中性子ハロー核における対相関とテンソル力相関

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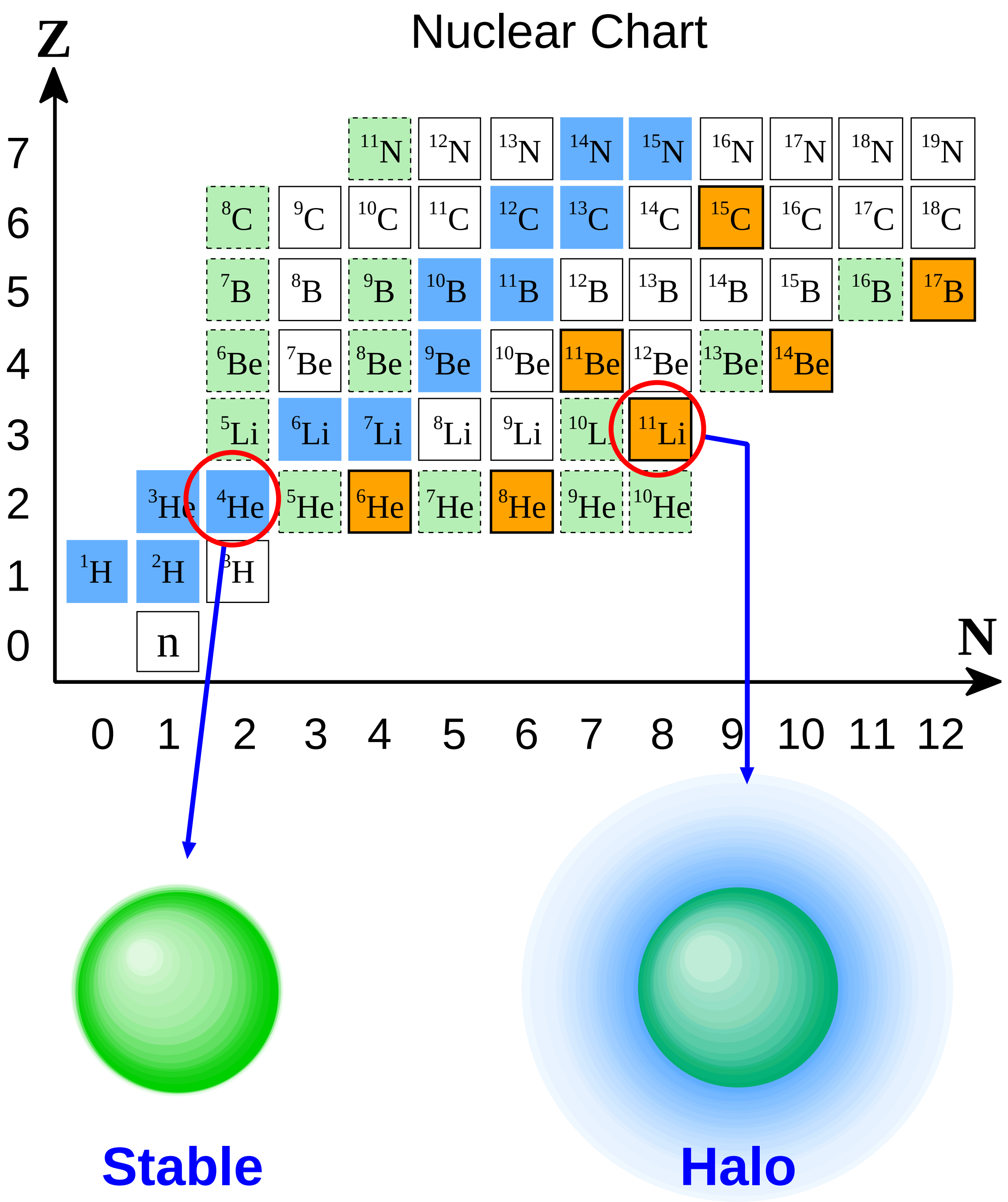
• Contents

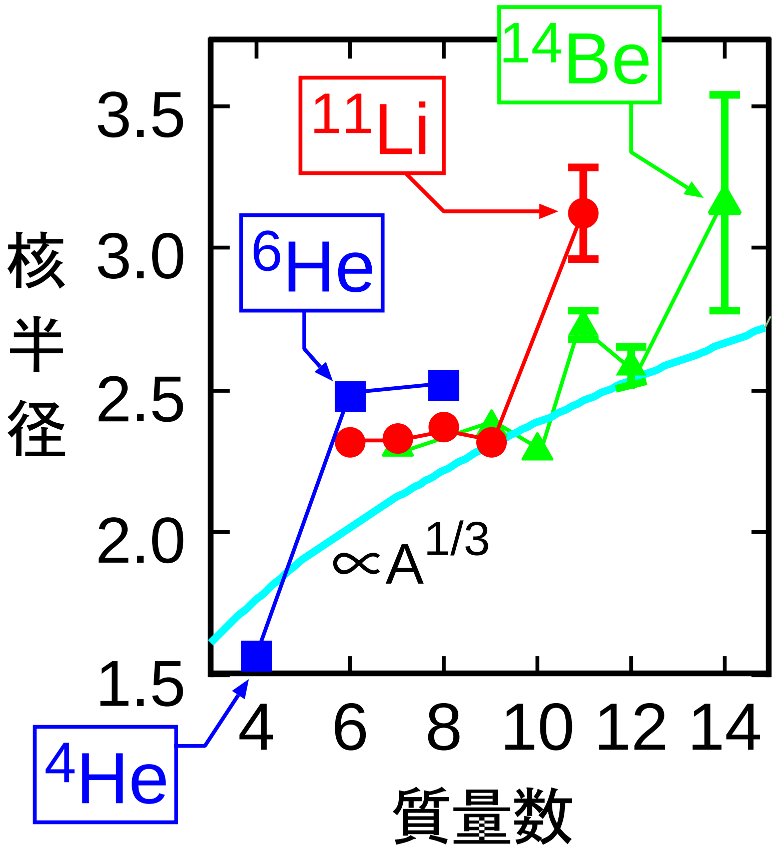
- core+n+n picture of halo nuclei.
  - Naive three-body approach to ^{6}He, ^{11}Li.

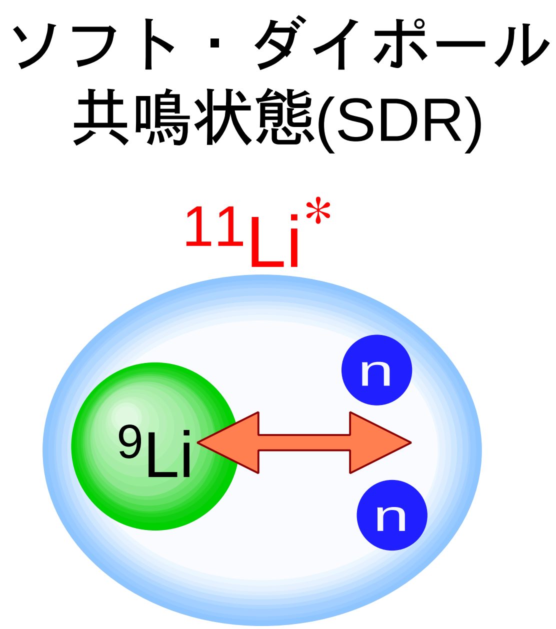
- Pairing correlation for the level inversion in ^{10,11}Li.
  - coupled-channel ^{9}Li$^{(*)}$+n+n model
  - pairing-blocking effect in ^{10}Li, ^{11}Li.

- Tensor correlation in drip-line nuclei.
  - contribute to inversion phenomena in ^{10,11}Li ?
  - ^{4}He, ^{8}He, (^{9}Li) with tensor correlation.



