少数多体系観点からのハイパー核構造研究の現状と将来

肥山詠美子（理研）

・S=-1、S=-2セクターでこれまでに何が分かったのか？
・何が分かっていないのか（と私は思うのか）？

少数粒子系物理的観点で・・。

私も明確な答えは持っていない。
したがって、私が分かっていないと思うことをここで発表することで、
みんなで議論・整理し、その後、何を目指すために、
どういう研究を推し進めていくべきかを話し合いたいと
思う。

S=-1セクションについて

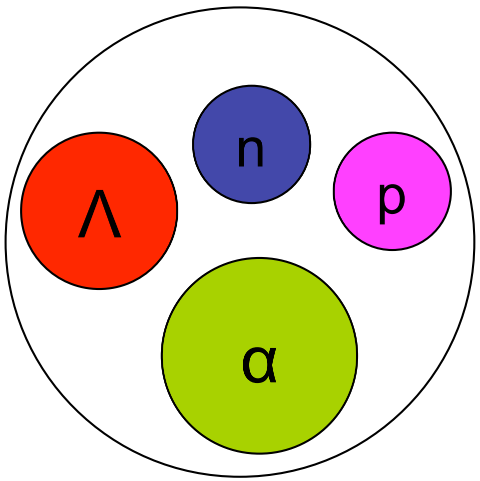
・どこまで分かったか？（と私は思う）

軽いハイパー核について

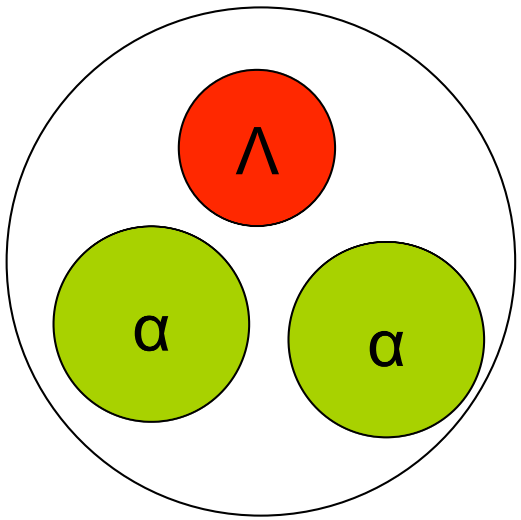
$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathrm{s}_\Lambda + \mathrm{s}_N) V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathrm{s}_\Lambda - \mathrm{s}_N) V_{\mathrm{ALS}} + S_{12} V_{\mathrm{tensor}} + \cdots\cdots$$

核構造の精密計算からそれぞれのtermの望ましい強さを決めて行った.

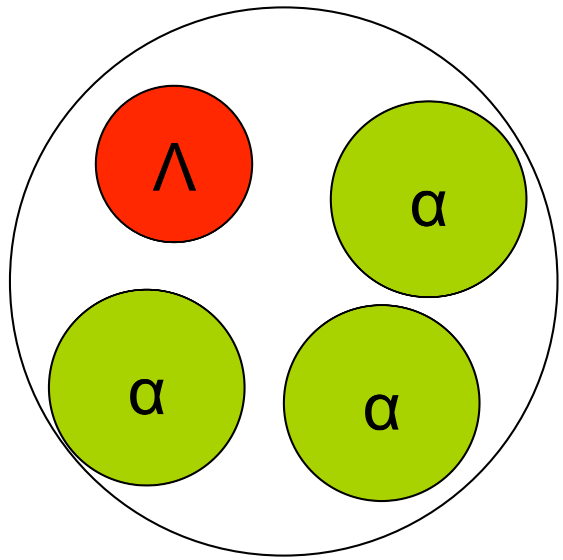
$^{7}_{\Lambda}$Li



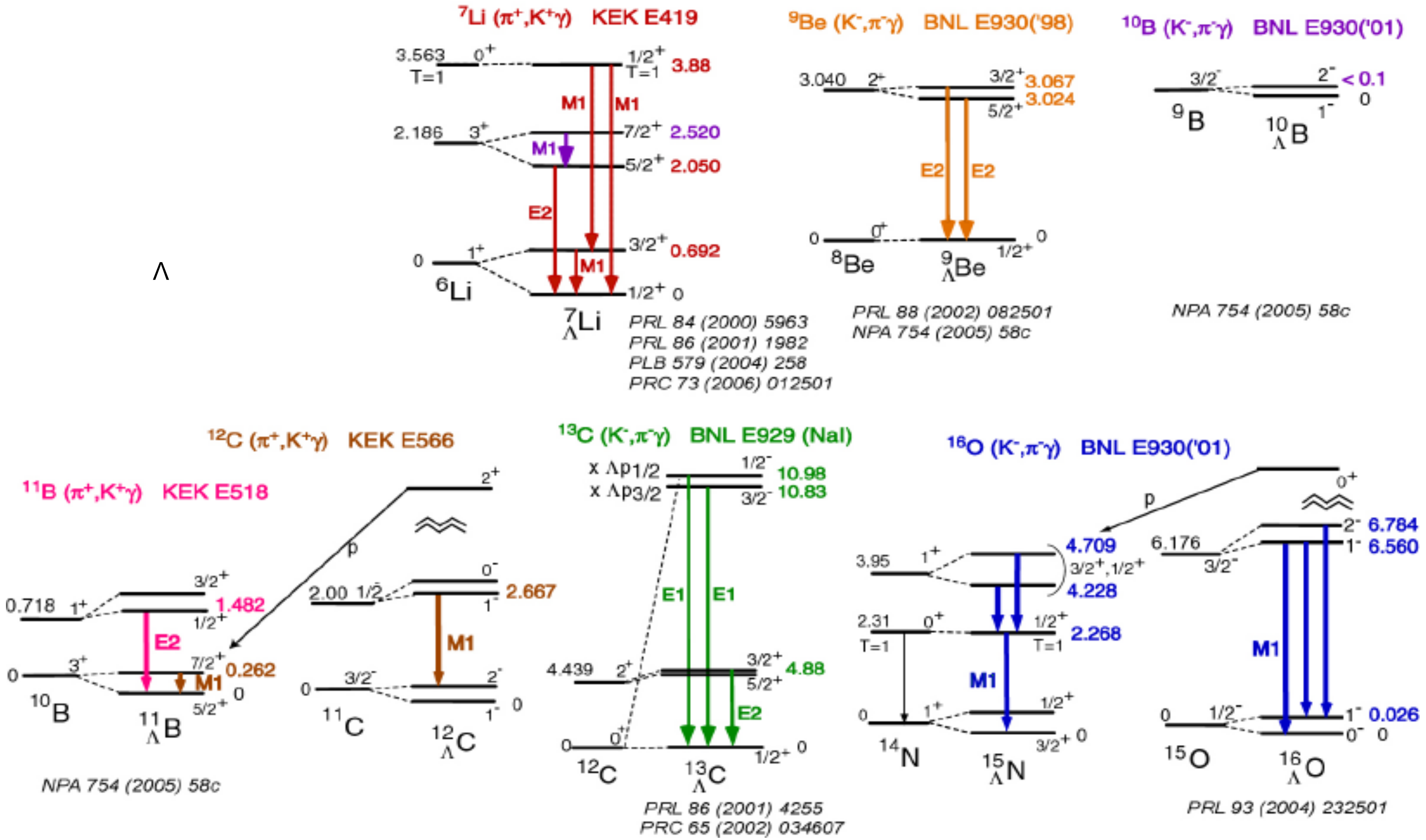
$^{9}_{\Lambda}$Be



$^{13}_{\Lambda}$C



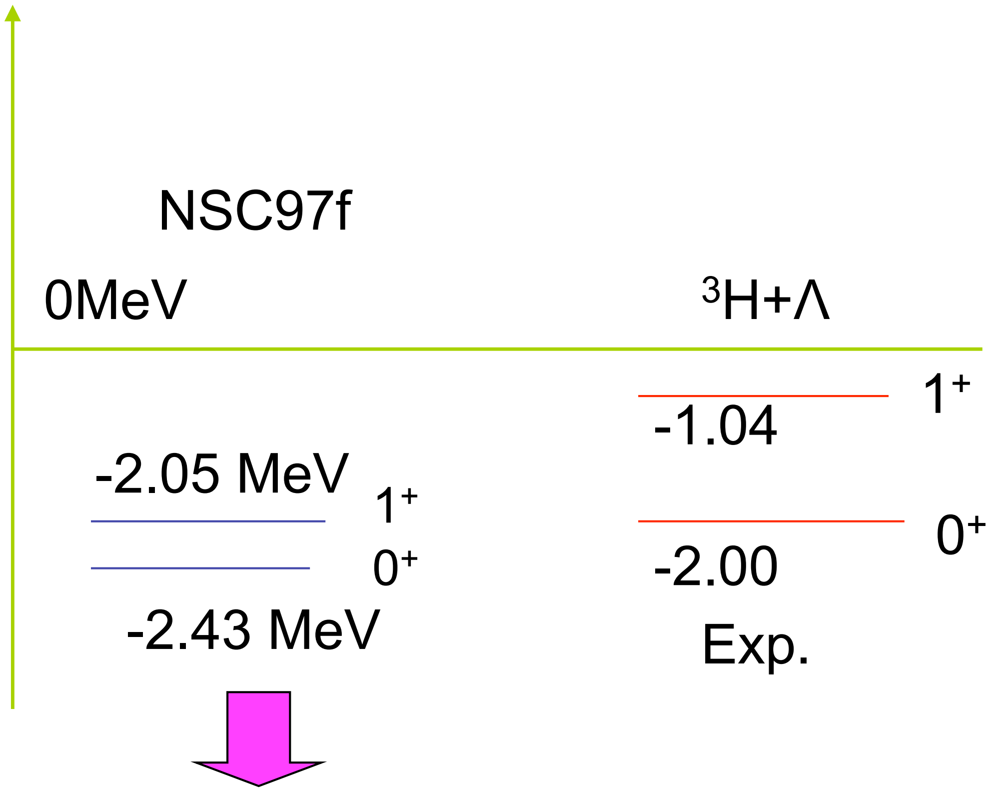
Hypernuclear γ-ray data since 1998

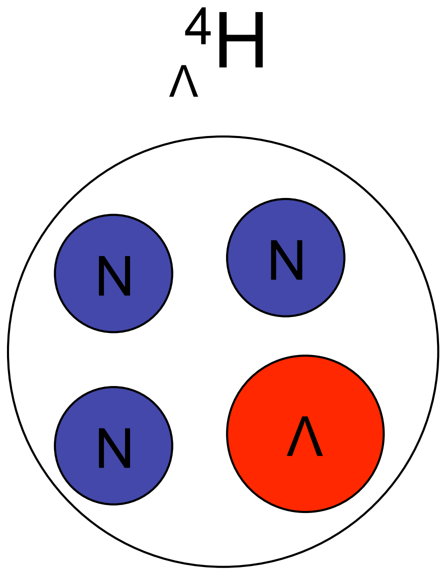


$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathrm{s}_\Lambda + \mathrm{s}_N) V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathrm{s}_\Lambda - \mathrm{s}_N) V_{\mathrm{ALS}} + S_{12} V_{\mathrm{tensor}} + \cdots$$

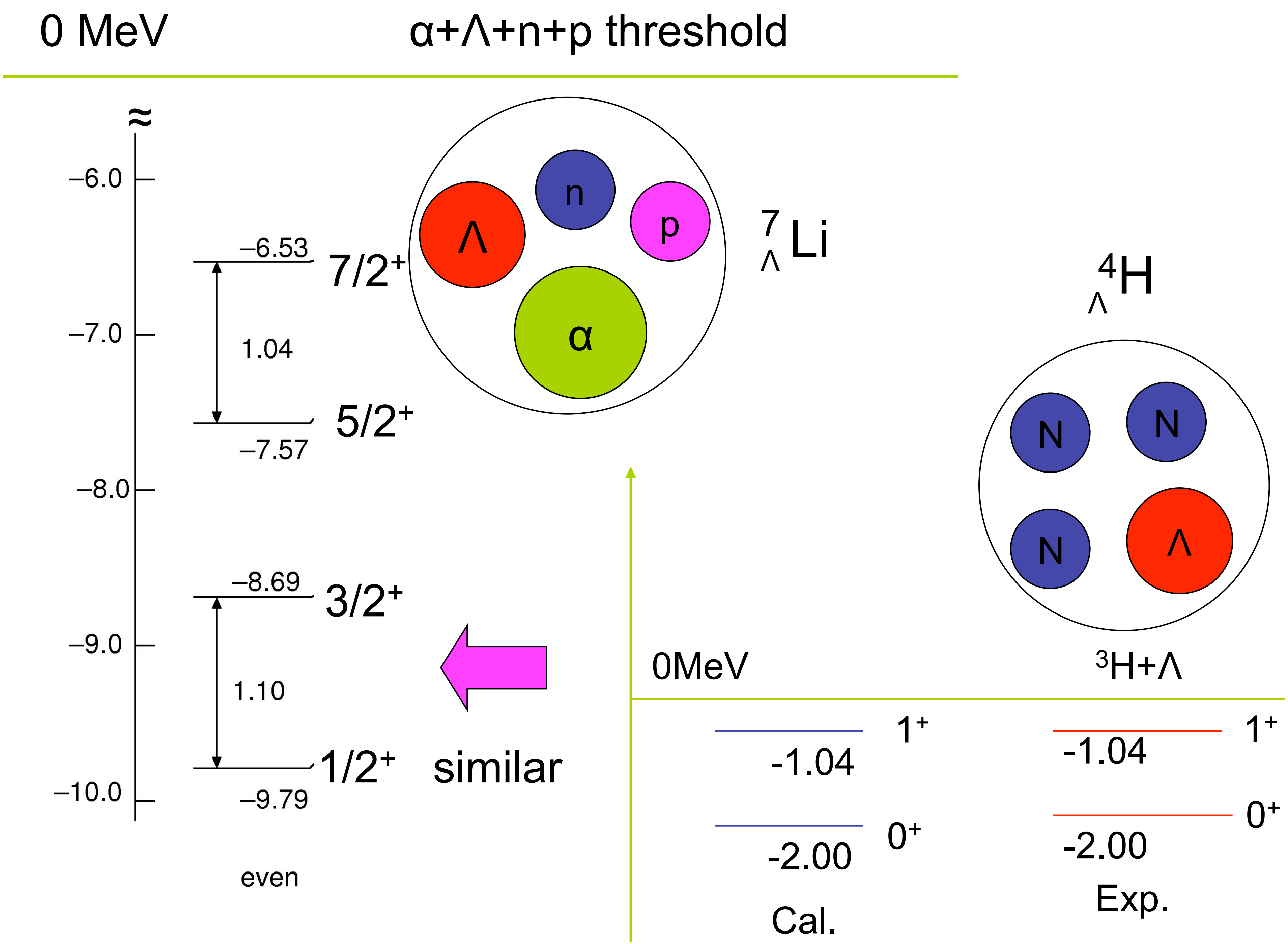
- Millener (p-shell model),
- Hiyama (few-body)

