Comments from the theoretical side

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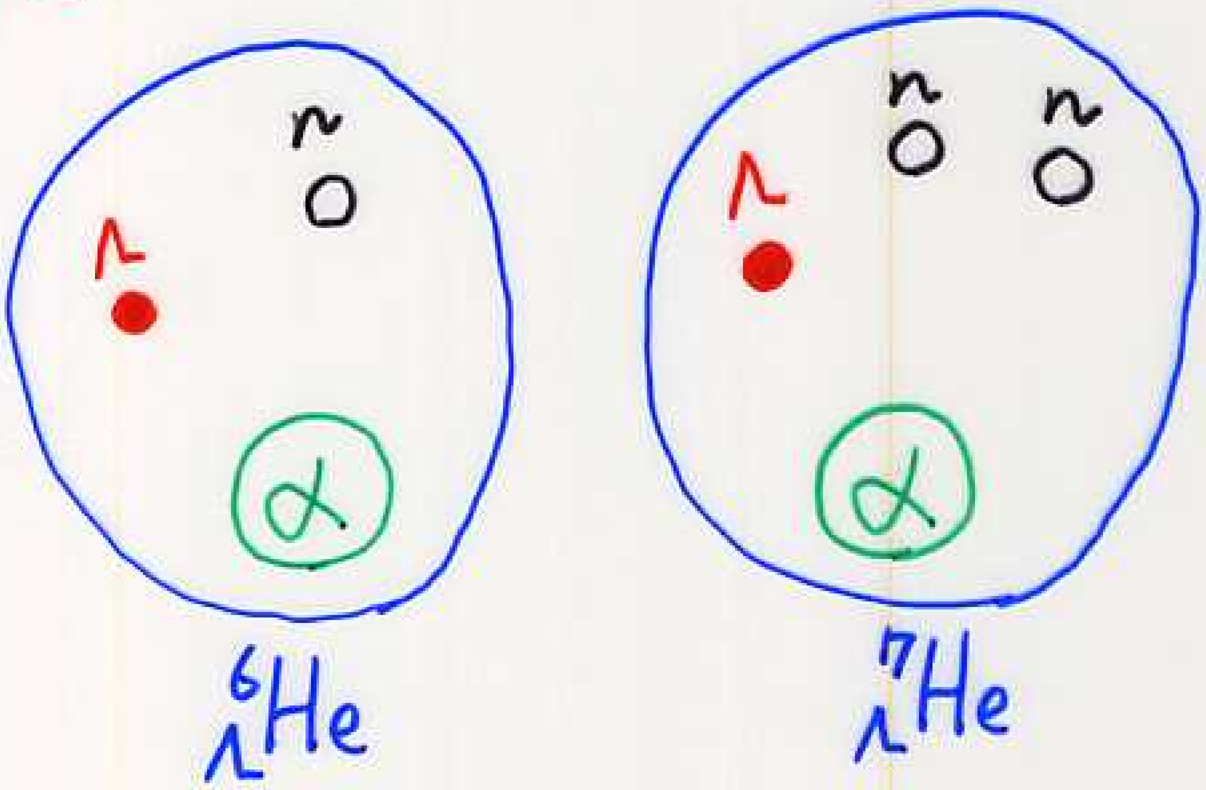
Discussion on my suggestion to future experiments from the theoretical side.

My suggestion to future experiments:

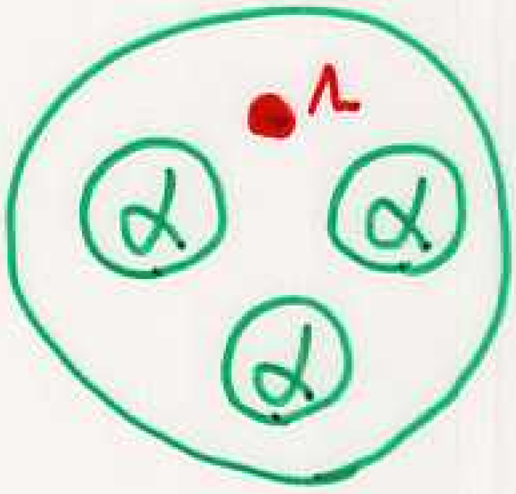
suggestion-1) To observe n- and p-rich hypernuclei

Example



Suggestion - 2) To observe many excited-states in light Λ hypernuclei

Example



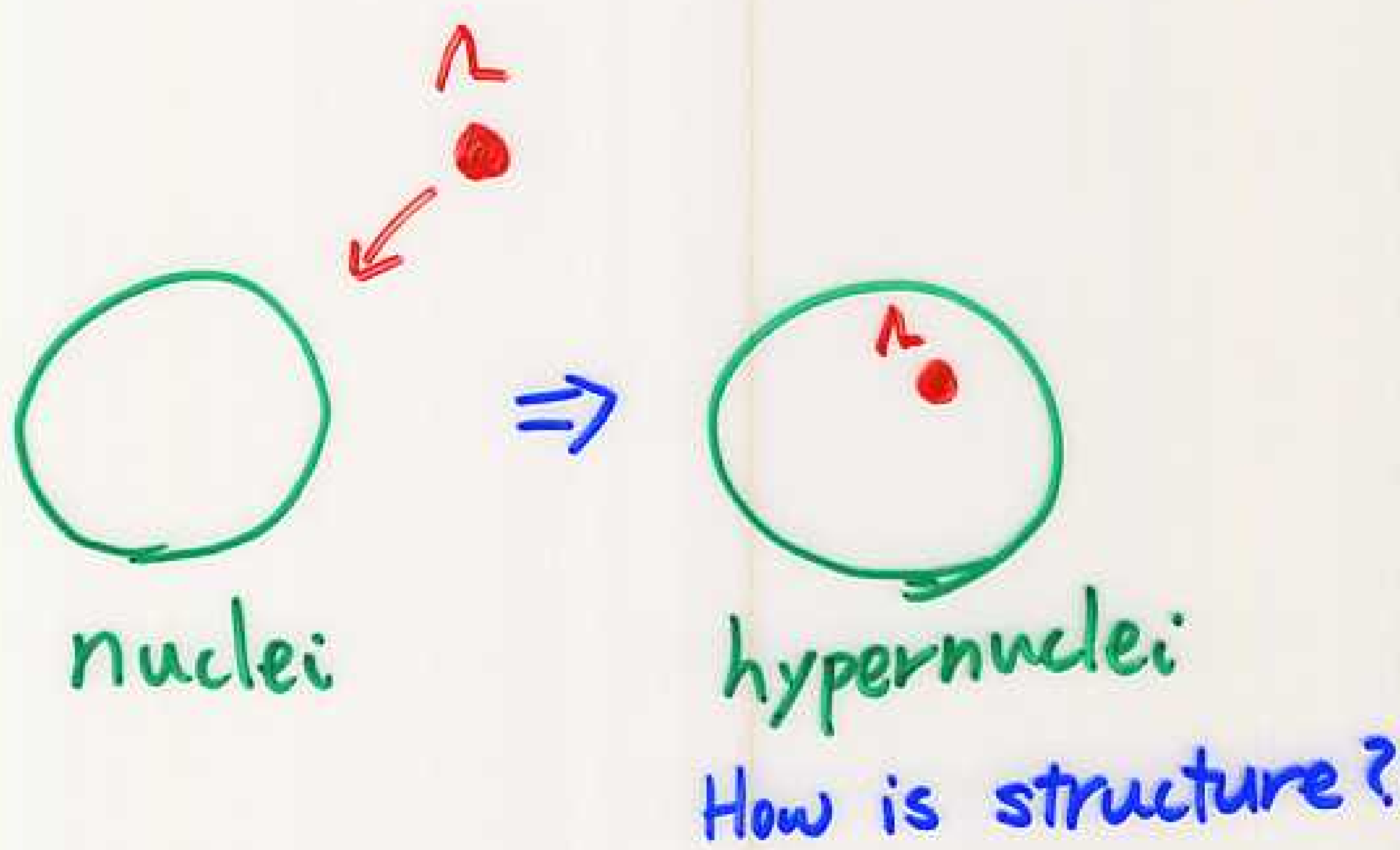
$^{13}_{\Lambda}C$

To observe $1/2^+$, $5/2^-$ and $7/2^-$ in $^{13}_{\Lambda}C$ which is composed of 0_2^+, 3^- states of ^{12}C and 0s Λ particle.

Suggestion - 1) To observe n- and p-rich hypernuclei

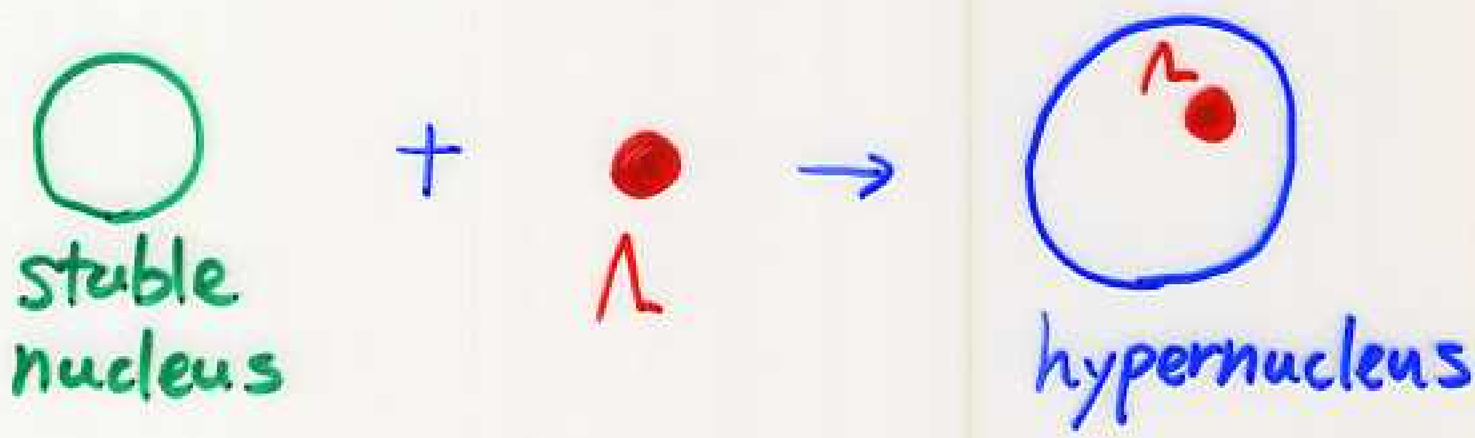
One of the major purpose of hypernuclear physics

To inject an impurity particle, hyperon, into the core nucleus and study new dynamical change of the nuclear structure caused by the impurity member



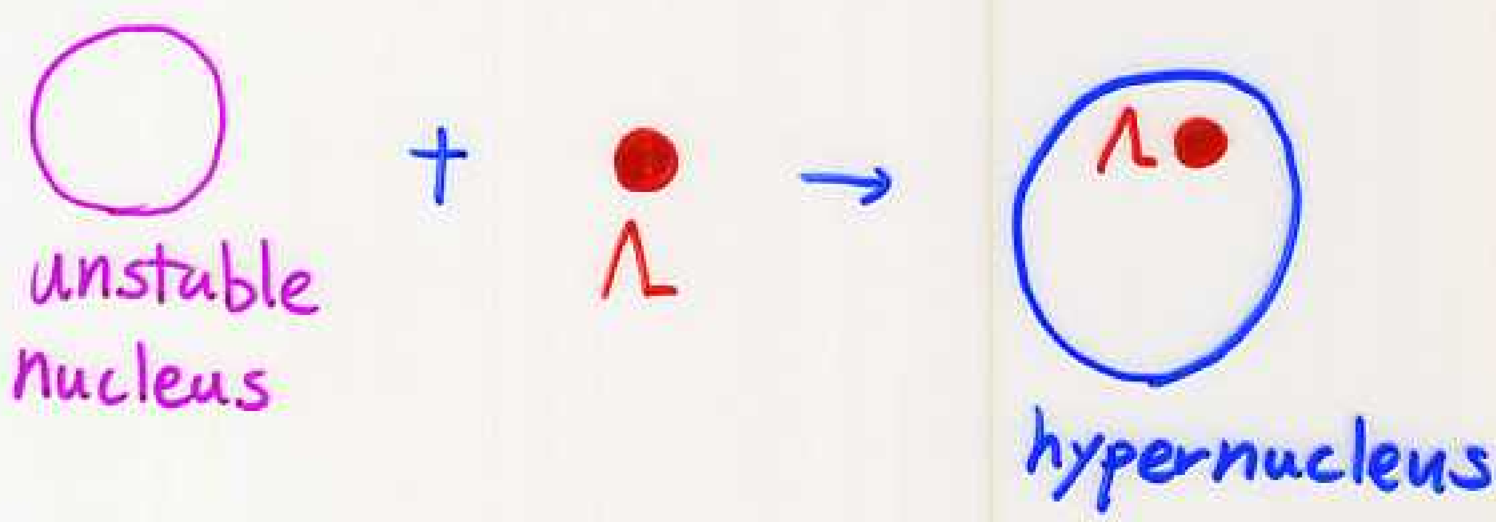
Glue-like role property provide us with another interesting subject.

