H and $_{\Lambda\Lambda}{}^{5}$He for Ξα Isle-type potentials and the Isle-type Λ-core potentials.

Nuclear Instruments and Methods in Physics Research A 1073 (2025) 170196

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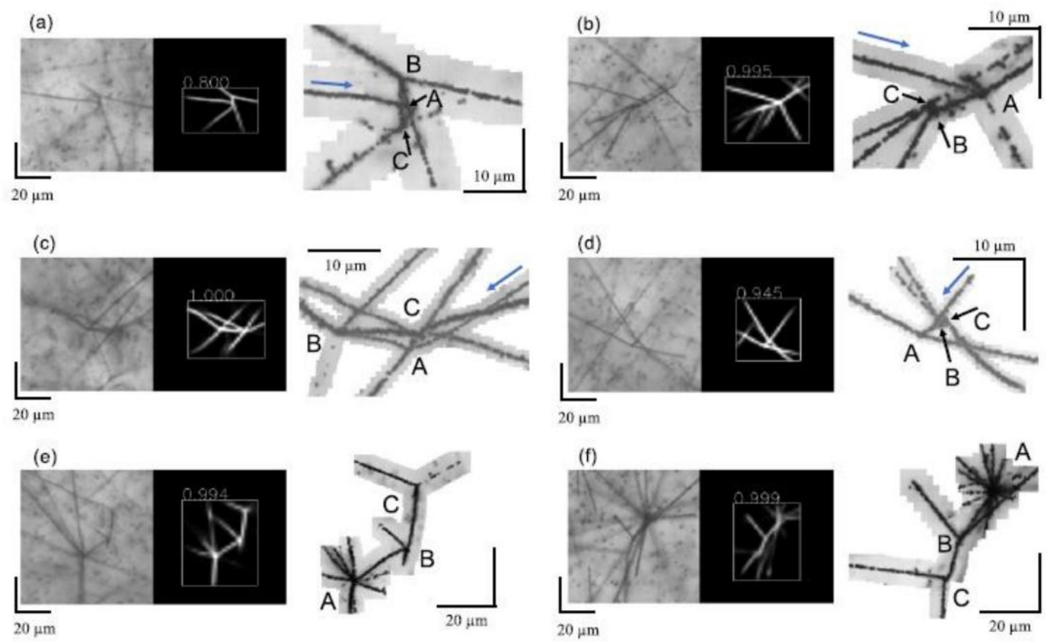
Full Length Article

A novel application of machine learning to detect double-Λ hypernuclear events in nuclear emulsions

Yan He [a,b,*], Vasyl Drozd [b,c], Hiroyuki Ekawa [b], Samuel Escrig [b,d], Yiming Gao [b,e,f], Ayumi Kasagi [b,g], Enqiang Liu [b,e,f], Abdul Muneem [b], Manami Nakagawa [b], Kazuma Nakazawa [b,h], Christophe Rappold [d], Nami Saito [b], Takehiko R. Saito [a,b,i,j], Shohei Sugimoto [b,j], Masato Taki [g], Yoshiki K. Tanaka [b], He Wang [b,e,f], Ayari Yanai [b,j], Junya Yoshida [b,k], Hongfei Zhang [a,l]



ML for ΛΛ

Conclusions

- Hypernuclei remain the main source of information on hyperonic interactions (but: density is proportional to nuclear one, nuclear cores are from valley of stability)
- Extending the hypernuclear map up to drip-lines provides data on fine interaction features (density dependence, CSB and so on)
- Information on ΛΛ, ΞN and ΣN interactions is very much needed – we are waiting for data on the corresponding hypernuclei
- New player in the experiment: Heavy Ion collisions – data on the lightest systems (the clearest information on interactions)

THANK YOU FOR YOUR ATTENTION!

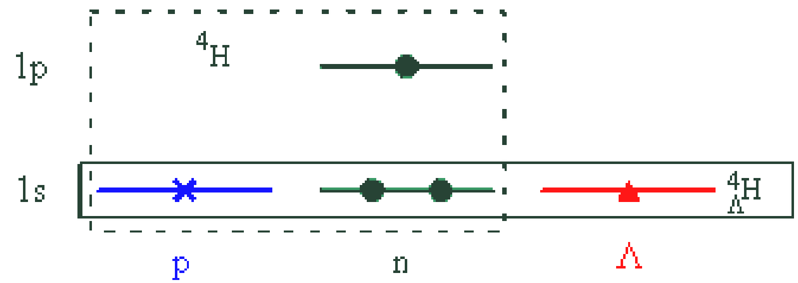
Back-up

Notation

$^{A}_{\Lambda}Z$

- A: Total number of baryons (nucleon & hyperon)
- Z: Total charge
- Λ: hyperon (other examples -- Σ, Ξ, ...)