Nuclear Chart
Z
N
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12
11N 12N 13N 14N 15N 16N 17N 18N 19N
8C 9C 10C 11C 12C 13C 14C 15C 16C 17C 18C
7B 8B 9B 10B 11B 12B 13B 14B 15B 16B 17B
6Be 7Be 8Be 9Be 10Be 11Be 12Be 13Be 14Be
5Li 6Li 7Li 8Li 9Li 10Li 11Li
3He 4He 5He 6He 7He 8He 9He 10He
1H 2H 3H
n
Stable
Halo

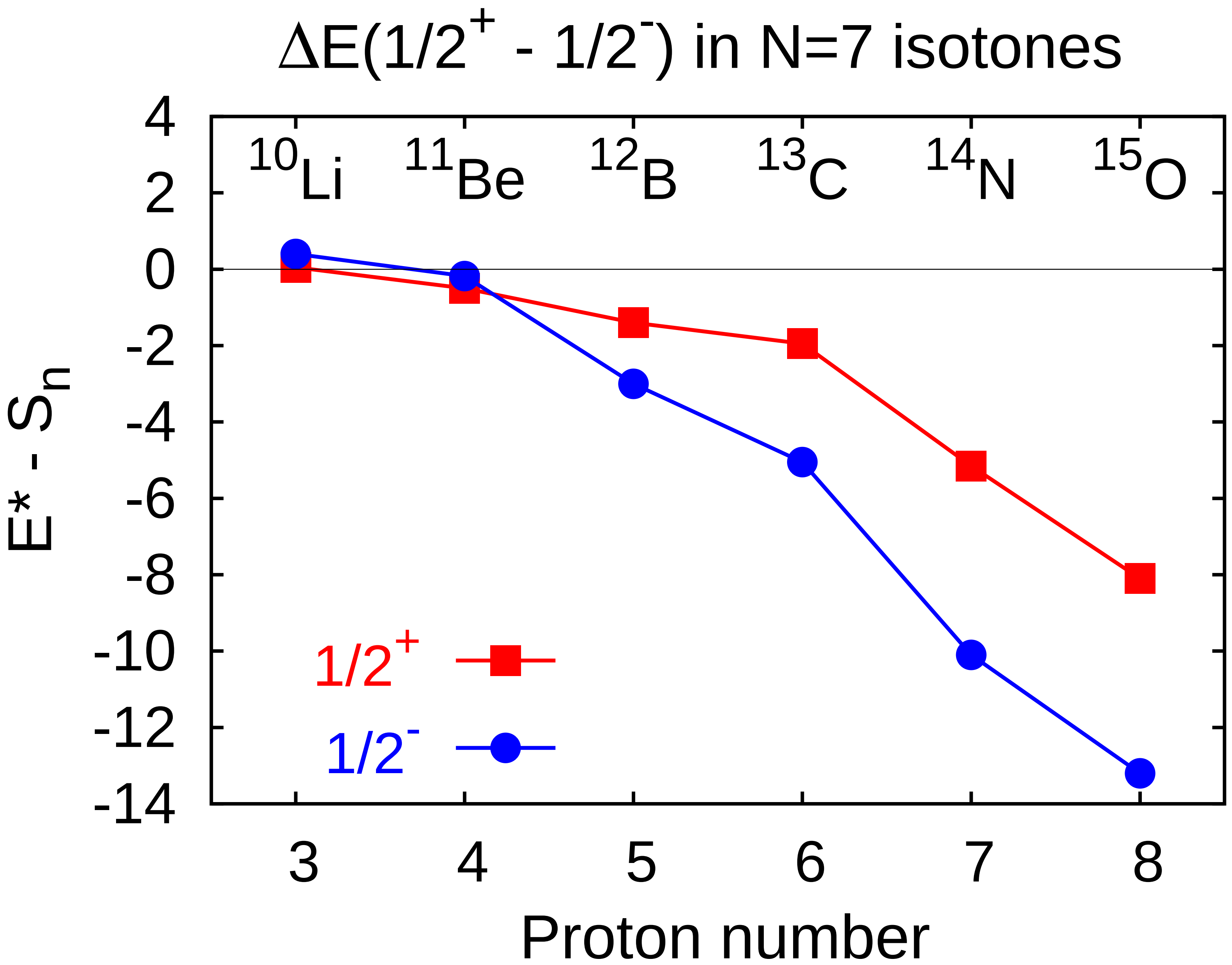




- Binding energy

  ^{6}He : 1.0 MeV measured from ^{4}He+n+n

  ^{11}Li : 0.3 MeV measured from ^{9}Li+n+n

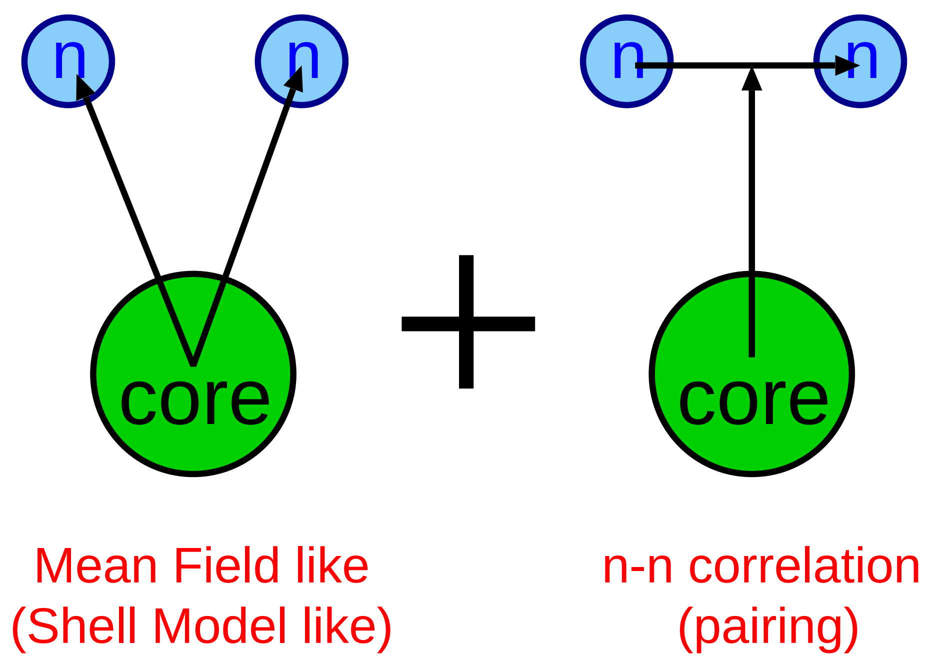


ΔE(1/2+ - 1/2-) in N=7 isotones
10Li
11Be
12B
13C
14N
15O
4
2
0
-2
-4
-6
-8
-10
-12
-14
E* - Sn
1/2+
1/2-
3
4
5
6
7
8
Proton number