So far,

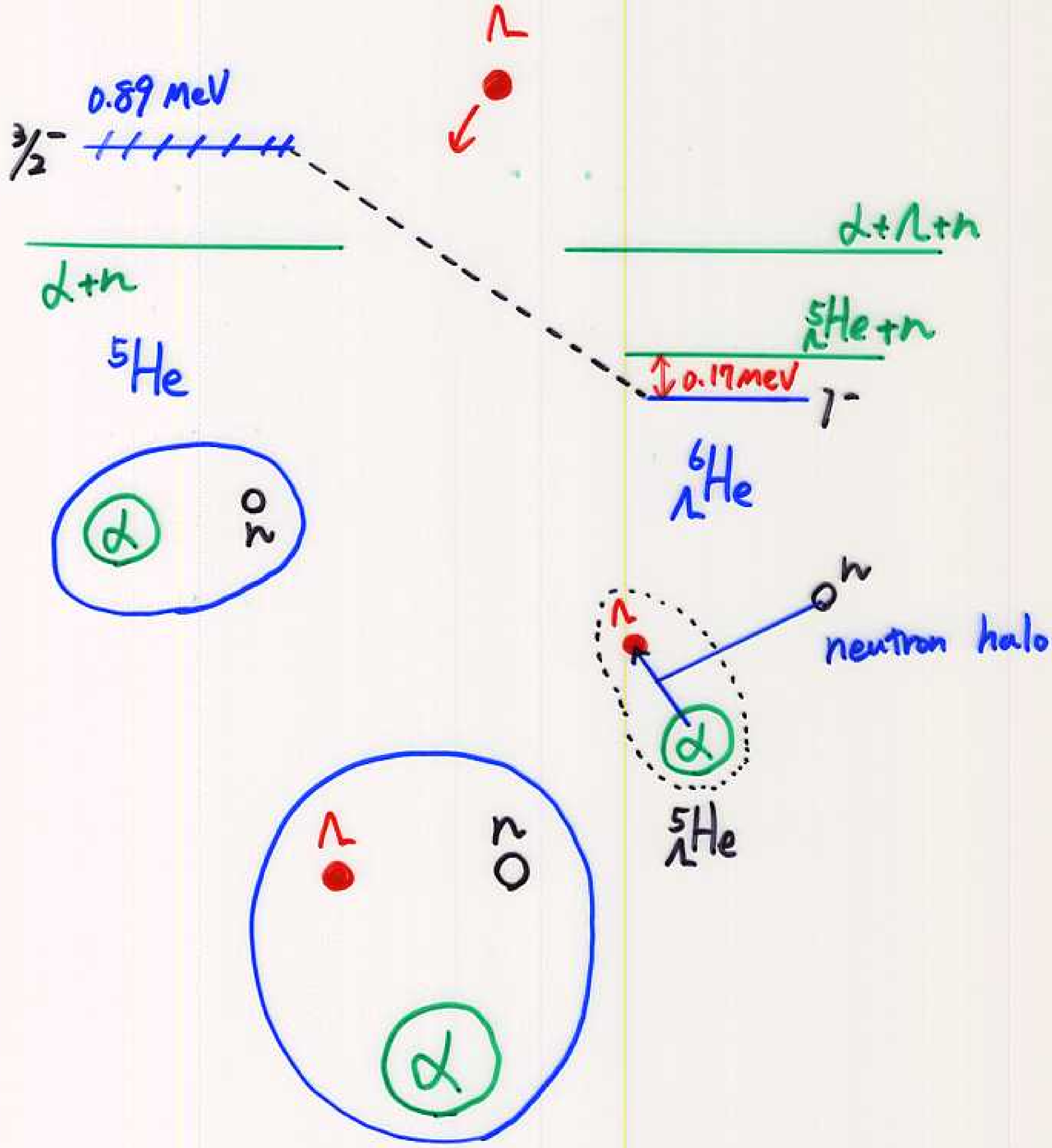


How is structure?

Now,

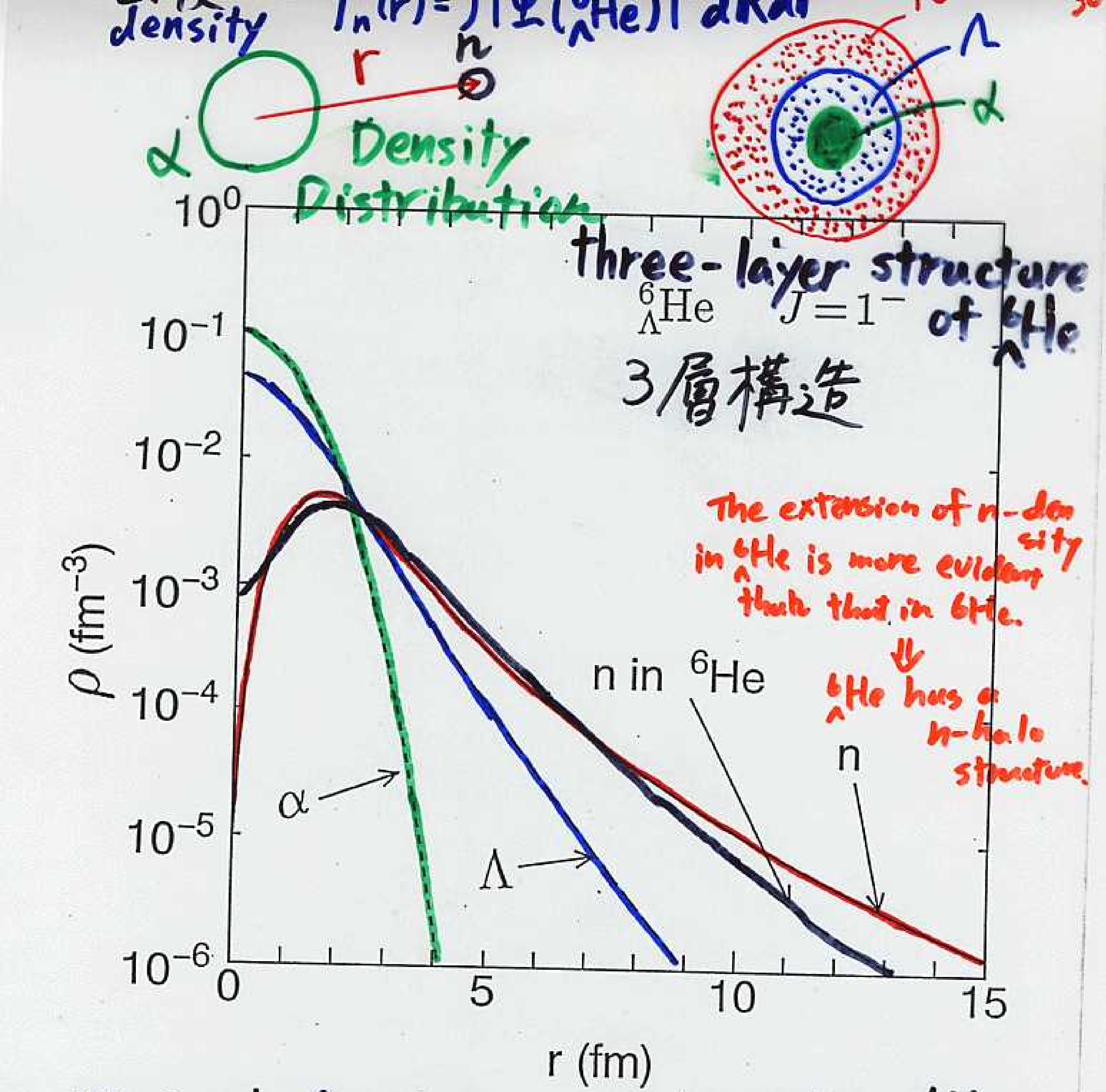


Let us consider to inject the Λ particle to the unstable nucleus.



How do the 3 particles locate to each other?

Is there neutron halo in $^{6}_{\Lambda}He$ hypernucleus?



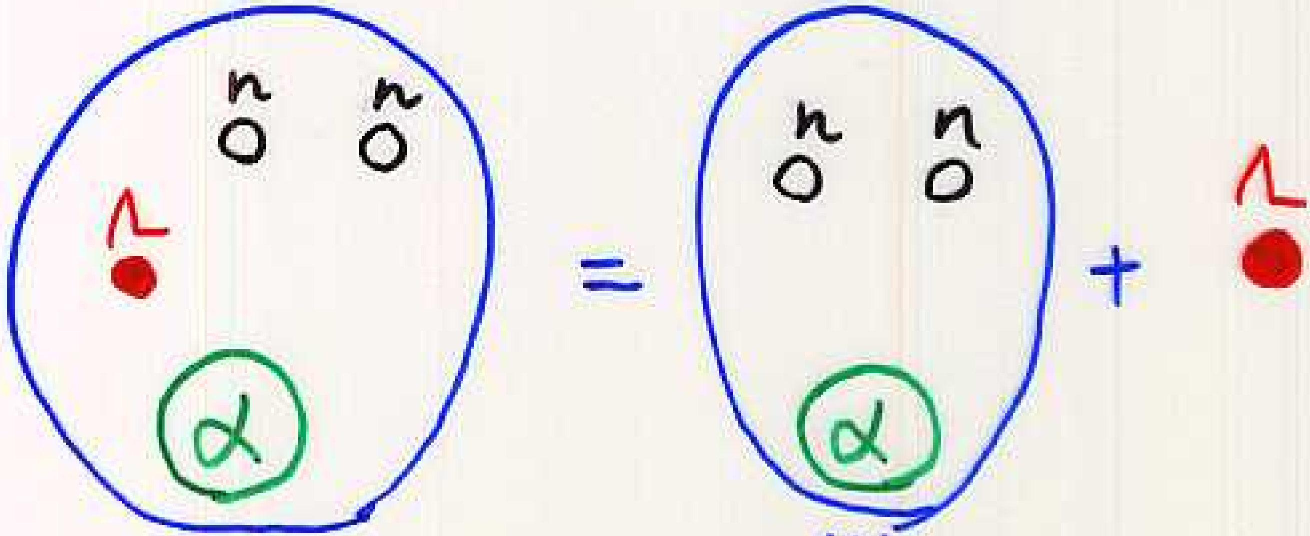
r.m.s α-Λ 2.8 fm halo nuclei ^{6}He

α-n 5.0 fm → α-n 4.5fm

larger than ^{6}He

Fig. 2

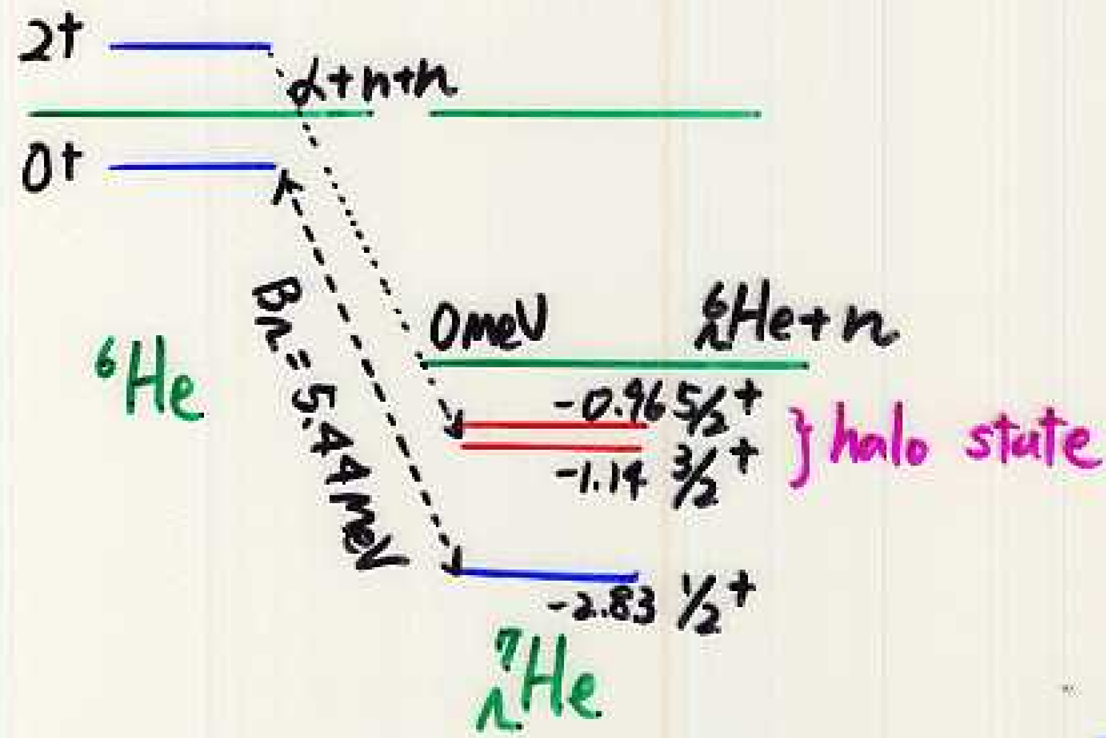
To confirm the n-halo structure, we show the r.m.s here.



