Stability of Light Exotic Λ-hypernuclei with Unstable Cores

S.V. SIDOROV[1,2,3], D.E. LANSKOY[1], T.YU. TRETYAKOVA[1,2,3]

[1] Faculty of Physics, Moscow State University, Moscow, Russia
[2] Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[3] Joint Institute for Nuclear Research, Dubna, Russia

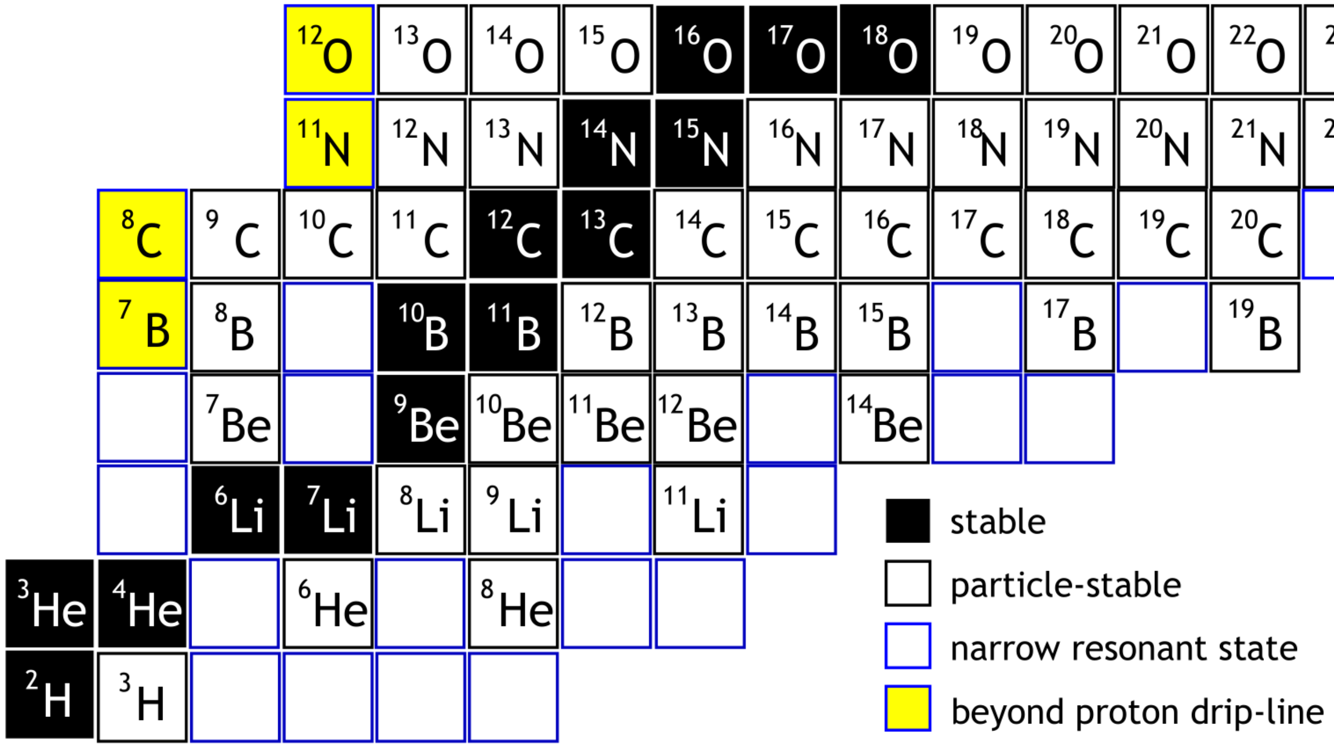
SEPTEMBER 20, 2021

Motivation:

New experimental capabilities for production of exotic hypernuclei in heavy ion collisions

