Light hypernuclei from cluster model approach

E. Hiyama (RIKEN)

(1) $^{4}He\,(e,e'K^{+})\,{}^{4}_{\Lambda}H$

(2) $^{4}He(\pi^{+},K^{+})\,{}^{4}_{\Lambda}He$

(3) $^{7}Li(e,\,e'K^{+})\,{}^{7}_{\Lambda}He$

(4) $^{10}B\,(e,\,e'K^{+})\,{}^{10}_{\Lambda}Be$

} Analysis is in progress.

(5) $^{10}B(\pi^{+},K^{+})\,{}^{10}_{\Lambda}B$

To measure the B_{Λ} within 100 keV accuracy

Major goals of hypernuclear physics

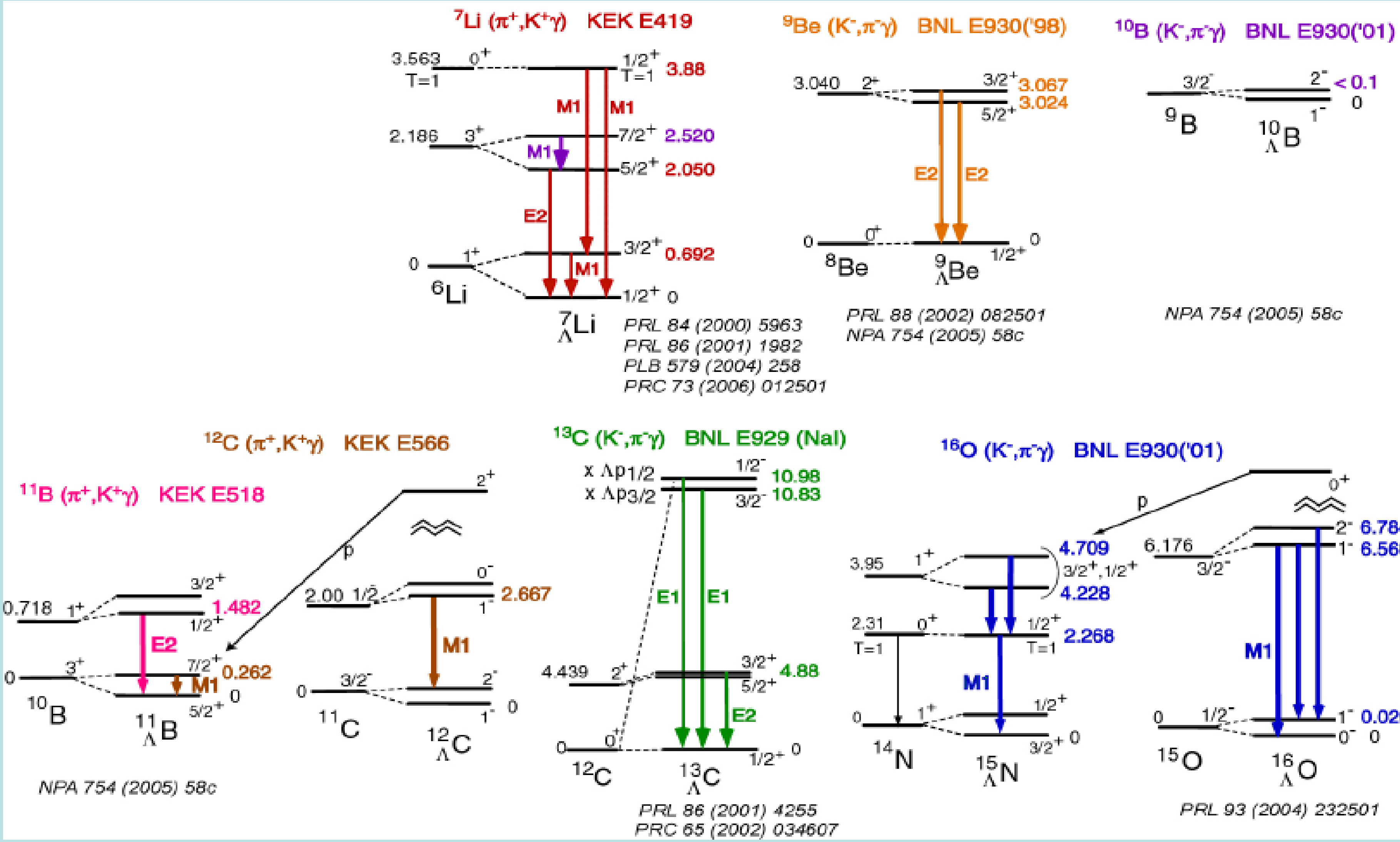
1) To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

2) To study the structure of multi-strangeness systems

Due to the difficulty of YN and YY 2-body scattering experiment
for the study of baryon-baryon interaction, the systematic investigation
of the structure of light hypernuclei is essential.

Hypernuclear γ-ray data since 1998



$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N) V_{\rm SLS} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N) V_{\rm ALS} + S_{12} V_{\rm tensor} + \cdots\cdots$$

- Millener (p-shell model),
- Hiyama (few-body)

ΛN interaction (effectively including ΛN -ΣN coupling)

$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N) V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N) V_{\mathrm{ALS}} + S_{12} V_{\mathrm{tensor}} + \cdots\cdots$$

Comparing the theoretical study using few-body technique and shell-model approach (done by Millener, Motoba) with the experimental results, we could succeed in extracting the information about ΛN interaction.

In S= -1 sector,
what are the open questions in YN interaction?

(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

J-PARC : Day-1 experiment

・E13 “γ-ray spectroscopy of light hypernuclei”
by Tamura and his collaborators

$^{11}_{\Lambda}B$ $^{4}_{\Lambda}He$

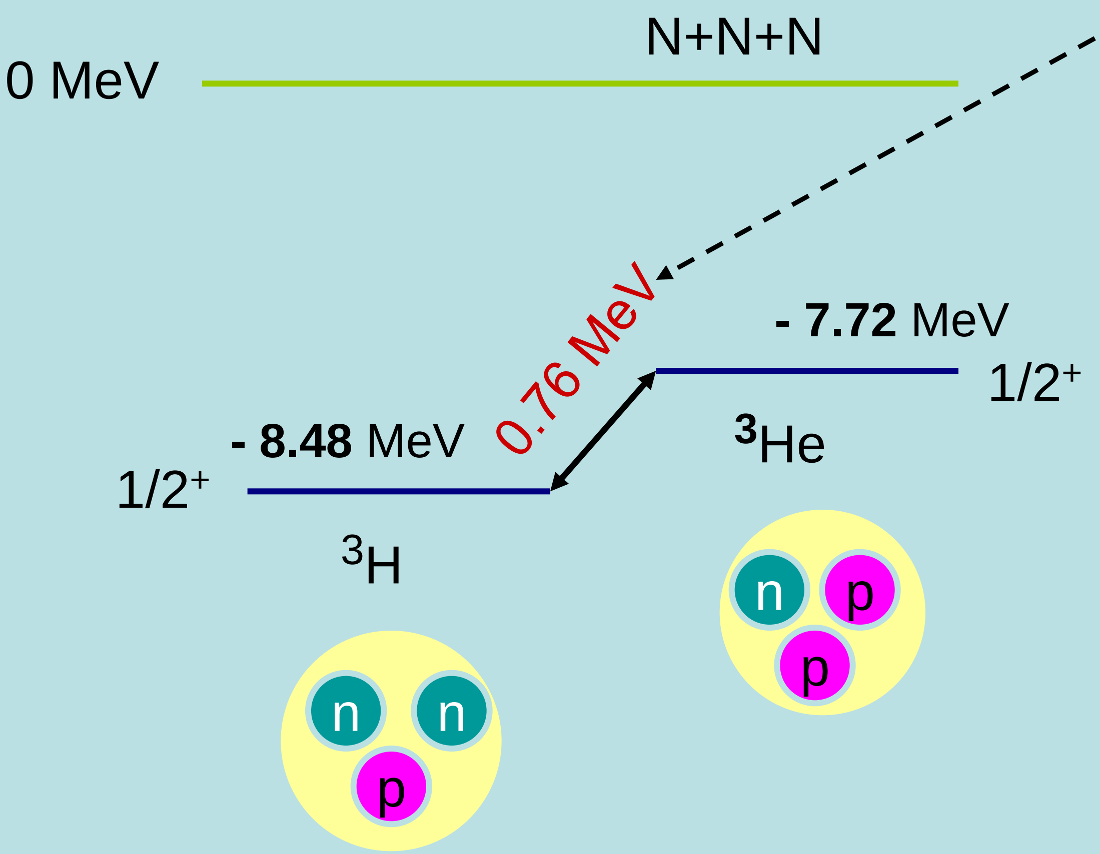
・E10 “Study on Λ-hypernuclei with the doubleCharge-Exchange reaction”
by Sakaguchi , Fukuda and his collaboratiors

$^{9}_{\Lambda}He$ $^{6}_{\Lambda}H$

(1) Charge Symmetry breaking

In S=0 sector

Exp.