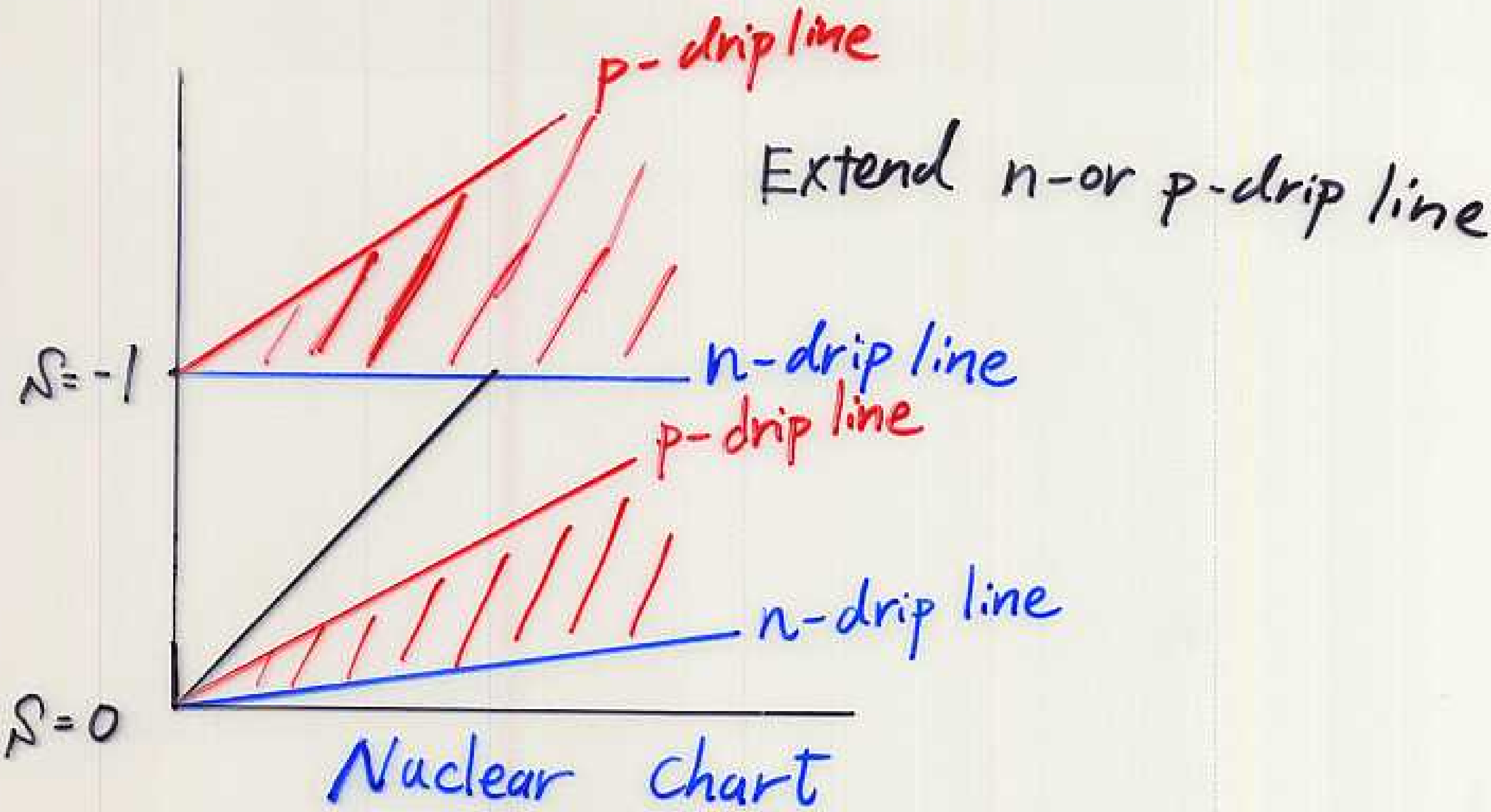
$^{7}_{\Lambda}He$ = lightest neutron-rich hypernucleus

There is no experimental data.

^{6}He lightest neutron-rich halo nucleus



This lightest neutron-rich halo hypernucleus, $^{7}_{\Lambda}He$ will be observed for the first time by the $^{7}Li(e, e'K^{+})^{7}_{\Lambda}He$ experiment.



S=0

Most of the n-rich or p-rich nuclei near the drip line have halo- or skin-structures.

What will happen, if we inject a Λ hyperon to those nuclei near the drip line?

S=-1

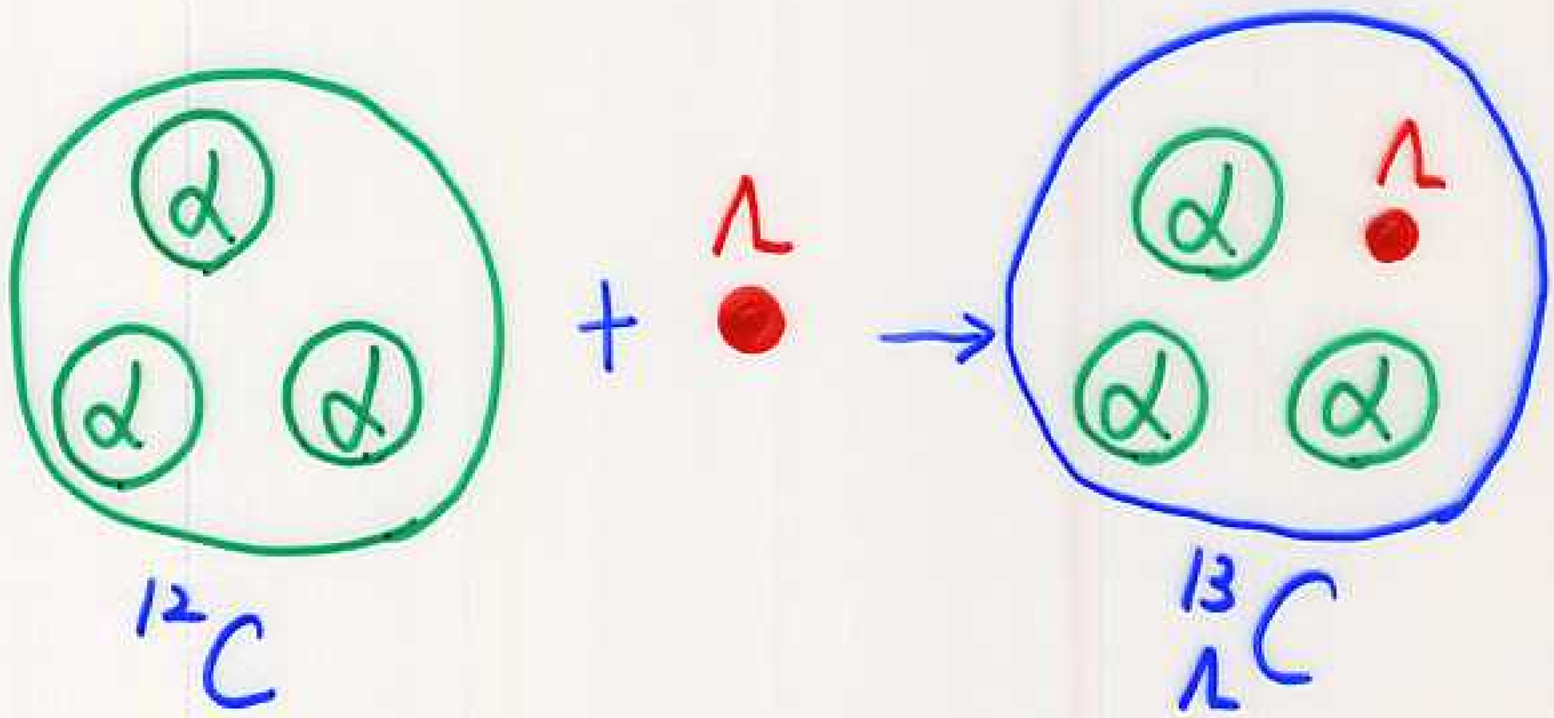
We can expect that the glue-like role of Λ extends the nucleon drip line.

⇓

We shall have many neutron-rich and proton-rich hypernuclei

Suggestion-2) To observe many excited-state in light Λ hypernuclei.

For example



How is structure?

Another type of nuclear response, which is seen in Λ binding energy

$^{13}_{\Lambda}C$ is interesting hypernucleus, because nuclear response against the added Λ particle is strongly dependent on the ^{12}C state.

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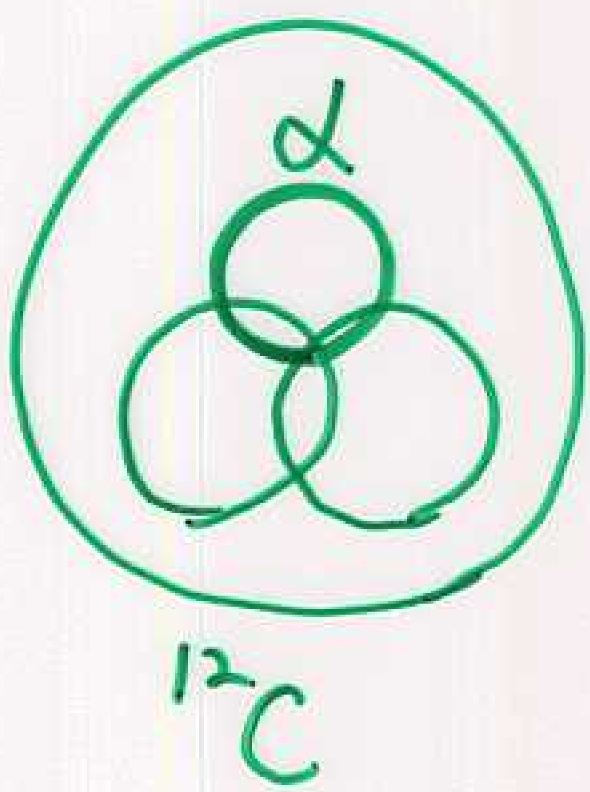
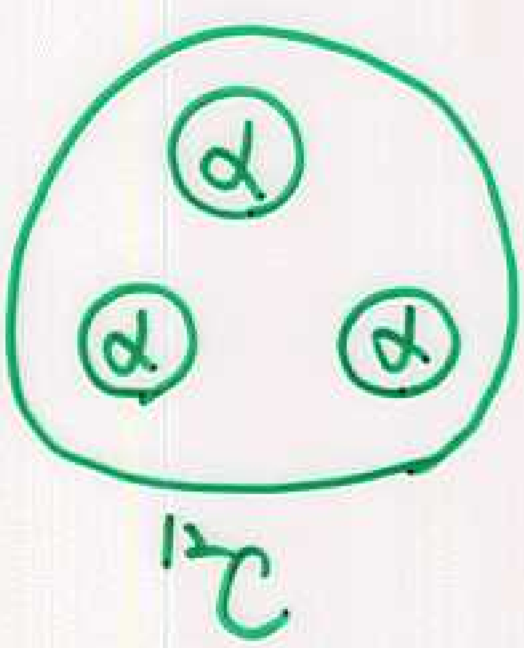
The response are quite different between the shell-like states and well-developed clustering states in ^{12}C.