- Some examples:
  1. $3p + 3n + 1\Lambda \rightarrow {}^{7}_{\Lambda}\text{Li}$
  2. $2p + 2n + 2\Lambda \rightarrow {}^{6}_{\Lambda\Lambda}\text{He}$
  3. $1p + 2n + 1\Sigma^{+}$
     $2p + 1n + 1\Sigma^{0}$
     $3p + 0n + 1\Sigma^{-}$
     $\Big\} \rightarrow {}^{4}_{\Sigma}\text{He}$

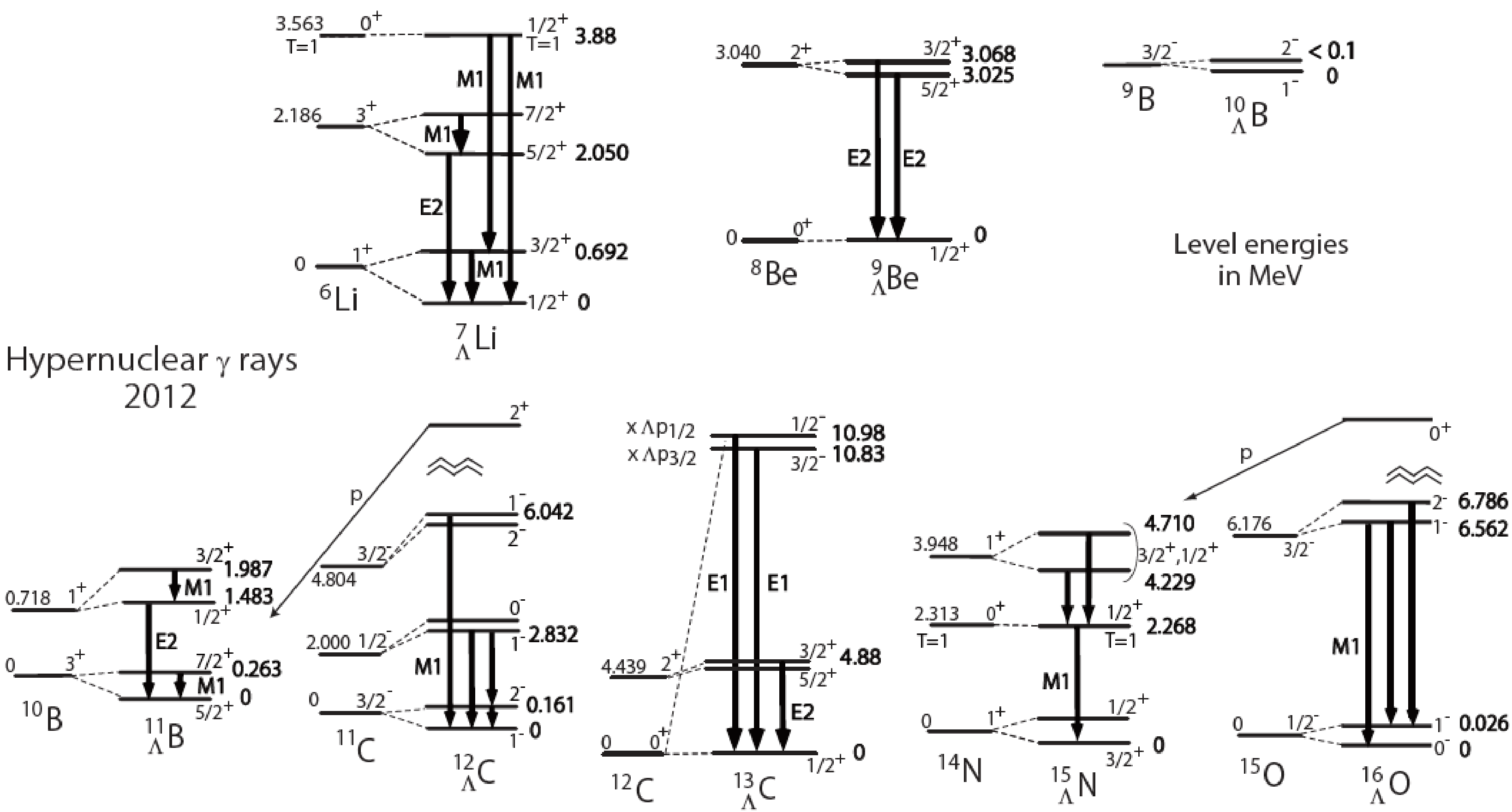


$$\text{L} \rightarrow pN + (\sim 40\ \text{MeV})$$

$$\text{L}N \rightarrow NN + 176\ \text{MeV}$$

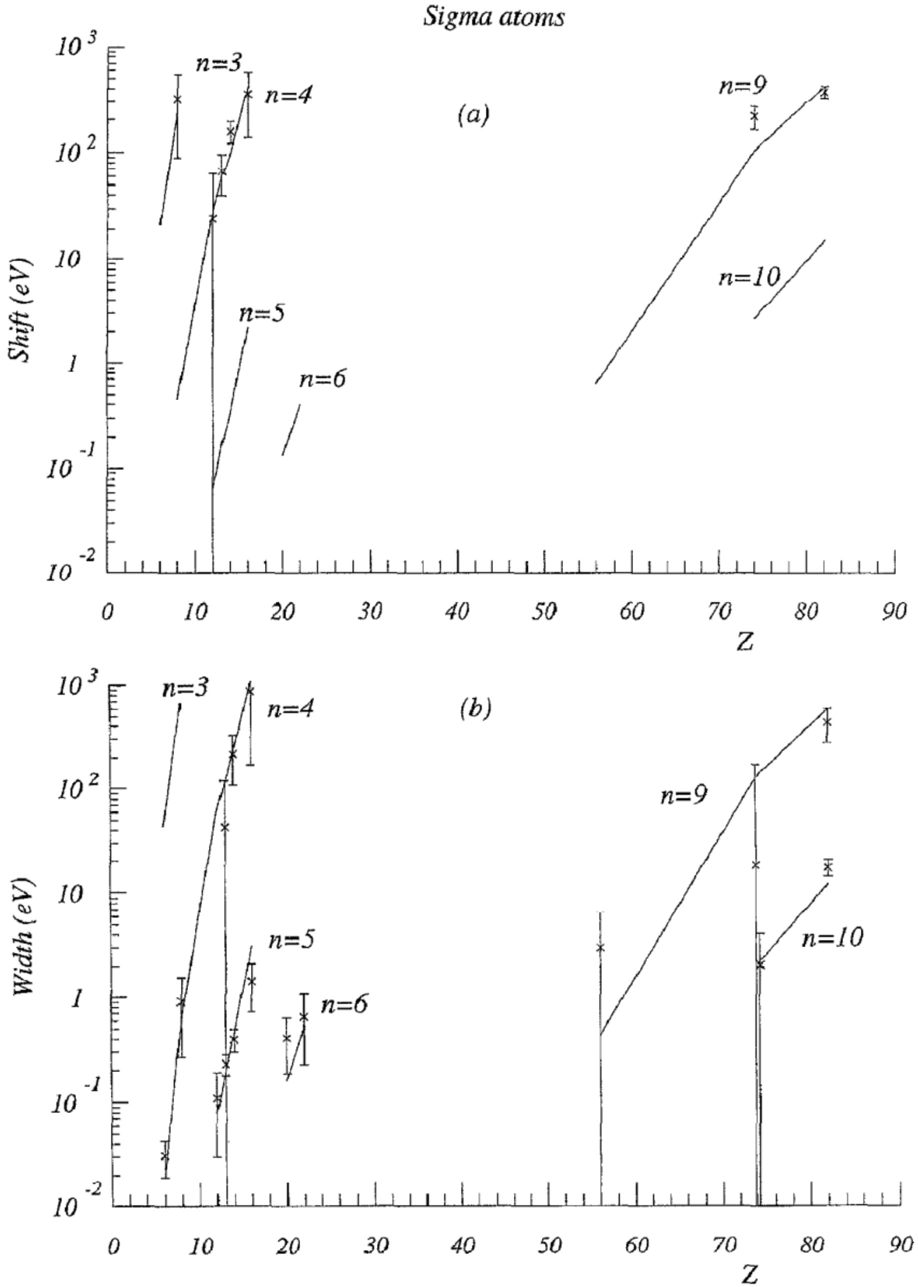
Λ-hypernuclei