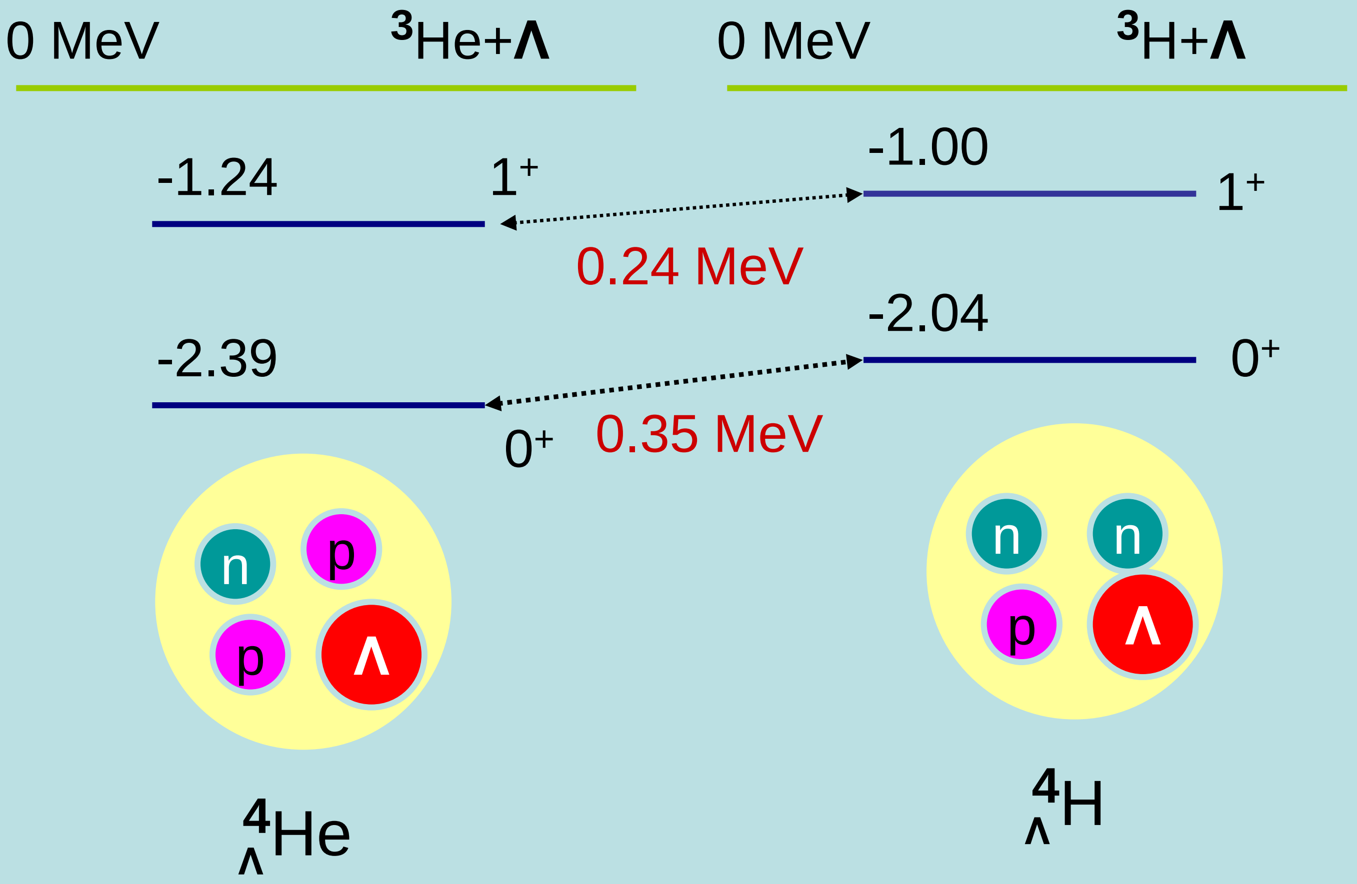


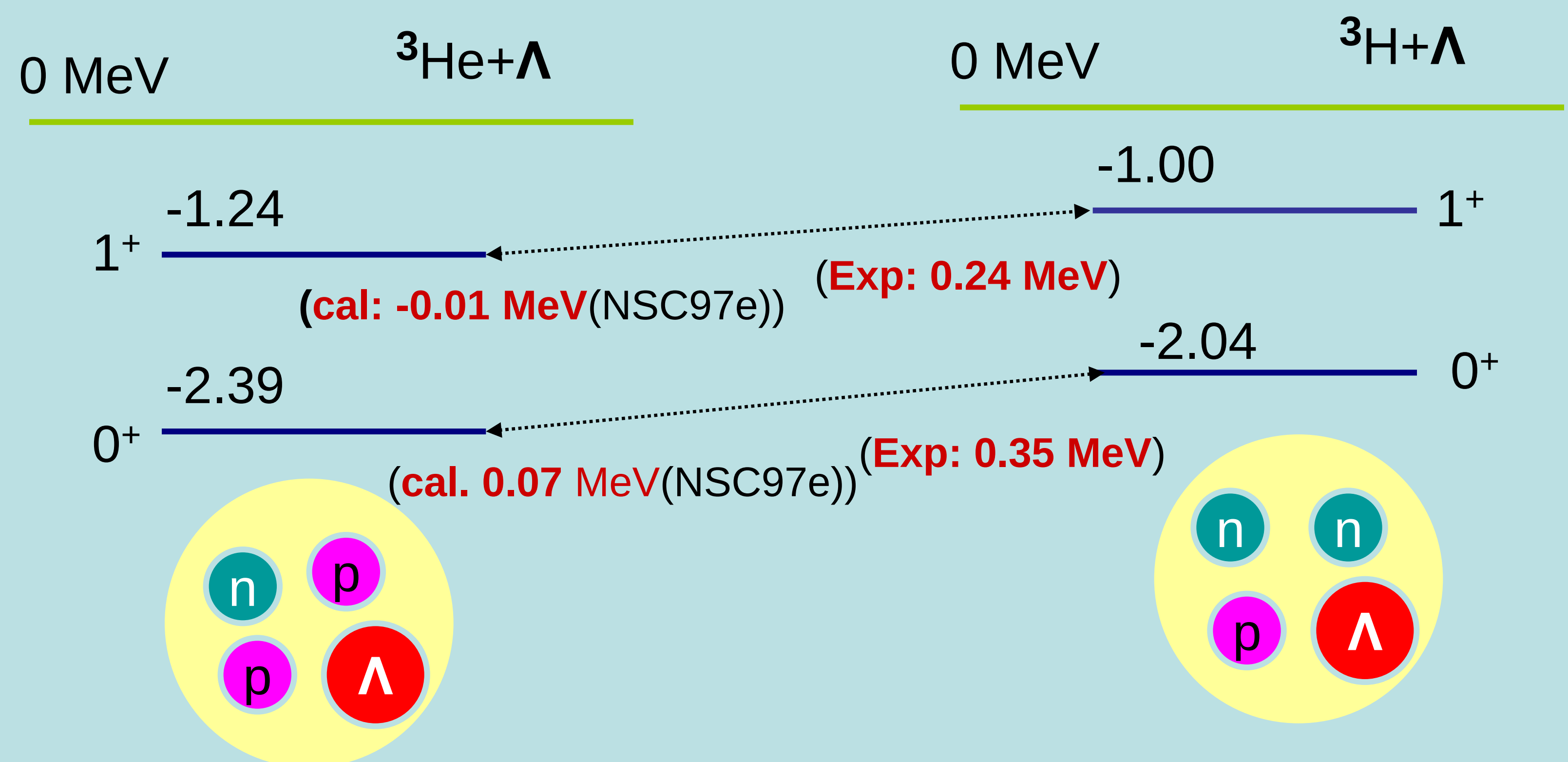
Energy difference comes from dominantly Coulomb force between 2 protons.

Charge symmetry breaking effect is small.

Charge Symmetry breaking

Exp.





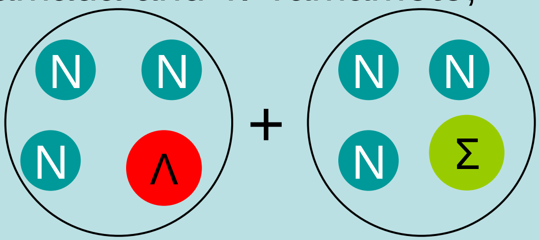
$^4_\Lambda$He

- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

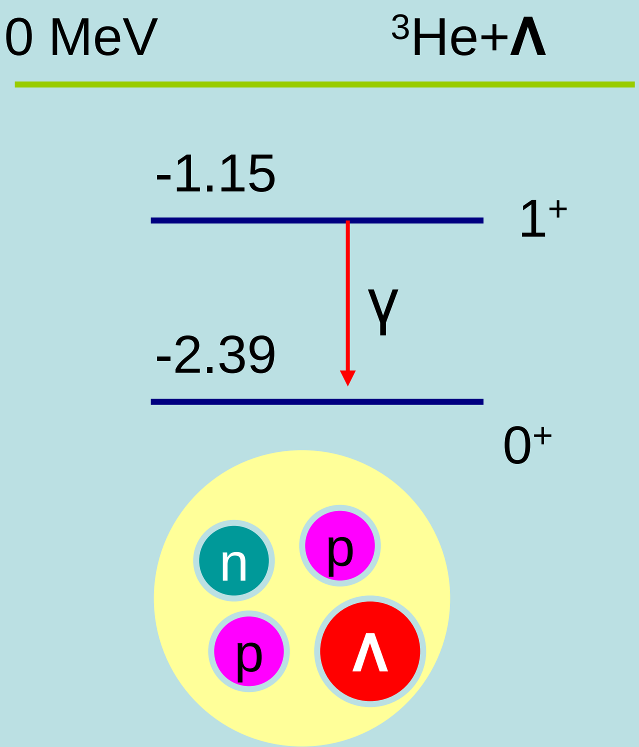
$^4_\Lambda$H

- E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. C65, 011301(R) (2001).

- H. Nemura. Y. Akaishi and Y. Suzuki, Phys. Rev. Lett.89, 142504 (2002).



Exp.



$^4_\Lambda$He

But, we need

B_Λ in $^4_\Lambda$He.

Recently, Tamura et al. pointed out that it is necessary to perform γ-ray experiment about this hypernucleus again .

“Because the measurement of this data was once reported in 1970’s.

At that time, the statistical quality of the $^4_\Lambda$He γ- ray spectrum was extremely poor ”

↓

J-PARC: Day-1 experiment

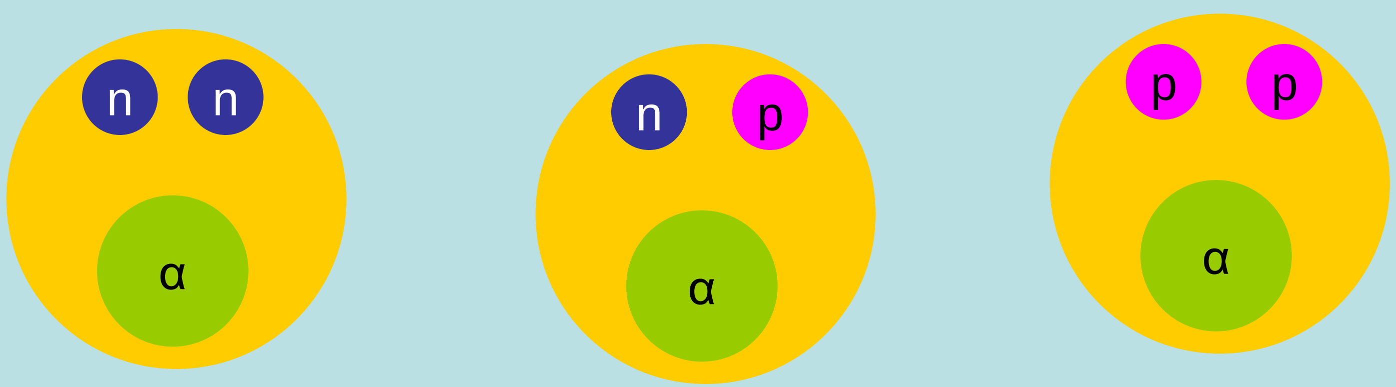
- E13 “γ-ray spectroscopy of light hypernuclei” by Tamura and his collaborators

We should wait for their data at J-PARC.