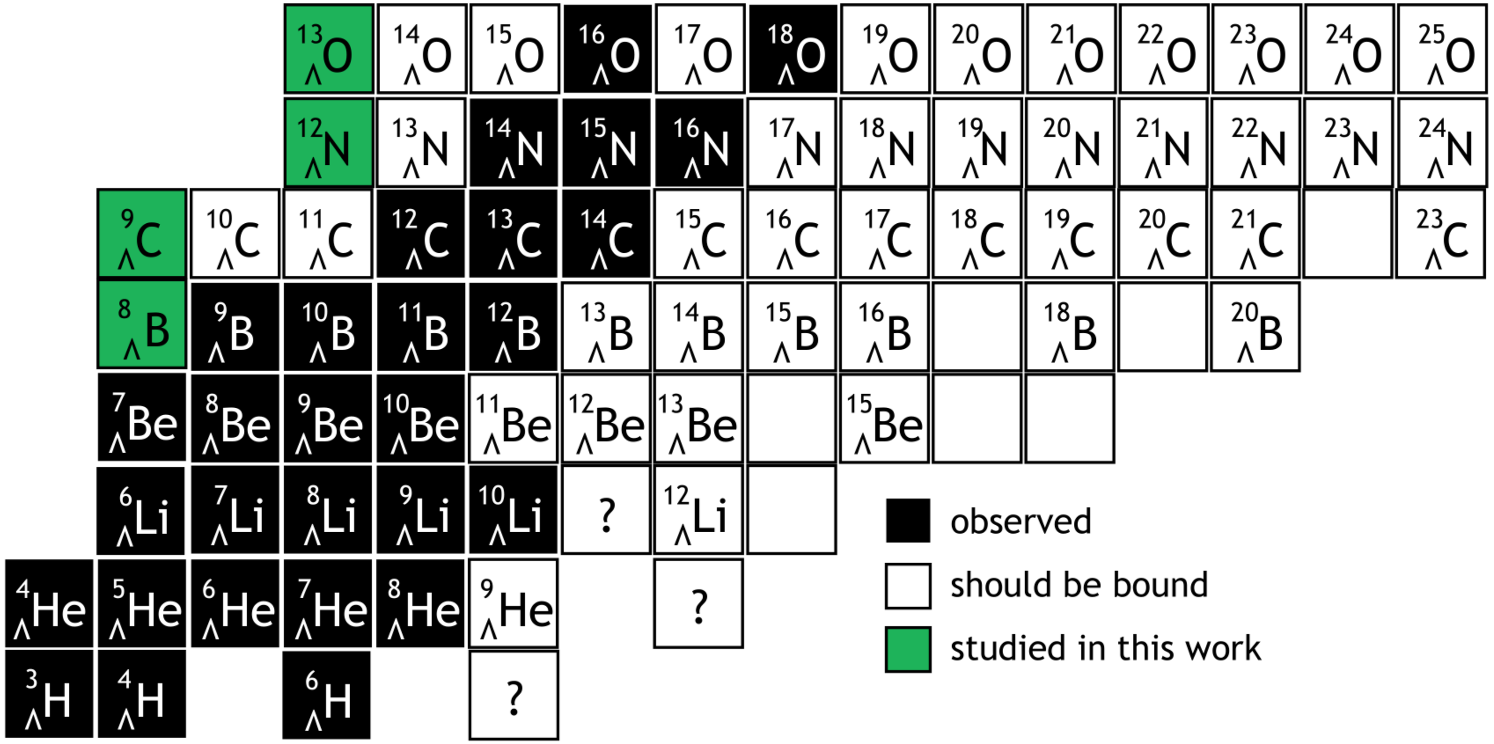
Goals:

- Predictions for hypernuclei with unbound nucleon cores
- Location of proton dripline on the hypernuclear chart for $5 \leq Z \leq 8$



Hypernuclear chart

- Particle stability of a nuclear core guarantees stable Λ hypernuclei
- Λ-hyperon may reinforce the nuclear binding
- Glue-like role of Λ-hyperon: the hyperon can stabilize an unbound core



Skyrme-Hartree-Fock approach for hypernuclei

- Nucleon-nucleon Skyrme potential (Vautherin and Brink, 1972):

$$V_{NN}(\boldsymbol{r_1},\boldsymbol{r_2}) = t_0(1+x_0P_\sigma)\delta(\boldsymbol{r_{12}}) + \frac{1}{2}t_1(1+x_1P_\sigma)(\boldsymbol{k}'^2\delta(\boldsymbol{r_{12}}) + \delta(\boldsymbol{r_{12}})\boldsymbol{k}^2)$$
$$+t_2(1+x_2P_\sigma)\boldsymbol{k}'\delta(\boldsymbol{r_{12}})\boldsymbol{k} + \frac{1}{6}t_3\rho^\alpha(\boldsymbol{R})(1+x_3P_\sigma)\delta(\boldsymbol{r_{12}}) + iW(\sigma_1+\sigma_2)[\boldsymbol{k}'\times\delta(\boldsymbol{r})\boldsymbol{k}]$$