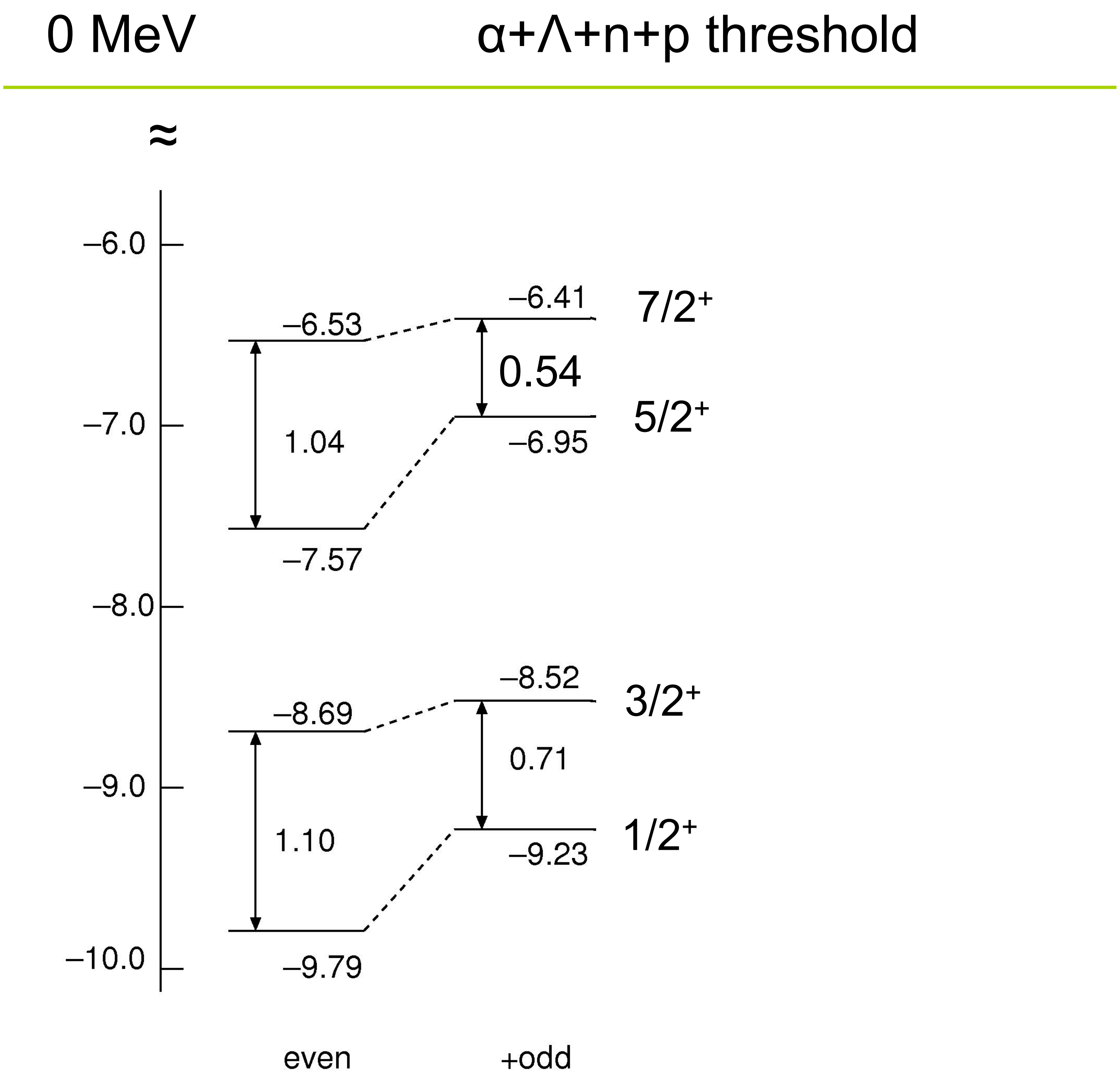
$V_0+\sigma_\Lambda\cdot\sigma_N V_s$





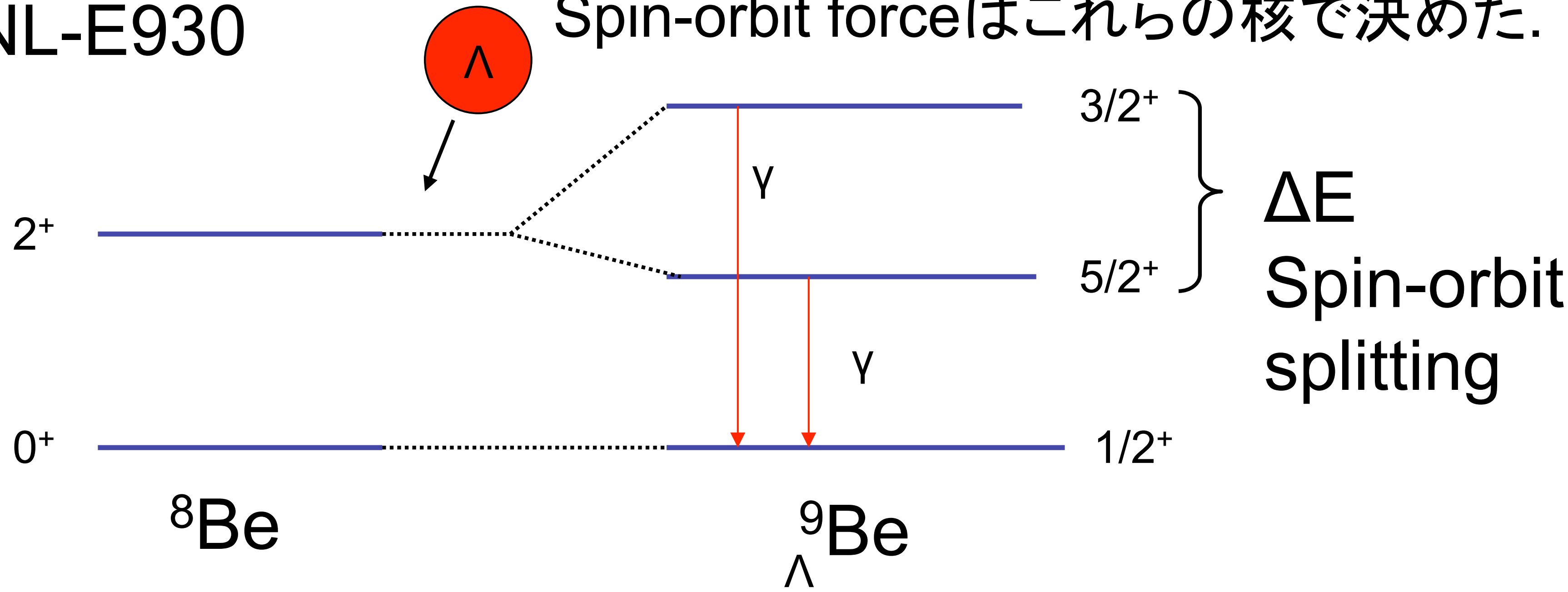
Adjusted so as to reproduce the observed data of $^4_\Lambda H$


0 MeV
α+Λ+n+p threshold
−6.0
−7.0
−8.0
−9.0
−10.0
−6.53
7/2+
1.04
5/2+
−7.57
−8.69
3/2+
1.10
1/2+
−9.79
even
similar
Λ
n
p
α
7
Λ
Li
4
Λ
H
N
N
N
Λ
0MeV
3H+Λ
1+
-1.04
0+
-2.00
Cal.
1+
-1.04
0+
-2.00
Exp.

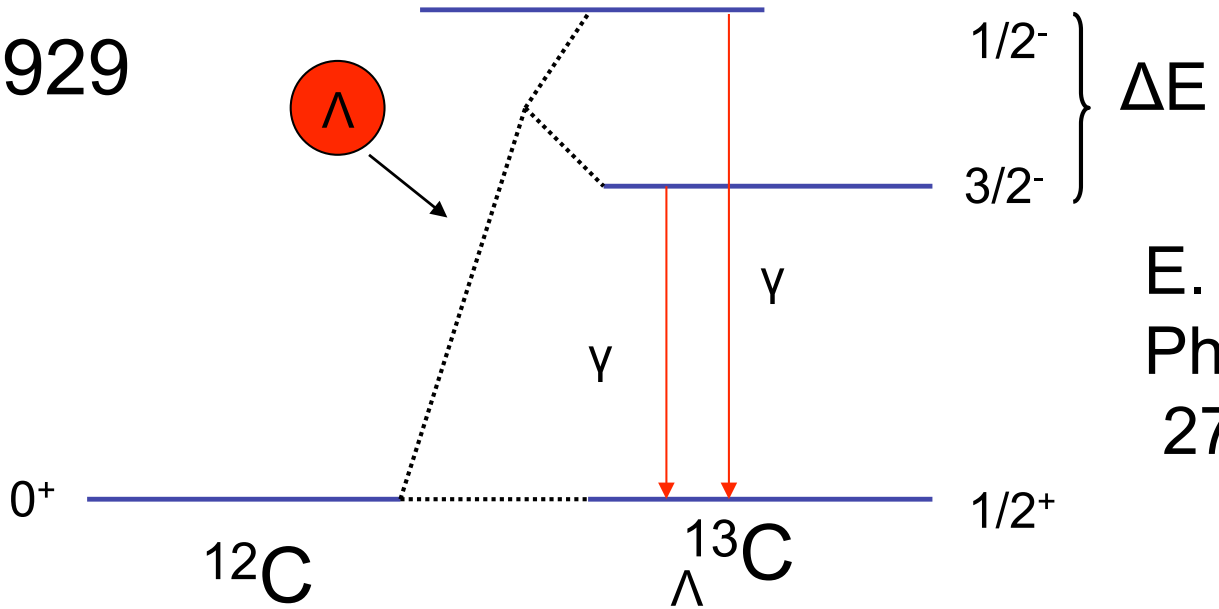

0 MeV
α+Λ+n+p threshold
≈
–6.0
–7.0
–8.0
–9.0
–10.0
–6.53
1.04
–7.57
–6.41
0.54
–6.95
7/2+
5/2+
–8.69
1.10
–9.79
–8.52
0.71
–9.23
3/2+
1/2+
even
+odd

Spin-orbit forceはこれらの核で決めた.

BNL-E930



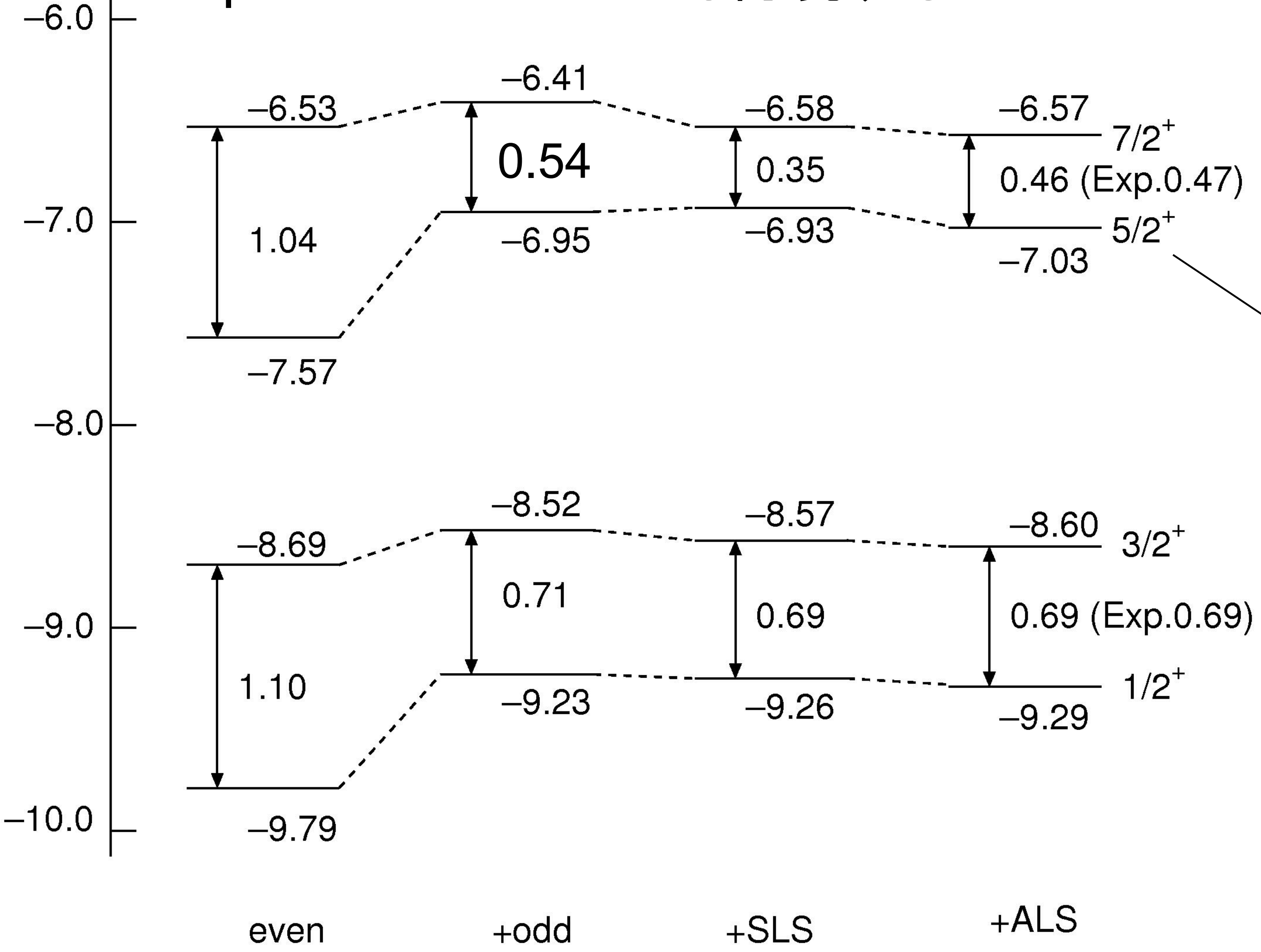
BNL-E929

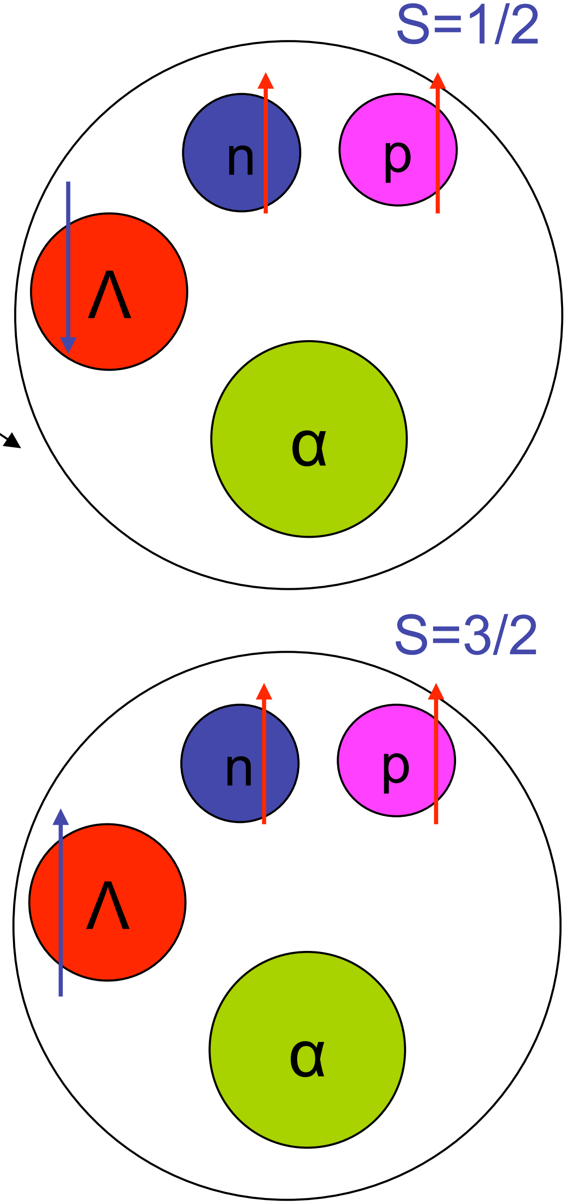


E. Hiyama et al.
Phys. Rev. Lett. 85,
270 (2000)

0 MeV α+Λ+n+p threshold

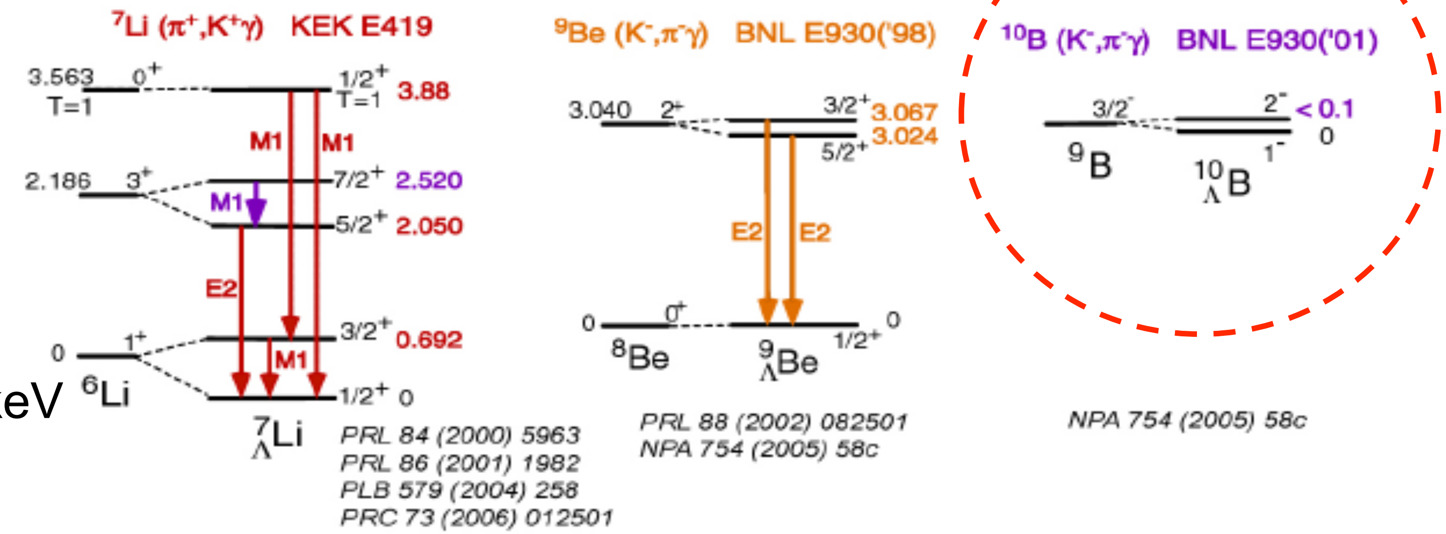
≈ $_{\Lambda}^{9}$Beや $_{\Lambda}^{13}$Cで決めたspin-orbit forceは $_{\Lambda}^{7}$Liの spin doublets stateも再現する.