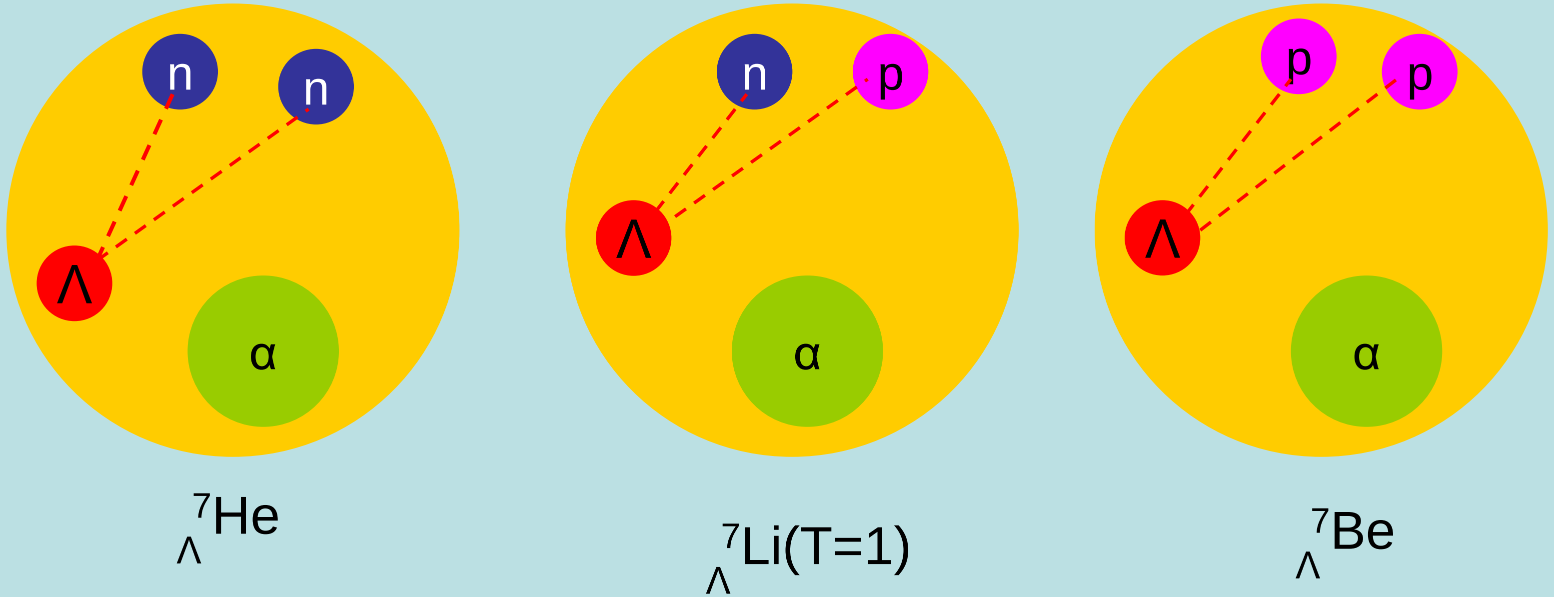
It is interesting to investigate the charge symmetry breaking effect in p-shell Λ hypernuclei as well as s-shell Λ hypernuclei.

For this purpose, to study structure of A=7 Λ hypernuclei is suited.

Because, core nuclei with A=6 are iso-triplet states.

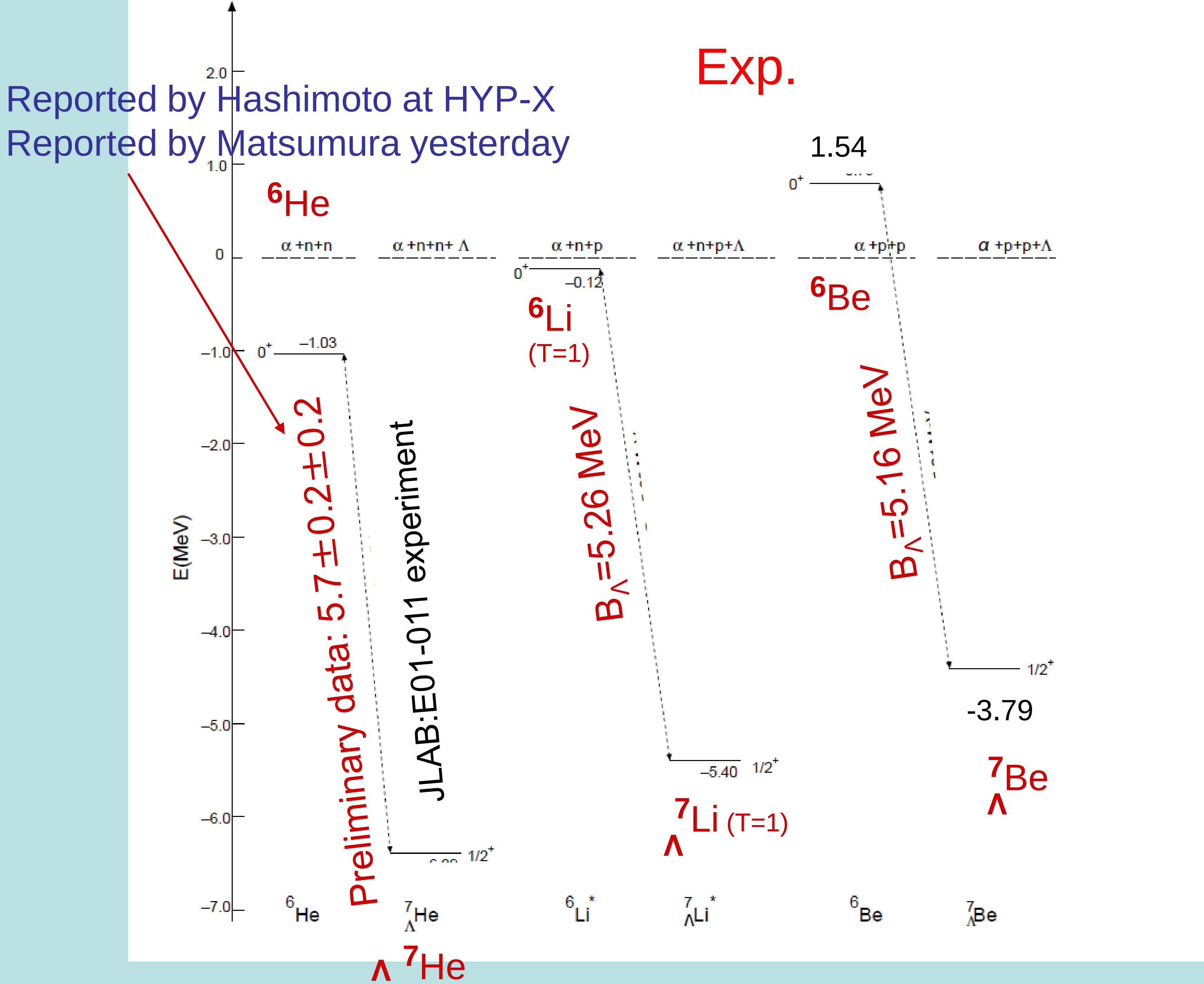


^{6}He　　^{6}Li(T=1)　　^{6}Be



Then, A=7 Λ hypernuclei are also iso-triplet states.

It is possible that CSB interaction between Λ and valence nucleons contribute to the Λ-binding energies in these hypernuclei.

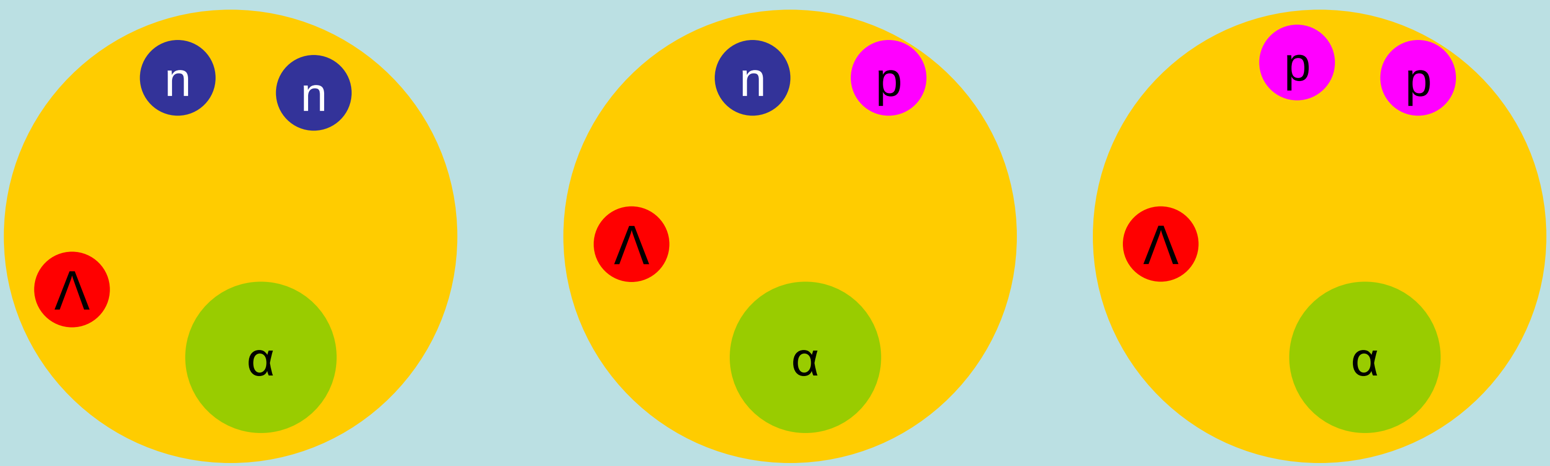


Exp.
Reported by Hashimoto at HYP-X
Reported by Matsumura yesterday
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
E(MeV)
6He
α +n+n
α +n+n+ Λ
α +n+p
α +n+p+Λ
α +p+p
α +p+p+Λ
0+
−1.03
1/2+
Preliminary data: 5.7±0.2±0.2
JLAB:E01-011 experiment
0+
−0.12
6Li
(T=1)
B_Λ=5.26 MeV
−5.40
1/2+
7Li (T=1)
Λ
1.54
0+
6Be
B_Λ=5.16 MeV
1/2+
-3.79
7Be
Λ
6He
7ΛHe
6Li*
7ΛLi*
6Be
7ΛBe
Λ 7He

Important issue:

To predict the Λ binding energy of $^{7}_{\Lambda}\mathrm{He}$ whose analysis is in progress at JLAB using ΛN interaction to reproduce the Λ binding energies of $^{7}_{\Lambda}\mathrm{Li}$ (T=1) and $^{7}_{\Lambda}\mathrm{Be}$

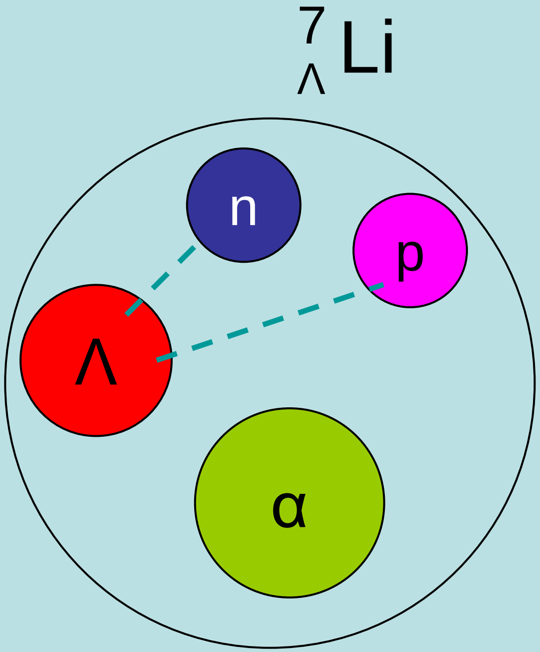
To study the effect of CSB in iso-triplet A=7 hypernuclei.