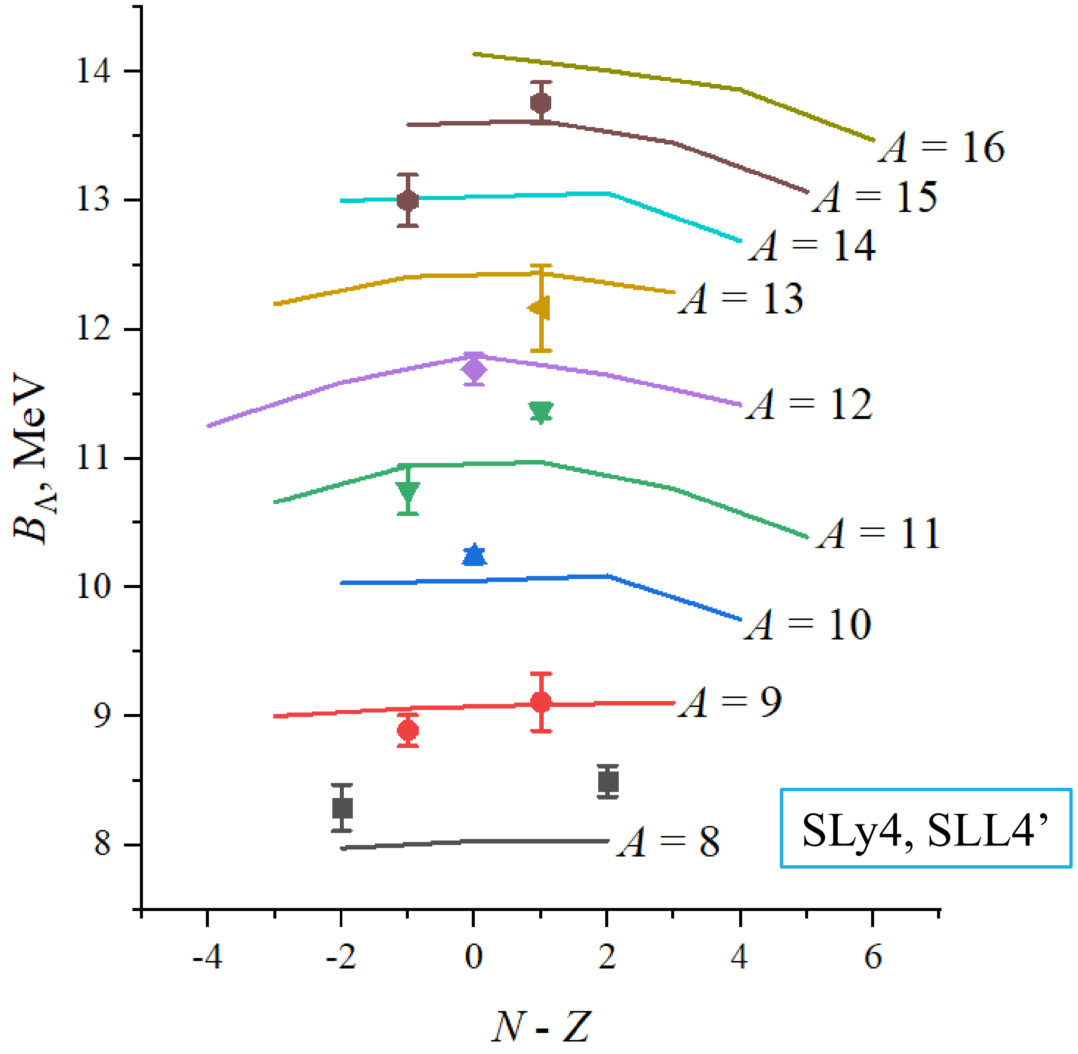
NN: SLy4, SkM*, SkIII

- Hyperon-nucleon Skyrme potential (Rayet, 1981):

$$V_{\Lambda N}(\boldsymbol{r_\Lambda},\boldsymbol{r_q}) = t_0^\Lambda(1+x_0^\Lambda P_\sigma)\delta(\boldsymbol{r_{\Lambda q}}) + \frac{1}{2}t_1^\Lambda(\boldsymbol{k}^2\delta(\boldsymbol{r_{\Lambda q}}) + \delta(\boldsymbol{r_{\Lambda q}})\boldsymbol{k}'^2)$$
$$+t_2^\Lambda\boldsymbol{k}'\delta(\boldsymbol{r_{\Lambda q}})\boldsymbol{k} + \frac{1}{6}t_3^\Lambda\rho^\alpha(\boldsymbol{R})\delta(\boldsymbol{r_{\Lambda q}})$$

ΛN: SLL4, SLL4’ (Schulze and Hiyama, 2014), YBZ5 (Yamamoto et al, 1988), LY1 (Lanskoy and Yamamoto, 1997), LY5r (Zhang et al, 2021), SkSH1 (Fernandez et al, 1989)