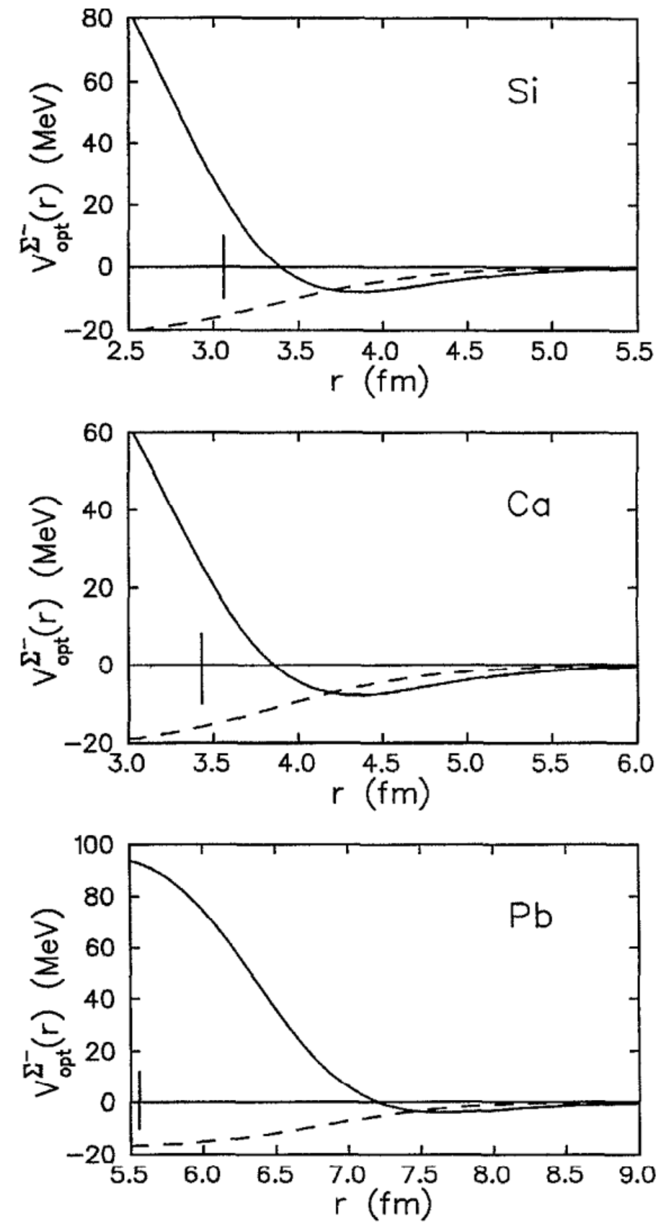
Λ spin-orbit splitting (keV): 150 in ${}^{13}_{\Lambda}$C & related 43 in ${}^{9}_{\Lambda}$Be



H. Tamura, in HandBook in Nuclear Physics. Springer 2023

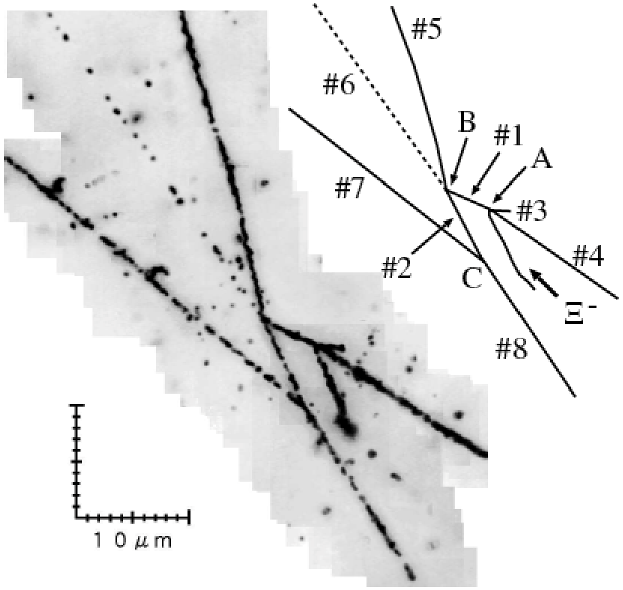
Σ^- Atoms





Batty, Friedman, Gal Phys Rep 287(1997)385

Double-strangeness hypernuclei



Nagara event, $^{\;\;6}_{\Lambda\Lambda}$He, (KEK-E373) PRL 87 (2001) 212502

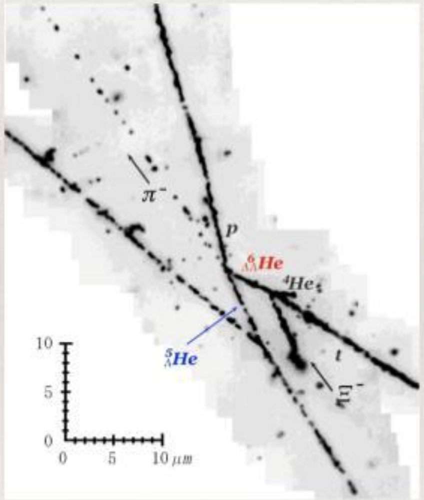
$B_{\Lambda\Lambda}(^{\;\;6}_{\Lambda\Lambda}\mathrm{He}_{g.s.})$**=6.91±0.16 MeV, unambiguously determined.**

- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \to {}^{\;\;6}_{\Lambda\Lambda}\mathrm{He} + t + \alpha$
- **B:** **weak decay** ${}^{\;\;6}_{\Lambda\Lambda}\mathrm{He} \to {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$ **(no** ${}^{\;\;6}_{\Lambda\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + H$**)**
- **C:** ${}^{5}_{\Lambda}\mathrm{He}$ **nonmesic weak decay to 2** Z**=1 recoils + n.**