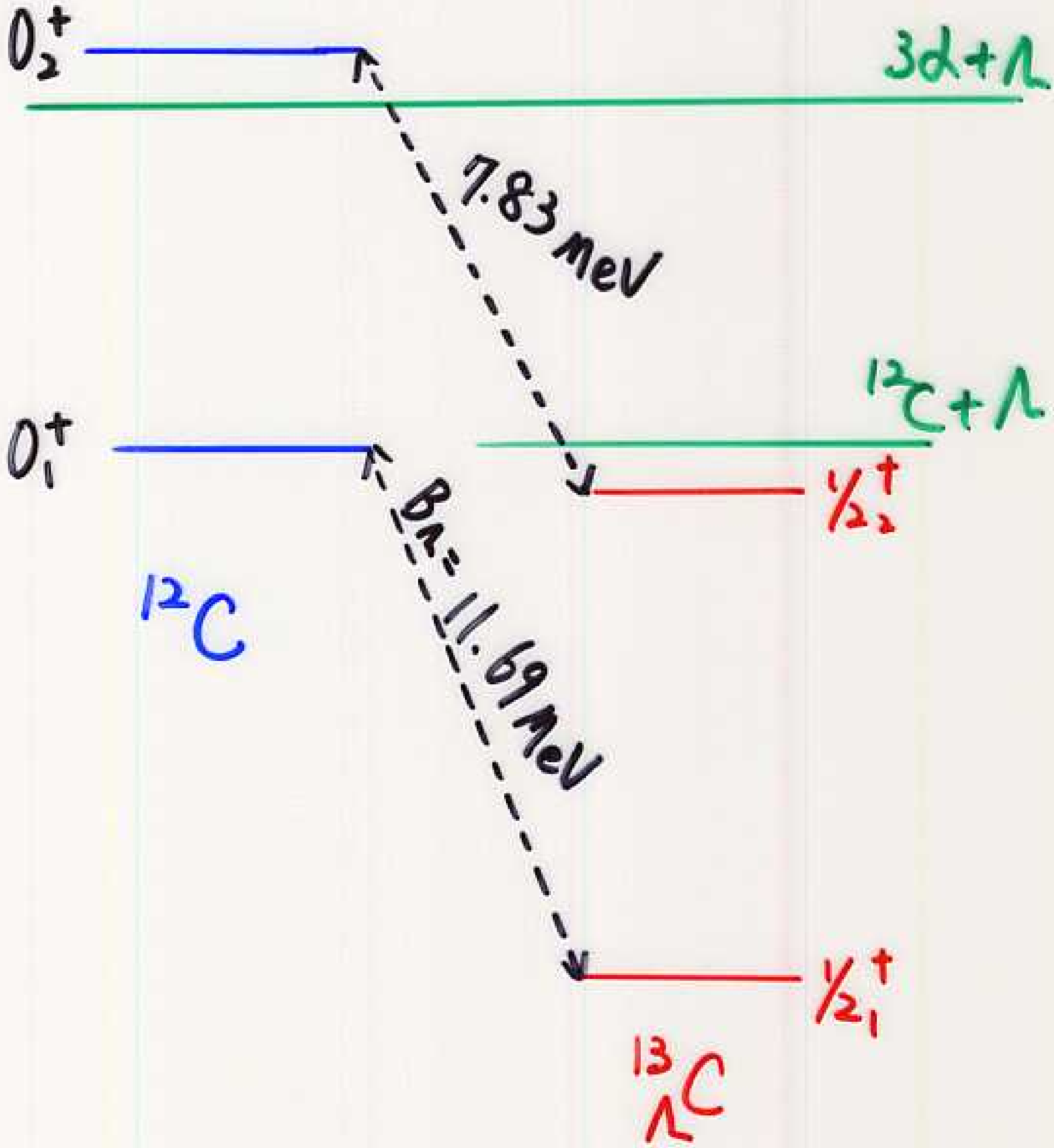


: ground state of ^{12}C (0_1^+)
〃
shell-like compact state

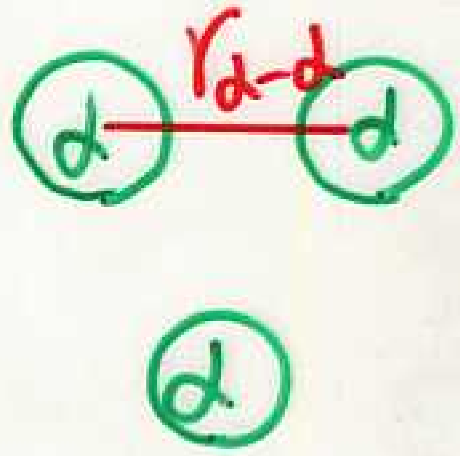


: Excited state of ^{12}C (0_2^+)
〃
loosely coupled α clustering state

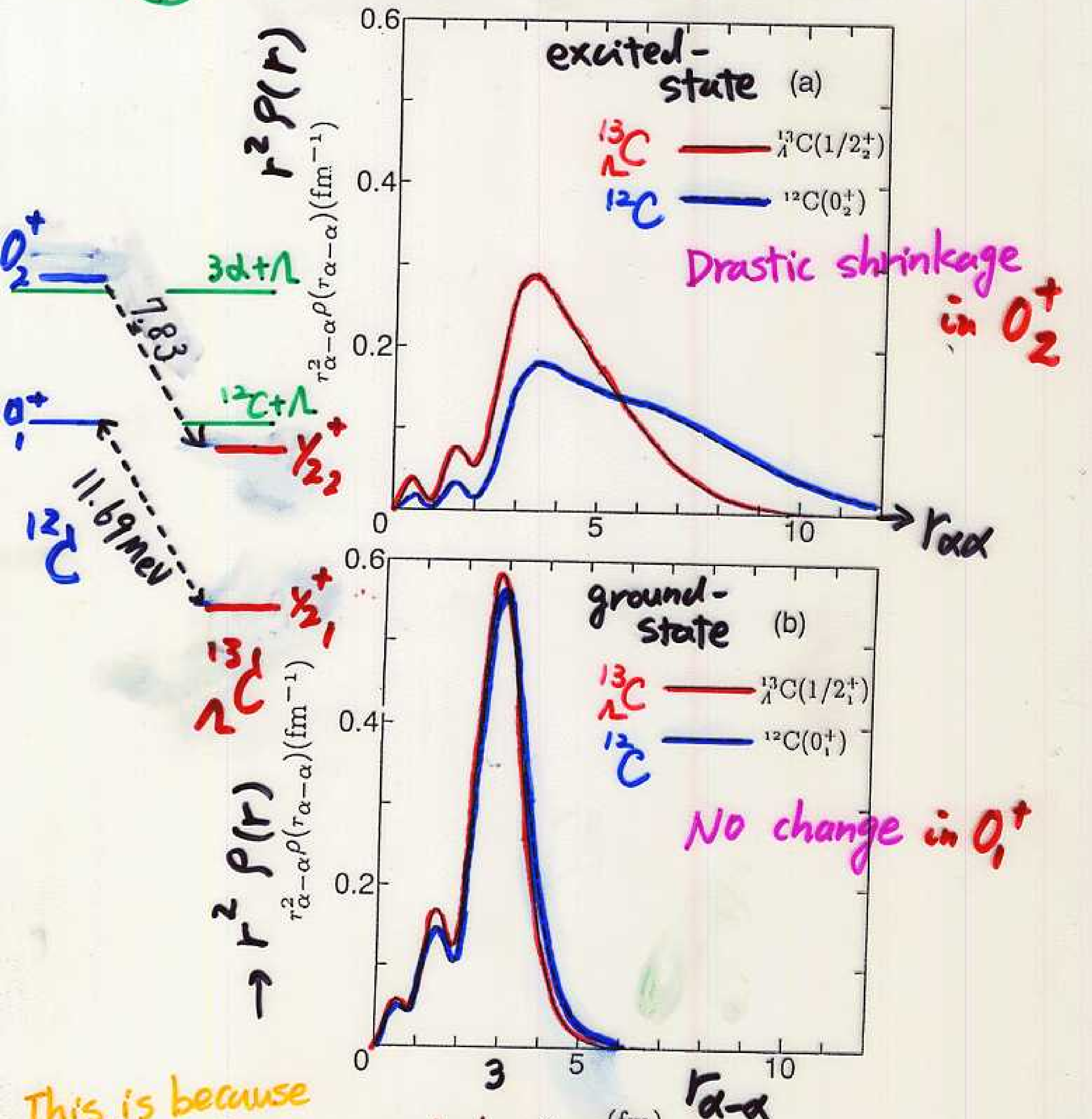
Λ binding energy of $^{13}_{\Lambda}C$



We show

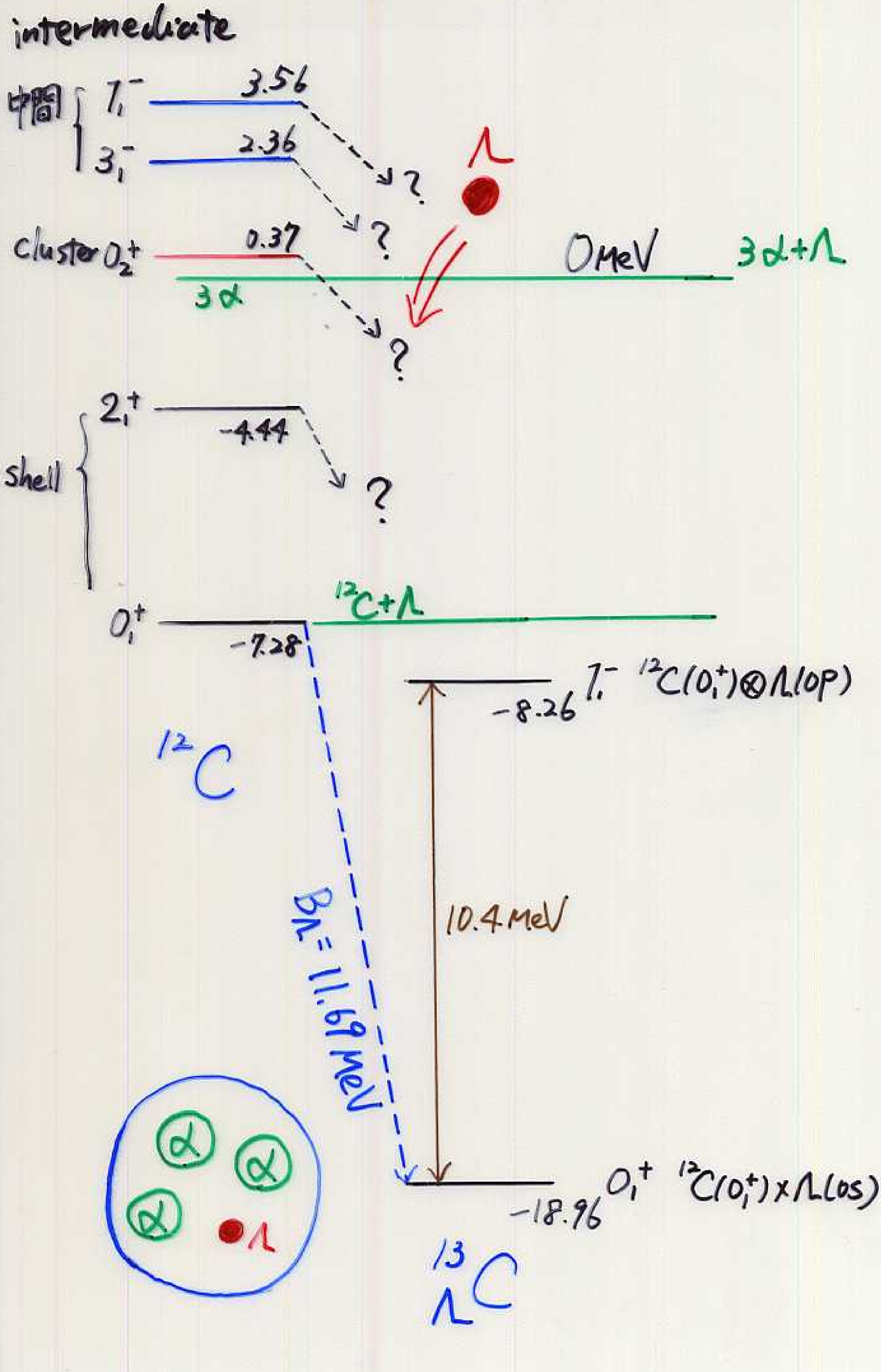


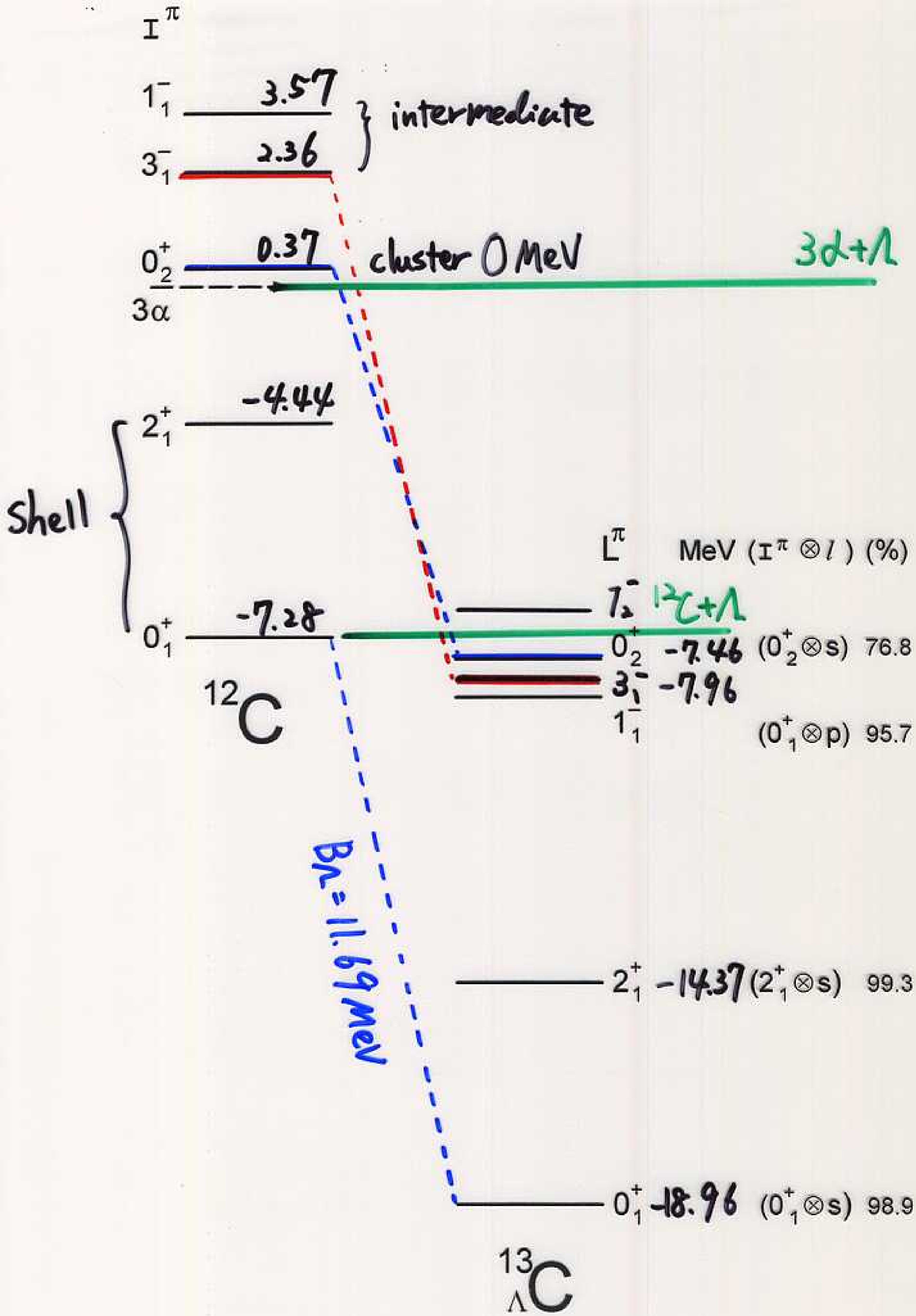
The density of α-α relative motion as a function of α-α distance (2-body correlation func.)



This is because

Nucleon density around the 0s Λ particle is larger than in the shell-like ground state than in the loosely coupling clustering state.


intermediate
中間
1₁⁻
3.56
3₁⁻
2.36
Λ
?
?
cluster 0₂⁺
0.37
0 MeV
3α+Λ
3α
?
2₁⁺
-4.44
shell
?
0₁⁺
-7.28
¹²C+Λ
1₁⁻ ¹²C(0₁⁺)⊗Λ(0p)
-8.26
¹²C
BΛ = 11.69 MeV
10.4 MeV
0₁⁺ ¹²C(0₁⁺)×Λ(0s)
-18.96
α
α
α
Λ
¹³ΛC

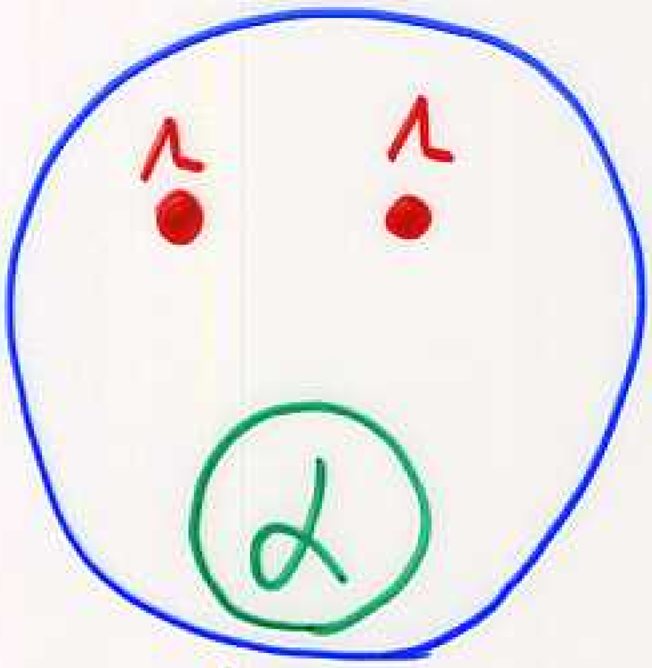


Iπ
1-1 3.57
3-1 2.36
intermediate
0+2 0.37
cluster 0 MeV
3α
3α+Λ
2+1 -4.44
Shell
0+1 -7.28
12C
Lπ MeV (Iπ ⊗ l) (%)
1-2 12C+Λ
0+2 -7.46 (0+2⊗s) 76.8
3-1 -7.96
1-1 (0+1⊗p) 95.7
BΛ=11.69MeV
2+1 -14.37 (2+1⊗s) 99.3
0+1 -18.96 (0+1⊗s) 98.9
13ΛC

States-dependent nuclear response against the added Λ particle is seen in many other hypernuclei.