- Description of Halo nuclei based on the "core+n+n" model

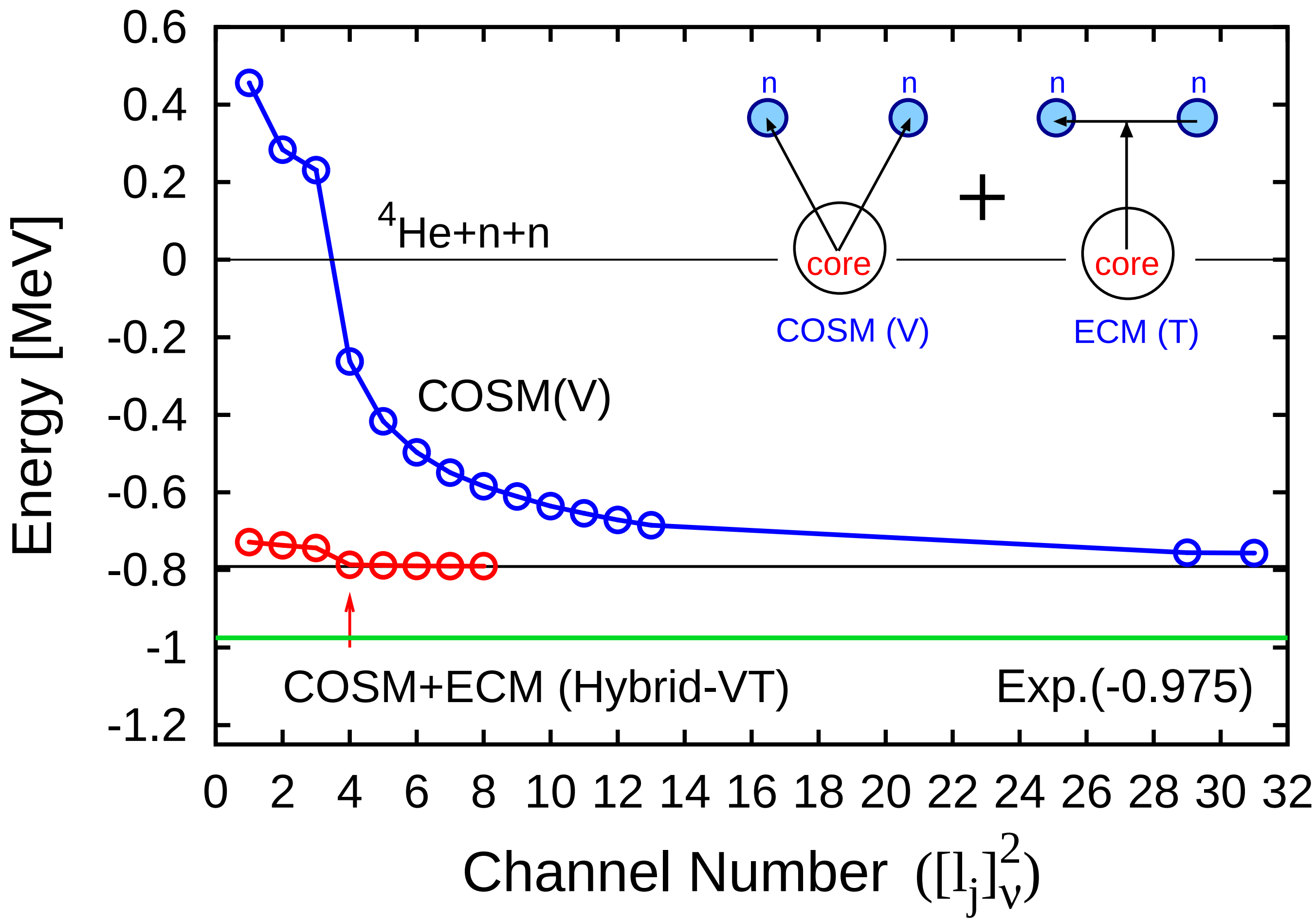
- ∘ ^{6}He : ^{4}He($(0s)^4$) + n + n.
  - Successful results for G.S., 2^+
- ∘ ^{11}Li : ^{9}Li + n + n.
  - Large $(1s)^2$-mixing in G.S.
  - Inversion phenomena in ^{10}Li and in N=7 isotone.
  - Problem of soft dipole resonance.

- ∘ Our approach.
  - "core+n+n" picture + introduce the correlation in the core part



[Ref]:K. Ikeda, NPA538,355c('92)

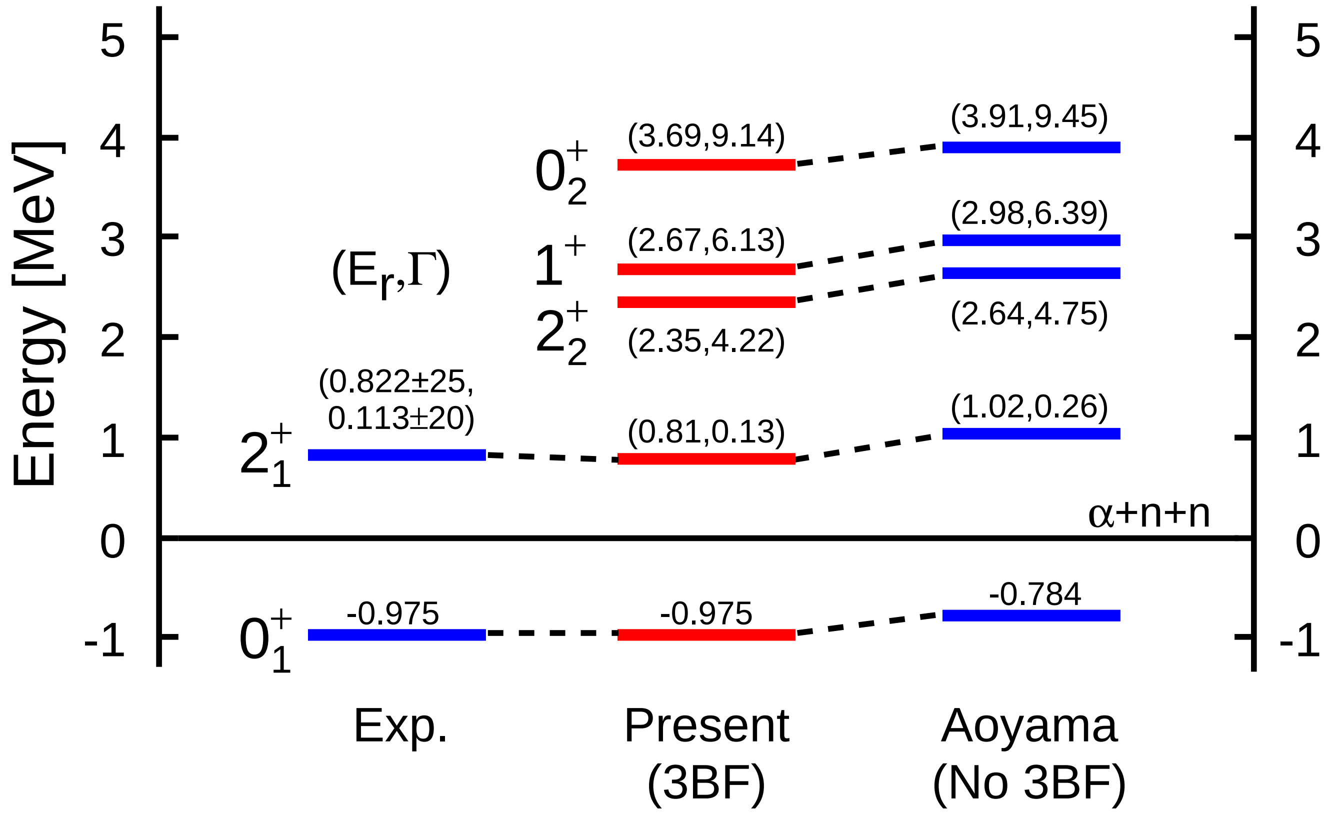
- Application to ^{6}He
  - ^{4}He+n+n with OCM : $\Phi(^6\text{He}) = \mathcal{A}\{\ \Phi(^4\text{He})\ \Phi(nn)\ \}$
  - Interaction: ^{4}He-n : KKNN potential, n-n : Minnesota



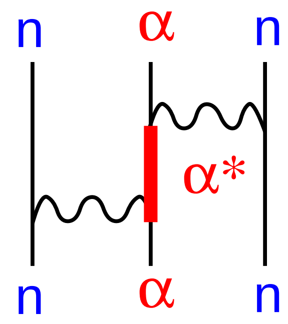
Pairing correlation for val-2n is important.