Double-strangeness hypernuclei

KEK E373

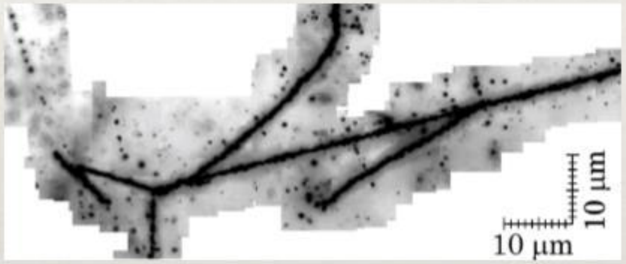
- “Nagara” event; $_{\Lambda\Lambda}{}^{6}He$
  - $\Delta B_{\Lambda\Lambda}$=0.67±0.17 MeV



J.K. Ahn et al., PRC 88 (2013) 014003.

KEK E373

- “Kiso” event; Ξ^{-}-^{14}N
  - $\Xi^{-}+{}^{14}N \rightarrow {}^{10}{}_{\Lambda}Be+{}^{5}{}_{\Lambda}He$



K. Nakazawa et al., PTEP (2015) 033D02

- B_{Ξ}=1.03 or 3.87 MeV $\pm\Gamma/2$
  - *Well beyond the atomic binding of 0.17 MeV*

Tools to access n-rich Λ hypernuclei

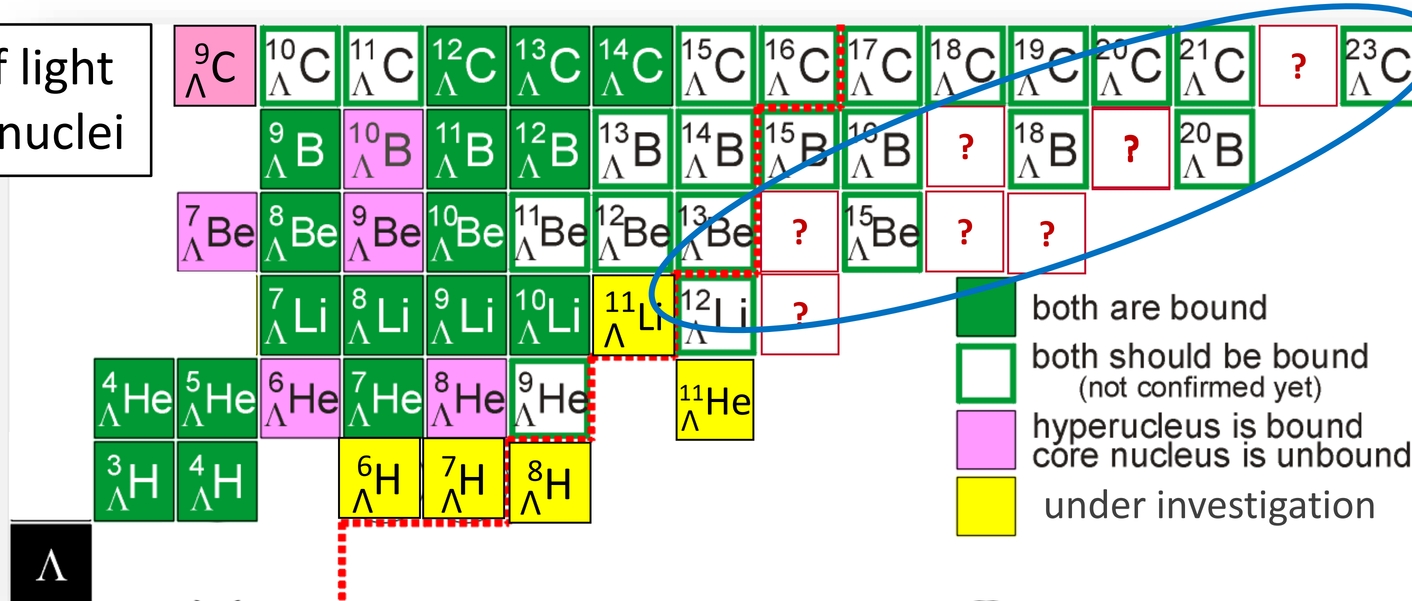
heavy-ion collisions vs meson- and electron- induced reaction

- Old emulsion experiments with stopped-K^- beams
  - Hypernuclear species were limited and yield was low
- **Charge-exchange reactions**
  - SCX: $(e,e'K^+)$, (K^-, π^0) DCX: (π^-,K^+), (K^-,π^+)
- **Relativistic heavy-ion collisions**