A=11 core nuclei are lightest nuclei to have both of shell-like compact states and clustering states

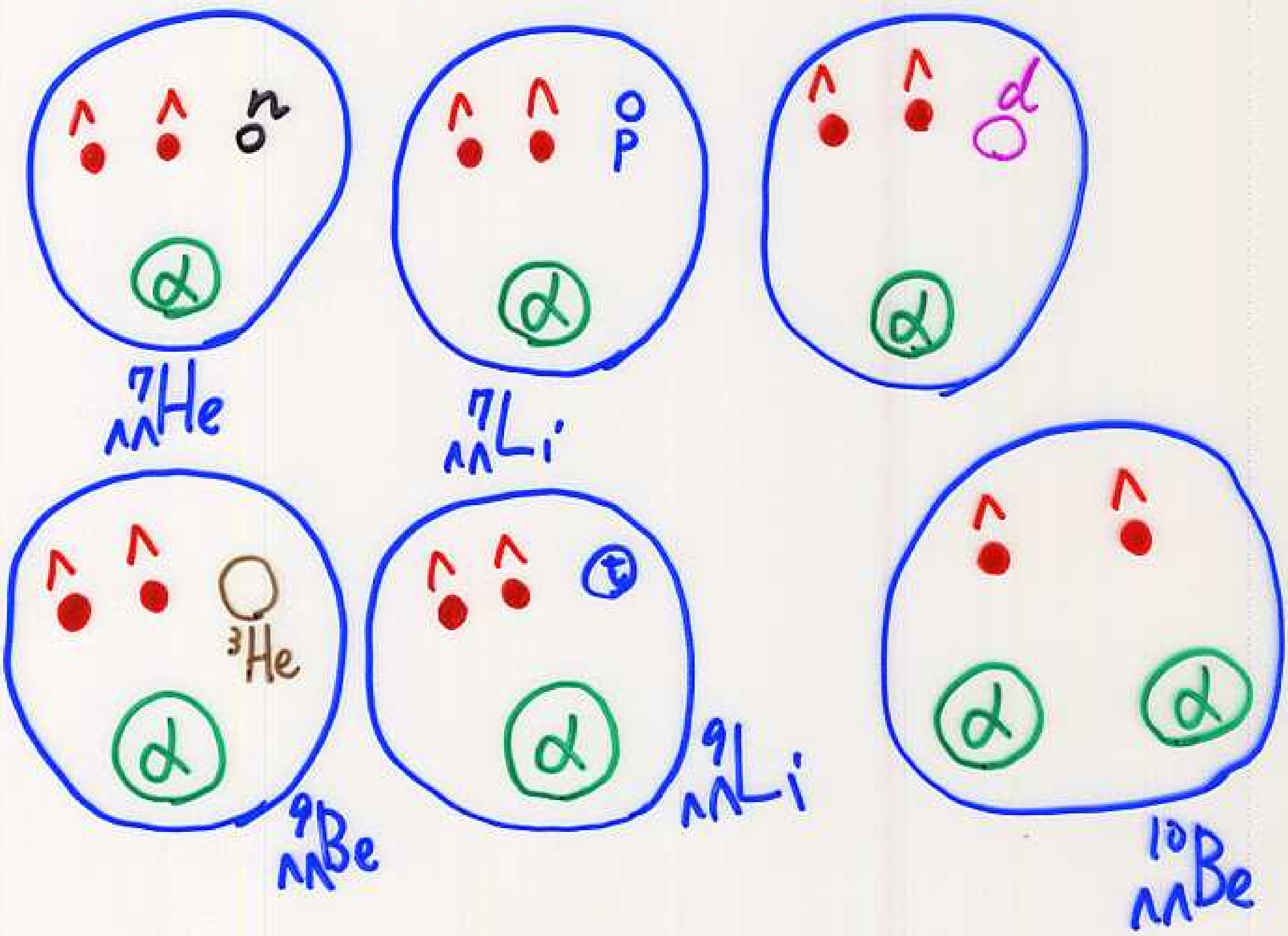
Suggestion-3) To observe many light double Λ hypernuclei

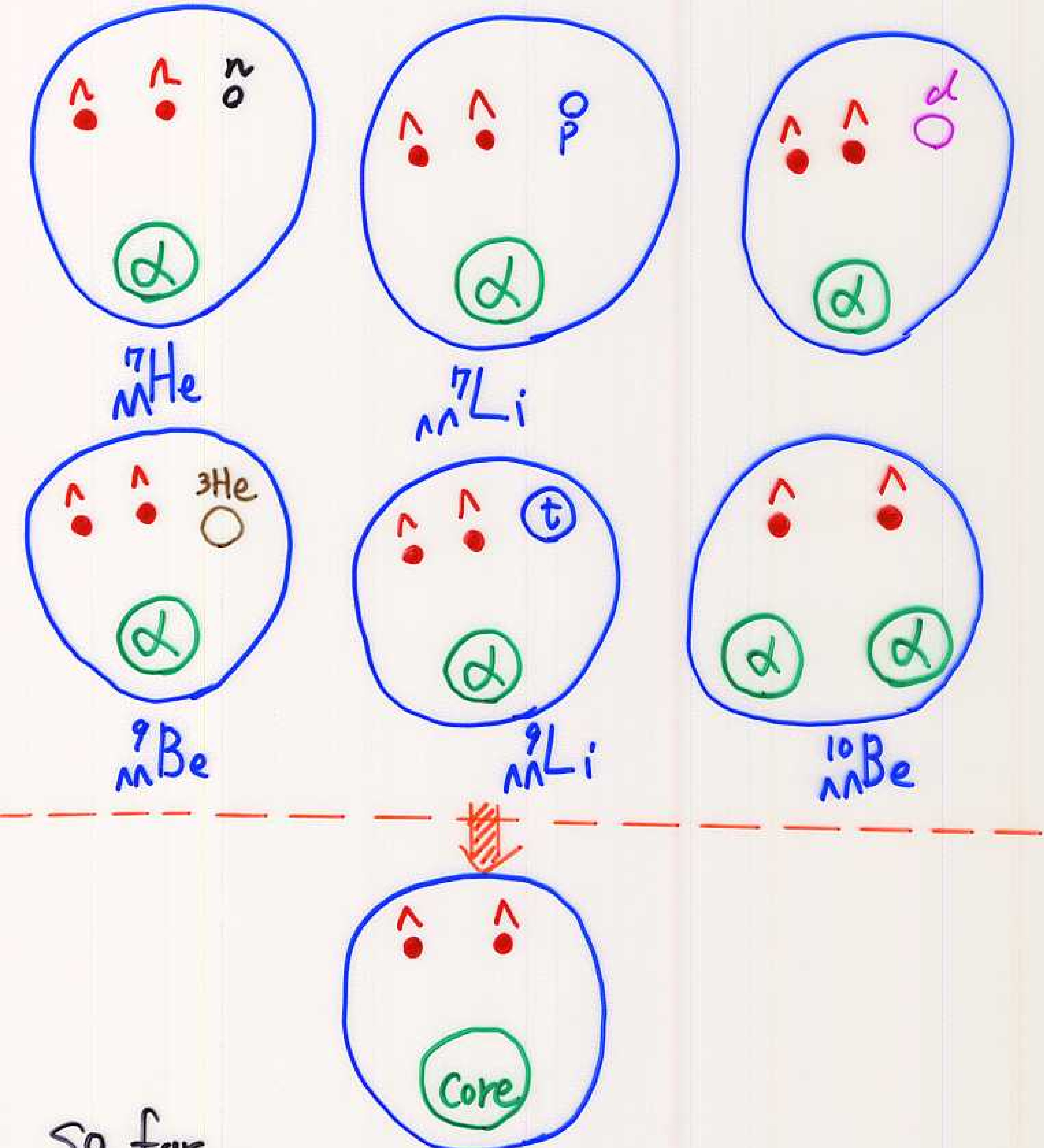


$^{6}_{\Lambda\Lambda}He$: Nagura event

$B_{\Lambda\Lambda} = 7.25 \pm 0.2$ MeV

$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.2$ MeV

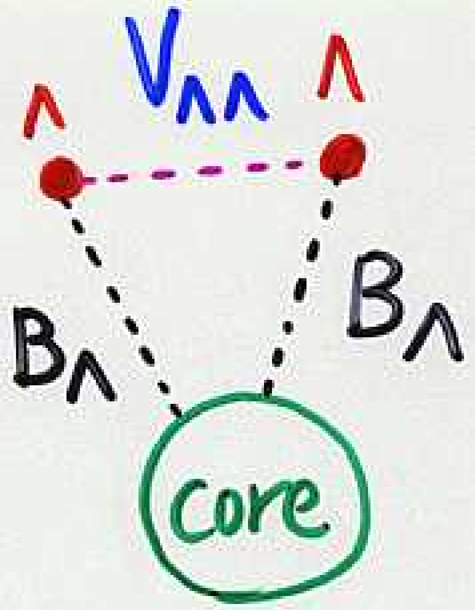




So far,

1) inert core nucleus + Λ + Λ

2) shell model



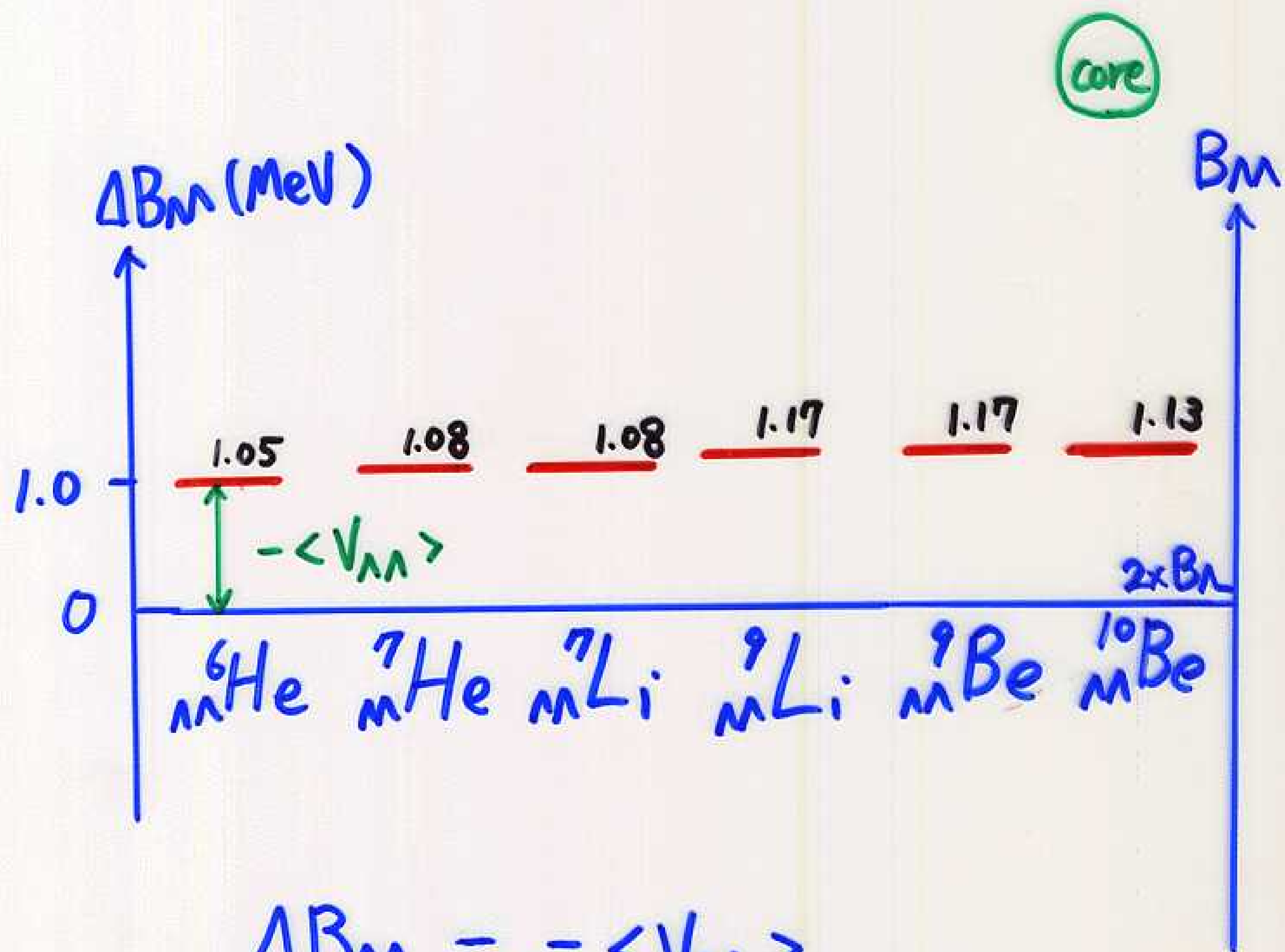
independently on the mass of hypernuclei

$$\Delta B_{\Lambda\Lambda} \equiv B_{\Lambda\Lambda} - \underbrace{2 \times B_{\Lambda}}_{= B_{\Lambda\Lambda}(V_{\Lambda\Lambda}=0)} \doteq -\langle V_{\Lambda\Lambda} \rangle$$

(1) This is true for hypernucleus in which the core nucleus does not shrink due to the addition of Λ particles.

(2) This is NOT true when the core nucleus shrinks due to the Λ particles participation.