[Ref]: S.Aoyama, S.Mukai, K.Katō, K.Ikeda, PTP93('95)99.

- Spectrum of ^{6}He



$$V_{\alpha nn}=v_0\, e^{-\nu\,(r_1^2+r_2^2)}$$



R_m= 2.46 [fm]

(Exp. : 2.48±0.03 [fm]

/ 2.33±0.04 [fm])

- Successes in ^{6}Li, ^{6}Be(T=1).

^{6}Be($0^+_{g.s.}$) : Theor.: $(E_r,\Gamma) = (1.290,\ 0.090)$ [MeV]

Exp. : $(E_r,\Gamma) = (1.370,\ 0.092)$ [MeV]

- Application to ^{11}Li

  - Naive three-body model : fails
    - ^{9}Li : $(0s_{1/2})^4\ (0p_{3/2})_\pi\ (0p_{3/2})^4_\nu$ $\Rightarrow$ 1 MeV underbinding.(resonance)
    - ^{9}Li-n : Folding potential P(s^2)$\sim$ 2% (No halo) .

  - Virtual s-state in ^{10}Li :
    - Invariant mass spectrum of ^{9}Li-n.
    - Theory: strong attraction for only 1s-wave in ^{9}Li-n interaction
      - Thompson-Zhukov('94) / Garrido-Fedorov-Jensen
      - Successful description of G.S. (P(s^2)$\sim$50%, halo)
      - Sharp dipole resonances
        $\Leftrightarrow$ disagreement with observed dipole transition of ^{11}Li.

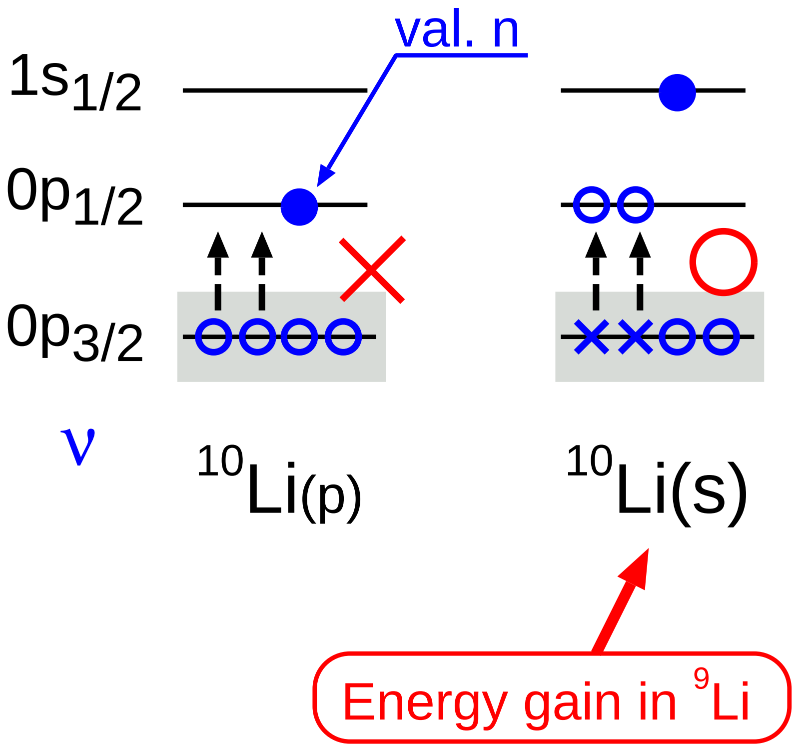
  - Other models
    - $t + \alpha + 4n$ (Varga-Suzuki-Lovas) : Success for G.S./ ^{10}Li(s) ?/ SDR?

  - Excited states – Experimental: 1.3 MeV (SDR? / partner of G.S.)

- Pairing correlation for the level inversion in ^{10,11}Li

◦ Configuration mixing in ^{9}Li

$C_0 : (0p_{3/2})^4_\nu + C_1 : (0p_{3/2})^2_\nu (0p_{1/2})^2_\nu.$



- ^{9}Li + n(p-wave) : Pauli-Blocking
- ^{9}Li + n(s-wave) : No Pauli-Blocking

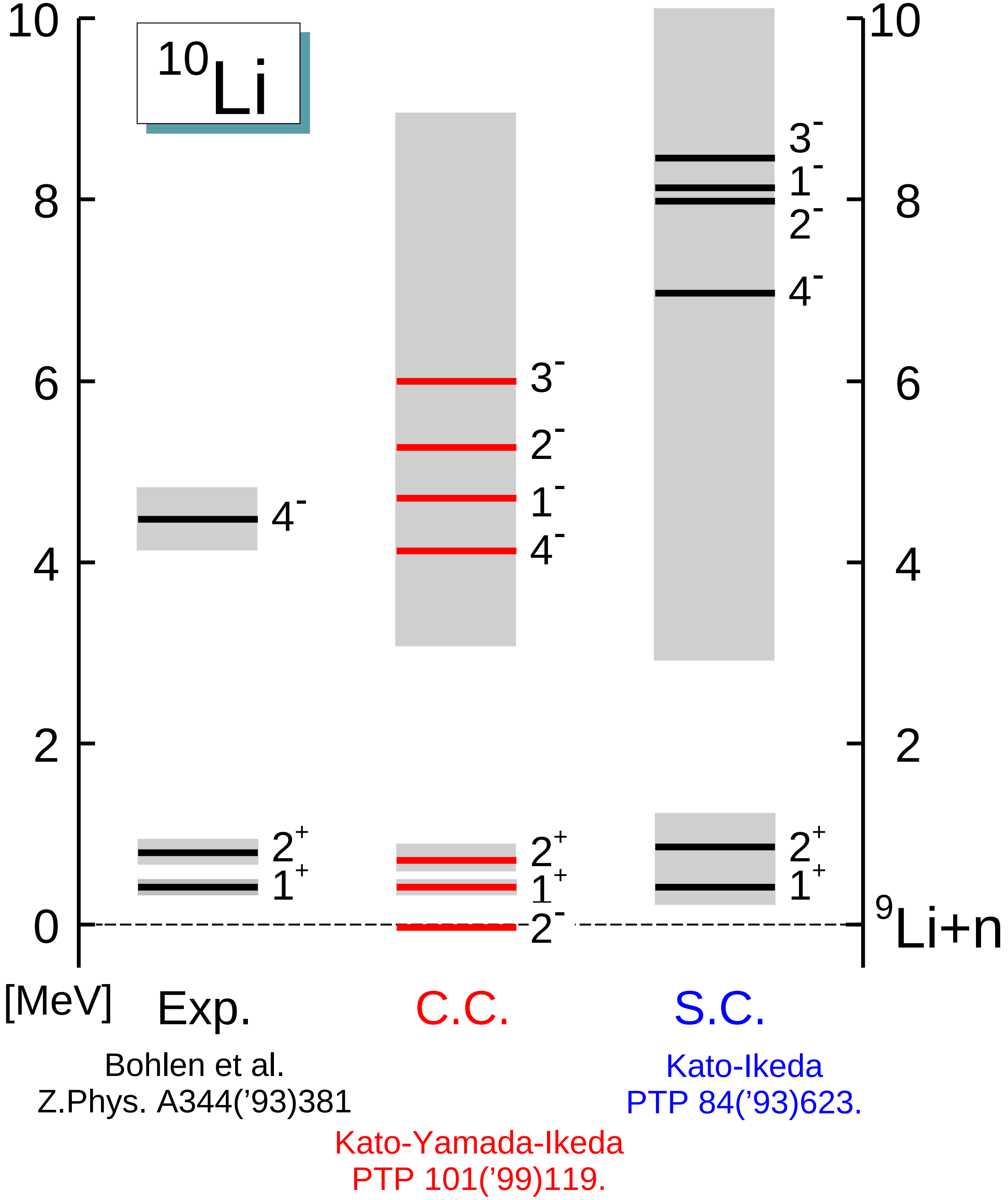
◦ ^{10}Li : ^{9}Li (C_0+C_1)+n with OCM

– Pairing : $|C_1|^2=25\%$ (Ref. C-K)