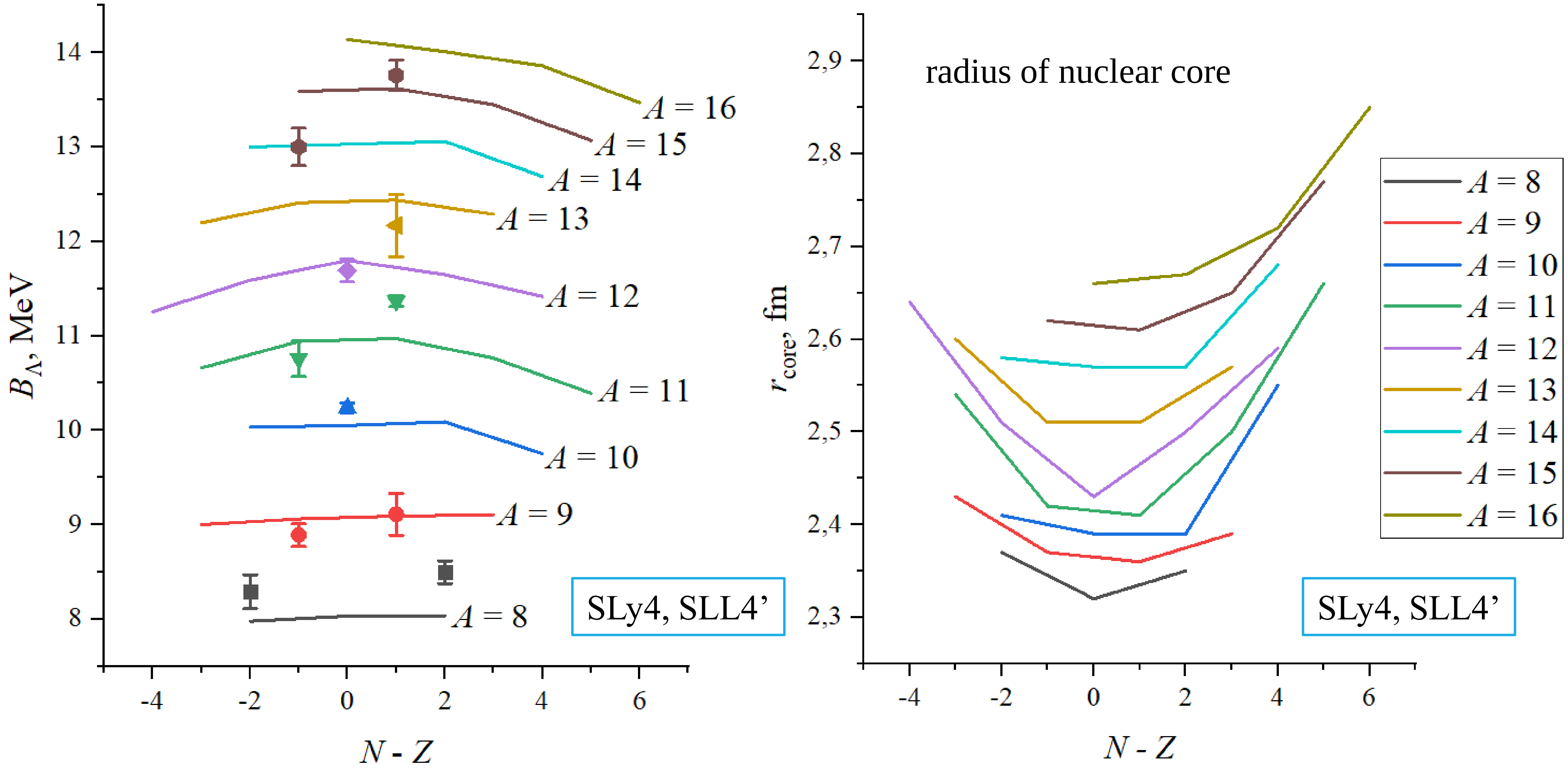
Hyperon binding energies in ${}^{A+1}_{\Lambda}Z$ hypernuclei



$$B_\Lambda({}^{A+1}_{\Lambda}Z) = B_{tot}({}^{A+1}_{\Lambda}Z) - B_{tot}({}^{A}Z)$$

- The difference in neighboring isobar chains is around 1 MeV for lighter hypernuclei, smaller as A increases
- Symmetric character of B_Λ with respect to isospin $N - Z$

Hyperon binding energies and radii of nuclear cores in ${}^{A+1}_{\Lambda}Z$ hypernuclei



Hypernuclei near the proton dripline

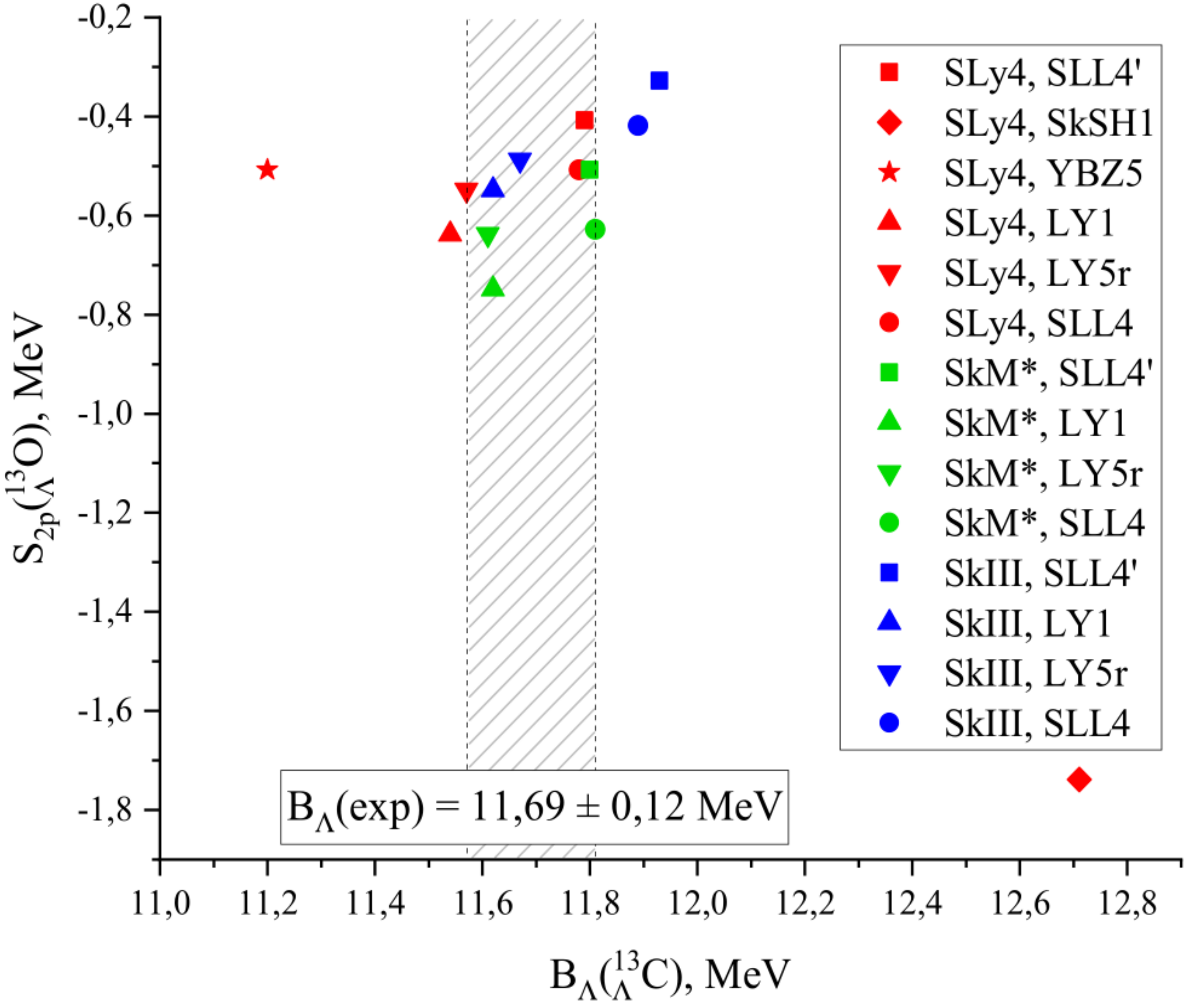
While we do not claim outright that hypernuclear HF approach gives precise predictions for proton (or two-proton) separation energies of hypernuclei, we set the following idea as the cornerstone of our method: hypernuclear HF allows to reproduce the hyperon binding energy B_Λ in light Λ-hypernuclei. Proton (two proton) separation energy S_p (S_{2p}) can then be found using the relation:

$$S_p\left({}^A_\Lambda Z\right) = S_p\left({}^{A-1}Z\right) + B_\Lambda\left({}^A_\Lambda Z\right) - B_\Lambda\left({}^{A-1}_{\Lambda}(Z-1)\right),$$
$$S_{2p}\left({}^A_\Lambda Z\right) = S_{2p}\left({}^{A-1}Z\right) + B_\Lambda\left({}^A_\Lambda Z\right) - B_\Lambda\left({}^{A-2}_{\Lambda}(Z-2)\right).$$

and experimental data for $S_p\left({}^A Z\right)$ and $S_{2p}\left({}^A Z\right)$.

Here, $S_p\left({}^{A-1}Z\right)$ or $S_{2p}\left({}^{A-1}Z\right)$ is always taken from experiment, while B_Λ is calculated within HF approach when there are no experimental data available. Comparison between calculated values and experimental data on B_Λ in neighbouring nuclei can be used to verify the accuracy of our estimates for S_p (or S_{2p}) in proton-rich hypernuclei.

2p separation energy in ${}^{13}_{\Lambda}\mathrm{O}$



${}^{12}\mathrm{O}$ is unstable with respect to 2 proton decay $\left(S_{2p}({}^{12}\mathrm{O}) = -1{,}638\ \mathrm{MeV}\right)$, and ${}^{13}_{\Lambda}\mathrm{O}$ is expected to decay similarly. On the left hand side we show

$$S_{2p}({}^{13}_{\Lambda}\mathrm{O}) = S_{2p}({}^{12}\mathrm{O}) + B_{\Lambda}({}^{13}_{\Lambda}\mathrm{O}) - B_{\Lambda}({}^{11}_{\Lambda}\mathrm{C})$$