$^{7}_{\Lambda}\mathrm{He}$ $^{7}_{\Lambda}\mathrm{Li}$(T=1) $^{7}_{\Lambda}\mathrm{Be}$

For this purpose, we study structure of A=7 hypernuclei within the framework of α+Λ+N+N 4-body model.

E. Hiyama, Y. Yamamoto, T. Motoba and M. Kamimura,PRC80, 054321 (2009)



ΛN interaction: Nijmegen '97f

Not original one but simulated one

The ΛN-ΣN coupling interaction can be renomalized into the ΛN-ΛN interaction effectively.

$$V_{\Lambda N}=V_0+\sigma_\Lambda\cdot\sigma_N V_s+(\sigma_\Lambda+\sigma_N)/2\cdot V_{SLS}+(\sigma_\Lambda-\sigma_N)/2\cdot V_{ALS}$$

Made by Yamamoto so as to reproduce the phase shifts given by the original one

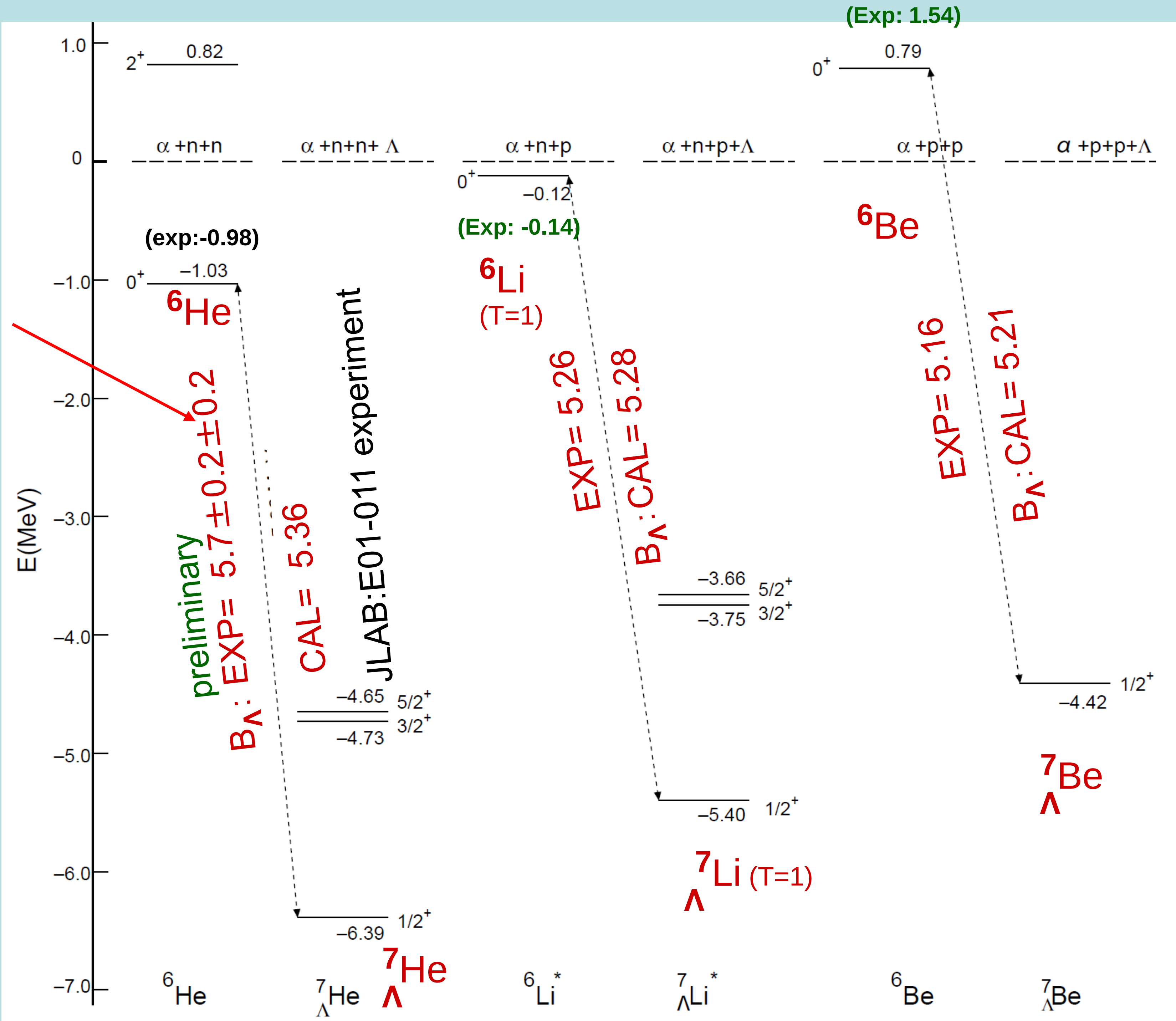
Strengths of V_s,V_{SLS},V_{ALS} are adjusted so as to reproduce of the observed data of $_{\Lambda}^{4}$H, $_{\Lambda}^{7}$Li(T=0), $_{\Lambda}^{9}$Be and $^{13}_{\Lambda}$C.

Now, it is interesting to see as follows:

(1)What is the level structure of A=7 hypernuclei without CSB interaction?

(2) What is the level structure of A=7 hypernuclei with CSB interaction?