$\Rightarrow$ ^{10}Li(2^-): Virtual states ($E=-0.2$ MeV, $a_s=-10$ fm)

[Ref]: H.Sagawa, B.A.Brown, H.Esbensen PLB309('93)1.
K.Katō, T. Yamada, K.Ikeda, PTP101('99)119.
H.Masui, S.Aoyama, T. Myo, K.Katō, K.Ikeda, NPA673('00)207.
T.Myo,S.Aoyama,T. Myo, K.Katō, K.Ikeda, PTP108('02)133.

- Spectrum of ^{10}Li.

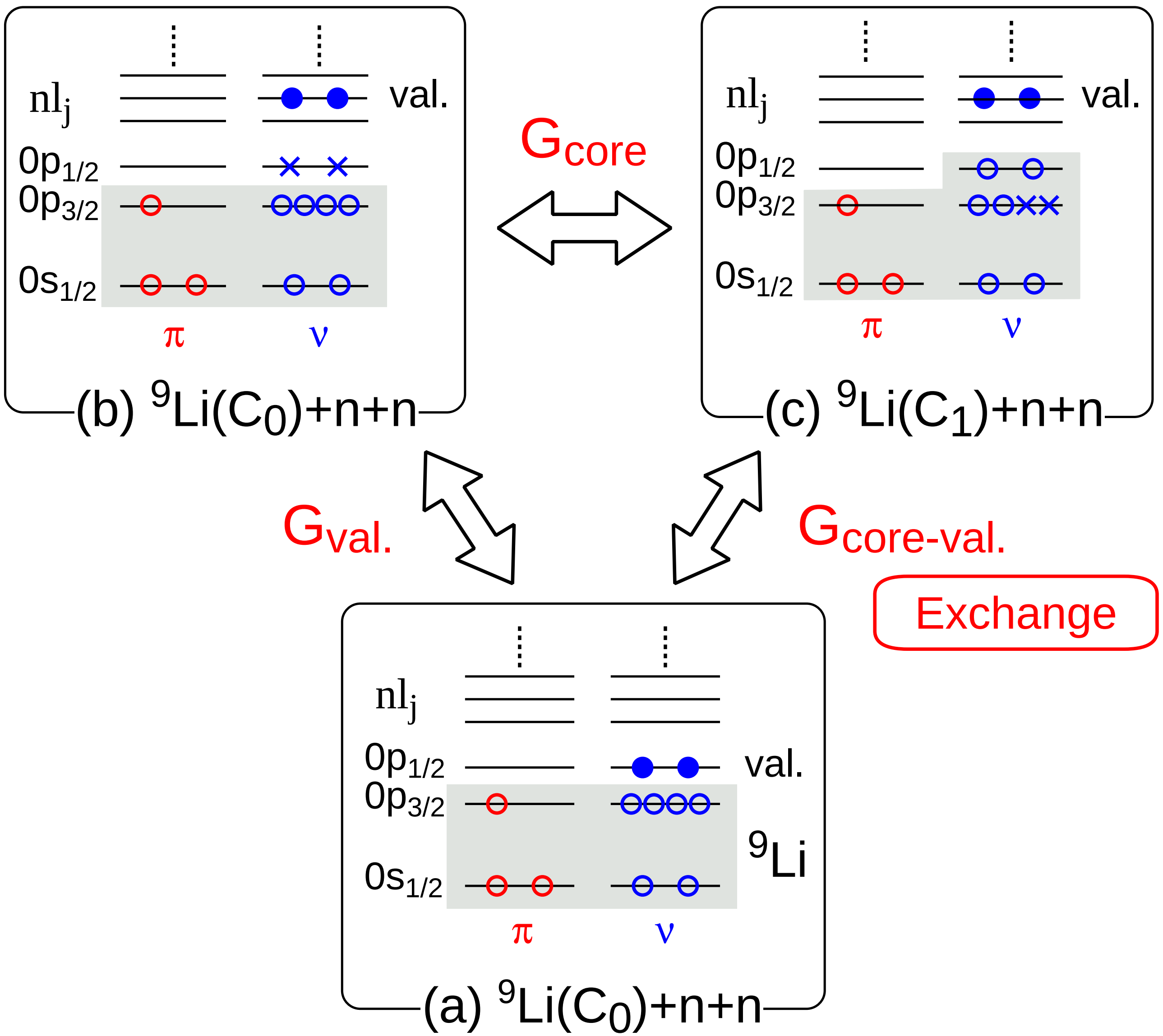


○ ^{10}Li(2^-): Virtual states
($E=-0.2$ MeV, $a_s=-10$ fm)

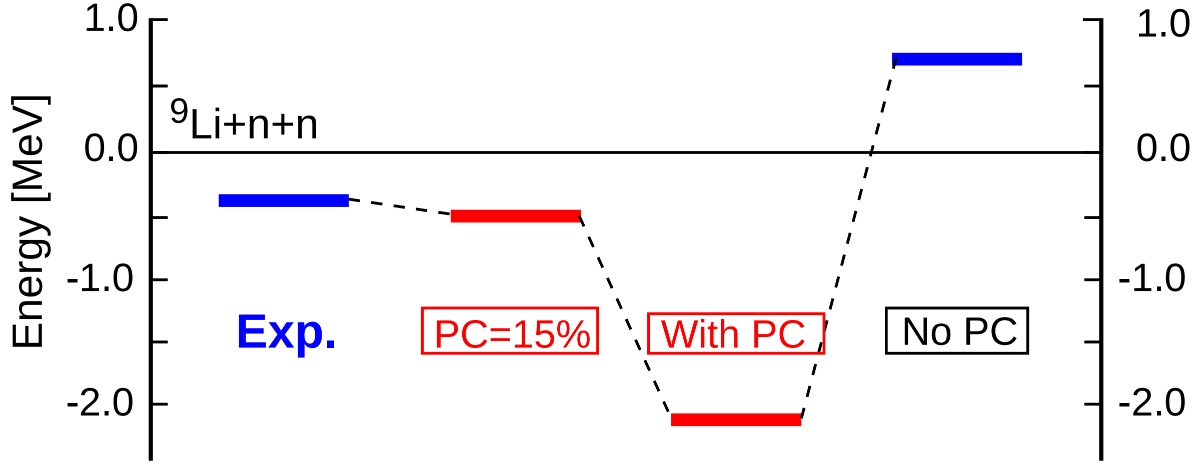
H.Masui, S.Aoyama, T. Myo, K.Katō, K.Ikeda, NPA673('00)207.