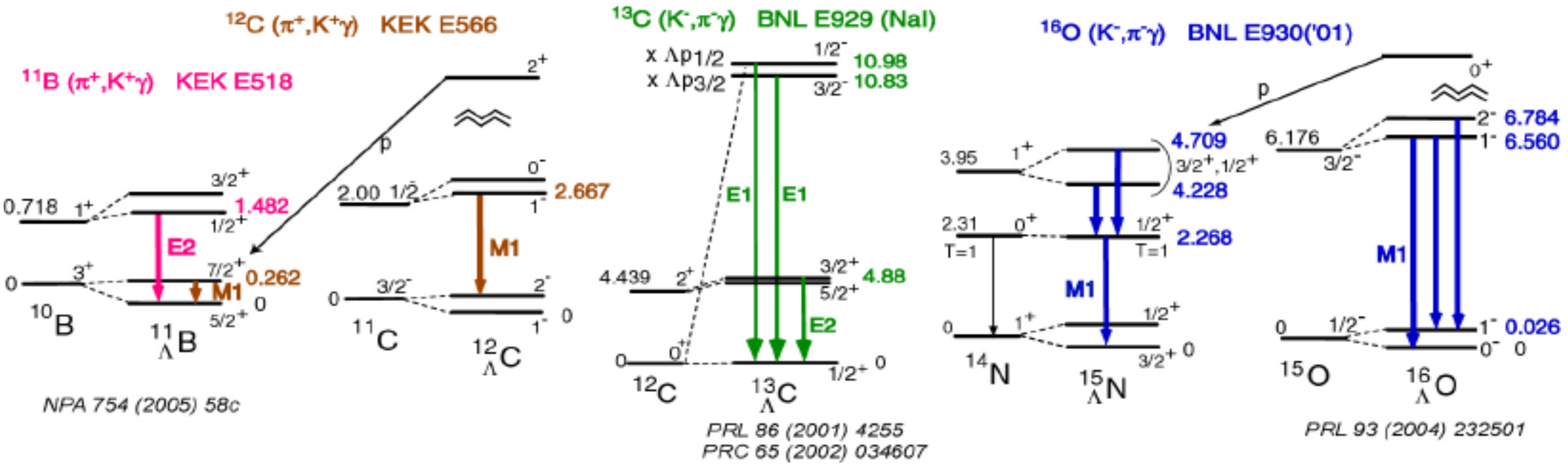




Hypernuclear γ-ray data since 1998

Millenerは
A=4,7,9の
分岐エネルギーを
再現するように
ΛN相互作用を
決める->$^{10}_{\Lambda}$Bの
分岐エネルギーが200keV
程度（実験とあわない）

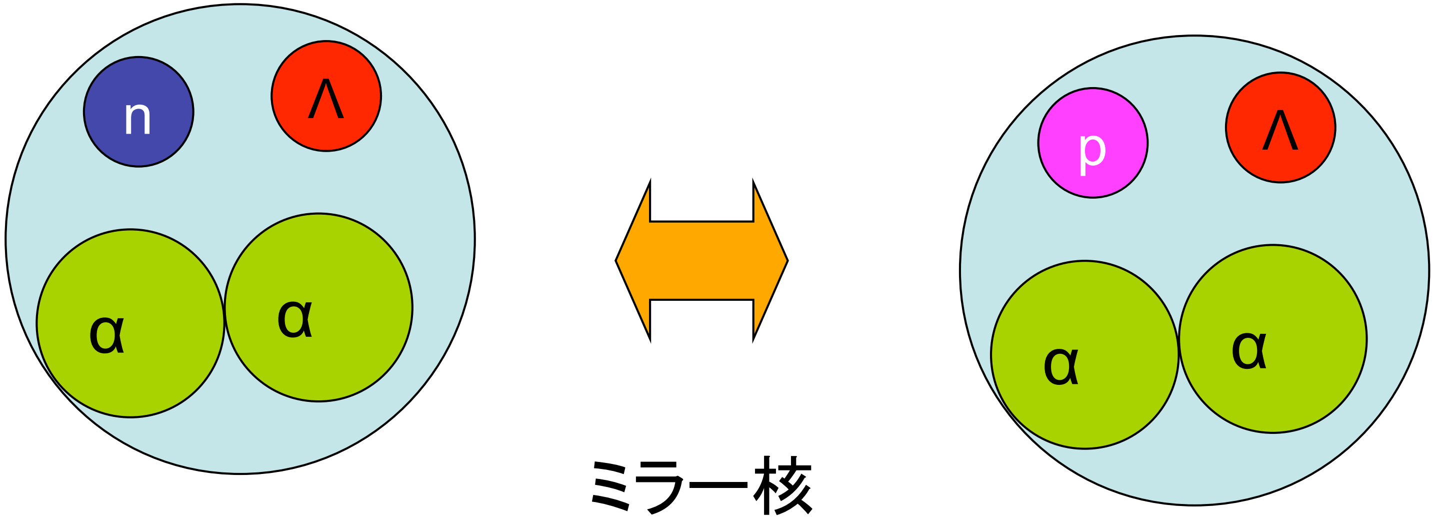




$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathrm{s}_\Lambda + \mathrm{s}_N) V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathrm{s}_\Lambda - \mathrm{s}_N) V_{\mathrm{ALS}} + S_{12} V_{\mathrm{tensor}} + \cdots$$

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

この問題に取り組む

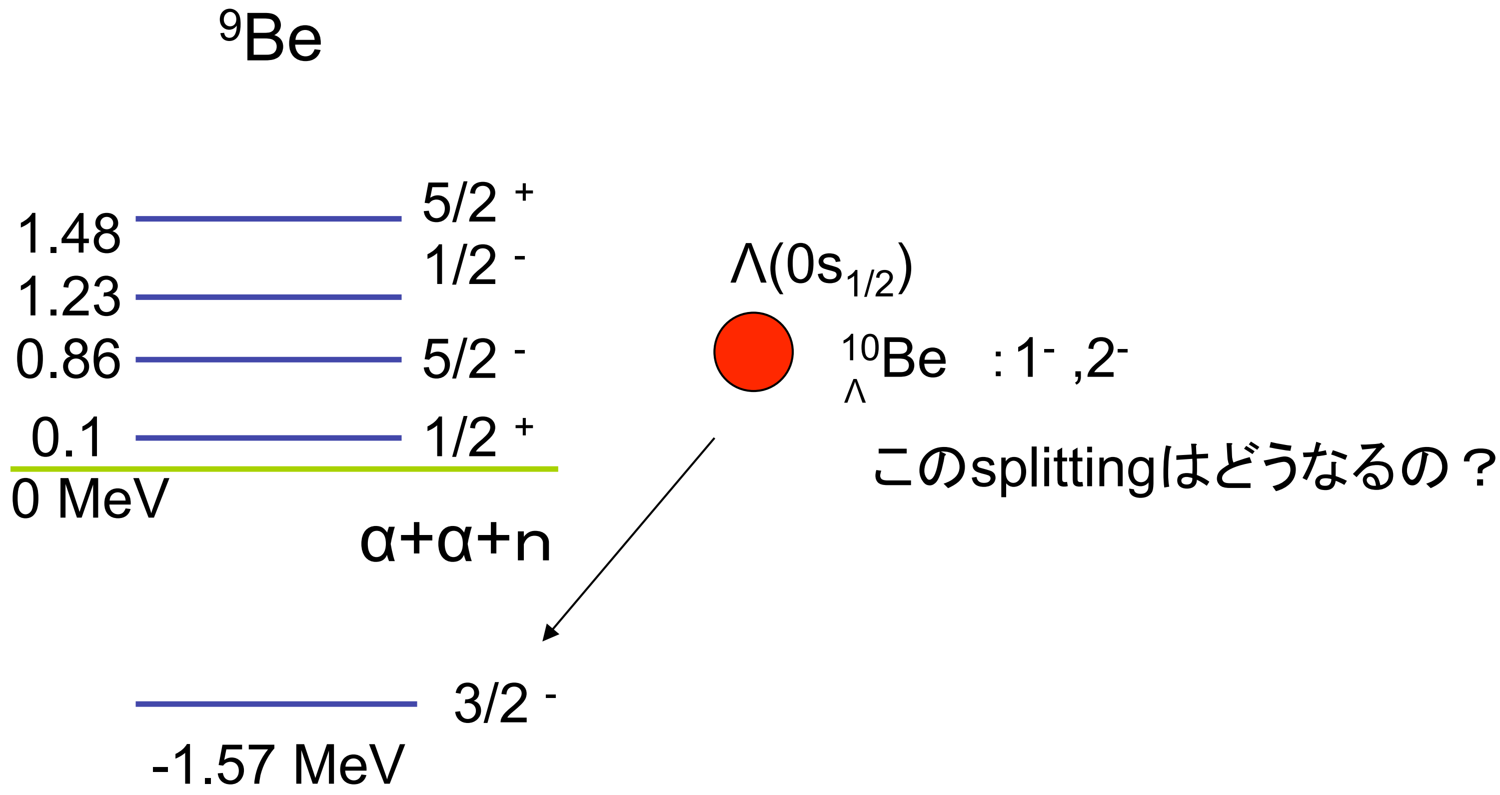


$^{10}_{\Lambda}\mathrm{Be}$

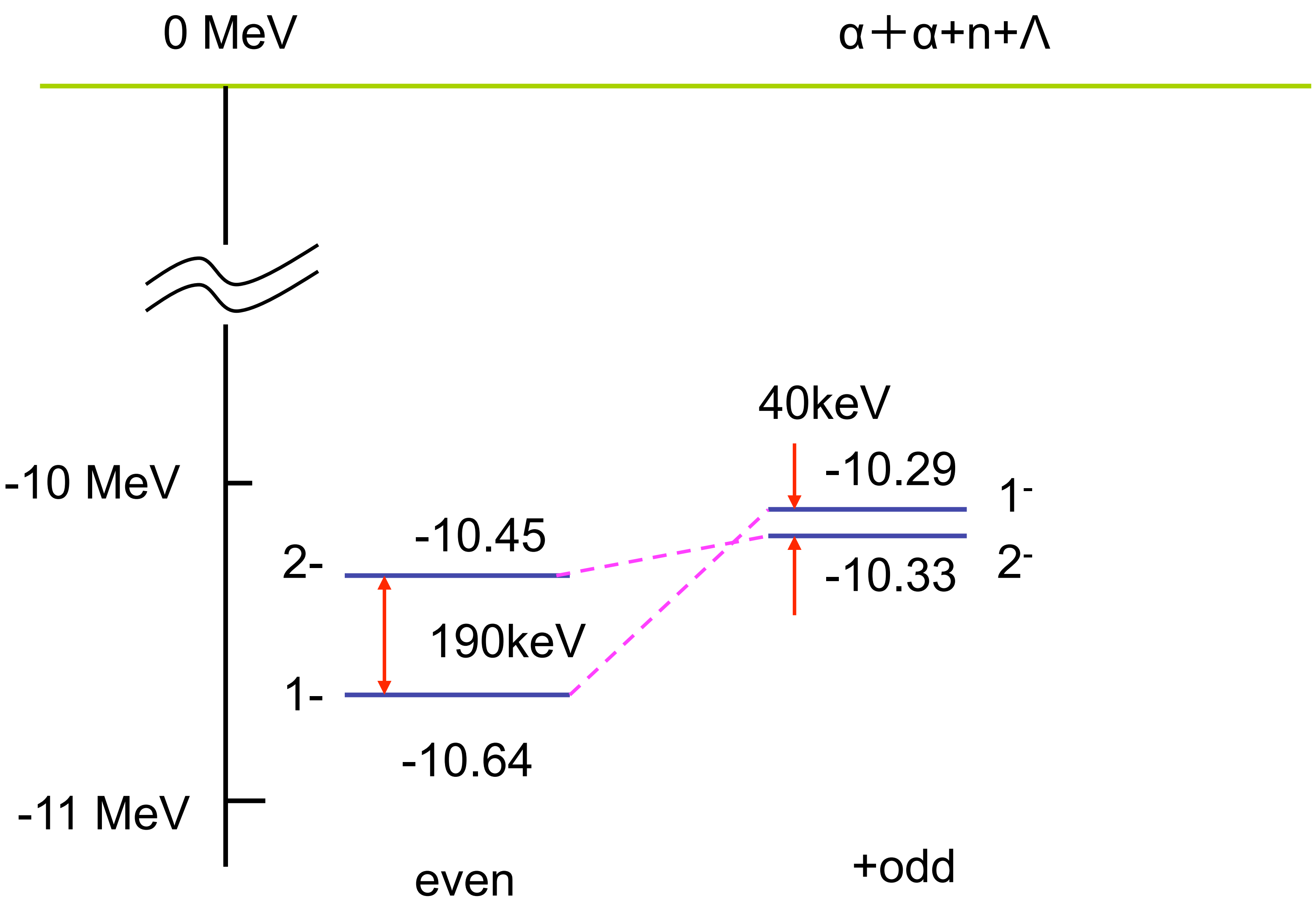
$^{10}_{\Lambda}\mathrm{B}$

$^{10}_{\Lambda}\mathrm{B}$を計算すべきだが、同じことは$^{10}_{\Lambda}\mathrm{Be}$でもいえるから、
まず、深く束縛している$^{10}_{\Lambda}\mathrm{Be}$から計算してみた。

Exp.



^{9}Be
1.48
5/2 +
1.23
1/2 -
0.86
5/2 -
0.1
1/2 +
0 MeV
α+α+n
3/2 -
-1.57 MeV
Λ(0s$_{1/2}$)
$^{10}_{\Lambda}$Be : 1$^-$,2$^-$
このsplittingはどうなるの？



A=4,7,9,13で決めたΛN相互作用でもA=10はうまく再現する。

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

(1)Charge symmetry breaking
(2) ΛN－ΣN coupling

・E13 "γ-ray spectroscopy of light hypernuclei" by Tamura and his collaborators
Day-1 experiment

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

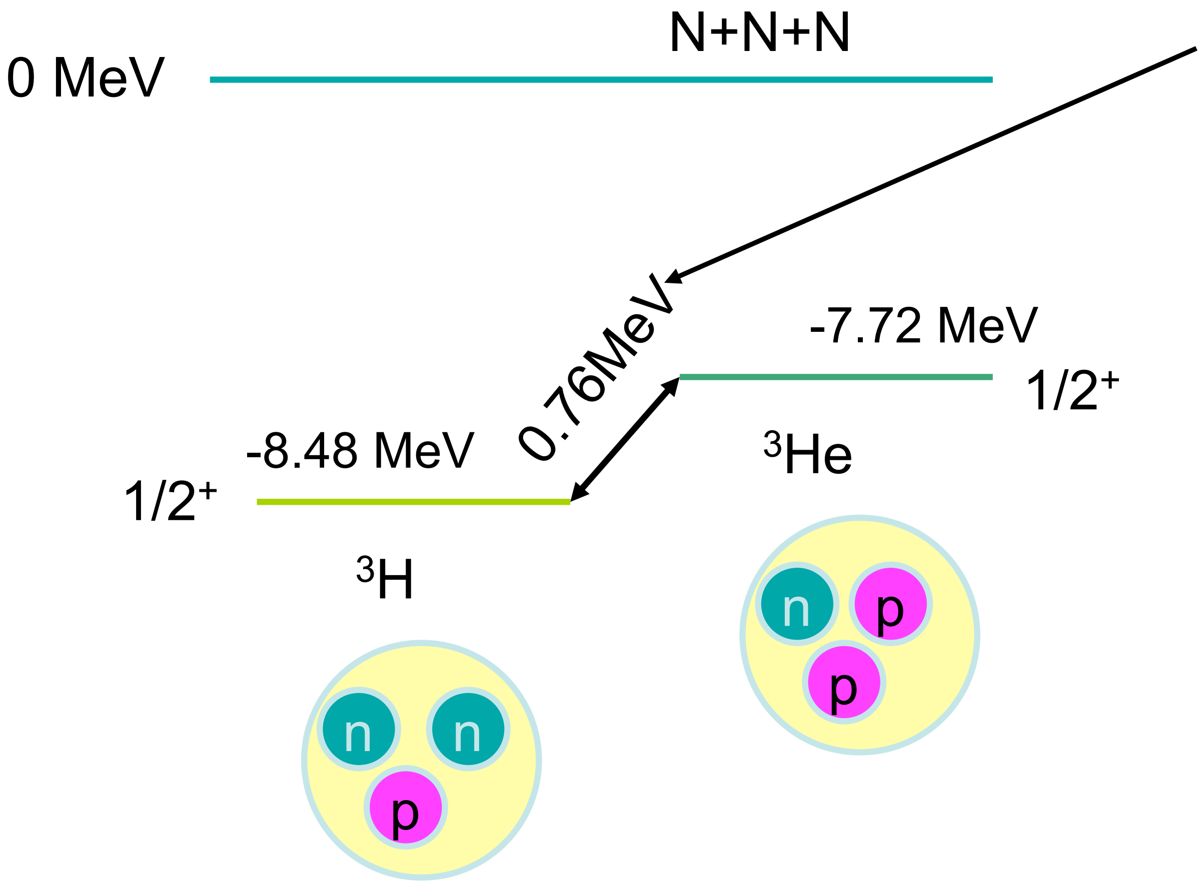
・E10 "Study on Λ-hypernuclei with the doubleCharge-Exchange reaction"
by Sakaguchi , Fukuda and his collaboratiors