SCX: Single Charge-eXchange
DCX: Double Charge-eXchange

L. Majling, Nucl. Phys. A585 (1995) 211c

Chart of light Λ hypernuclei

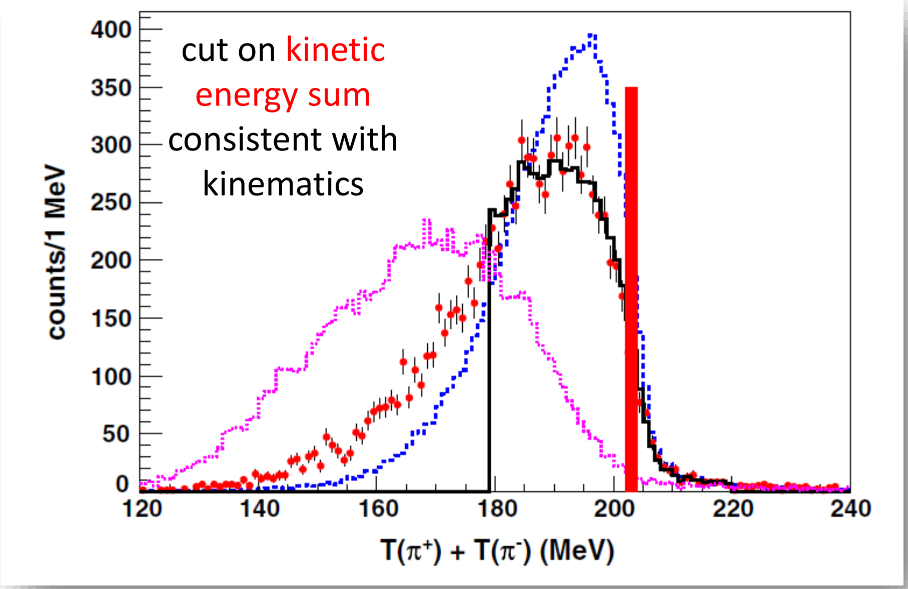


Neutron-rich hypernuclei

Study by using DCX reaction: $^{6}_{\Lambda}$H (1)

- **FINUDA**: M. Agnello et al. PRL 108 (2012) 042501
  - Study of the ^{6}Li(K^{-}_{stop},π^{+}) reaction

$$^{6}\mathrm{Li}(K^{-}_{\mathrm{stop}},\pi^{+})^{6}_{\Lambda}\mathrm{H} \qquad ^{6}_{\Lambda}\mathrm{H}\rightarrow{}^{6}\mathrm{He}+\pi^{-}$$



$$B_{\Lambda}(^{6}_{\Lambda}\mathrm{H}) = (4.0 \pm 1.1)\mathrm{MeV}$$

  - Reported 3 candidate events of $^{6}_{\Lambda}$H production

$$\mathrm{BR}(\mathrm{DCX},{}^{6}_{\Lambda}\mathrm{H})/\mathrm{BR}(\mathrm{NCX},{}^{12}_{\Lambda}\mathrm{C}) \approx 6\times10^{-3}$$

$$\mathrm{BR}(\mathrm{DCX},{}^{6}_{\Lambda}\mathrm{H})/\mathrm{BR}(\mathrm{NCX},{}^{4}_{\Lambda}\mathrm{He}) \approx 3\times10^{-4}$$

Neutron-rich hypernuclei

Study by using DCX reaction: $^{6}_{\Lambda}H$ (2)

- **J-PARC-E10:** H. Sugimura et al., PLB 729 (2014) 39
  - Missing-mass spectrum of the $^{6}Li(\pi^{-},K^{+})$ reaction