- Coupling of ^{9}Li core and valence-2n in ^{11}Li.

$$G_{pair} = G_{core} + G_{val.} + G_{core\text{-}val.}$$



- Pairing Correlation in $^{11}\mathrm{Li}_{g.s.}$



$(1s_{1/2})^2 \sim$ 2% Pair-ex.+2n ~ 3%

R_m = 2.69 [fm]

(Exp. : 3.12±0.16 [fm])

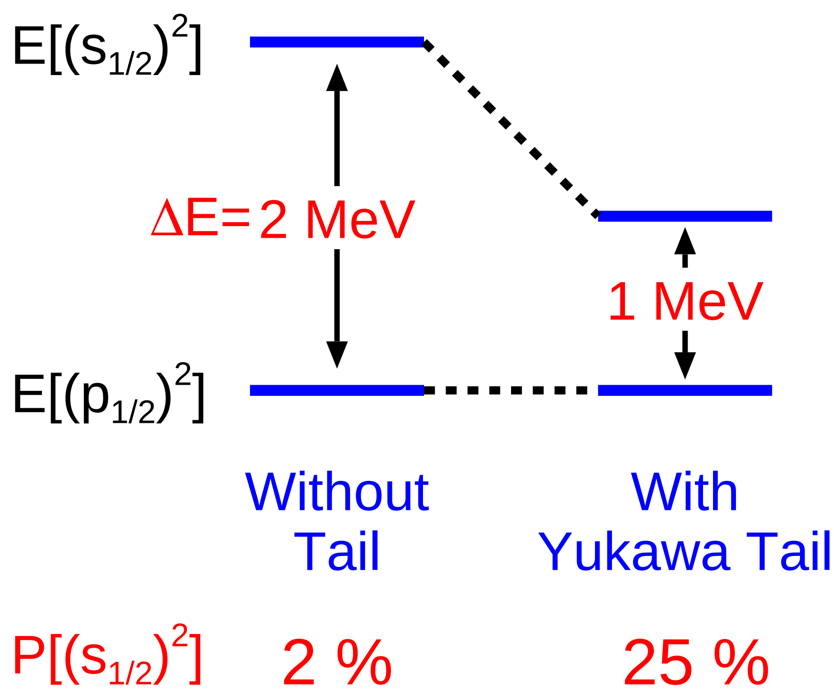
$V_{9Li\text{-}n} = V_{Fold} + V_{Tail}$ (S_n=4 MeV)

- $E(^{10}\mathrm{Li}(p)) = T_p + V_p + \Delta V(\mathrm{PB}) \equiv V_p^{eff}$
- $E(^{10}\mathrm{Li}(s)) = T_s + V_s$

⇒ *s*- and *p*-waves are degenerated

- $E(^{11}\mathrm{Li}(p^2)) = T_p + V_p + \Delta V(\mathrm{PB}) + T_p + V_p + V_p^{nr}$
- $E(^{11}\mathrm{Li}(s^2)) = T_s + V_s + T_s + V_s + V_s^{nn}$

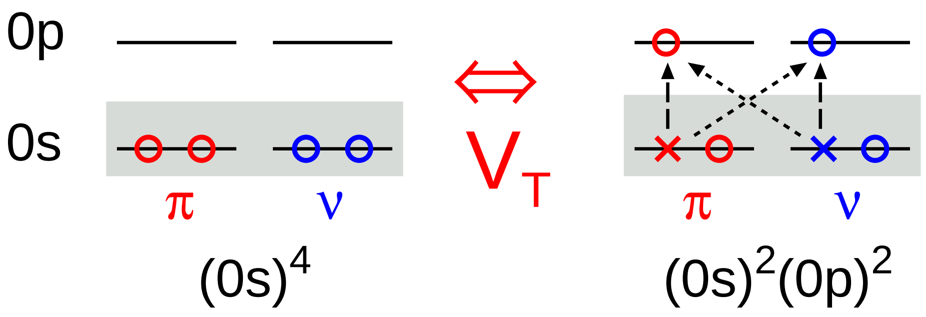
⇒ *p*-wave configuration gains energy



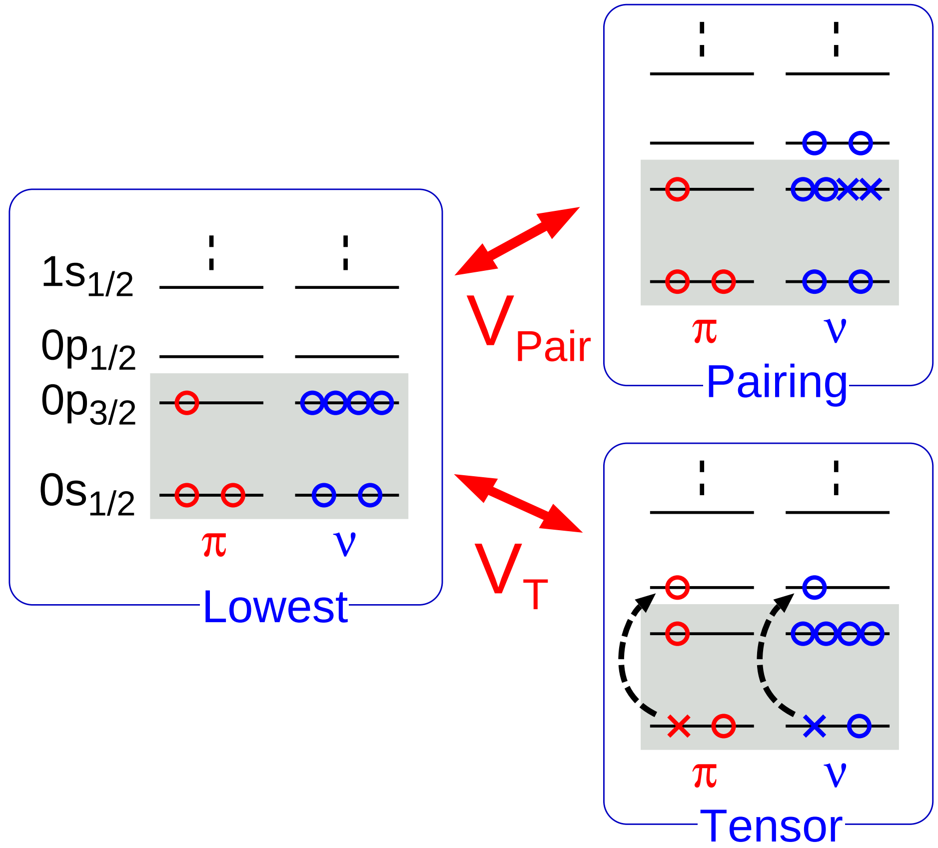
- Odd-Even difference of Pairing blocking

• Tensor correlation in ^{4}He and ^{9}Li core

– ^{4}He –



– ^{9}Li –



- $\langle V_T \rangle$ (^{3}E) is large (comparable to $\langle V_C \rangle$)