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

・・とはあるが、本当に決まるの？
何を決めることになるの？

(1) Charge Symmetry breaking

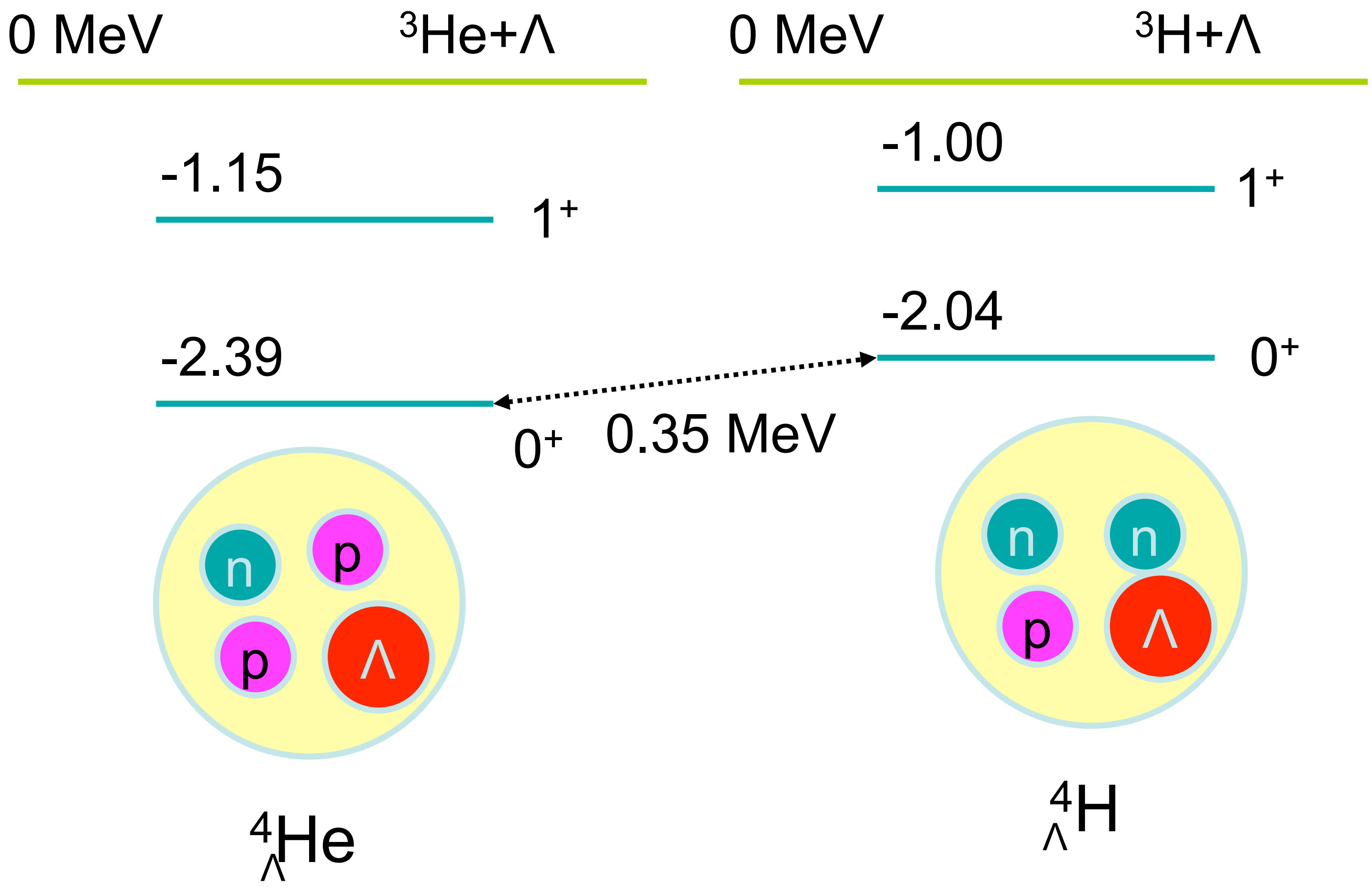
In S=0 sector



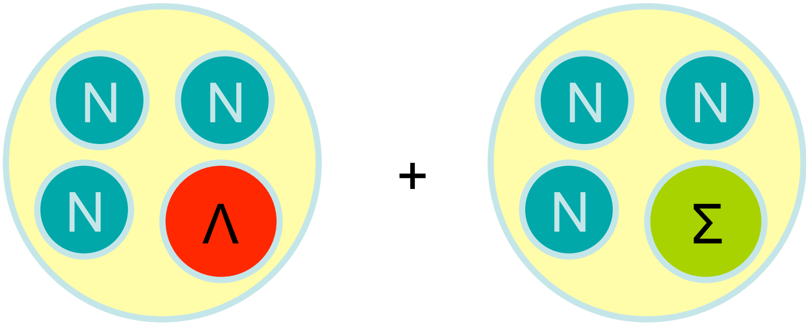
Energy difference comes from dominantly Coulomb force between 2 proton.
Charge symmetry breaking effect is very small.

In S=-1 sector

Exp.



In order to explain the energy difference, 0.35 MeV,



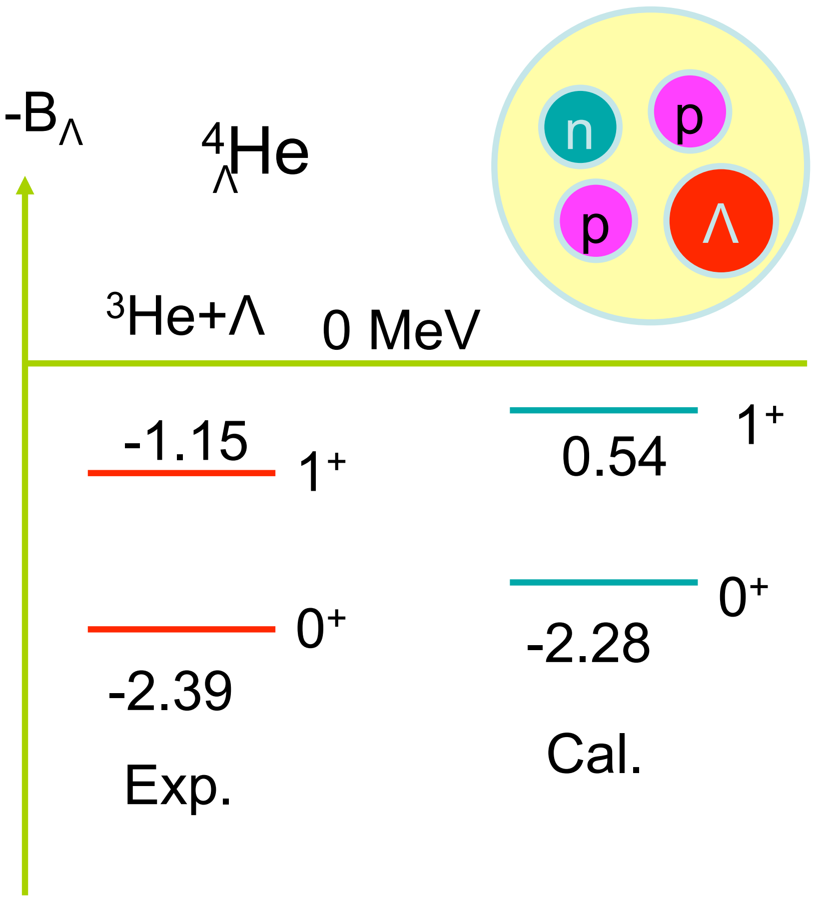
(3N+Λ)   (3N+Σ)

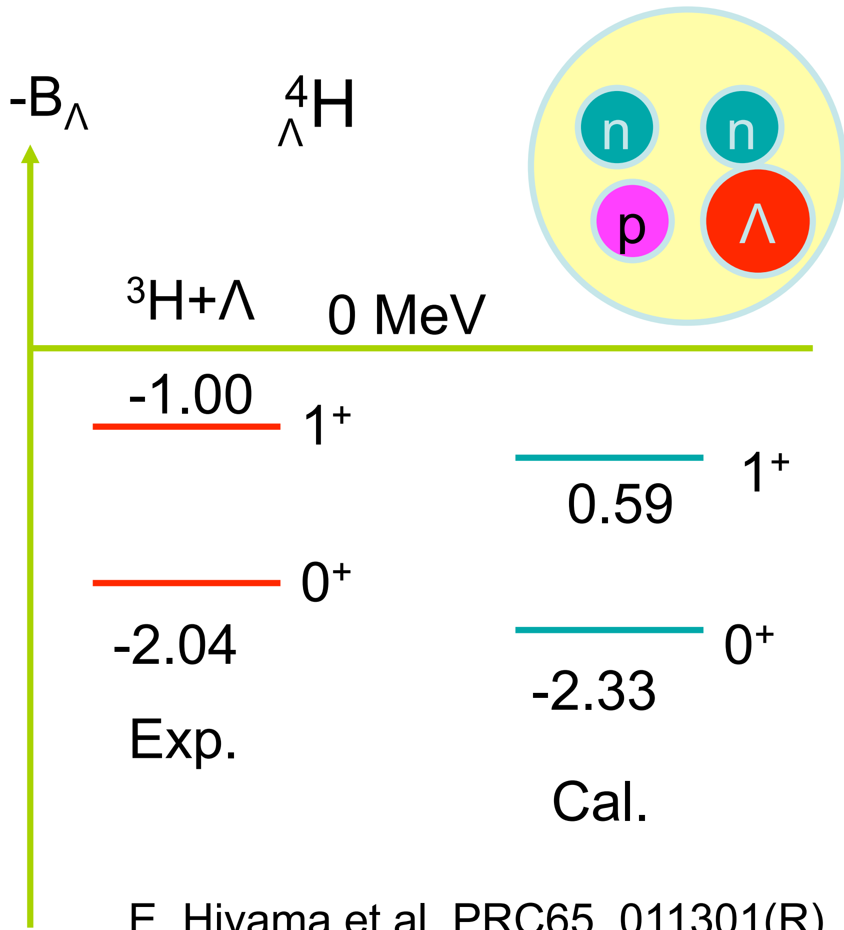
- E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. C65, 011301(R) (2001).

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

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

Coulomb potentials between charged particles (p, $\Sigma^{\pm}$) are included.





E. Hiyama et al. PRC65, 011301(R) (2001)

Λ-separation energy: B_Λ

The energy difference between the ground state of ${}^{4}_{\Lambda}\mathrm{He}$ and that of ${}^{4}_{\Lambda}\mathrm{H}$

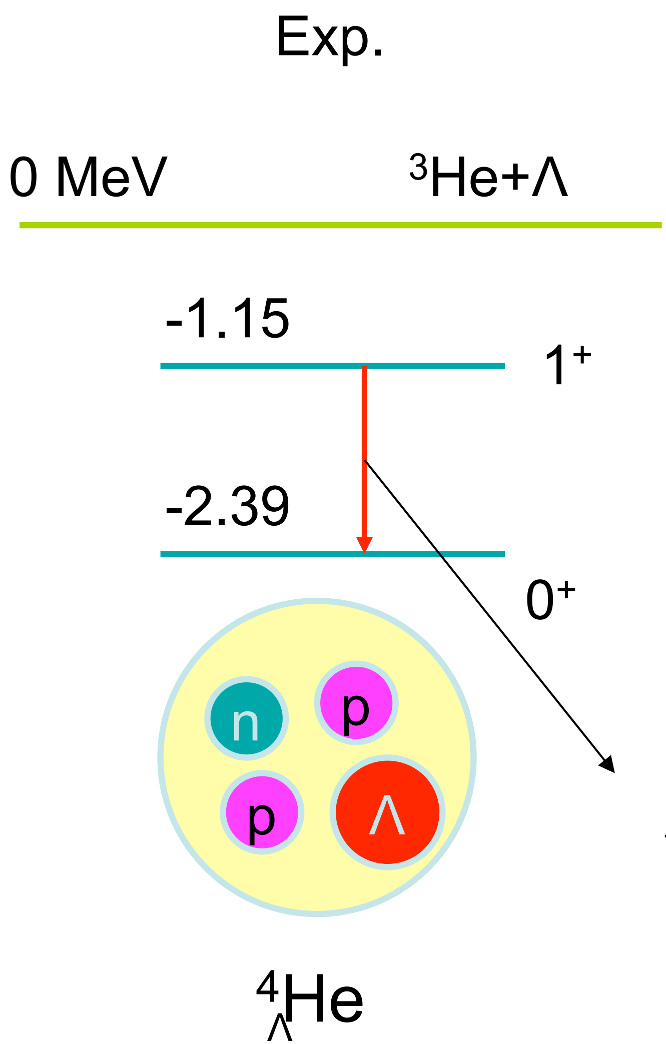
Exp. 2.39-2.05=+0.35 MeV

↕ inconsistent

Cal. 2.28-2.33 =-0.05 MeV

Nobody could succeed in reproducing the observed data.

Charge symmetry breaking effect?



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

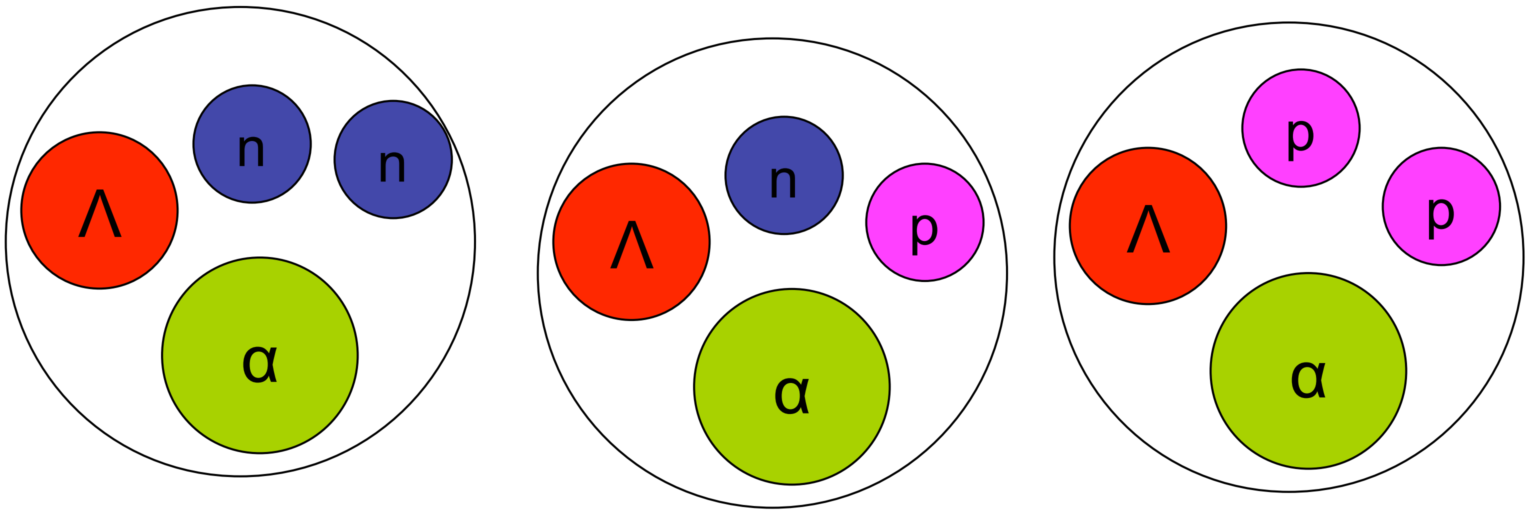
Because the measurement of this data was once reported in 1970's.
At that time, the statistical quality of the $^4_\Lambda$He γ- ray spectrum was extremely poor.