Result by 3-body model



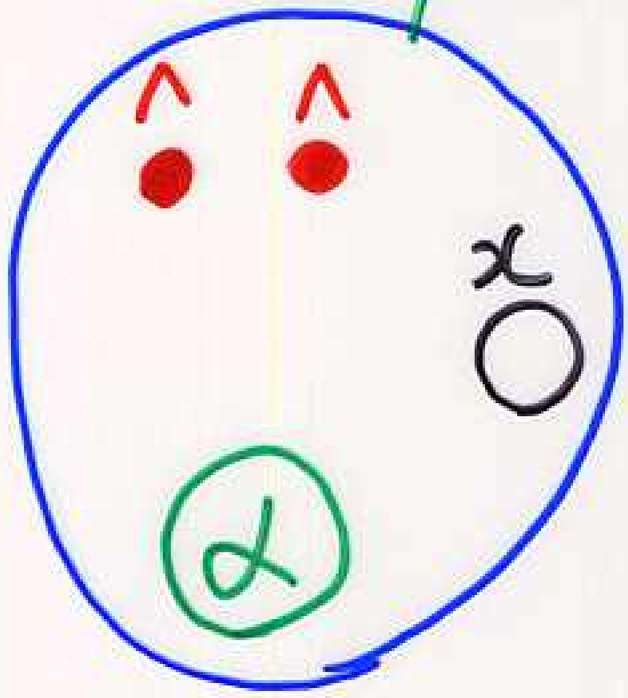
$$\Delta B_{\Lambda\Lambda} = -\langle V_{\Lambda\Lambda} \rangle$$

But, Valid only within the inert Core + Λ + Λ 3-body model

Next, I shall show you that this is NOT true when we take more realistic $\alpha + x + \Lambda + \Lambda$ 4-body model.

x = n, p, d, ^{3}He, t, α

4-body model



$\underbrace{\alpha + x}_{\text{core nucleus}} + \Lambda + \Lambda$

$^5He = \alpha + n$

$^5Li = \alpha + p$

$^6Li = \alpha + d$

$^7Li = \alpha + t$

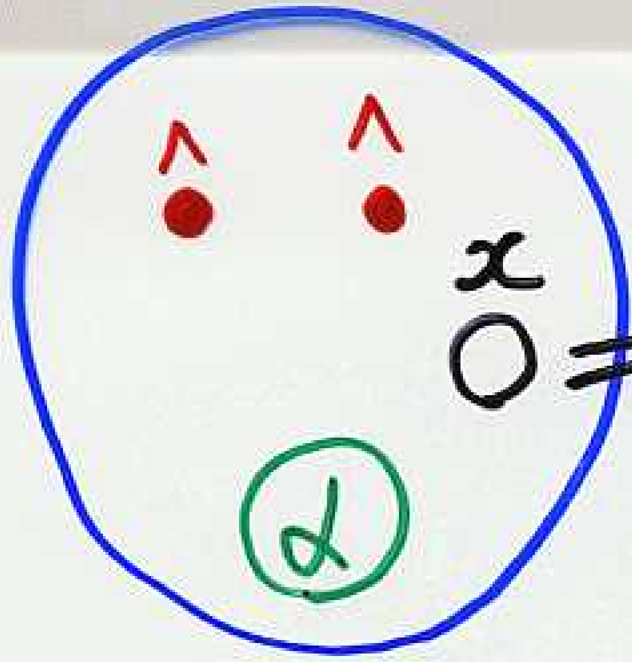
$^7Be = \alpha + {}^3He$

$^8Be = \alpha + \alpha$

$\Downarrow$

Often employed in the cluster-model study of light nuclei

4-body model



$\Rightarrow n, p, t, {}^3He, \alpha$

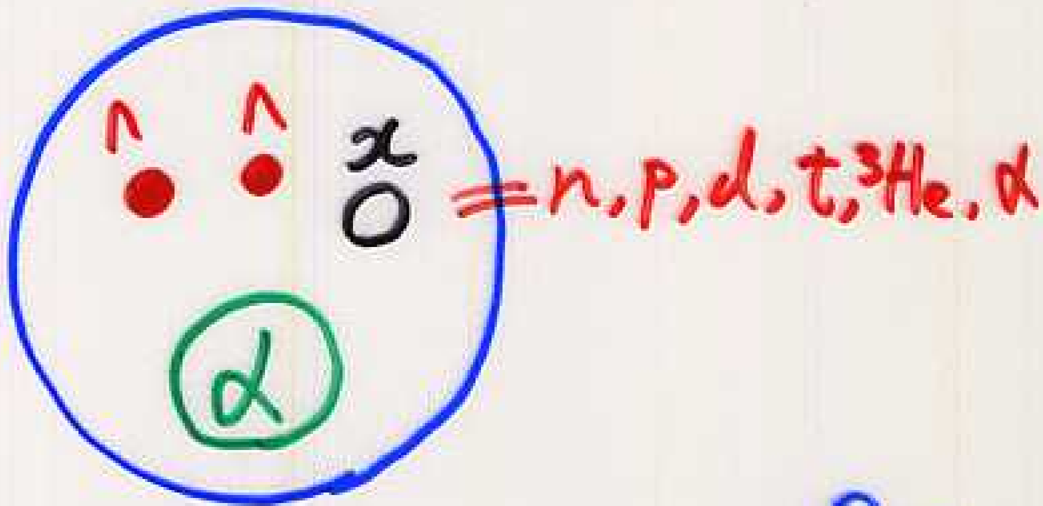
$V_{\alpha-x}$: potentials popularly used in the cluster model

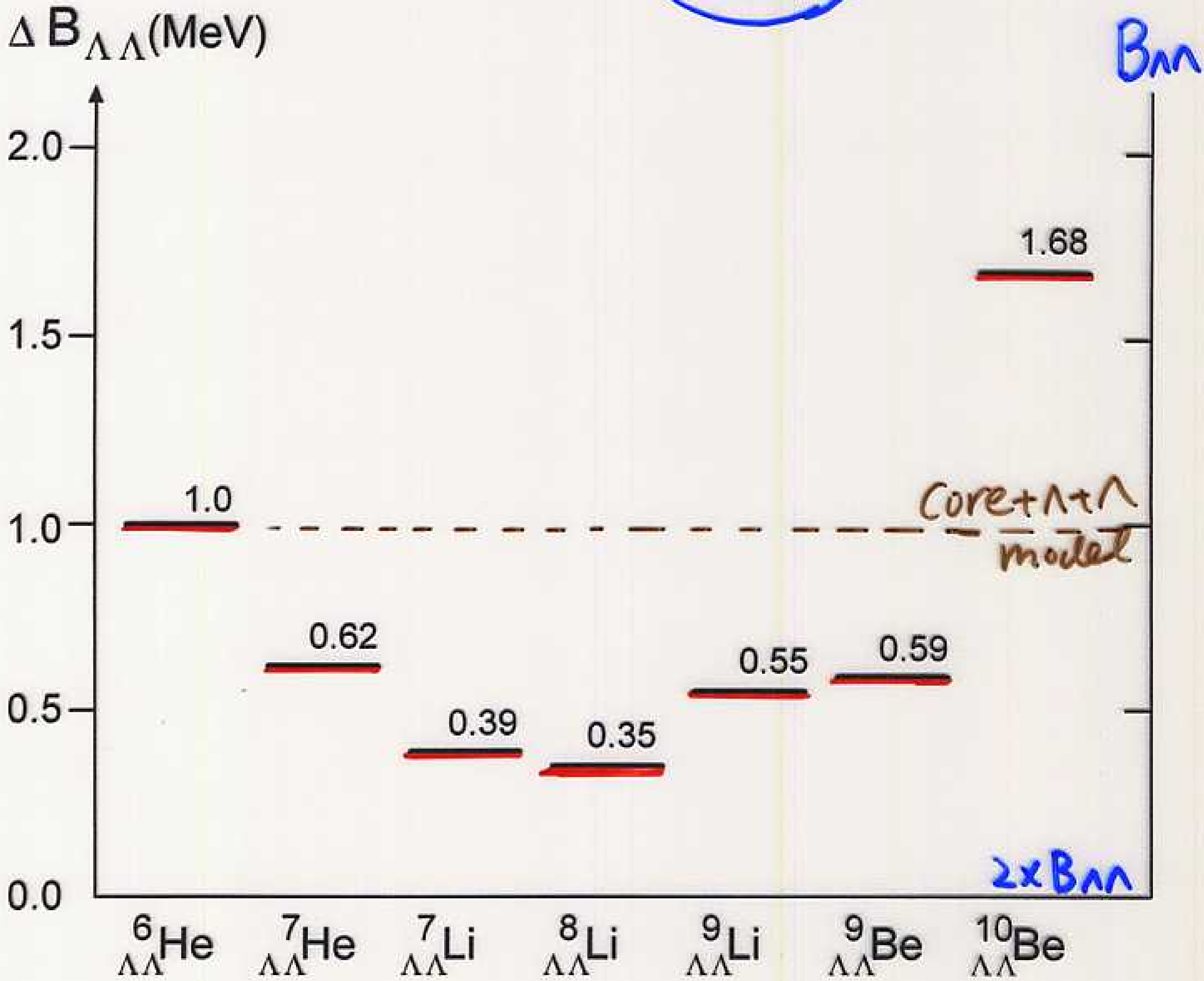
$V_{\alpha-\Lambda}, V_{x-\Lambda}$: derived by folding a familiar YNG ΛN interaction into the α or x-cluster densities

$V_{\Lambda\Lambda}$: the same ΛΛ interaction as was used in the 3-body model

reproduce the observed energies of low lying levels of any 2- and 3-body subsystems

4-body model

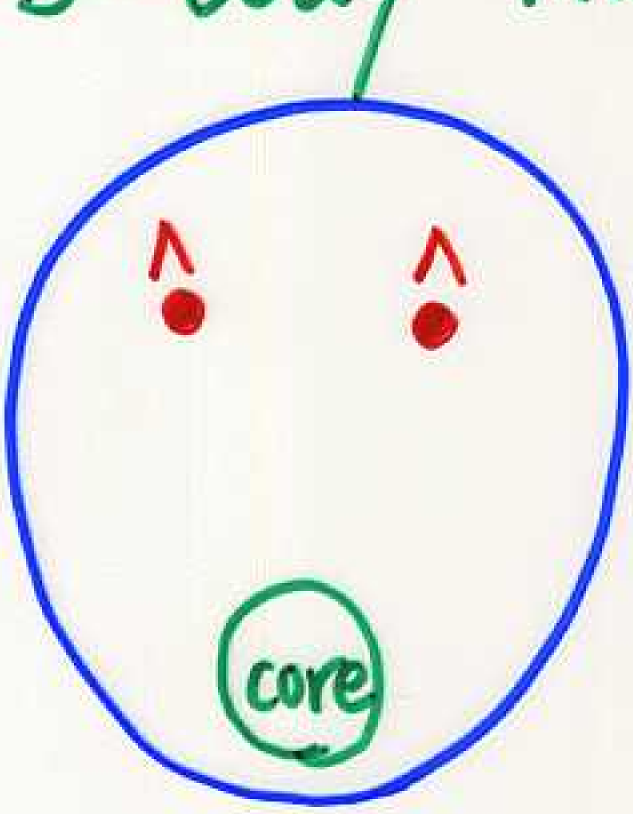




$\Delta B_{\Lambda\Lambda}$ is strongly dependent on individual hypernuclei.

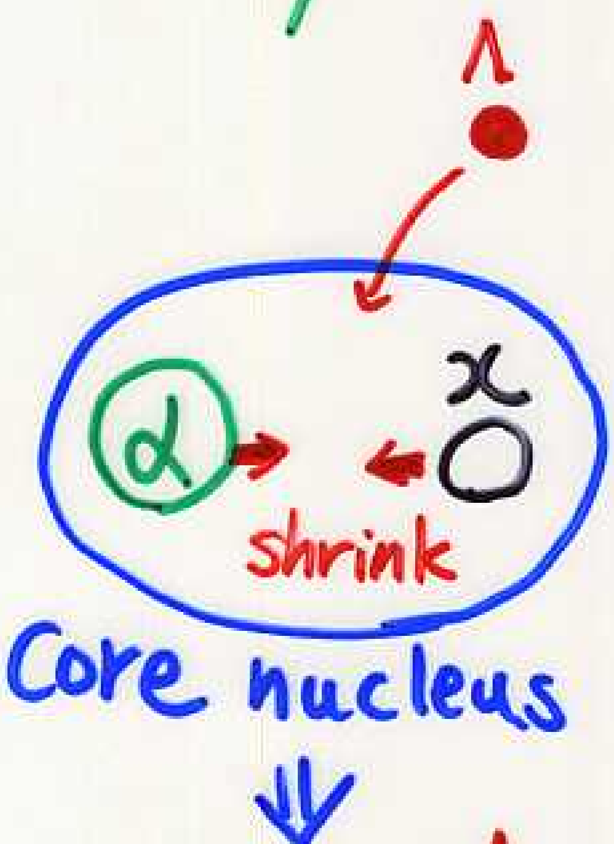
How should we consider about this interesting figure?