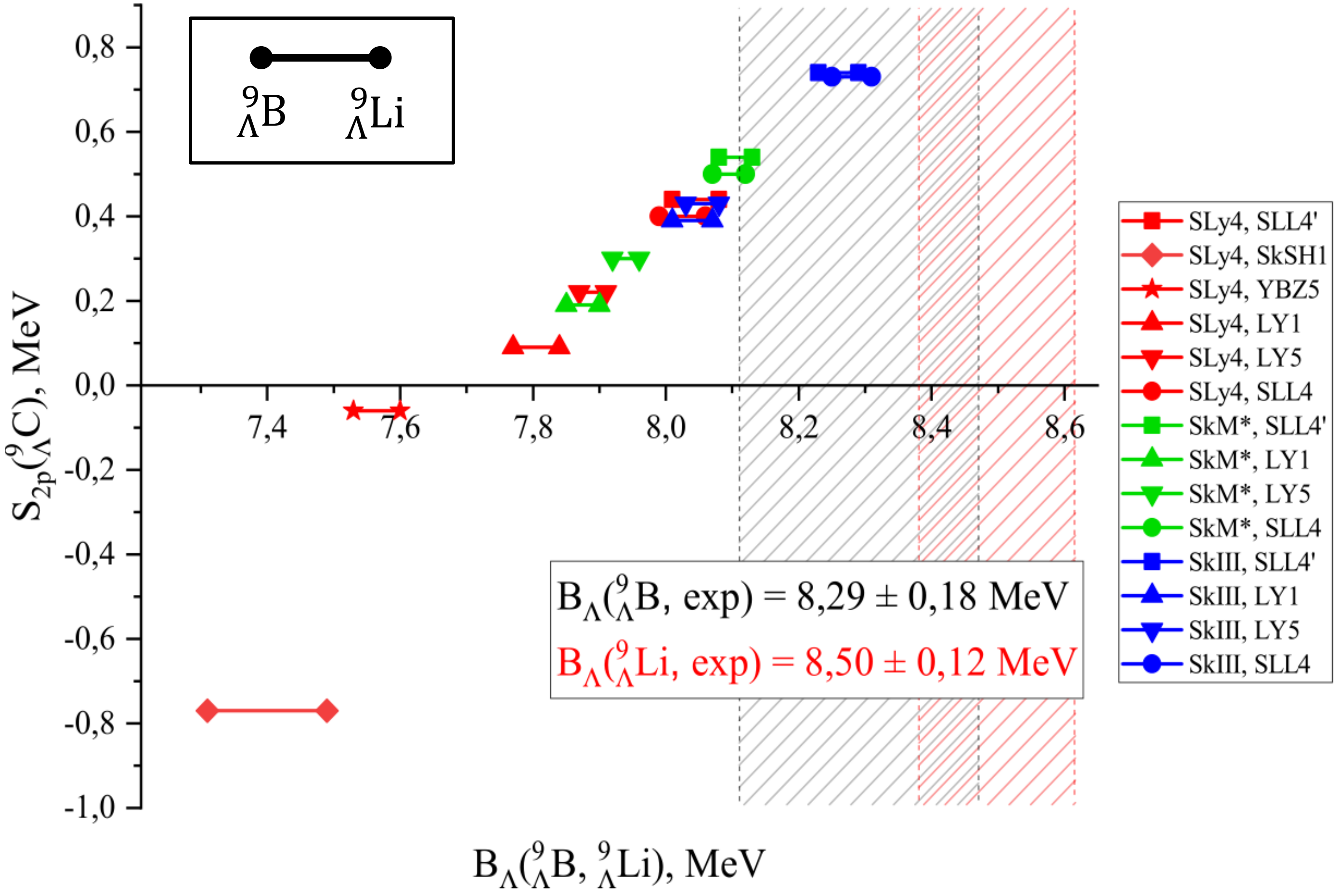
exp — calc

as a function of $B_{\Lambda}({}^{13}_{\Lambda}\mathrm{C})$ for different NN and ΛN Skyrme interactions. Most of the results are in good agreement with the experimental hyperon binding energy in ${}^{13}_{\Lambda}\mathrm{C}$.

${}^{13}_{\Lambda}\mathrm{O}$ is unbound

${}^{8}_{\Lambda}\mathrm{B}$, ${}^{12}_{\Lambda}\mathrm{N}$ are also unbound

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



While ^{8}C decays primarily by emitting 4 protons, $^{9}_{\Lambda}$C has 2 proton decay as critical decay mode, with bound $^{7}_{\Lambda}$Be as a daughter hypernucleus. On the left hand side we show

calc

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

exp (-2.14 MeV) exp (5.16 MeV)

as a function of B_Λ in $^{9}_{\Lambda}$B and $^{9}_{\Lambda}$Li for different NN and ΛN Skyrme interactions. The better $B_\Lambda(^{9}_{\Lambda}\mathrm{B})$ and $B_\Lambda(^{9}_{\Lambda}\mathrm{Li})$ are described, the stronger is the two-proton binding in $^{9}_{\Lambda}$C, indicating that $S_{2p}(^{9}_{\Lambda}\mathrm{C}) > 0$.

$^{9}_{\Lambda}$C is bound!

Skyrme ΛΛ-interaction for double-Λ hypernuclei

Due to glue-like role of Λ-hyperon, there is a chance to stabilize the hypernuclei ${}^{8}_{\Lambda}\mathrm{B}$, ${}^{12}_{\Lambda}\mathrm{N}$ and ${}^{13}_{\Lambda}\mathrm{O}$ by adding yet another Λ-hyperon. ΛΛ-interaction then needs to be taken into account

- Hyperon-hyperon Skyrme potential:

$$V_{\Lambda\Lambda}(\boldsymbol{r_1},\boldsymbol{r_2}) = \lambda_0\delta(\boldsymbol{r_{12}}) + \frac{1}{2}\lambda_1(\boldsymbol{k}'^2\delta(\boldsymbol{r_{12}}) + \delta(\boldsymbol{r_{12}})\boldsymbol{k}^2) + \lambda_2\boldsymbol{k}'\delta(\boldsymbol{r_{12}})\boldsymbol{k}$$

ΛΛ: SΛΛ1’, SΛΛ3’ (Lanskoy, 1998, Minato and Hagino, 2011)