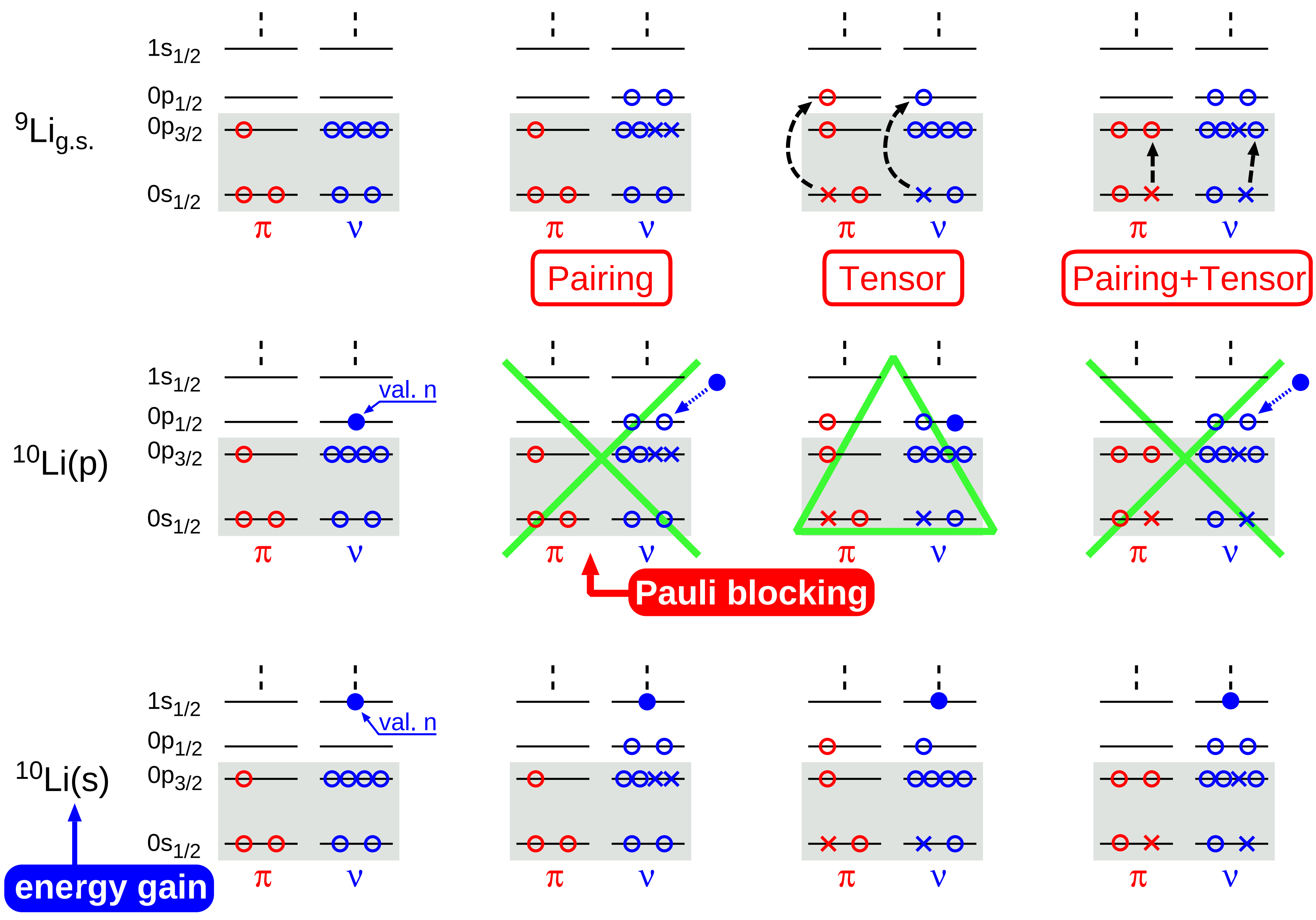
  ⇒ T=0 (*pn*) correlation is important
- Change parity of s.p.o due to ($\sigma \cdot r$)
- 2p-2h excitation from $(0s)^4$ from perturbation theory

  ⇒ Similarity to charge- and parity-mixed single particle orbit (Sugimoto/ Ogawa/ Akaishi/Dote)

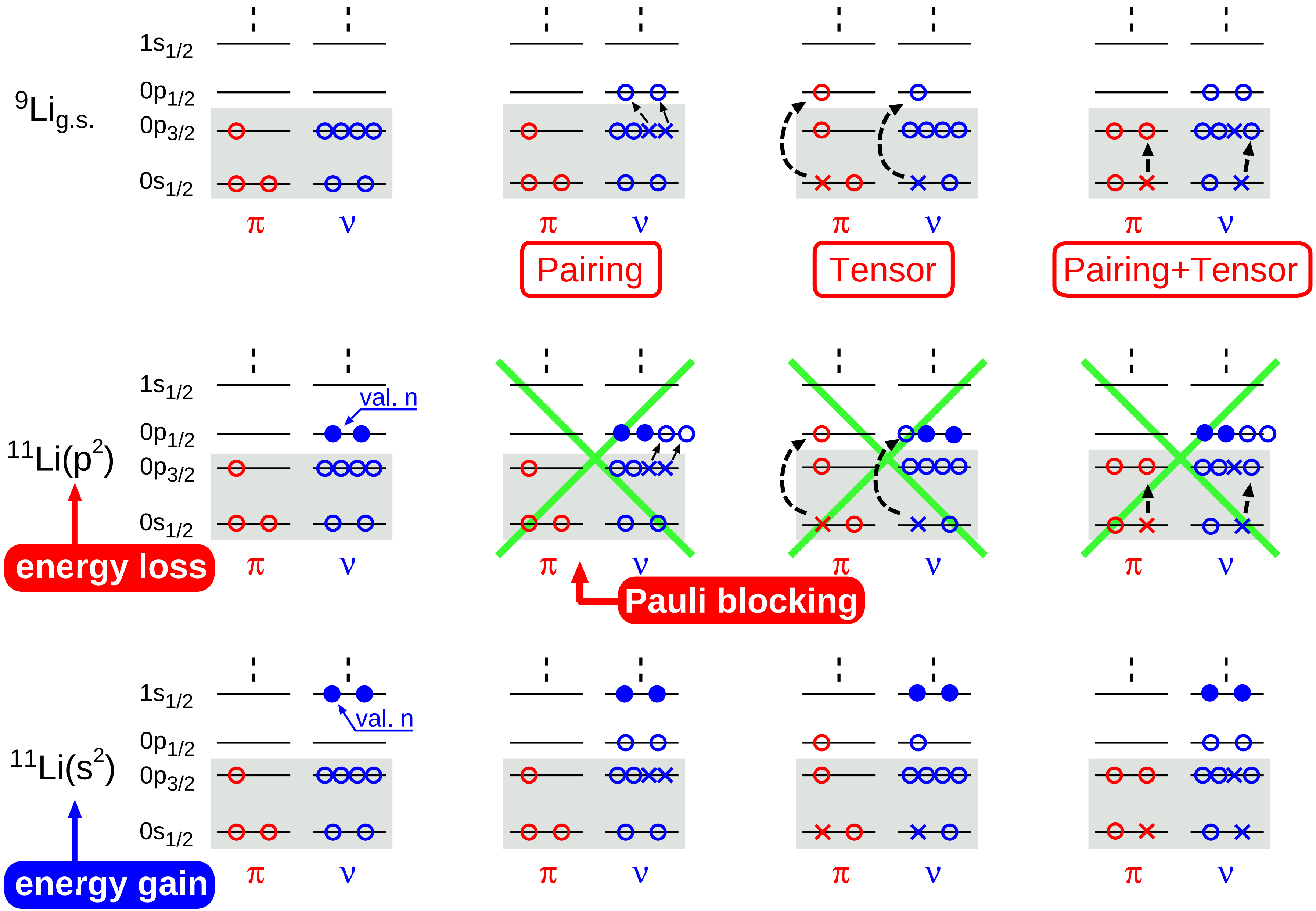
We consider...
0^+ Pairing(T=1)+Tensor(T=0) correlations

[Ref.] Y.Akaishi et. al, Inter. Review of Nucl. Phys. 4(1986)
H. Kamada et. al, PRC64(2001)044001