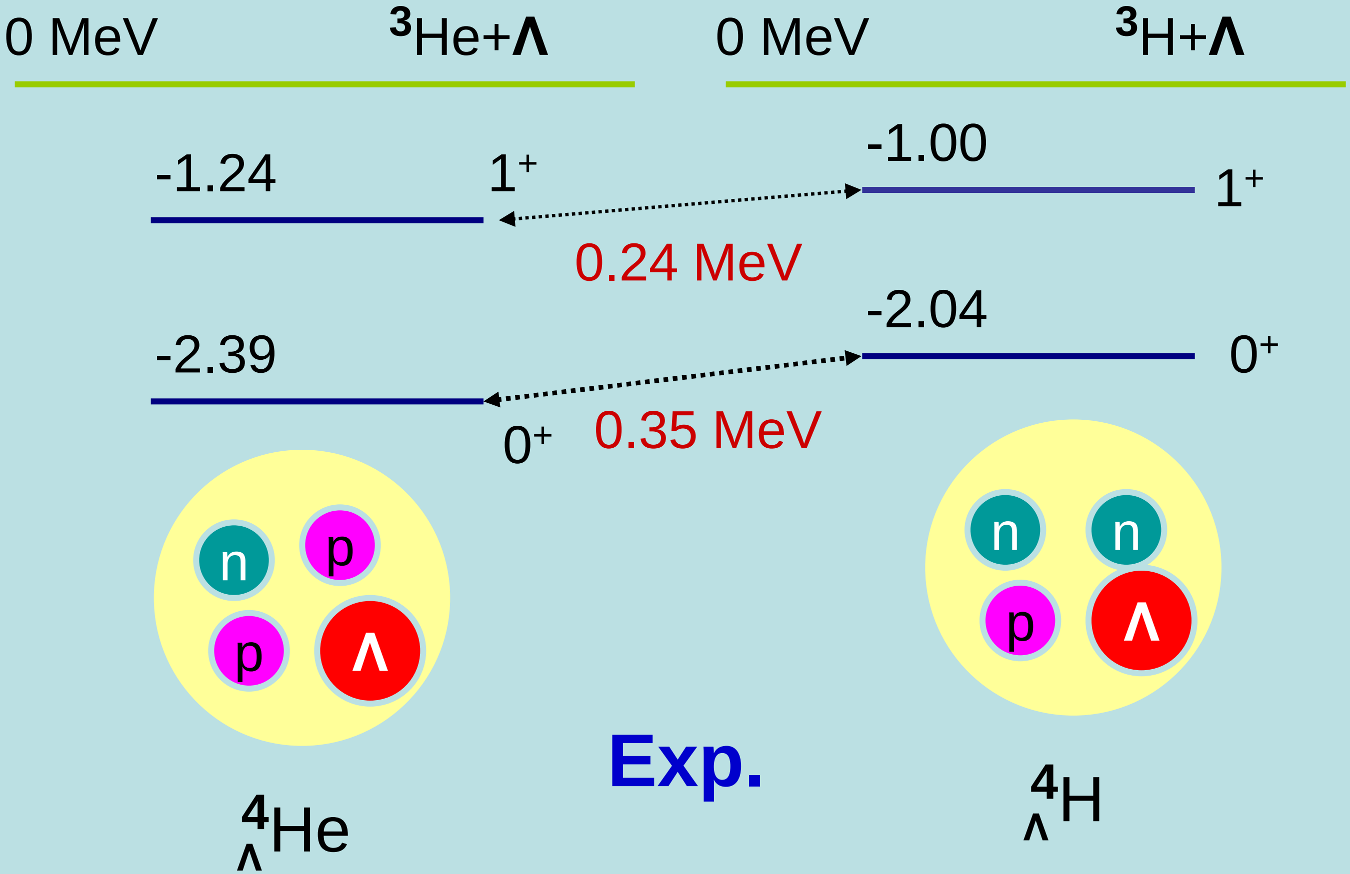
Reported by Hashimoto by HYP-X

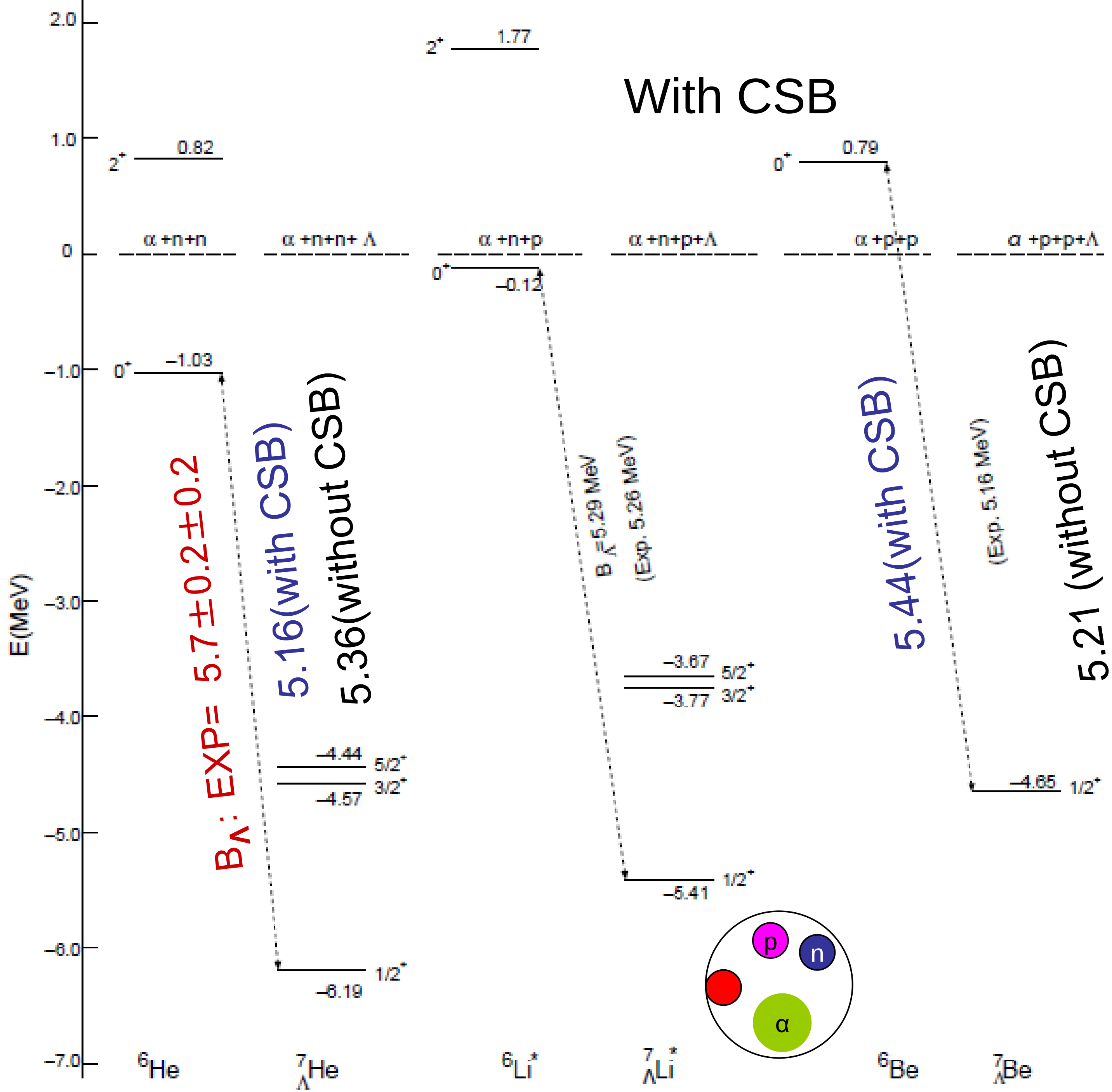


Next we introduce a phenomenological CSB potential with the central force component only.

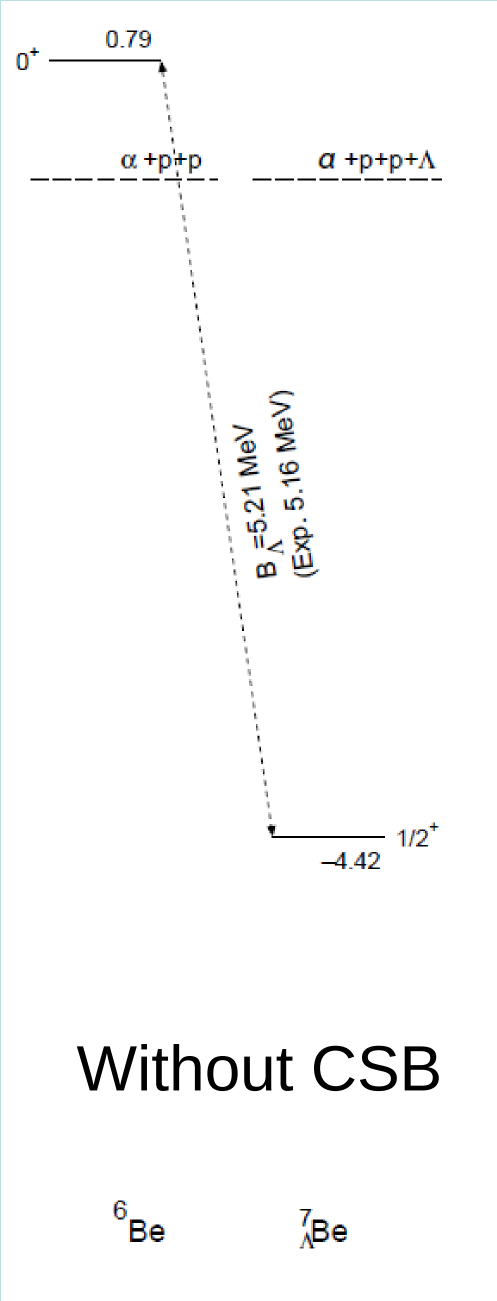
$$V^{\rm CSB}_{\Lambda N}(r) = -\frac{\tau_z}{2}\Big[\frac{1+P_r}{2}\big(v_0^{\rm even,CSB} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v^{\rm even,CSB}_{\sigma_\Lambda\cdot\sigma_N}\big)\,e^{-\beta_{\rm even}\, r^2} + \frac{1-P_r}{2}\big(v_0^{\rm odd,CSB} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v^{\rm odd,CSB}_{\sigma_\Lambda\cdot\sigma_N}\big)\,e^{-\beta_{\rm odd}\, r^2}\Big], \quad (3.3)$$

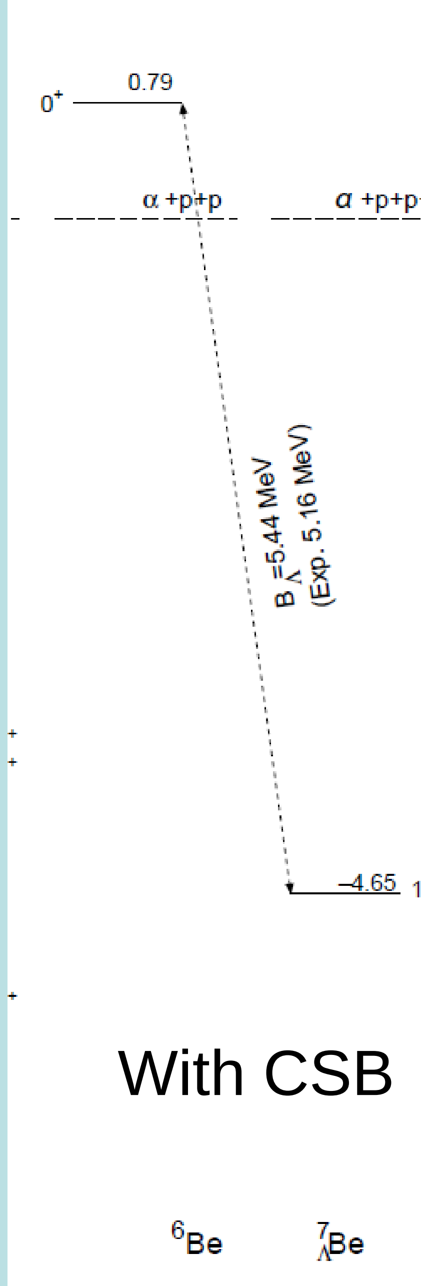
Strength, range are determined ao as to reproduce the data.

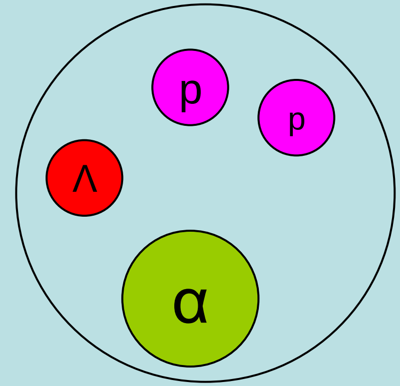




With CSB
E(MeV)
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
2+ 0.82
0+ −1.03
α +n+n
α +n+n+ Λ
−4.44 5/2+
−4.57 3/2+
−6.19 1/2+
2+ 1.77
α +n+p
0+ −0.12
α +n+p+Λ
−3.67 5/2+
−3.77 3/2+
−5.41 1/2+
0+ 0.79
α +p+p
α +p+p+Λ
−4.65 1/2+
BΛ : EXP= 5.7±0.2±0.2
5.16(with CSB)
5.36(without CSB)
BΛ=5.29 MeV
(Exp. 5.26 MeV)
5.44(with CSB)
(Exp. 5.16 MeV)
5.21 (without CSB)
p
n
α
6He
7ΛHe
6Li*
7ΛLi*
6Be
7ΛBe