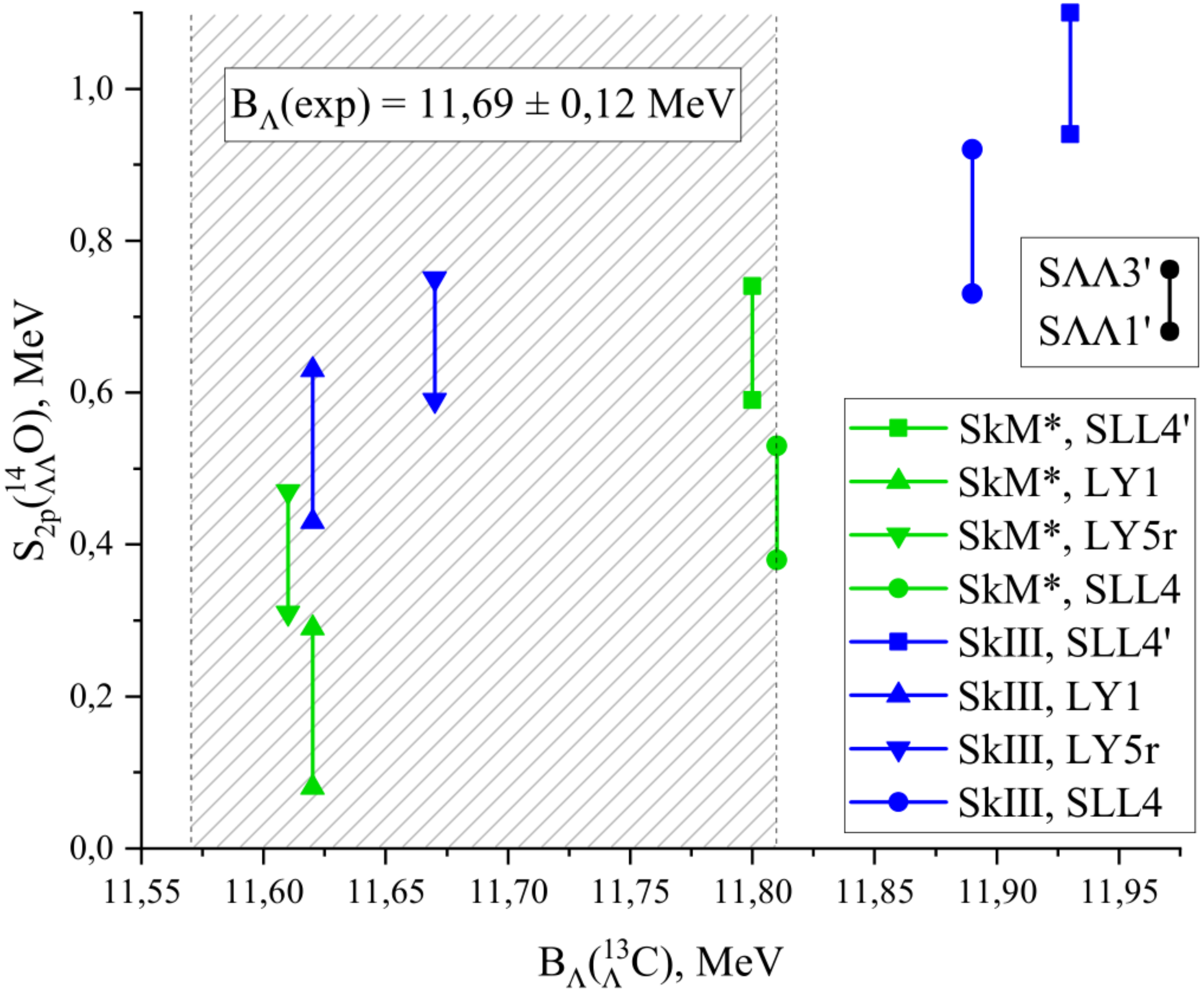
Proton (two proton) separation energy S_p (S_{2p}) can then be found using the relation:

$$S_p\left({}^{A}_{\Lambda\Lambda}Z\right) = S_p\left({}^{A-2}Z\right) + B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) - B_{\Lambda\Lambda}\left({}^{A-1}_{\Lambda\Lambda}(Z-1)\right),$$
$$S_{2p}\left({}^{A}_{\Lambda\Lambda}Z\right) = S_{2p}\left({}^{A-2}Z\right) + B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) - B_{\Lambda\Lambda}\left({}^{A-2}_{\Lambda\Lambda}(Z-2)\right);$$

Here, 2 hyperon binding energy is:

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

2p separation energy in ${}^{14}_{\Lambda\Lambda}\mathrm{O}$



exp

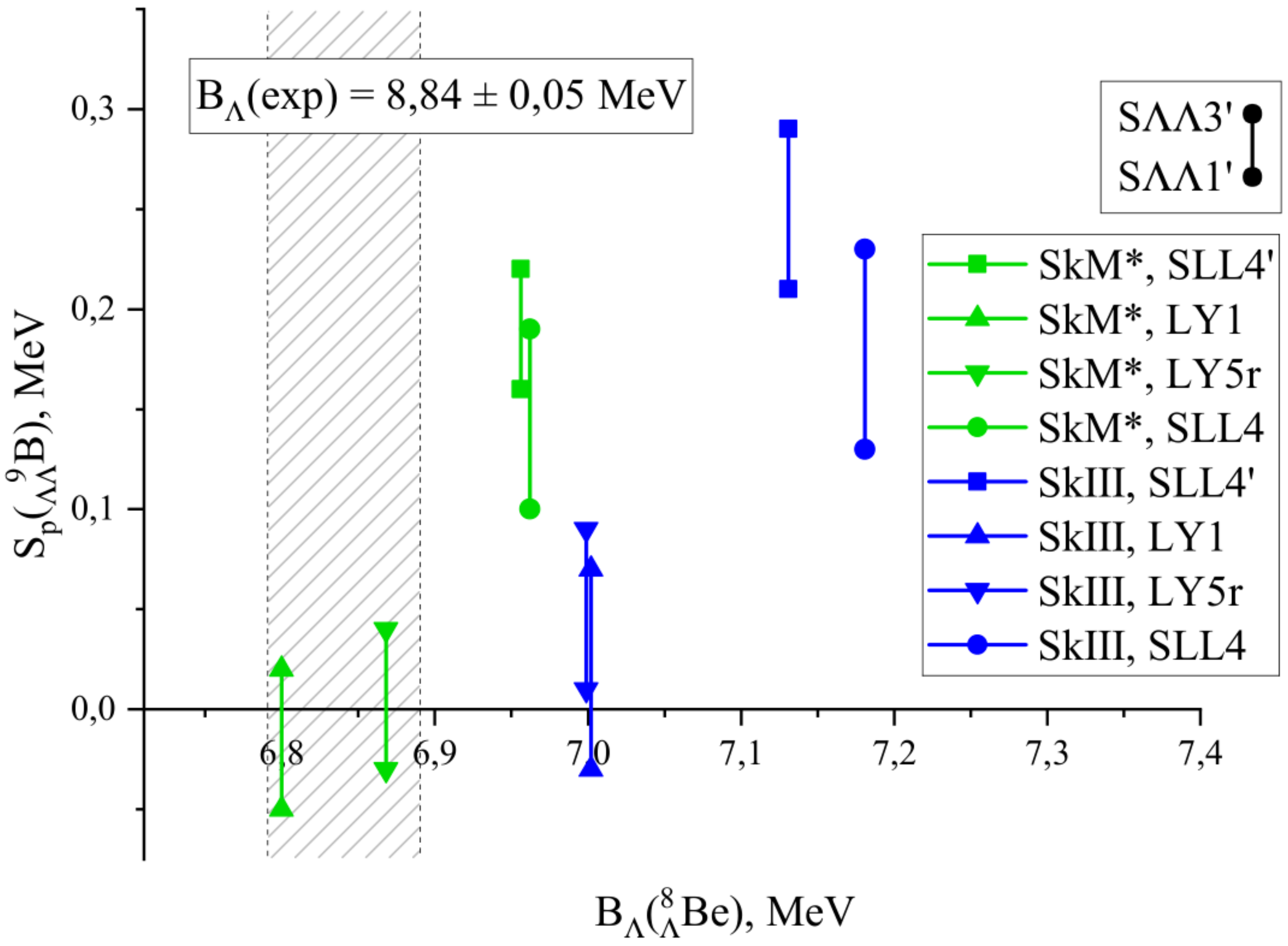
$$S_{2p}({}^{14}_{\Lambda\Lambda}\mathrm{O}) = S_{2p}({}^{12}\mathrm{O}) + B_{\Lambda\Lambda}({}^{14}_{\Lambda\Lambda}\mathrm{O}) - B_{\Lambda\Lambda}({}^{12}_{\Lambda\Lambda}\mathrm{C})$$

calc

as a function of $B_\Lambda({}^{13}_{\Lambda}\mathrm{C})$ for different NN and ΛN Skyrme interactions. Earlier we concluded ${}^{13}_{\Lambda}\mathrm{O}$ is unbound; addition of another hyperon stabilizes the hypernucleus.

${}^{14}_{\Lambda\Lambda}\mathrm{O}$ is bound!

Proton separation energy in $_{\Lambda\Lambda}^{9}B$



exp (-2.01 MeV)

$$S_p(_{\Lambda\Lambda}^{9}\mathrm{B}) = S_p(\,^7\mathrm{B})$$
$$+B_{\Lambda\Lambda}(_{\Lambda\Lambda}^{9}\mathrm{B}) - B_{\Lambda\Lambda}(_{\Lambda\Lambda}^{8}\mathrm{Be})$$

calc

as a function of $B_\Lambda(_\Lambda^8\mathrm{Be})$ for different NN and ΛN Skyrme interactions. While we concluded $_\Lambda^8$B is unbound,

$_{\Lambda\Lambda}^{9}$B is possibly bound.

Hypernucleus $_{\Lambda\Lambda}^{13}$N is found to be unbound.

Conclusions

Hypernuclear Hartree-Fock approach was utilized to study the properties of light proton-rich Λ-hypernuclei.

- Hyperon binding energy vs isospin dependence is more pronounced for the cases with more dramatic density changes, and the corresponding nuclei should be chosen as sources of information on ΛN interaction

- Among the studied hypernuclei:
  - $Z = 5$: ${}^{8}_{\Lambda}\mathrm{B}$ is unbound, ${}^{9}_{\Lambda\Lambda}\mathrm{B}$ could possibly be bound,
  - $Z = 6$: ${}^{9}_{\Lambda}\mathrm{C}$ is bound, therefore ${}^{10}_{\Lambda\Lambda}\mathrm{C}$ is also evidently bound,
  - $Z = 7$: ${}^{12}_{\Lambda}\mathrm{N}$ and ${}^{13}_{\Lambda\Lambda}\mathrm{N}$ are unbound,
  - $Z = 8$: ${}^{13}_{\Lambda}\mathrm{O}$ is unbound, while ${}^{14}_{\Lambda\Lambda}\mathrm{O}$ is bound.

Thank you for your attention