このγ線を測定することで、
相対エネルギーを精度よく測る。
しかし、CSBを知るためには、
B_Λが本当のところ、知りたい

・E13 "γ-ray spectroscopy of light hypernuclei" by Tamura and his collaborators
Day-1 experiment

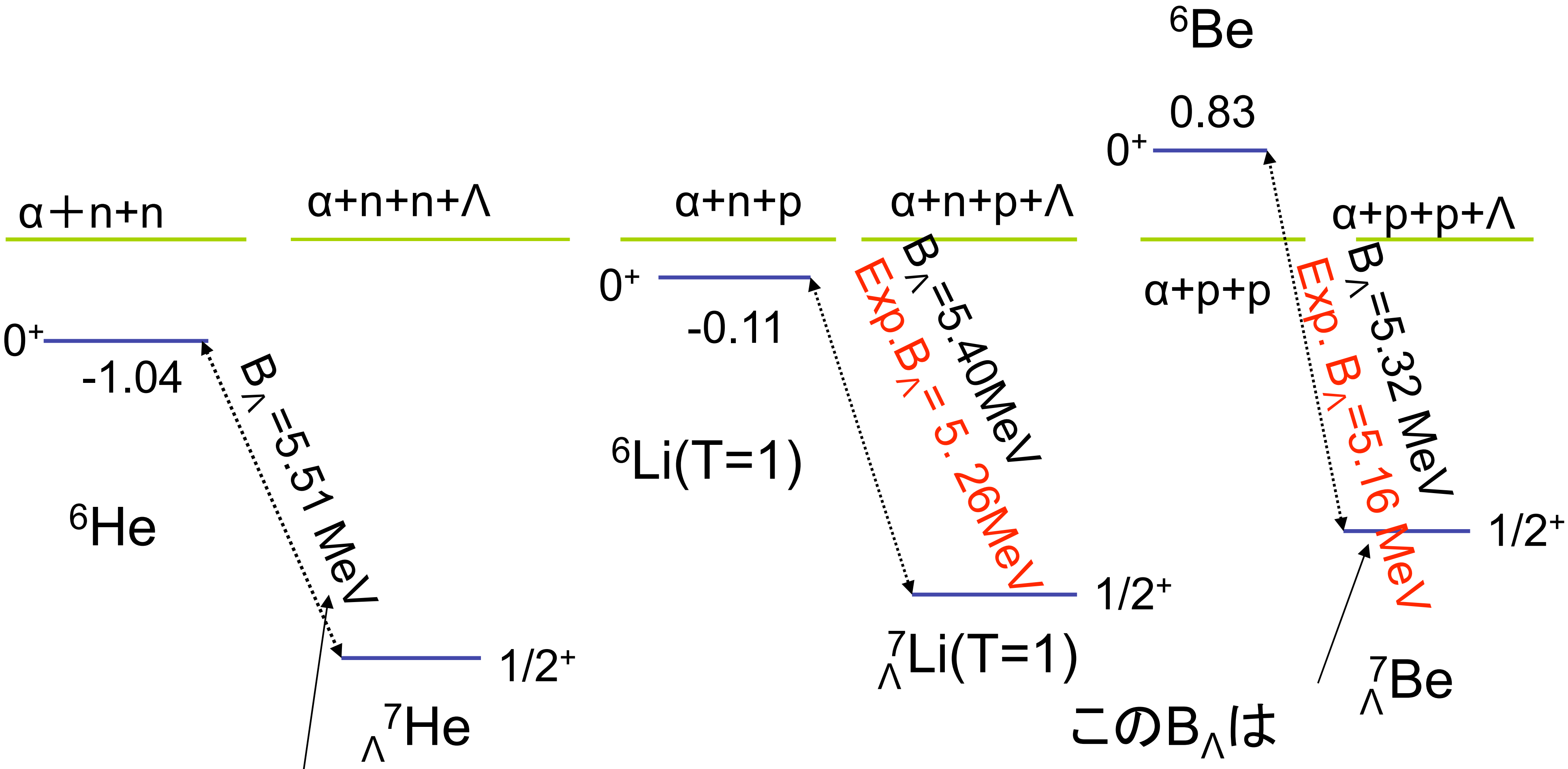
We should wait for their data at J-PARC.

そこで、CSBを知るために、下記のハイパー核の
B_Λ測定を提案（ずっと昔に谷田さんが提案したらしい、が
忘れた）。



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

A=4,7,9,10、13を再現するΛN相互作用を使用する。



このBΛは
doubtful

実験で、このBΛが分かれば、
CBSの効果が分かる。

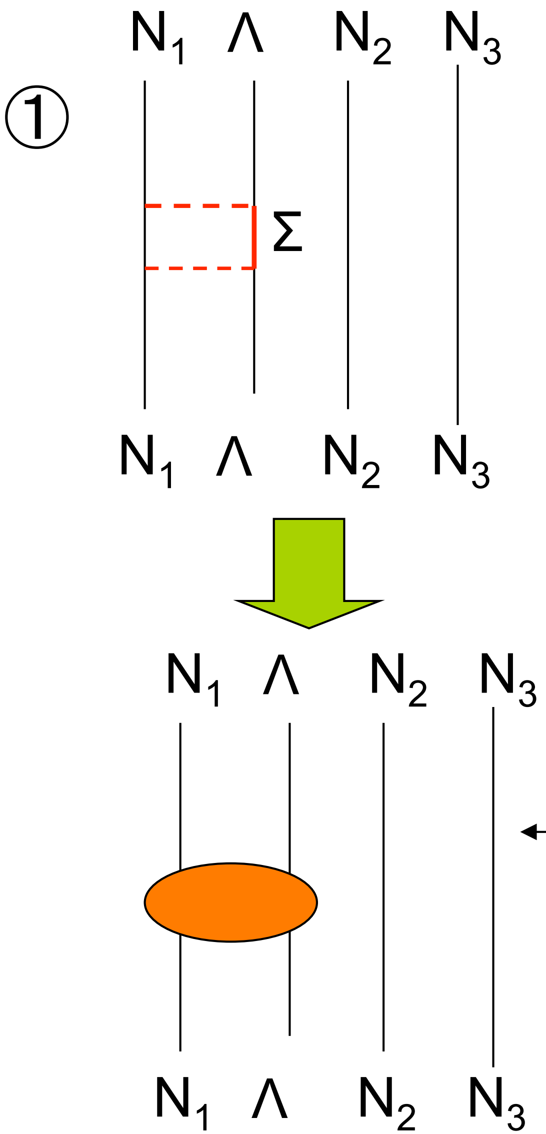
本来CBSが効けば、
BΛは大きくなるはず

JLABでの実験が
待ち望まれる。

しかし、Λ7Beの実験は不可能

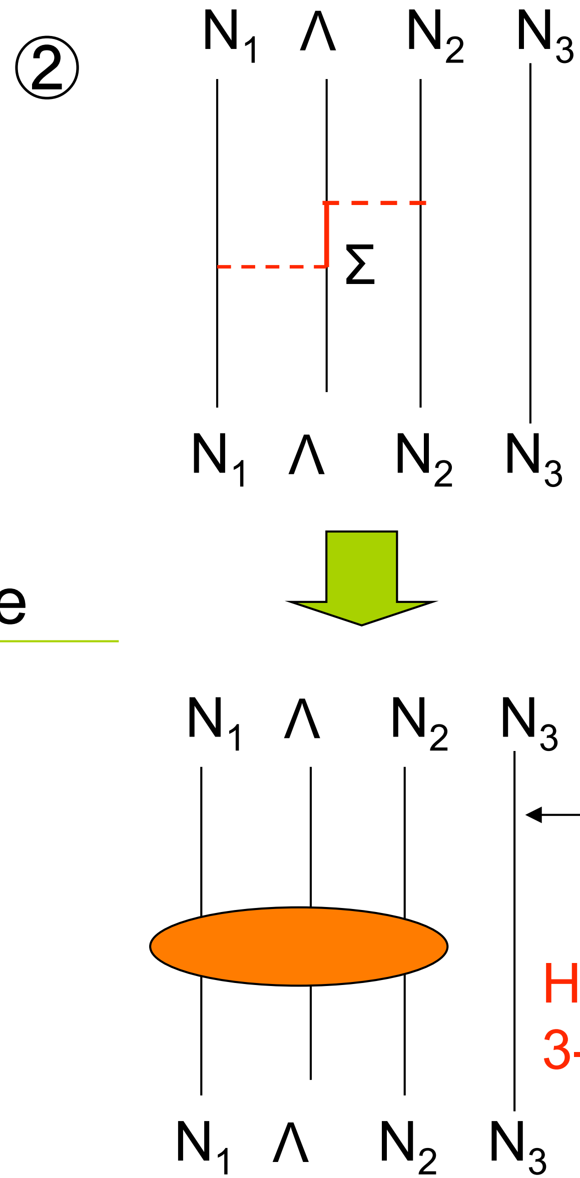
(2) ΛN-ΣN coupling

2通りある。



← Effective 2-body ΛN force

3N+Λ space

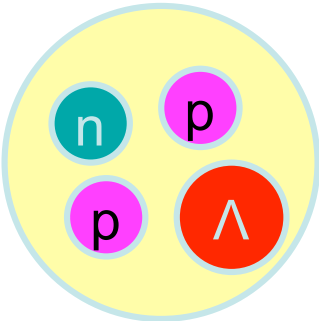


← Effective 3-body ΛNN force

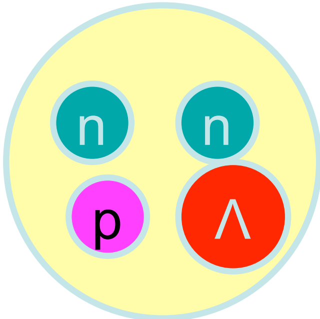
How large is the 3-body effect?

Recently, Akaishi et al. pointed out that the contribution of the effective ΛNN three-body force is large in the ground state of A=4 Λ hypernuclei.

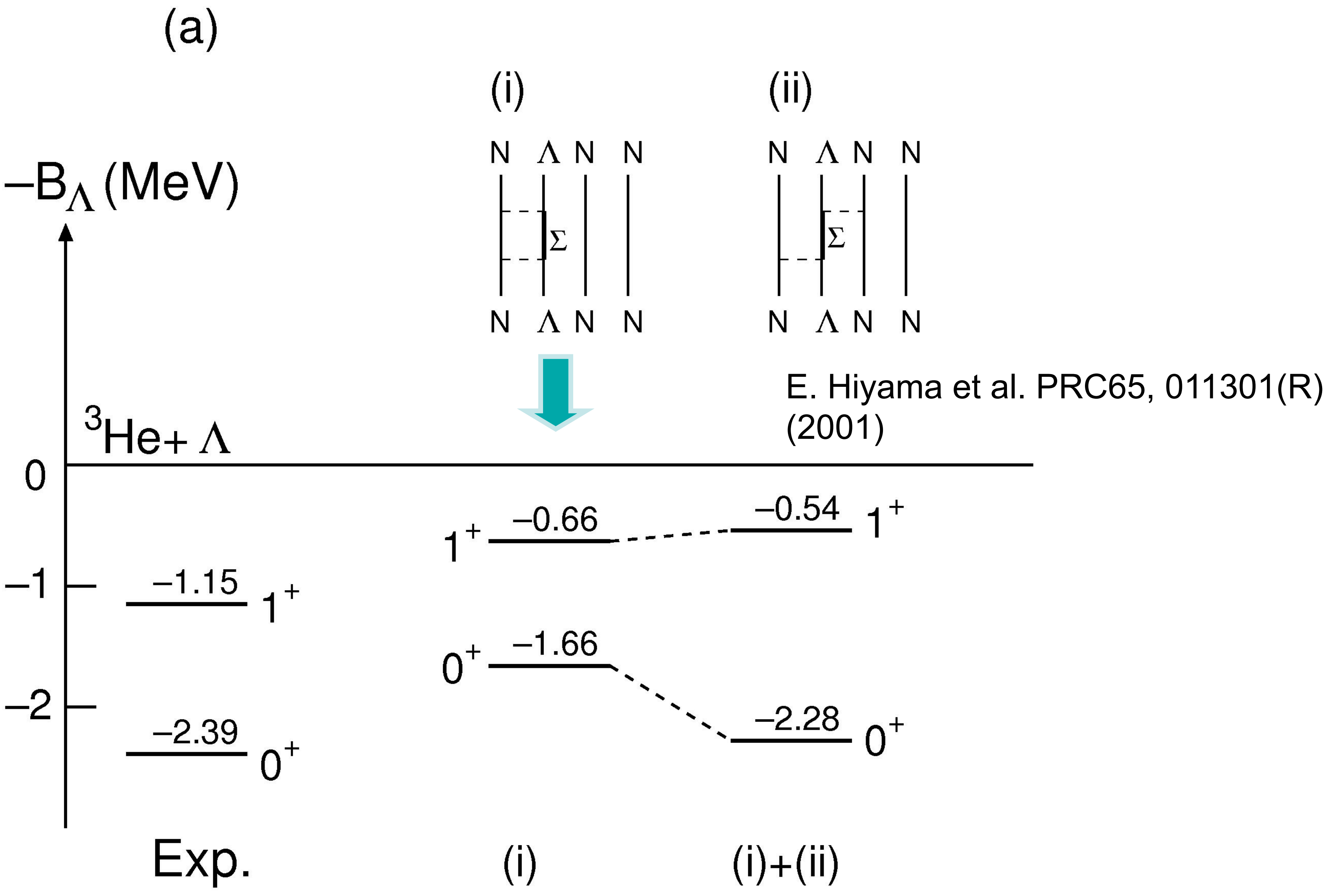
Akaishi et al. Phys. Rev. Lett. 84, 3539 (2000).



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



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



$^4_\Lambda$He

The systematic study of structure of light hypernuclei is necessary.

・E13 “γ-ray spectroscopy of light hypernuclei” by Tamura and his collaborators
Day-1 experiment

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

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

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

これらの核で、ΛN－ΣN結合のどの部分を明らかにしようとするのか？

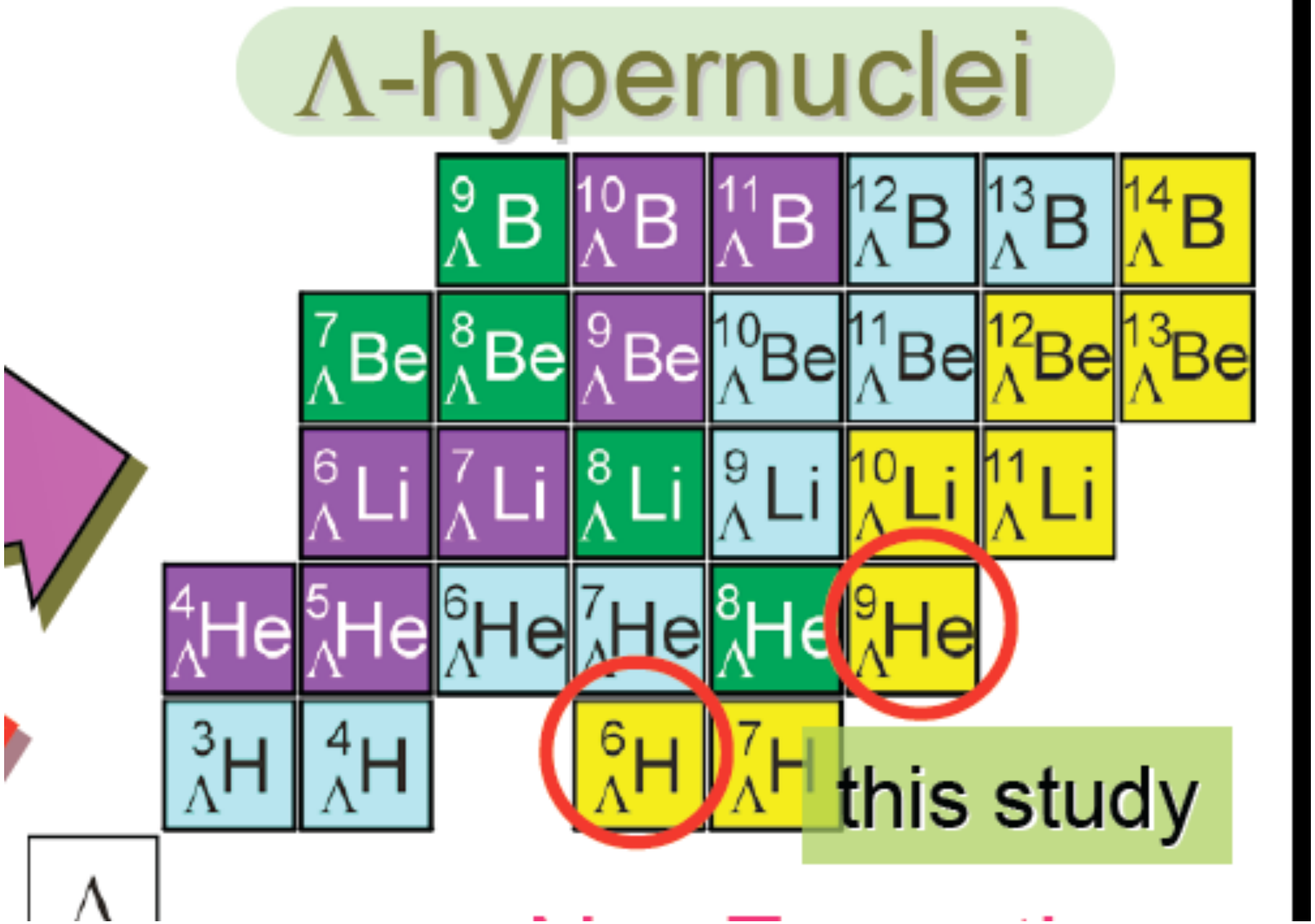
ΛN-ΣN結合が2体力に繰り込めることがdominantであれば、この結合をあからさまに入れて解く必要もないだろうに･･。