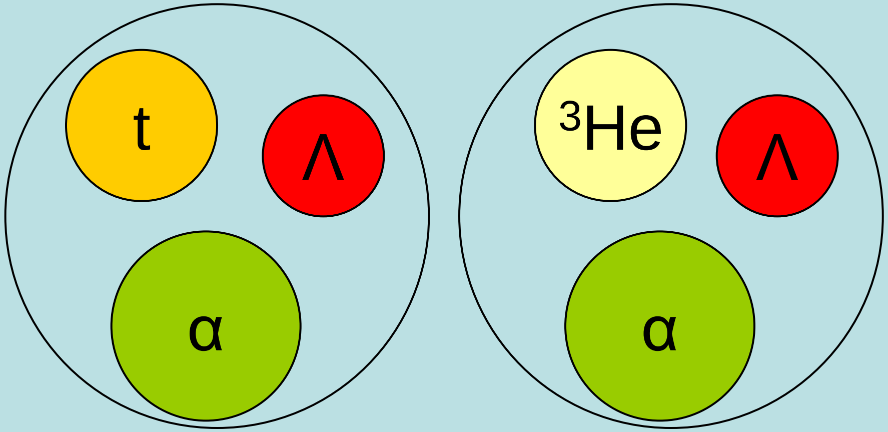


$^7_\Lambda$Be

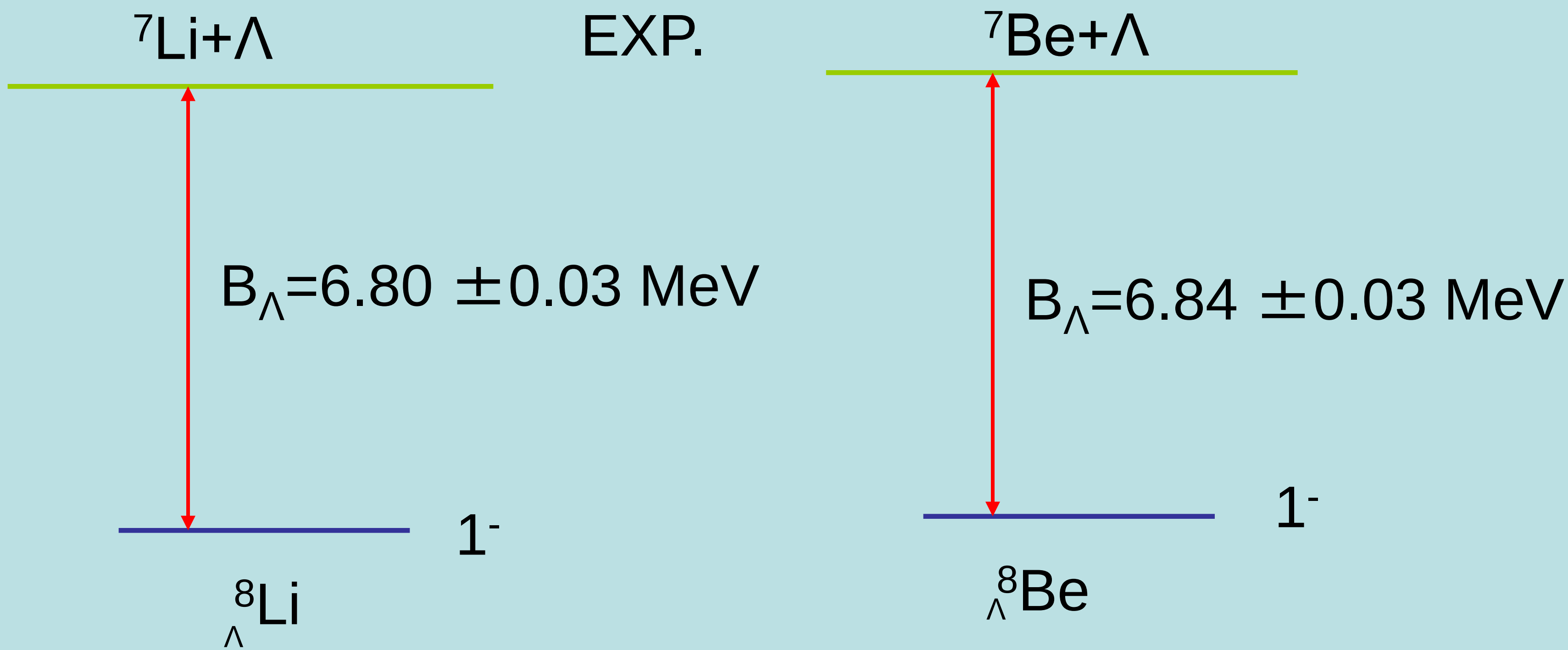
The experimental B_Λ value is found to be reproduced results without the CSB effect and to be inconsistent with the results with CSB.

In order to reproduce the binding energy of $^7_\Lambda$Be, the CSB interaction seems to be vanishing or opposite sign from that in the A=4 systems.

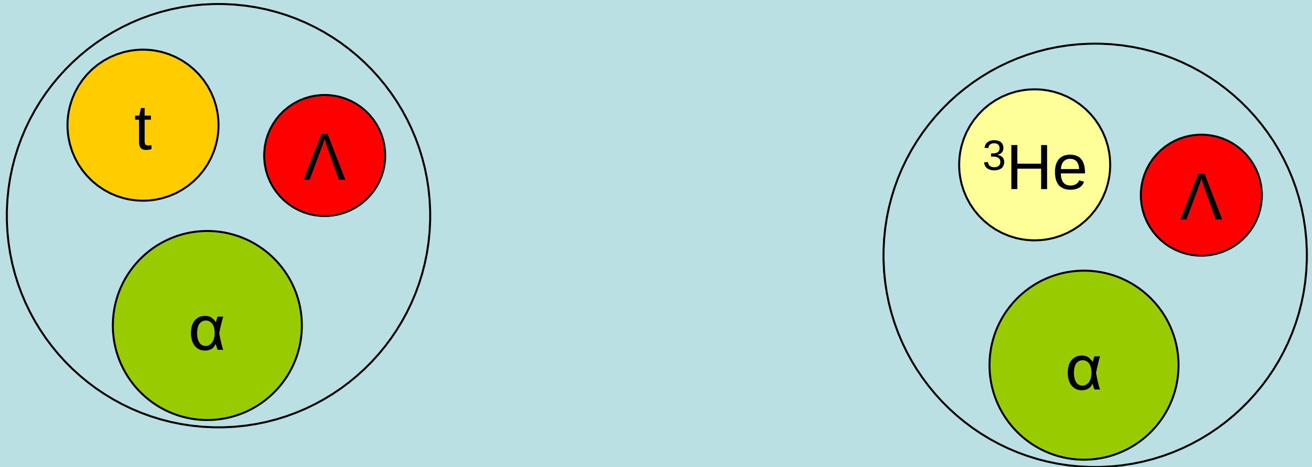
For further study of CSB effect in p-shell Λ hypernuclei, let's study another mirror hypernuclei, ${}^{8}_{\Lambda}Li$ and ${}^{8}_{\Lambda}Be$.



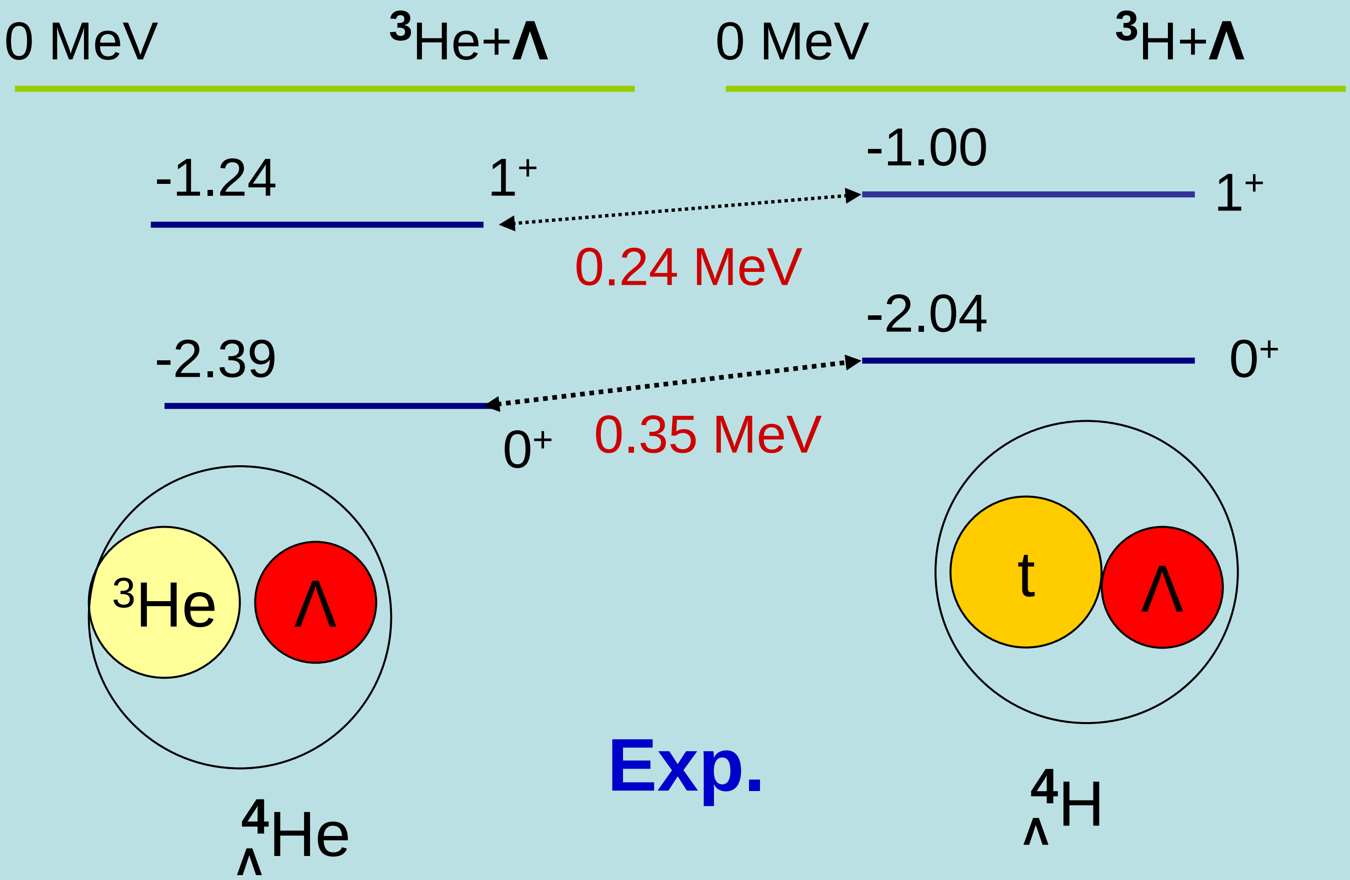
${}^{8}_{\Lambda}Li$ ${}^{8}_{\Lambda}Be$