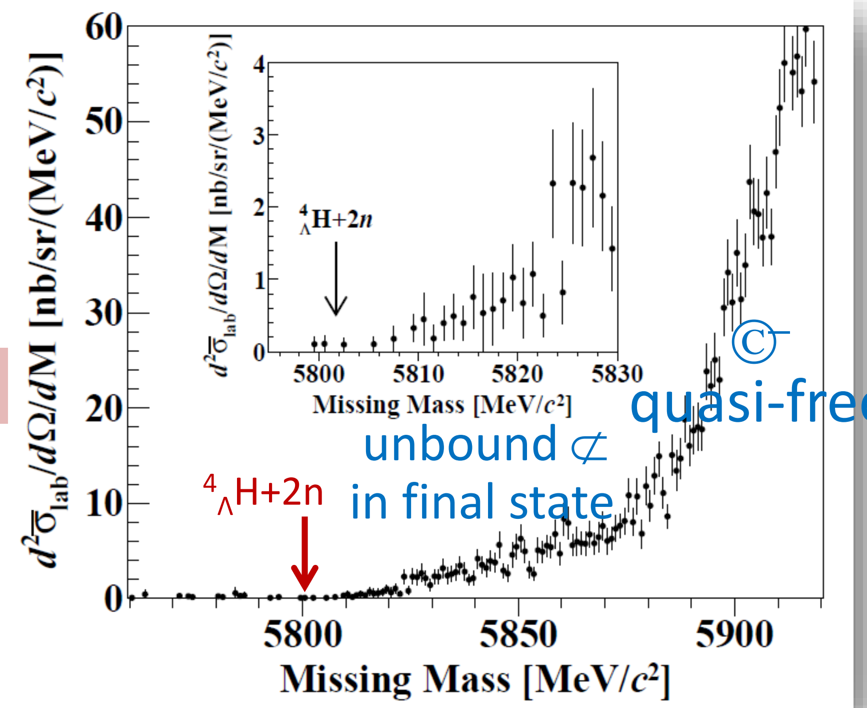
No clear peak of $^{6}_{\Lambda}H$ production in threshold region

cross section is extremely smaller than it was expected

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}) \Big/ \frac{d\sigma}{d\Omega}(\mathrm{NCX}) < 1.5\times10^{-4}$$

DCX: (π^{-},K^{+}) NCX: (π^{+},K^{+}) for $^{12}_{\Lambda}C$

$^{6}Li(\pi^{-},K^{+})X$
θ_{LAB}=2-14 deg.