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

２体力として繰り込めるとすると、Millenerの計算でtensorが小さいのは本当だろうか？
ΛN－ΣN結合は、tensor型である。したがって、繰り込みは、Tensorにも効くだろう。
実際に、${}^4_\Lambda$H、${}^4_\Lambda$HeでΛNのtensorがかなり効くことは経験上知っている。

もう一度、tensorまで入れて、系統的計算が必要だと思っている。

・ΛN-ΣN結合（３体力＋２体力）に関する情報を引き出すためには、中性子過剰ラムダハイパー核の系統的研究が必要？



Drip-lineを系統的に計算して求める。
殻模型が適している？

Figure
By Sakaguchi

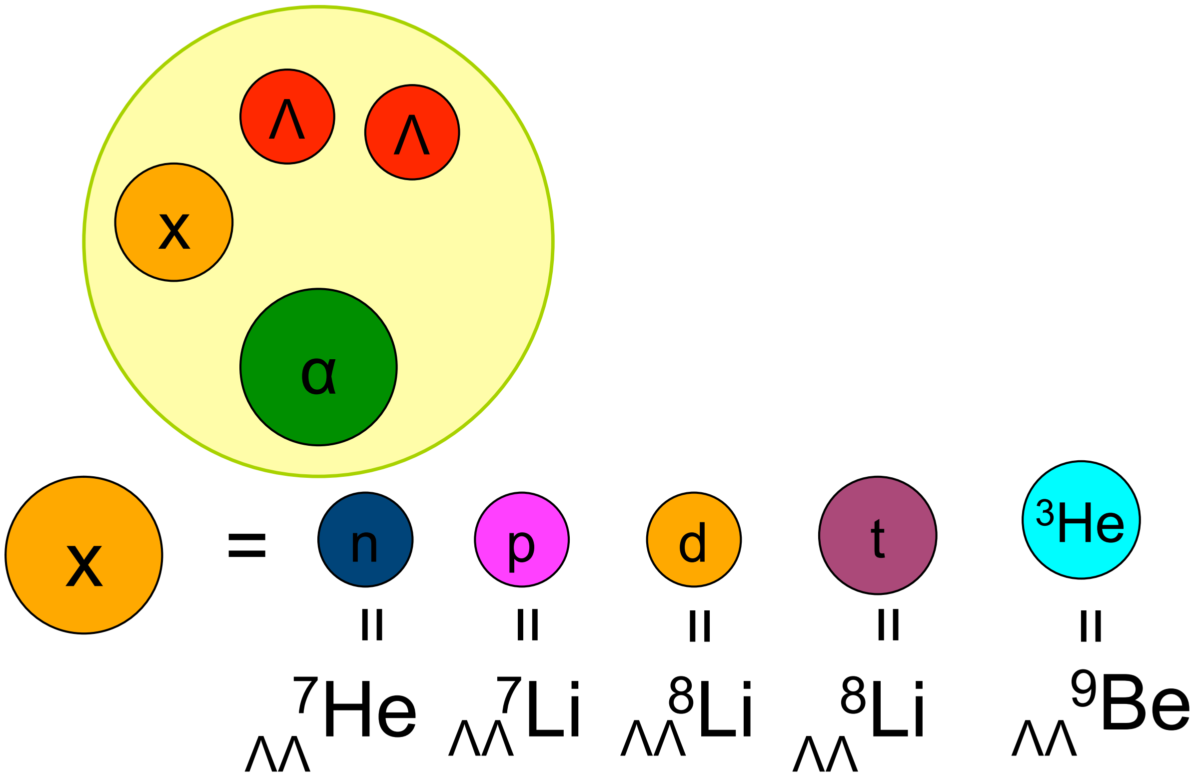
In S=-2 sector, the most important subjects still to be studied

(1)ΛΛ—ΞN coupling

(2)ΞN-ΞN interaction

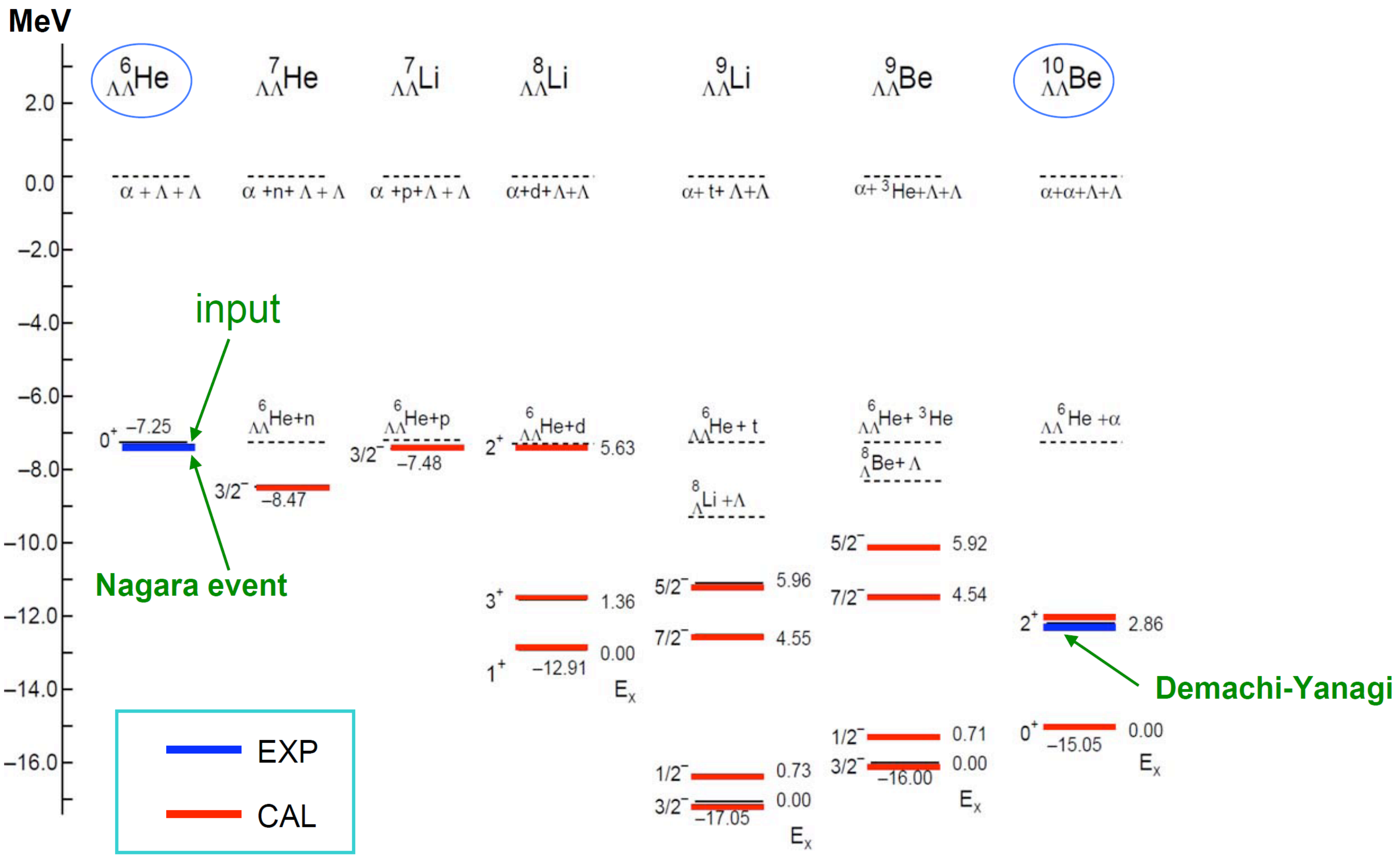
Therefore, the 4-body calculation has predictive power.
Hoping to observe new double Λ hypernuclei in future experiments,
I have predicted level structures of these double Λ hypernuclei
within the framework of the α+x+Λ+Λ 4-body model.

E. Hiyama, M. Kamimura, T. Motoba, T.Yamada and Y. Yamamoto
Phys. Rev. C66, 024007 (2002)



Spectroscopy of ΛΛ-hypernuclei

E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) 024007



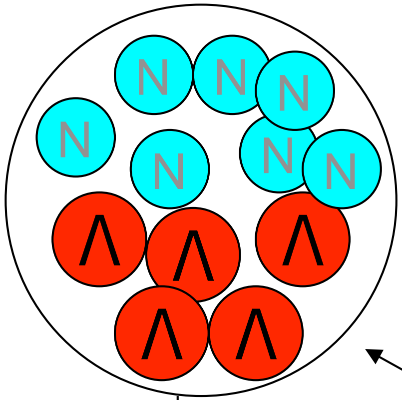
By comparing this theoretical prediction and future experimental data, we can interpret the spectroscopy of those double **Λ** hypernuclei.

ダブルΛ核については、実験待ち。
しかし、実験はweak decay processを見るはず。
ダブルΛ核のweak decayの理論的研究はなされてきたのか？

なされていないなら、今後の実験解析のために行うべきではないか？

(1)ΛΛ-ΞN coupling

One of the major goals in hypernuclear physics
To study structure of multi-strangeness systems
(extreme limit : neutron star)

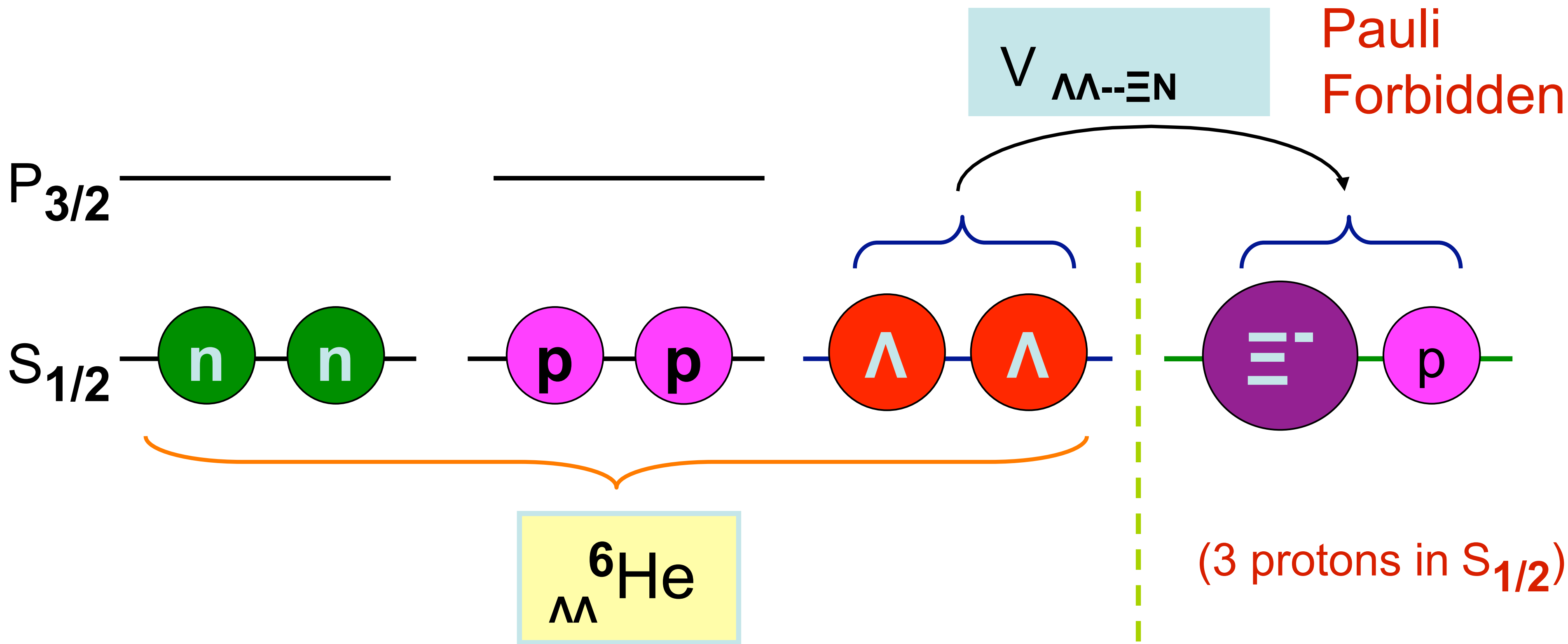


Multi-strangeness systems

threshold energy difference is very small!

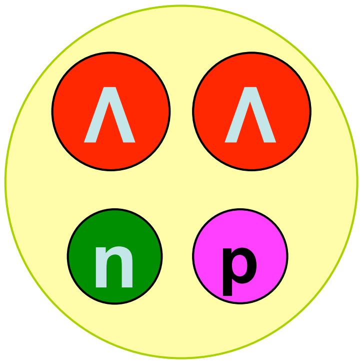
It is considered that
ΛΛ→ΞN particle conversion
is strong in multi-strangeness system.

Effect of ΛΛ—ΞN coupling is small in ${}^{6}_{\Lambda\Lambda}He$ which was observed as NAGARA event.

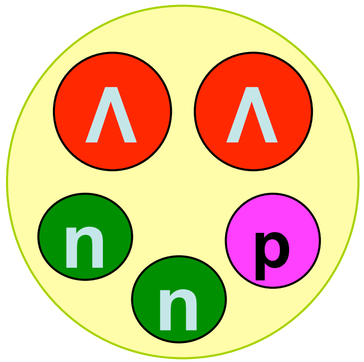


- I.R. Afnan and B.F. Gibson, Phys. Rev. C67, 017001 (2003).
- Khin Swe Myint, S. Shinmura and Y. Akaishi, nucl-th/029090.
- T. Yamada and C. Nakamoto, Phys. Rev.C62, 034319 (2000).

For the study of **ΛΛ**−**Ξ**N coupling interaction, s-shell double **Λ** hypernuclei such as $_{\Lambda\Lambda}^{4}\mathrm{H}$ and $_{\Lambda\Lambda}^{5}\mathrm{H}$ ($_{\Lambda\Lambda}^{5}\mathrm{He}$) are very suitable.

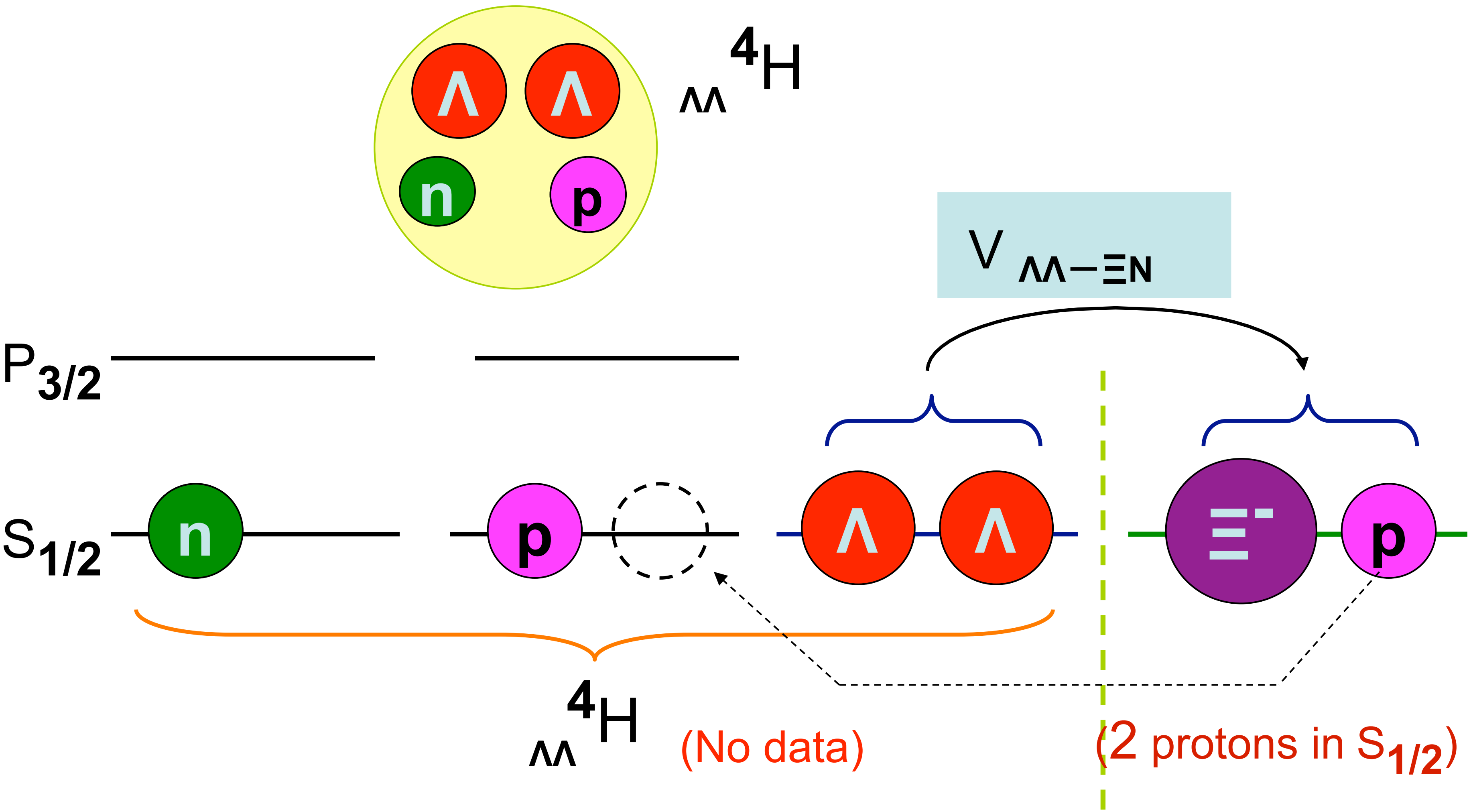


$_{\Lambda\Lambda}^{4}\mathrm{H}$



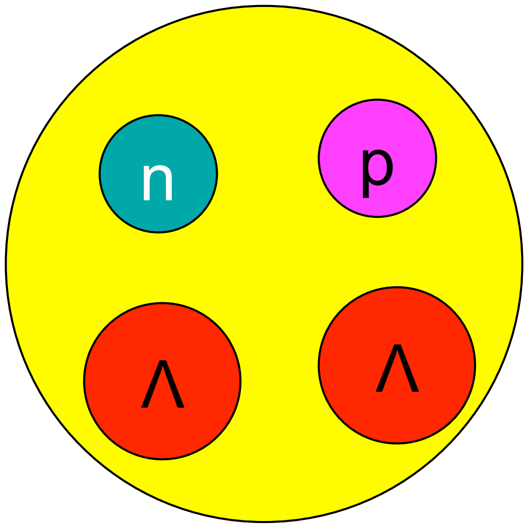
$_{\Lambda\Lambda}^{5}\mathrm{H}$ ($_{\Lambda\Lambda}^{5}\mathrm{He}$)

- I.N. Filikhin and A. Gal, Phys. Rev. Lett. 89, 172502 (2002)
- Khin Swe Myint, S. Shinmura and Y. Akaishi, Eur. Phys. J. A16, 21 (2003).
- D. E. Lanscoy and Y. Yamamoto, Phys. Rev. C69, 014303 (2004).
- H. Nemura, S. Shinmura, Y. Akaishi and Khin Swe Myint, Phys. Rev. Lett. 94, 202502 (2005).