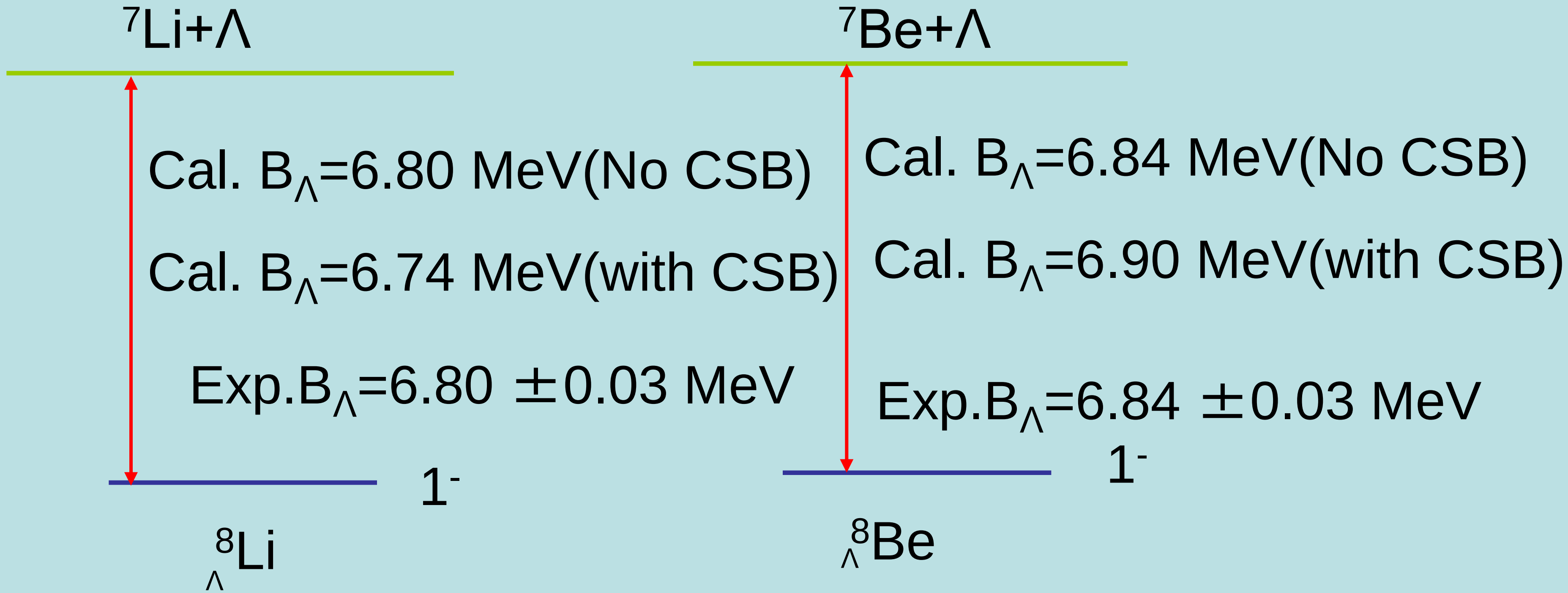


Energy difference is very small, then it seems that there is no effect of CSB in A=8 hypernuclei.

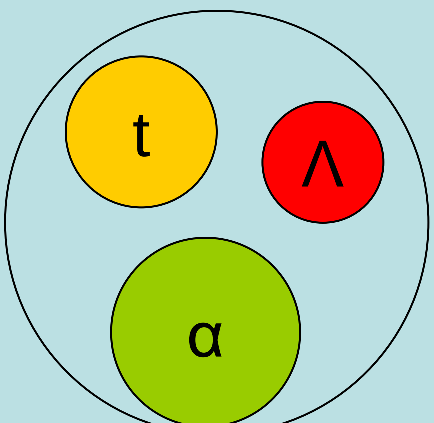


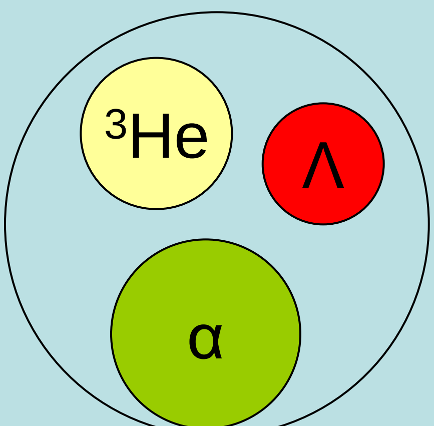
$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\mathrm{even,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\right) e^{-\beta_{\mathrm{even}}\, r^2} + \frac{1-P_r}{2}\left(v_0^{\mathrm{odd,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{odd,CSB}}\right) e^{-\beta_{\mathrm{odd}}\, r^2}\right], \tag{3.3}$$





The calculated energy difference with CSB is 0.16 MeV which is inconsistent with the data.





Why CSB interaction which reproduce the energy difference of A=4 hypernuclei do not reproduce the energy difference in p-shell hypernuclei such as A=7 and A=8 systems?

(1)In my calculation, ΛN-ΣN coupling effect is not included explicitly and mass difference of Σ.

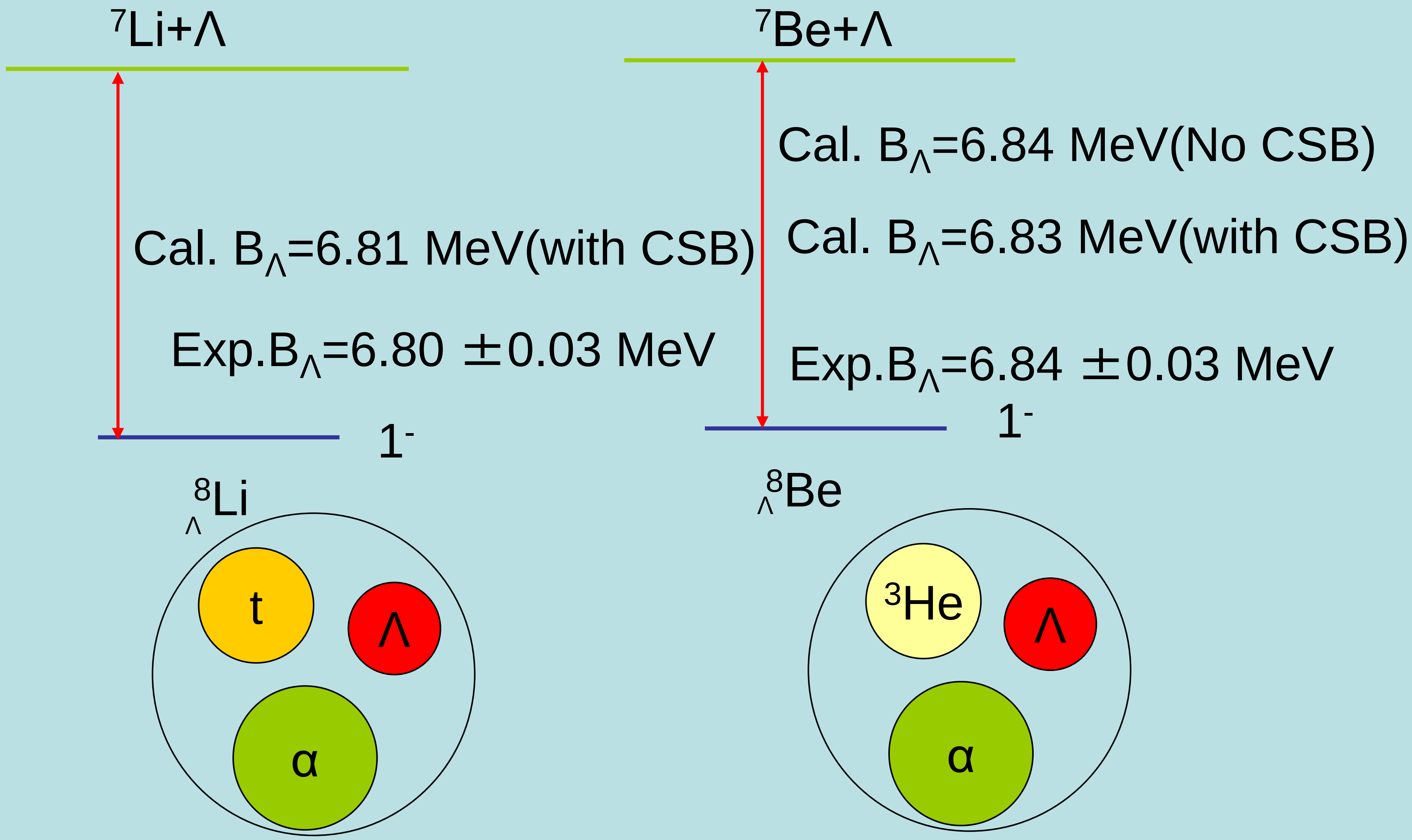
(2)Experimentalists say that experimental B_Λ of $^4_\Lambda$He might be doubtful. Then, they consider to measure B_Λ of this hypernucleus again.

But, it is very difficult to produce this hypernucleus.

(3) odd-state CSB interaction whose contribution is negligible in A=4 hypernuclei, contribute to p-shell Λ hypernuclei with opposite sign of the even state of CSB interaction.

$$
\begin{aligned}
&V_{\Lambda x}^{\mathrm{CSB}}(\mathbf{r},\mathbf{r}') = \qquad\qquad (3.5\\
&\frac{1}{2}\Big[\big(V_0^{\mathrm{even,CSB}} + \mathbf{s}_\Lambda\cdot\mathbf{s}_x V_S^{\mathrm{even,CSB}}\big)\, e^{-\mu_{\mathrm{even}} r^2}\,\delta(\mathbf{r}-\mathbf{r}')\\
&+\ \big(U_0^{\mathrm{even,CSB}} + \mathbf{s}_\Lambda\cdot\mathbf{s}_x U_S^{\mathrm{even,CSB}}\big)\, e^{-\gamma_{\mathrm{even}}(\mathbf{r}+\mathbf{r}')^2-\delta_{\mathrm{even}}(\mathbf{r}-\mathbf{r}')^2}\Big]\\
&+\ \frac{1}{2}\Big[\big(V_0^{\mathrm{odd,CSB}} + \mathbf{s}_\Lambda\cdot\mathbf{s}_x V_S^{\mathrm{odd,CSB}}\big)\, e^{-\mu_{\mathrm{odd}} r^2}\,\delta(\mathbf{r}-\mathbf{r}')\\
&+\ \big(U_0^{\mathrm{odd,CSB}} + \mathbf{s}_\Lambda\cdot\mathbf{s}_x U_S^{\mathrm{odd,CSB}}\big)\, e^{-\gamma_{\mathrm{odd}}(\mathbf{r}+\mathbf{r}')^2-\delta_{\mathrm{odd}}(\mathbf{r}-\mathbf{r}')^2}\Big]
\end{aligned}
$$

Odd state CSB interaction is introduced phenomenologically so as to reproduce the B_Λ value of ${}^{8}_{\Lambda}\mathrm{Li}$ and ${}^{8}_{\Lambda}\mathrm{Be}$.