• 3-body model

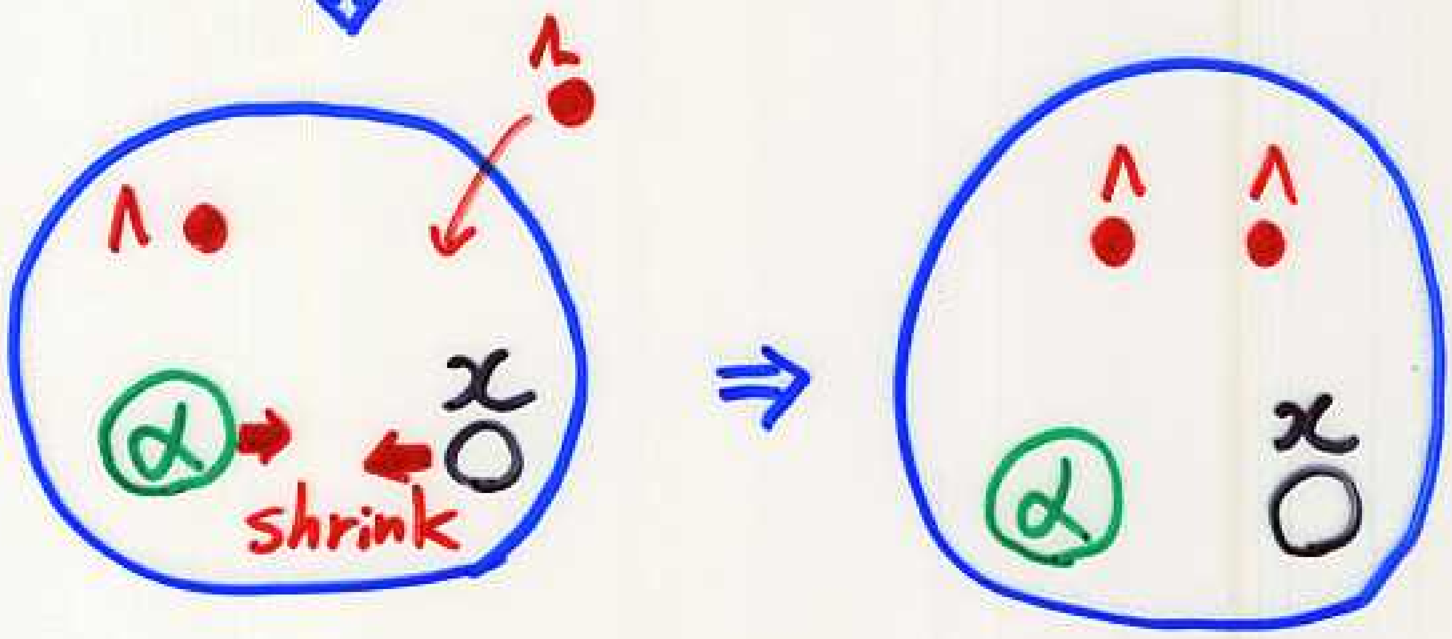


Structure of core nucleus is fixed even if Λ particles are injected.

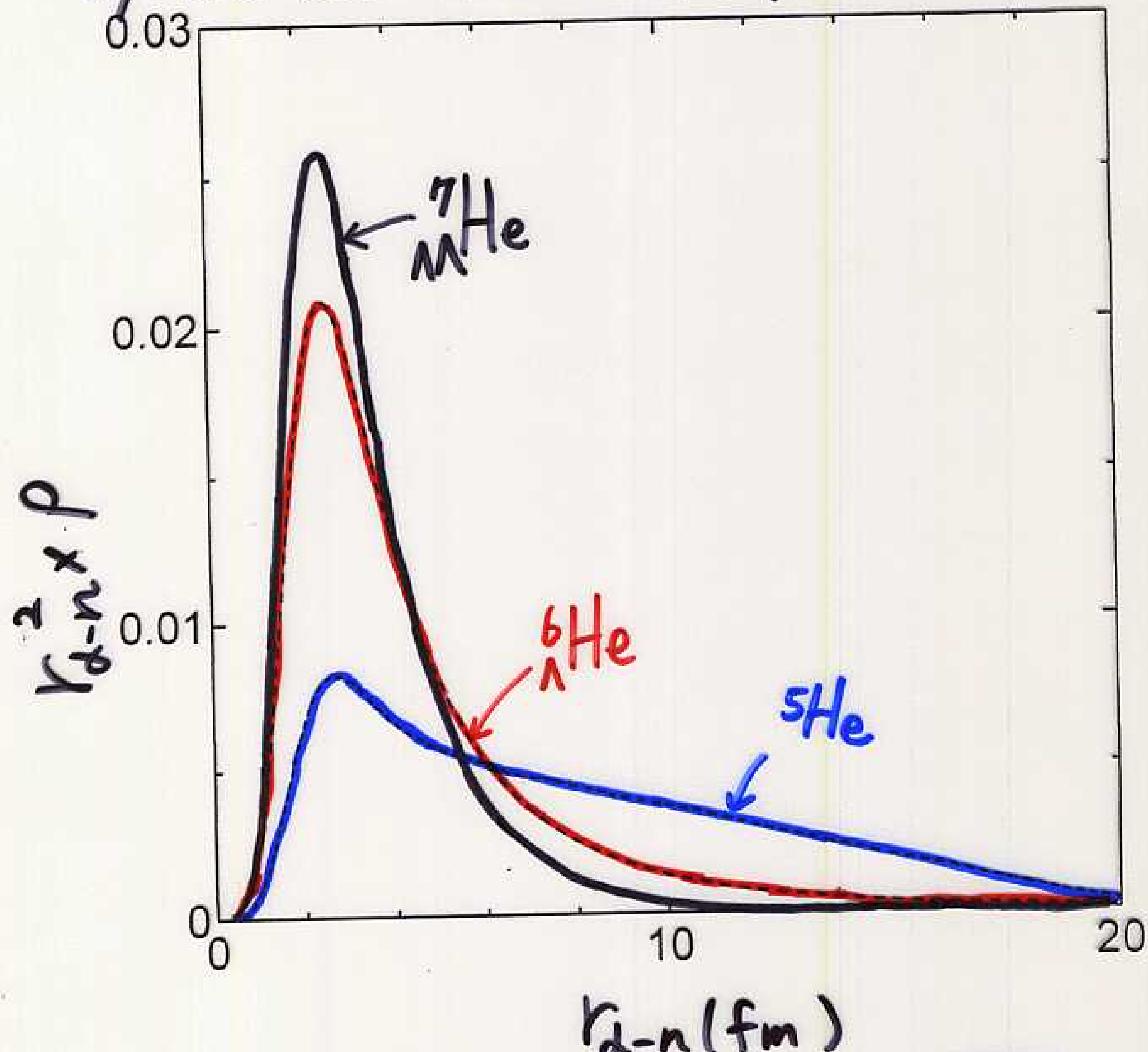
• 4-body model

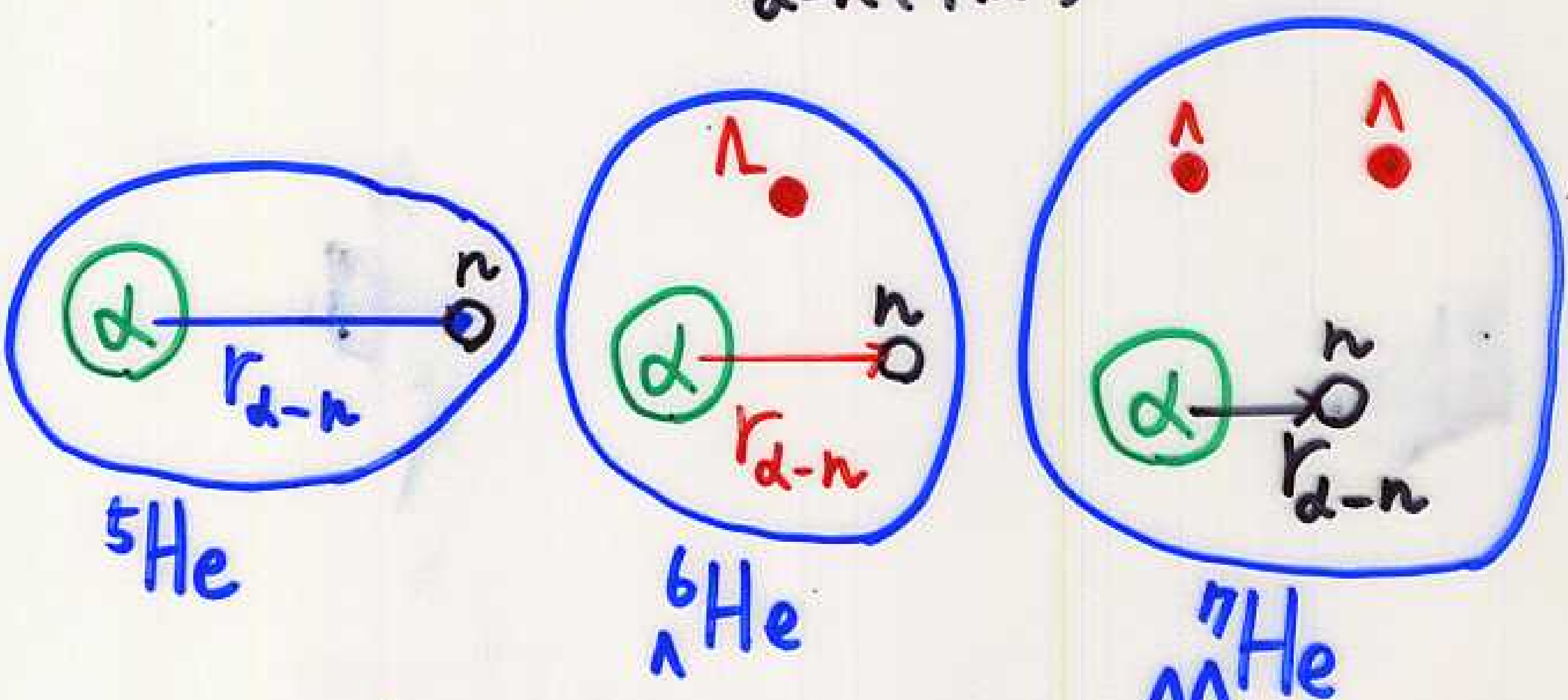


We allow the core nuclei to change, namely, to shrink.



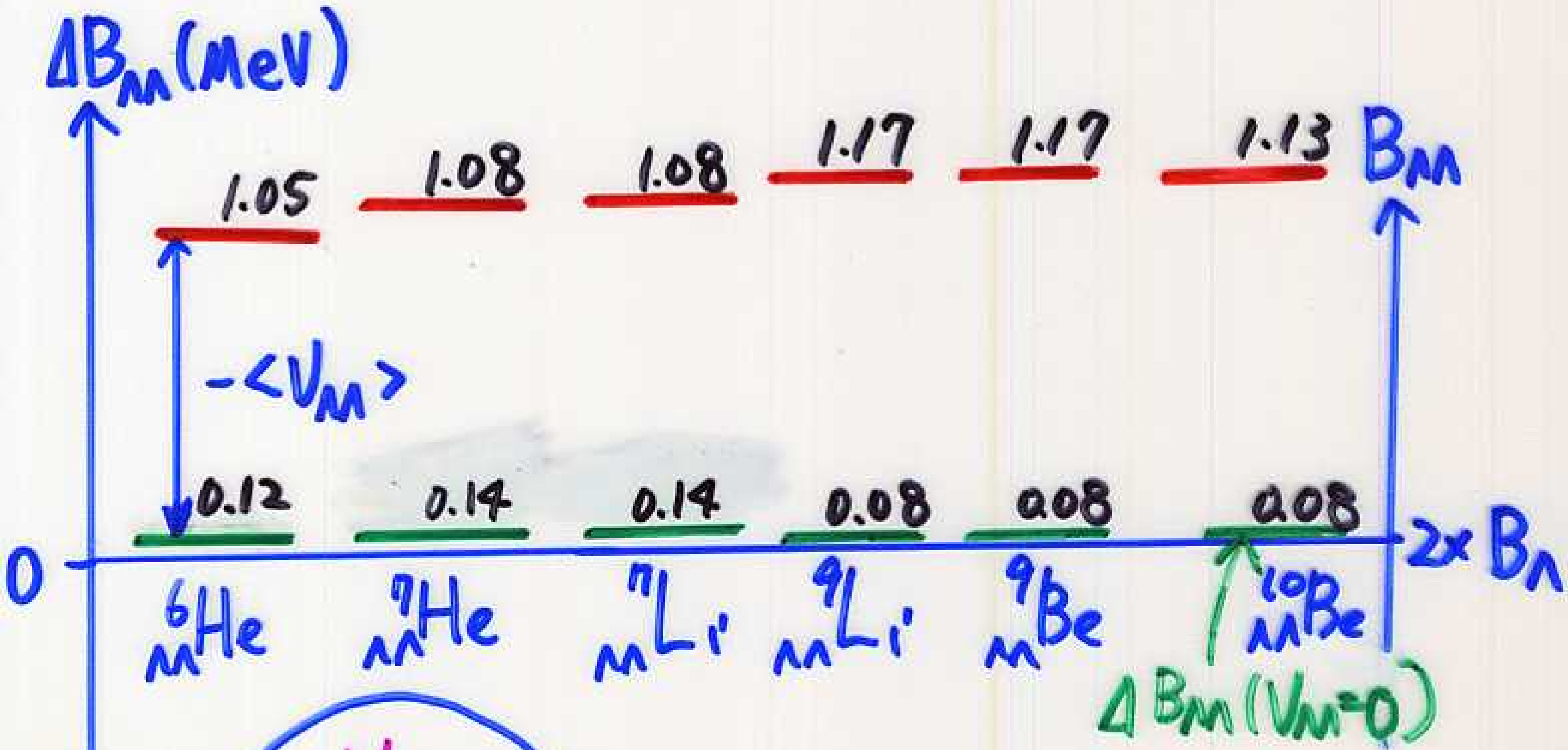
shrinkage of the core nucleus density by the addition of Λ particle

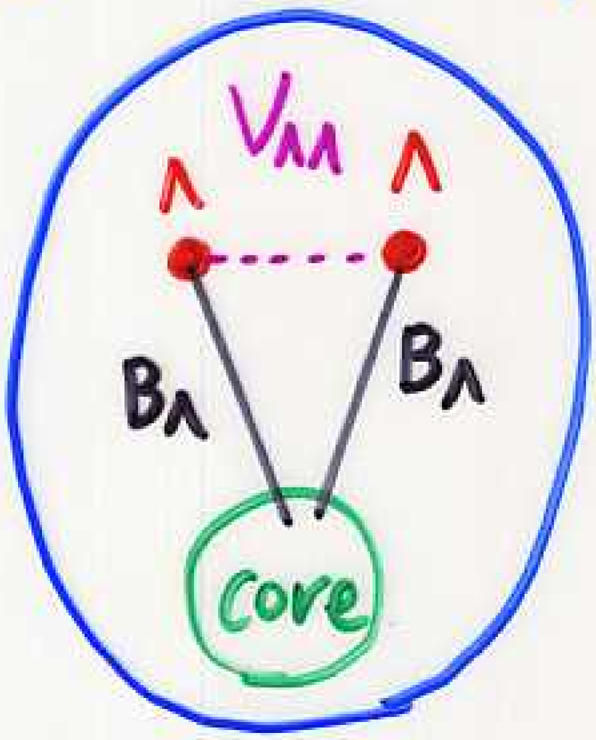




$r_{\alpha-n}(^{5}He) > r_{\alpha-n}(^{6}_{\Lambda}He) > r_{\alpha-n}(^{7}_{\Lambda\Lambda}He)$