Due to NO Pauli plocking, the ΛΛ−ΞN coupling can be large in $_{\Lambda\Lambda}^{4}$H

B.F. Gibson, I.R. Afnan, J.A.Carlson and D.R.Lehman, Prog. Theor. Phys. Suppl. 117, 339 (1994).



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

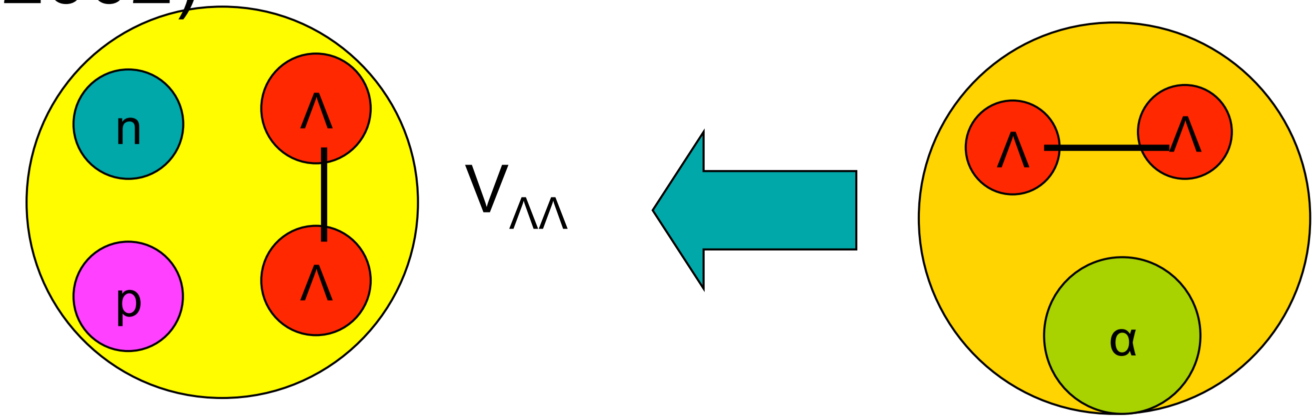
The important issue:

Does the YY interaction which designed to reproduce the binding energy of $_{\Lambda\Lambda}{}^{6}He$ make $_{\Lambda\Lambda}{}^{4}H$ bound?

And how does the effect of ΛΛ—ΞN coupling play important role in the binding energy of $_{\Lambda\Lambda}{}^{6}He$ and $_{\Lambda\Lambda}{}^{4}H$?

1)I.N. Filikhin and A. Gal, Phys. Rev. Lett. 89, 172502 (2002)

2)H. Nemura, Y. Akaishi et al., Phys. Rev. C67, 051001 (2002)

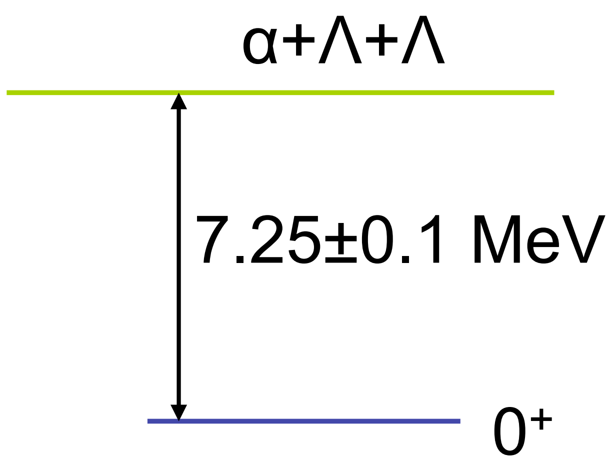


$_{\Lambda\Lambda}^{6}He$

NAGARA event

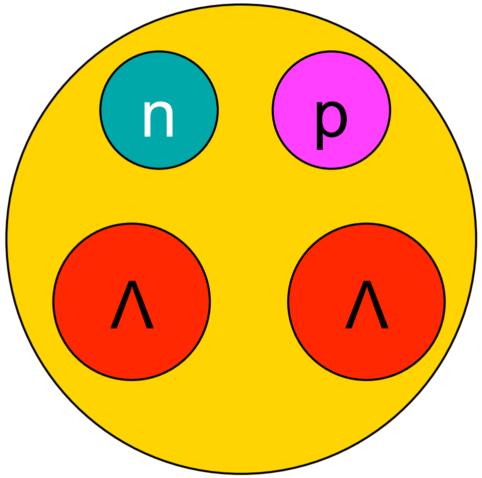
NOT BOUND !

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



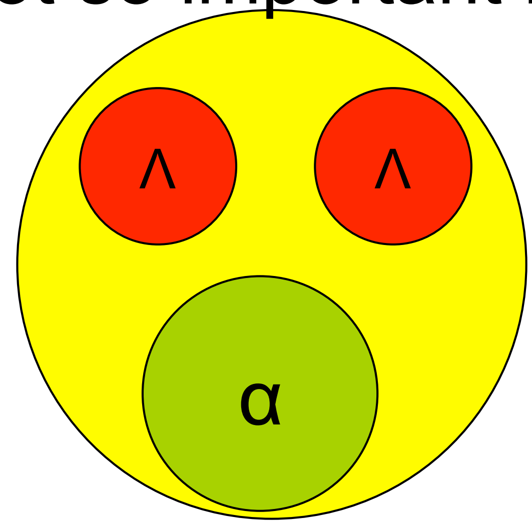
Did not include ΛΛ-ΞN coupling

ΛΛ-ΞN coupling => ・significant in ${}_{\Lambda\Lambda}^{4}H$

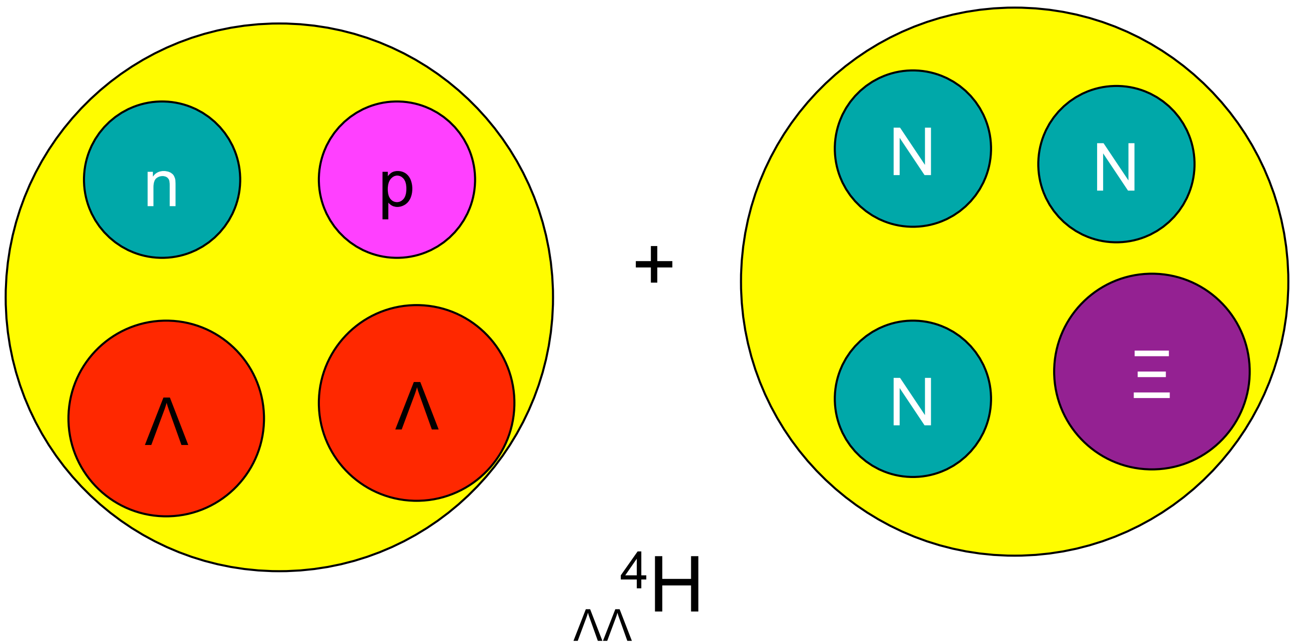


${}_{\Lambda\Lambda}^{4}H$

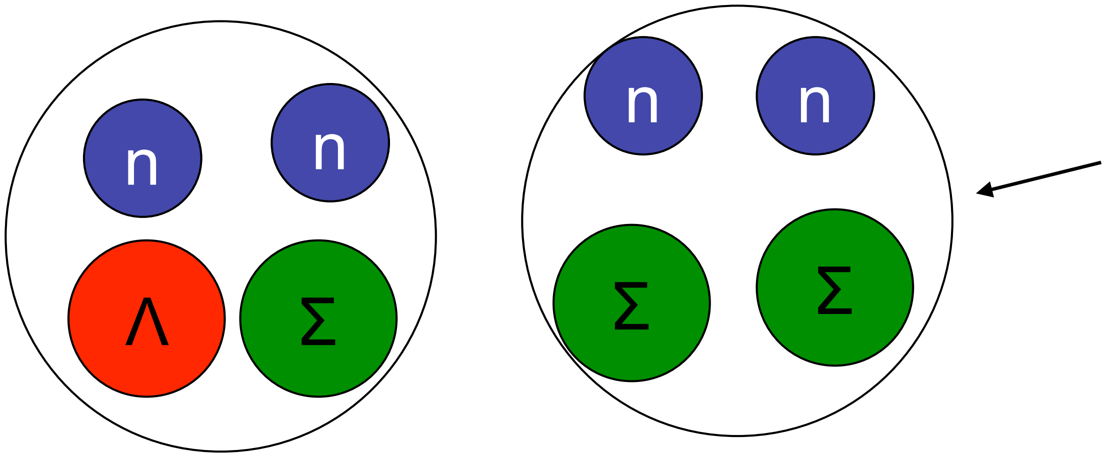
・Not so important in ${}_{\Lambda\Lambda}^{6}He$



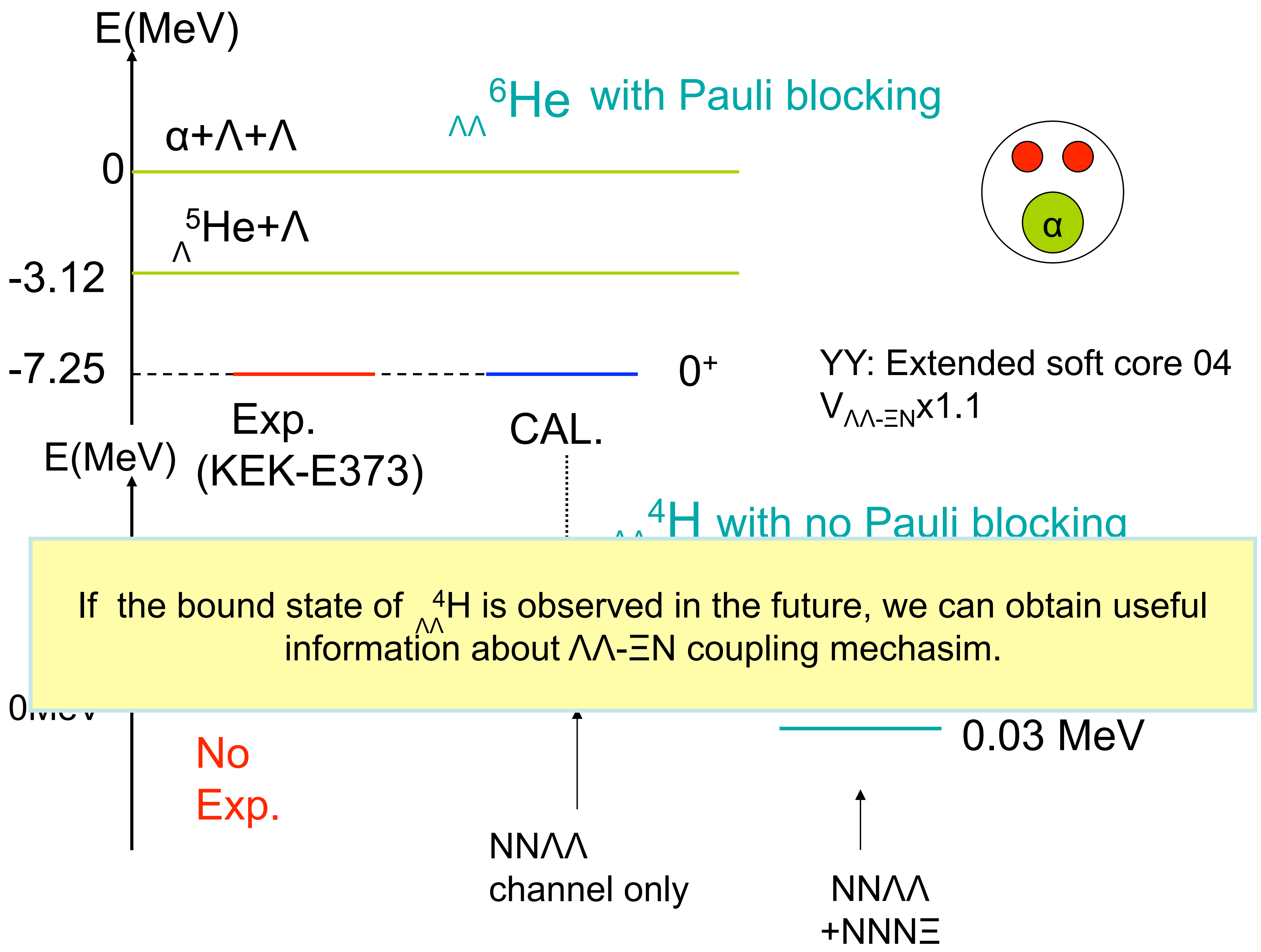
${}_{\Lambda\Lambda}^{6}He$



One of the most numerically difficult 4-body problem



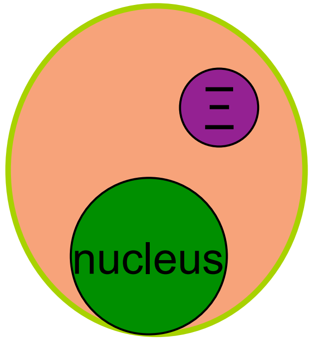
E. Hiyama
Dr. Nemura



If the bound state of $_{\Lambda\Lambda}{}^{4}$H is observed in the future, we can obtain useful information about ΛΛ-ΞN coupling mechasim.