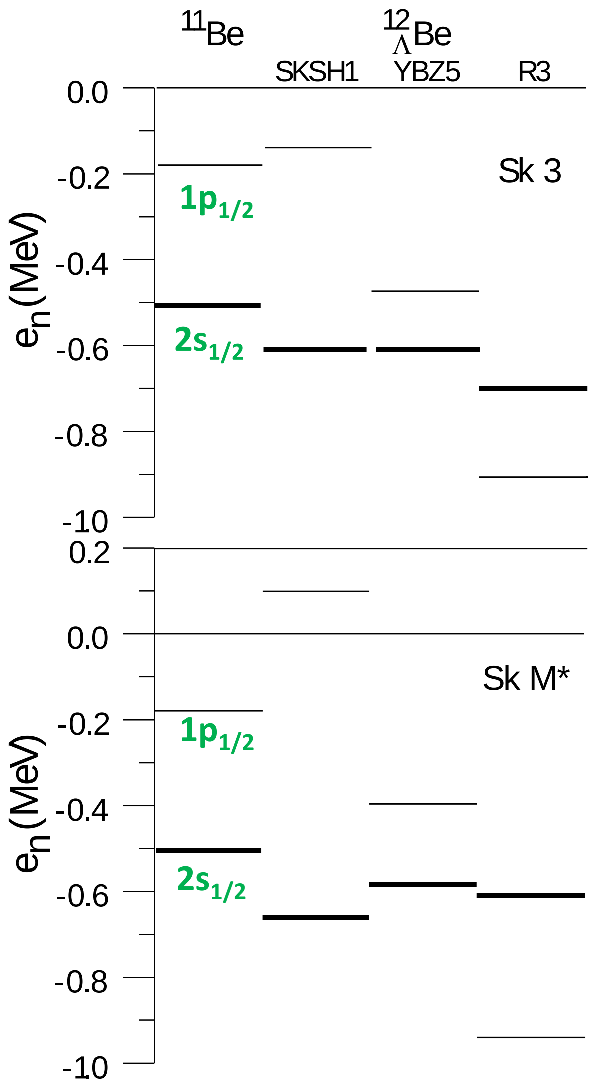


A. Sakaguchi, HYP-XII, 2015

Neutron-rich hypernuclei

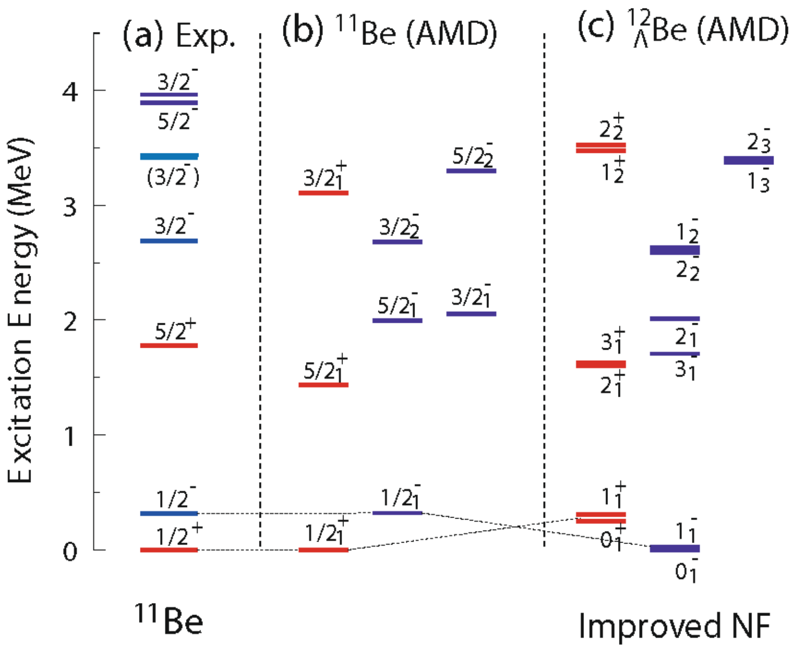
Structure 12Be-L
SkHF, AMD

Tretyakova, Lanskoy EPJ A 5, 391 (1999)



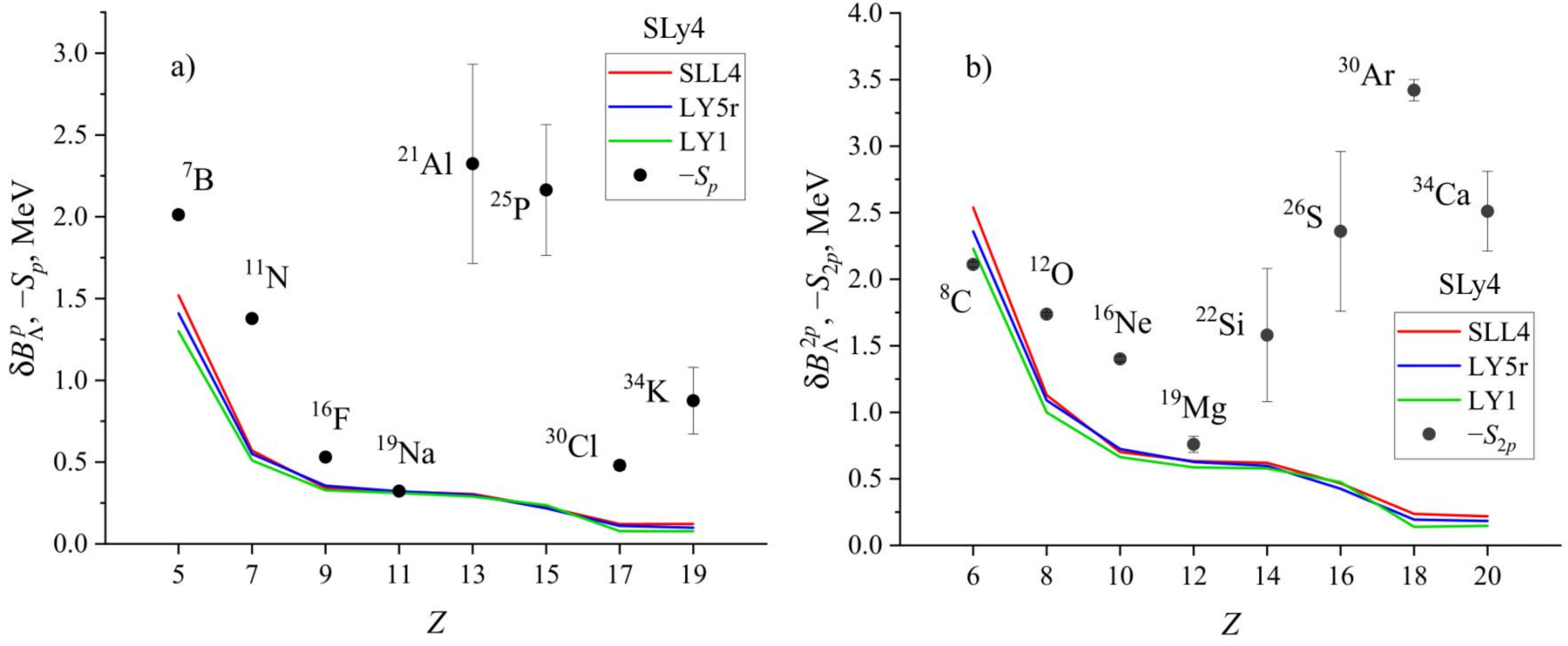
$^{12}{}_{\Lambda}$Be : I=3/2

Parity inversion in ^{11}Be. Ground state is $1/2^+$ instead for $1/2^-$. What's happening in $^{12}{}_{\Lambda}$Be? Measurement of low-lying 0^-, 1^-, 0^+ and 1^+ states may be possible.



Isaka et al, FBS 2013

Proton-rich Λ hypernuclei



Lanskoy, Sidorov, Tretyakova EPJ A. 2022