• 3-body model

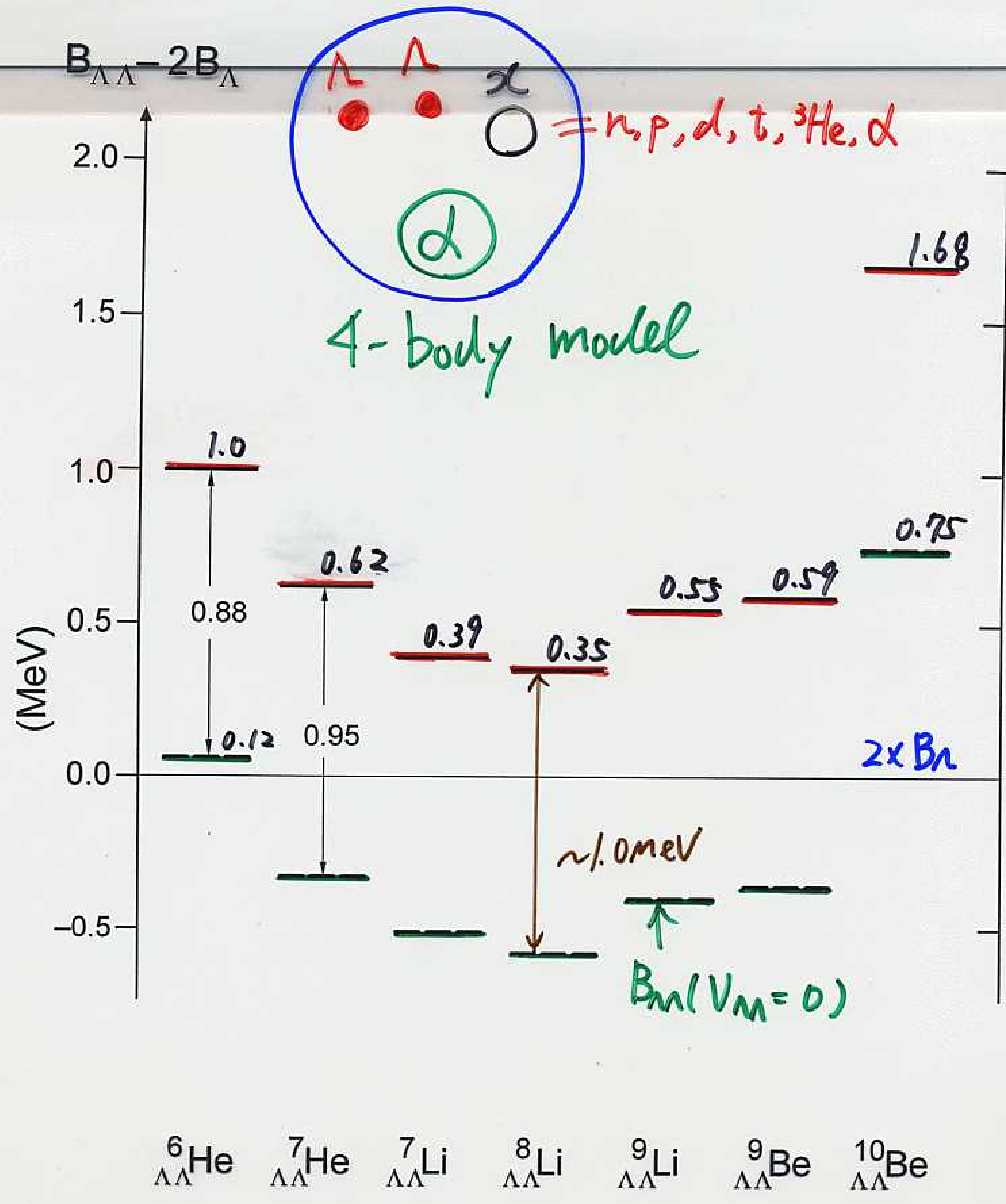




$$-\langle V_{\Lambda\Lambda} \rangle = \Delta B_{\Lambda\Lambda} - \Delta B_{\Lambda\Lambda}(V_{\Lambda\Lambda}=0)$$

• 4-body model

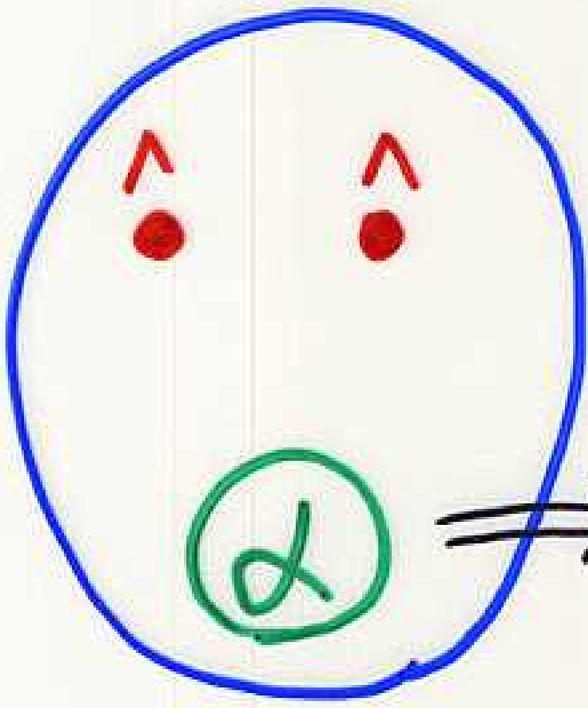
The structure change of core nucleus is possible to occur due to the Λ-α and Λ-x interactions even if $V_{\Lambda\Lambda}$ is switched off.



New definition

$$\Delta \tilde{B}_{\Lambda\Lambda} = B_{\Lambda\Lambda} - B_{\Lambda\Lambda}(V_{\Lambda\Lambda}=0) = -\langle V_{\Lambda\Lambda} \rangle$$

One comment on the "Nagara event" for ${}^{6}_{\Lambda\Lambda}He$



⟹ The shrinkage of the hard α core is negligible.

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda} \simeq -\langle V_{\Lambda\Lambda} \rangle$$

The fact that the ${}^{6}_{\Lambda\Lambda}He$ was discovered first is a very lucky case.

Are there any other double Λ hypernuclei in which the structure of the core nuclei is not changed by the participation of Λ particles?

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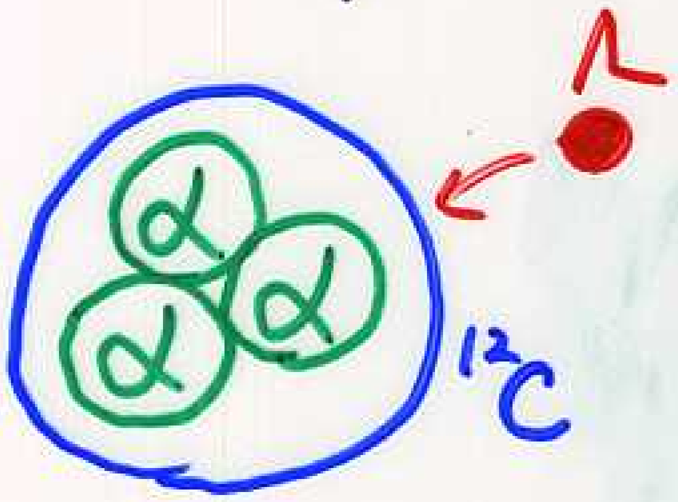
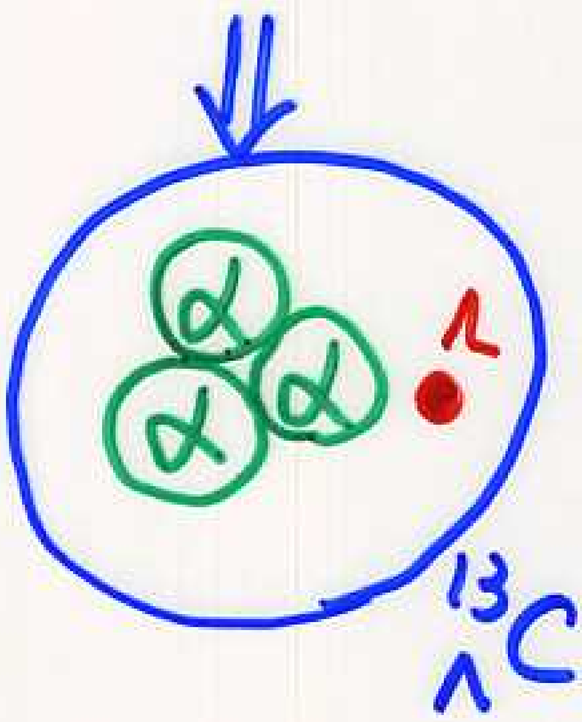


ground state of ^{12}C

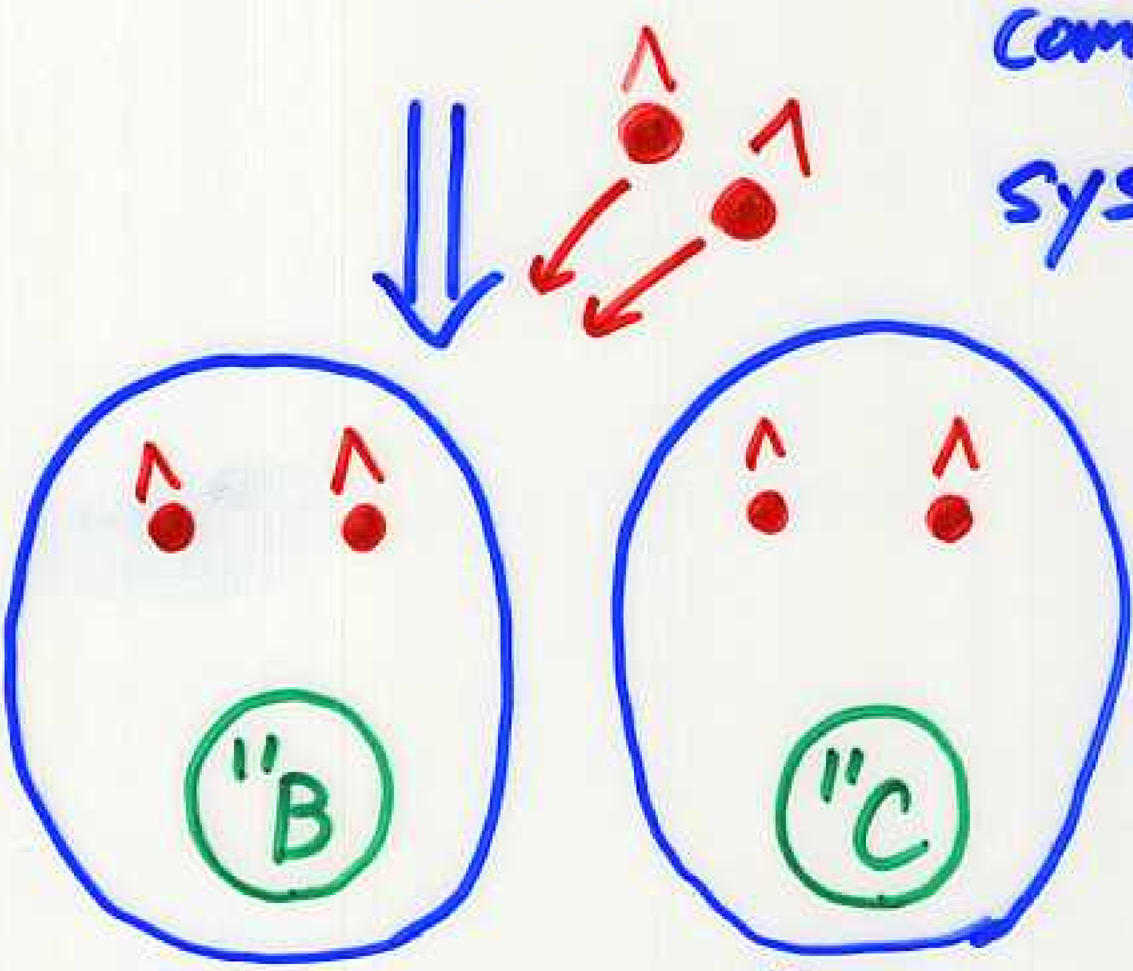
Compactly bound system which is well described by the shell model



nuclear shrinkage does not occur.

Similar situation

^{11}B , ^{11}C : ground state is compactly bound system.



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

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}^{\text{Exp.}} - 2\times B_{\Lambda}^{\text{Exp.}} = -\langle V_{\Lambda\Lambda}\rangle$$

Lighter hypernuclei than mass 13

$$\Delta\tilde{B}_{\Lambda\Lambda} = B_{\Lambda\Lambda}^{\text{Exp.}} - B_{\Lambda\Lambda}^{\text{CAL}}(V_{\Lambda\Lambda}=0) = -\langle V_{\Lambda\Lambda}\rangle$$

Concluding remark of my talk

Two kinds of suggestions on future experiments to discover more double Λ hypernuclei.

(1) If you want to get informations on the strength of Λ Λ interaction without the help of theoreticians, then, I recommend you to discover mass 13 or heavier double Λ hypernuclei.

(2) But, if you want not only to obtain such informations but also to enjoy interesting physics, and if you do not mind the help of theoreticians, then I recommend you to discover these double Λ hypernuclei.