In S=-2 fields, the most important subjects to be still studied

(2)ΞN-ΞN interaction



Ξ hypernucleus

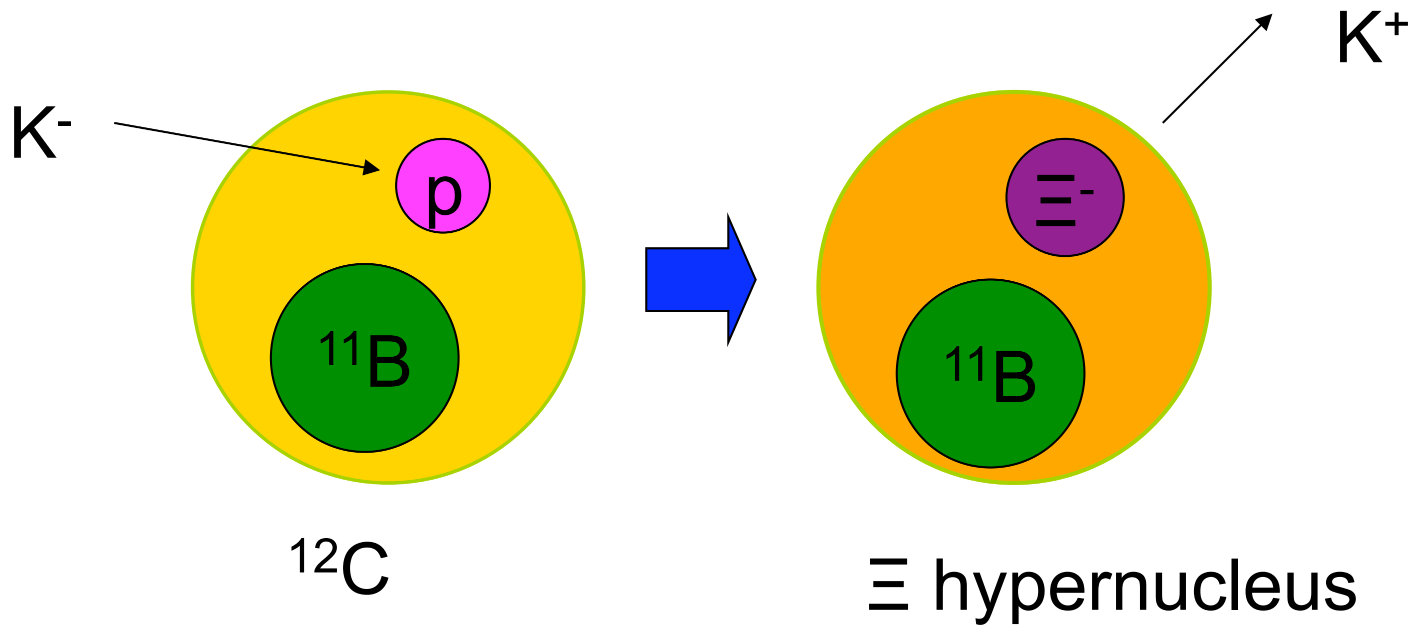
For the study of ΞN interaction, it is important to study structure of Ξ hypernuclei.

However, so far there was no observed Ξ hypernuclei.
Then, it is important to predict theoretically what kinds of Ξ hypernuclei will exist as bound states.

Approved proposal at J-PARC

- E05 "Spectroscopic study of Ξ-Hypernucleus, ^{12}Be, via the $^{12}C(K^-,K^+)$ Reaction" by Nagae and his collaborators

Day-1 experiment



First observation of Ξ hypernucleus

This observation will give information about ΞN interaction.

It is desirable to consider the experiment to produce another Ξ hypernucei after Day-1 experiment.

I know that all experimentalists are so busy in setting up Day-1 experiment and have no time to do future plan. But, I hope you to memorize in your heart….

Theoretical important issue:

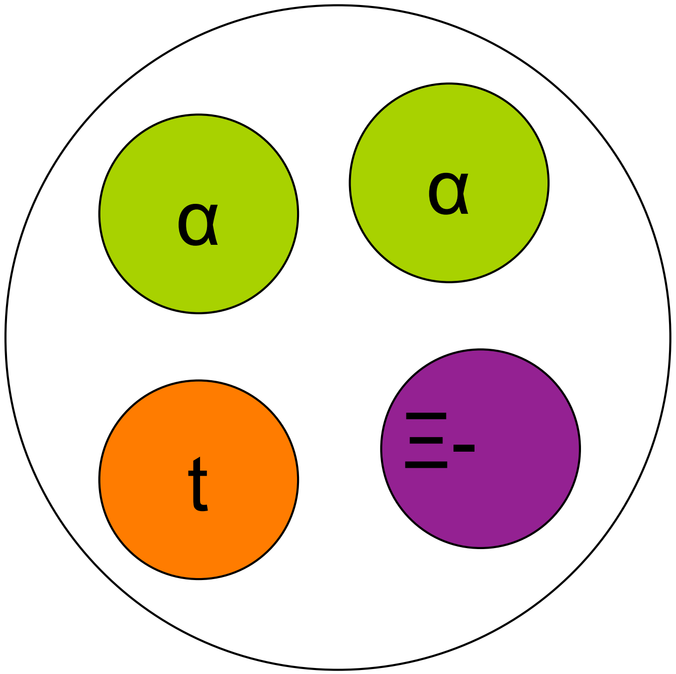
(1) What kind of Ξ hypernuclei including $^{12}_{\Xi}Be(^{11}B+\Xi^-)$ exist as bound state theoretically?

(2)What part of ΞN interaction can we determine from structure of Ξ hypernuclei?

(3) Is it possible to produce Ξ hypernuclei experimentally?

$^{12}C(K^-,K^+)\,{}^{12}_{\Xi^-}Be$ Day-1 experiment

What part information of ΞN interaction do we extract?



T=1, J=1$^-$

$$V_{\Xi N}=V_0+\sigma\cdot\sigma V_{\sigma\cdot\sigma}+\tau\cdot\tau V_1+(\sigma\cdot\sigma)(\tau\cdot\tau)V_2$$

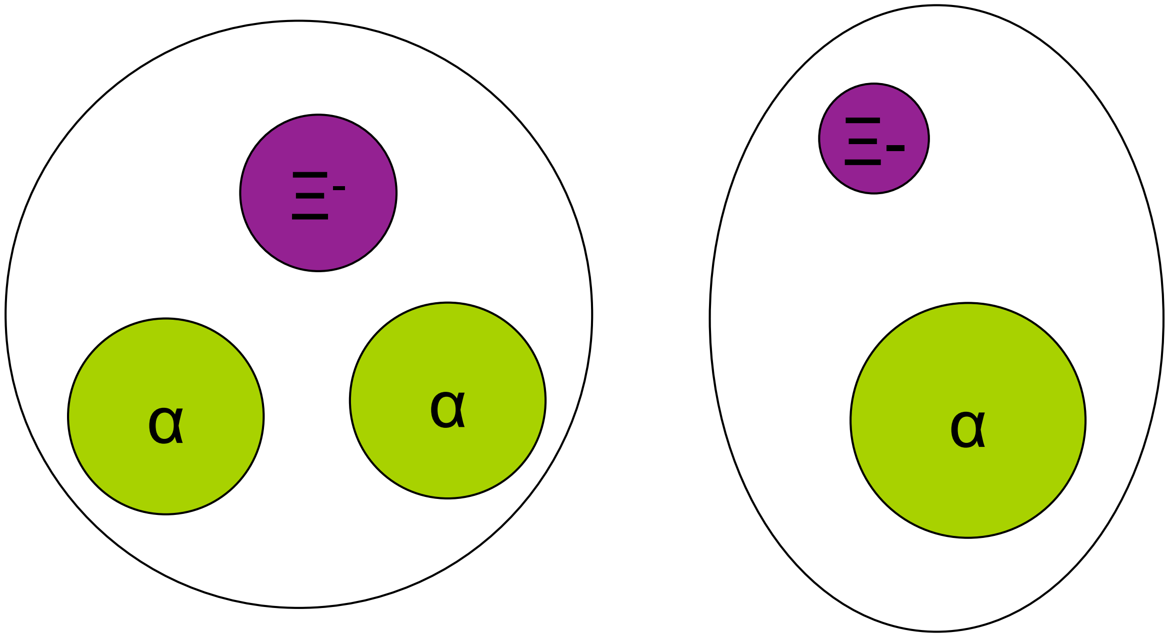
All of these parts contribute to the binding energy of ${}^{12}_{\Xi^-}Be$.

If we get this system as bound state, We know $V_{\Xi N}$ is attractive.

But, we want to know desirable strength of V_0.

spin-,isospin-averaged ΞN interaction

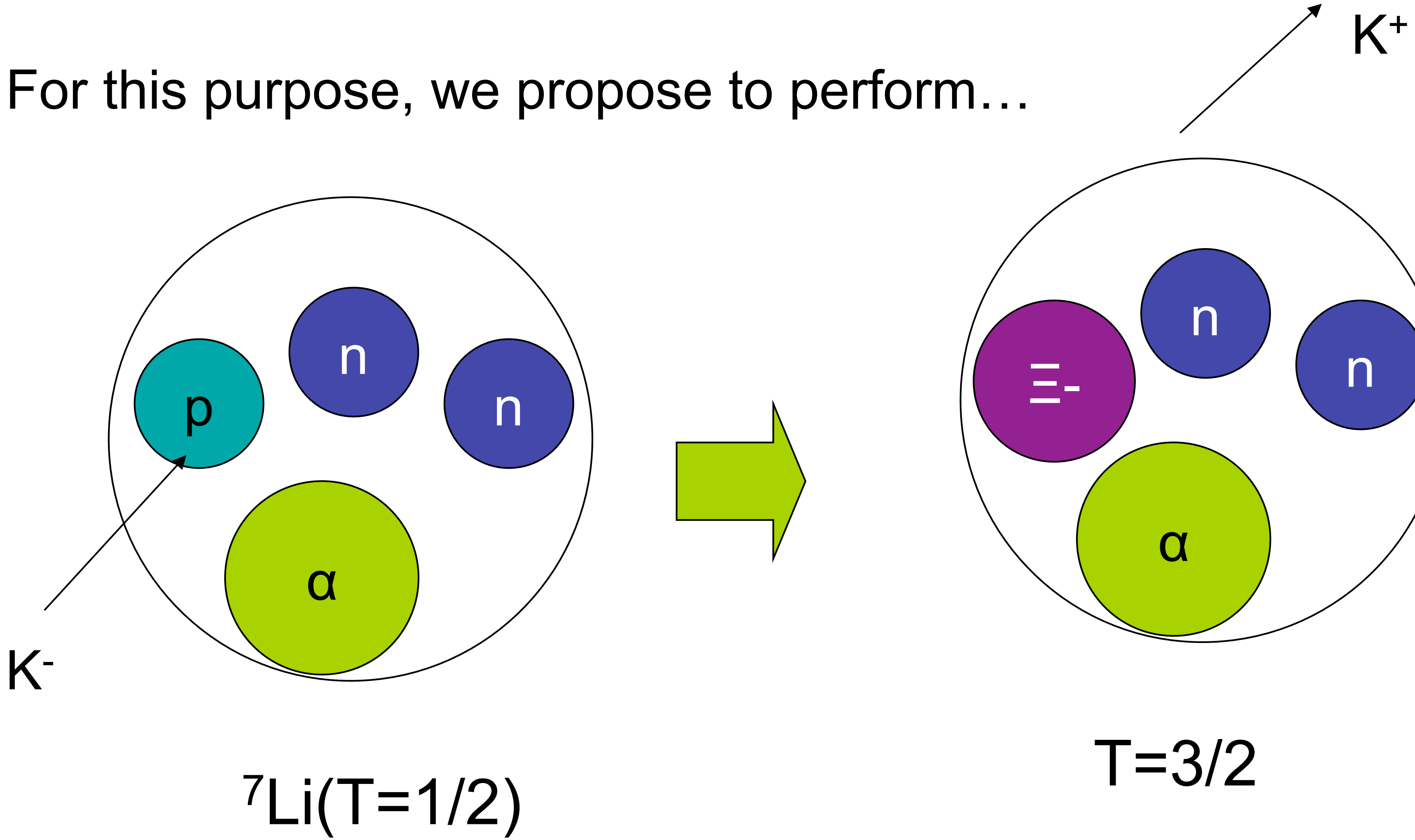
In order to obtain information about V_0,

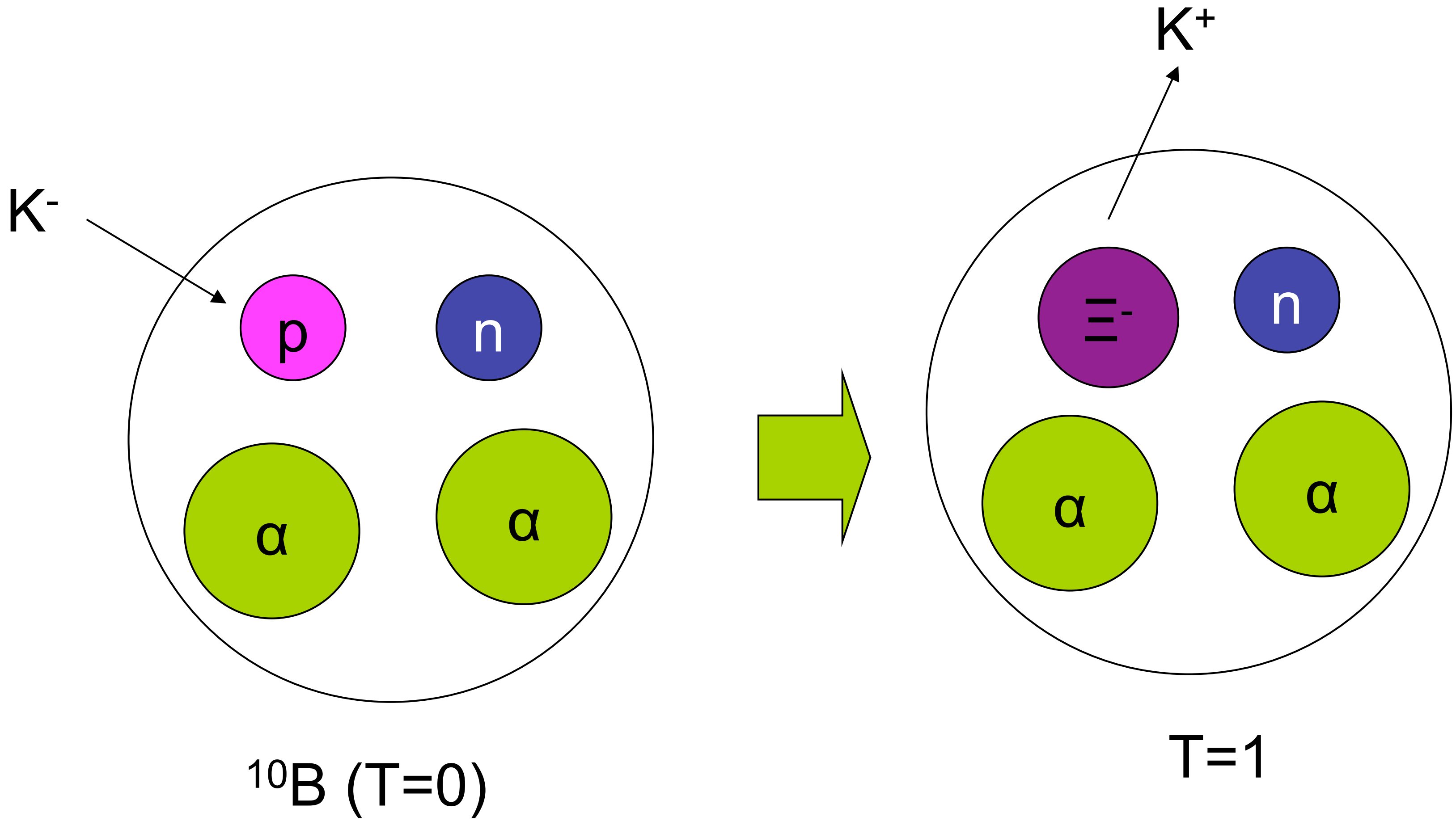


The study of these Ξ hypernuclear structure is suitable.
But, there is NO target to produce them.

How do we extract information about V_0 ?

For this purpose, we propose to perform…





K-
p
n
α
α
^{10}B (T=0)
K+
Ξ-
n
α
α
T=1

ともかく、三ハイパー核については、
Day-1実験の結果を見ないと、重いほうに行くべきか、
軽い方にいくべきか、先が見えないように思える。
したがって、結果待ち。（というのが私の意見）

将来

S=-3に向けて何が面白い？

トリプルΛ核

ΛΛのspin-orbit forceを測る。でも、S=-1の2番煎じ？

ααΛ核にΛ粒子を入れていったときのΛの1粒子軌道の研究？（不安定核研究に近いが・・）

チャーム核、オメガ核

ともかく、相互作用をもらって解いてみる必要があるかも・・。

S=-1ハイパー核で重いほうでのγ線分光

実験的に困難な核が多いので、まず、実験できそうな核をリストアップしてほしい。
理論家はその中で面白そうなことを後付けで行い、大騒ぎするので。

これまで、「こんな核のγ線を測ると面白い」、といっても「実験が難しい」といわれて、rejectされ続けた経験から。