^{7}Li+Λ
Cal. B_{Λ}=6.81 MeV(with CSB)
Exp.B_{Λ}=6.80 ±0.03 MeV
1^{-}
$^{8}_{\Lambda}$Li
t
Λ
α
^{7}Be+Λ
Cal. B_{Λ}=6.84 MeV(No CSB)
Cal. B_{Λ}=6.83 MeV(with CSB)
Exp.B_{Λ}=6.84 ±0.03 MeV
1^{-}
$^{8}_{\Lambda}$Be
^{3}He
Λ
α

If there is still CSB effect in A=4 hypernuclei, in order to describe the B_Λ in A=8 hypernuclei, we need an opposite sign of the even state CSB interaction determined at A=4 hypernuclei.

But, the present framework for A=8 hypernuclei has a sort of limitation in the sense that the triton (^{3}He) cluster is assumed to have 3 nucleons of the same size of those in α.

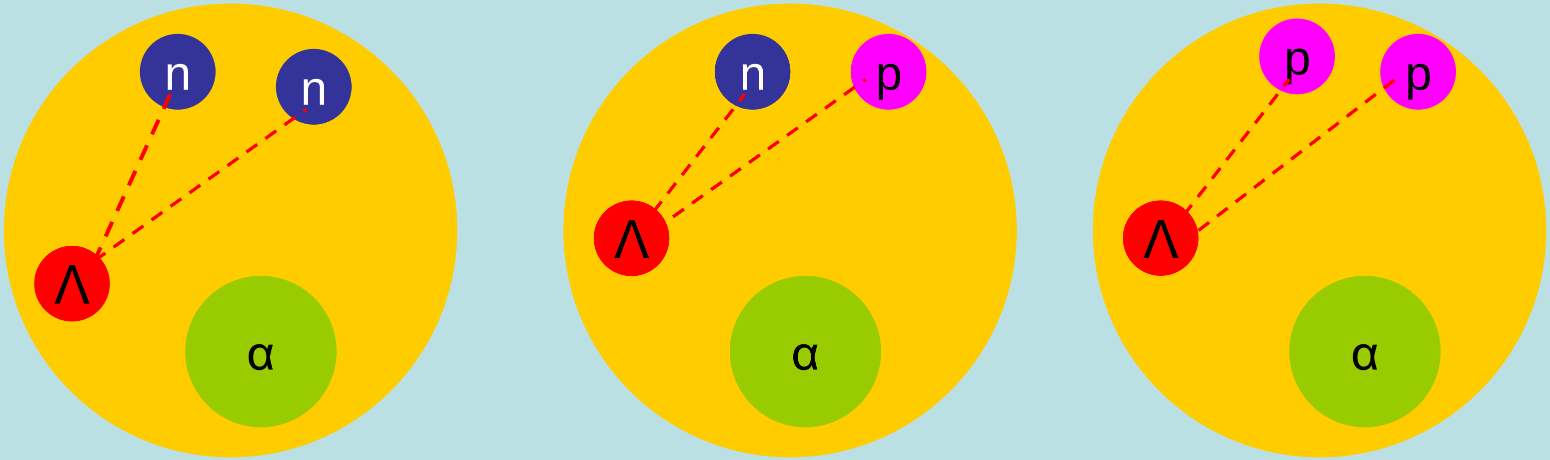
However, the results for A=7 and 8 are qualitatively consistent with each other.

Namely,

In A=7 hypernuclei, the calculated B_Λ is inconsistent with the data including CSB even state interaction.

Then, if we introduce the odd state CSB interaction which has opposite sign of the even state CSB interaction, it is possible to reproduce the data.

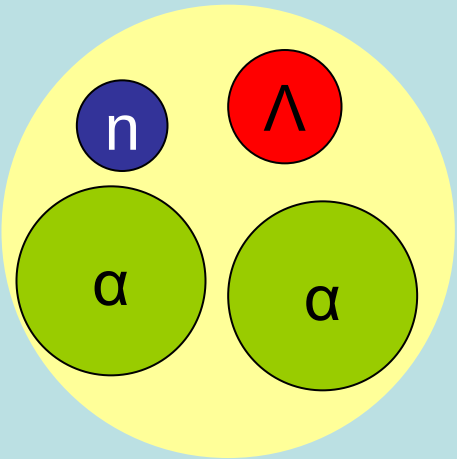
For this study, we hope that observed data of B_Λ in ${}^{7}_{\Lambda}\mathrm{He}$ will be determined within 100keV accuracy at JLAB.



${}^{7}_{\Lambda}\mathrm{He}$ ${}^{7}_{\Lambda}\mathrm{Li}(T=1)$ ${}^{7}_{\Lambda}\mathrm{Be}$

On the basis of coming data, it might be possible to get information on the odd-state CSB interaction.

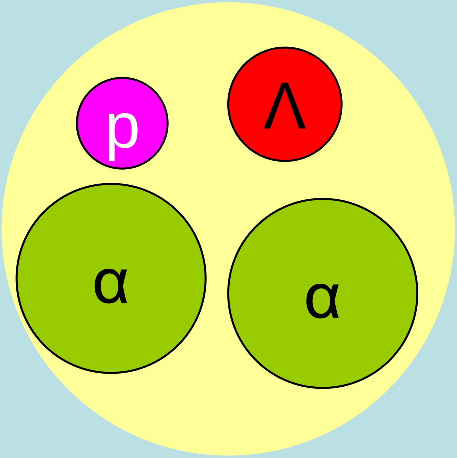
Another example to clarify the even- and odd-state CSB interaction is to study ${}^{10}_{\Lambda}\mathrm{Be}$ and ${}^{10}_{\Lambda}\mathrm{B}$.



${}^{10}_{\Lambda}\mathrm{Be}$

Exp. B_Λ=9.11±0.22 MeV
Number of event (emulsion data): 3

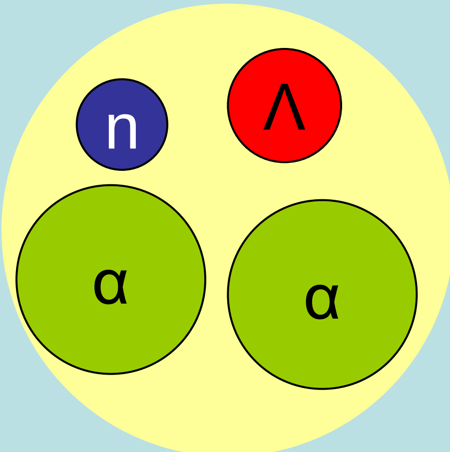
At JLAB, the analysis is in progress.



${}^{10}_{\Lambda}\mathrm{B}$

Exp. B_Λ=8.89±0.12 MeV
Number of event (emulsion data): 10

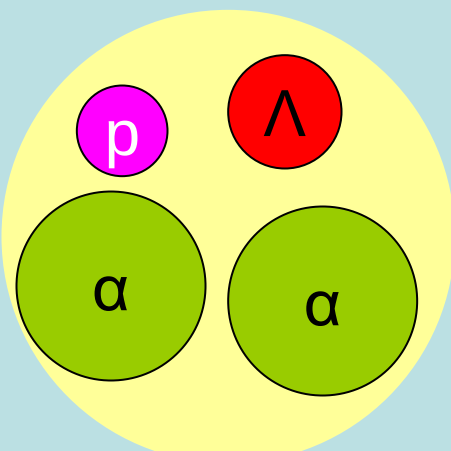
Calculated result:



$^{10}_{\Lambda}$Be

Exp. B_{Λ}=9.11±0.22 MeV

Cal: B_{Λ}=8.76 MeV



$^{10}_{\Lambda}$B

Exp. B_{Λ}=8.89±0.12 MeV

Cal: B_{Λ} : in progress

Concluding remark

For the study of CSB interaction, we need B_Λ within 100keV accuracy.

For this purpose, $(e,e'K^+)$ reaction might be powerful tool.

For the study of CSB interaction,

(1) $^4He(e,e'K^+)^4_\Lambda H$ ⟶ Maintz?

(2) $^4He(\pi^+,K^+)\,^4_\Lambda He$ ⟶ Where? Possible?
or emulsion experiment again?

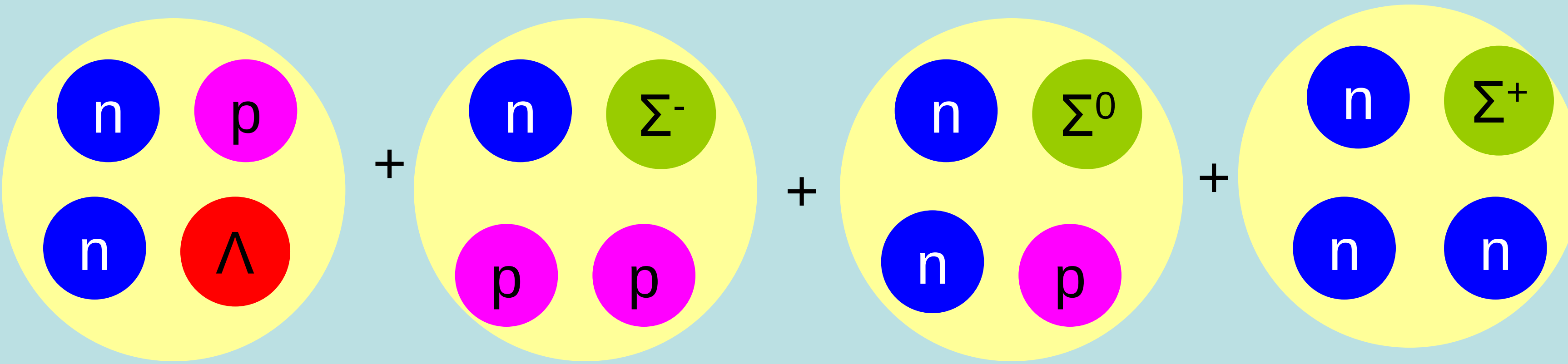
We want to know B_Λ accurately in s-shell Λ hypernuclei.

$^{10}B\ (e, e'K^{+})\ ^{10}_{\Lambda}Be$ ⟶ Analysis is in progress.

$^{10}B(\pi^{+},K^{+})\ ^{10}_{\Lambda}B$ ⟶ Where?

For detailed study of CSB effect in A=4 hypernuclei

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



${}^{4}_{\Lambda}\mathrm{He}$

realistic NN and YN interaction such as ESC08a