• Effect of Tensor Correlation in ^{10}Li



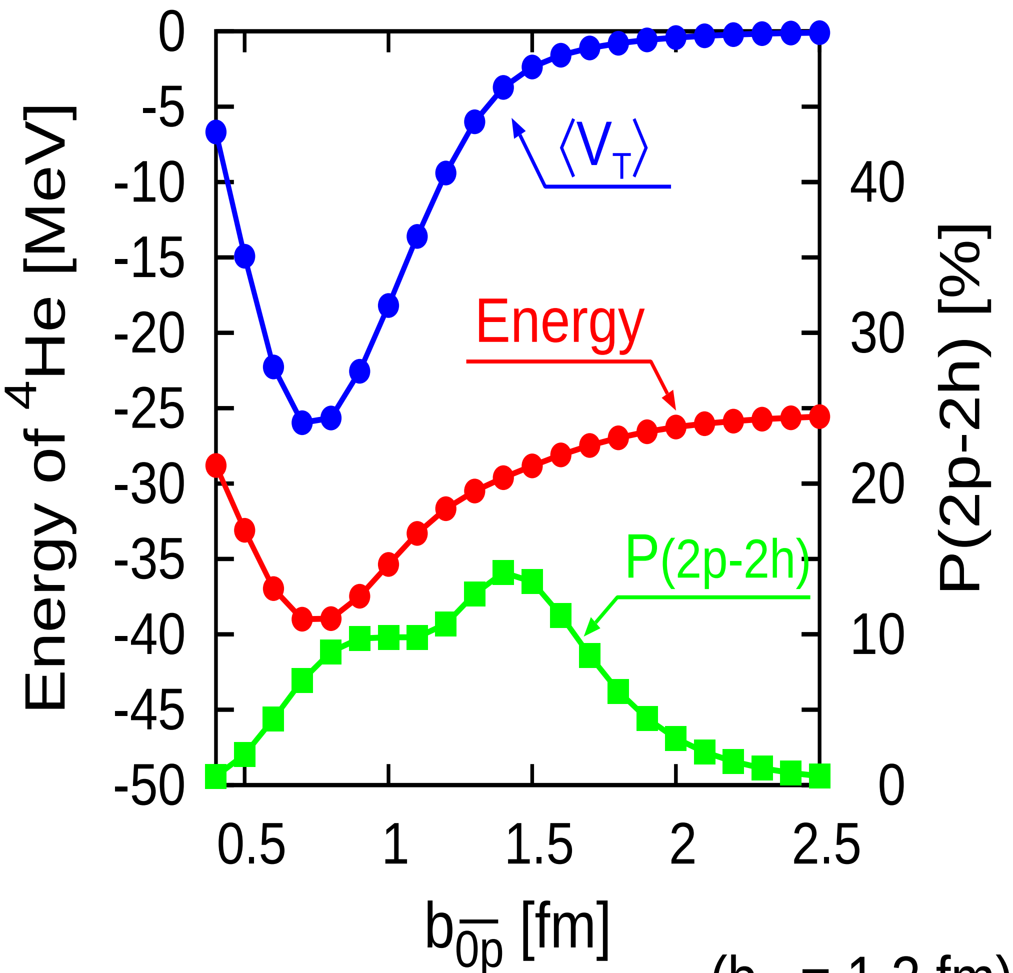
• Effect of Tensor Correlation in ^{11}Li



• We expect that tensor correlation can lower the s^2-component in ^{11}Li

- Model to incorporate the tensor correlation
  - Criterion : ^{4}He (P[D]$\sim$10-13%)
    - Extension of Terasawa, Nagata's works (^{5}He LS splitting)
    - Application to ^{6}He=^{4}He$^{(*)}$+n+n.
  - Wave Function for core part (^{4}He, ^{9}Li)
    - H.O.basis with different length parameters $\{b_i\}$, such as $b_{0s} \neq b_{\overline{0p}} \ldots$ to include the higher shell effect.
    - for ^{4}He, $0s_{1/2}+\overline{0p}_{1/2}+\overline{0p}_{3/2}$ up to 2p-2h.
      - $\Phi(^4\text{He}) = \Sigma_\alpha \, C_\alpha \, \psi_\alpha(\{b_i\}) \; = C_1 \, (0s)^4 + C_2 \, (0s)^2(\overline{0p}_{1/2})^2 + \cdots$
      - $\dfrac{\partial \langle H-E \rangle}{\partial b_i} = 0 \;, \quad \dfrac{\partial \langle H-E \rangle}{\partial C_\alpha} = 0$
  - Similarity to Sugimoto-Ikeda-Toki's CPPHF (nucl-th/0402076)

• ^{4}He G.S.(0^+) with Volkov-2+Furutani+G3RS



(b_{0s}= 1.2 fm)

○ Amplitudes with $b_{\overline{0p}_{1/2}} = b_{\overline{0p}_{3/2}} = 0.8$ fm

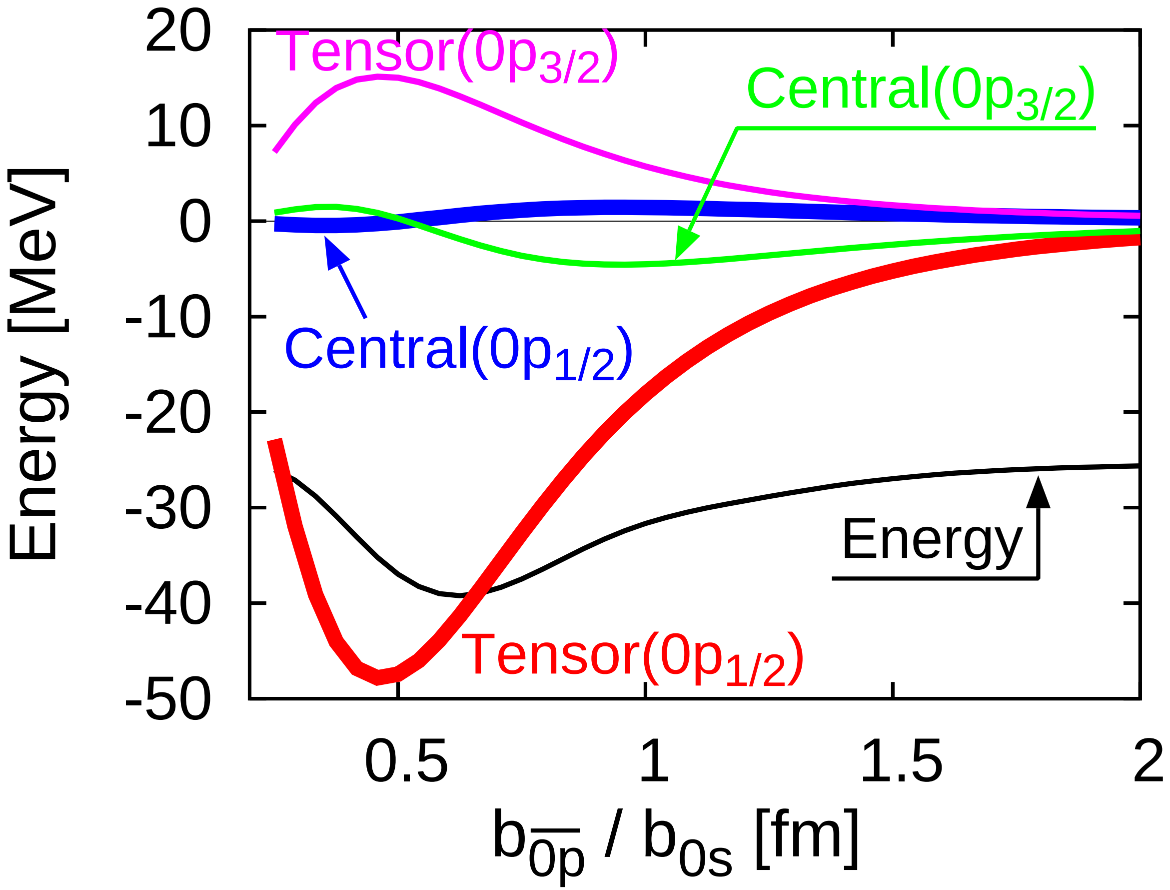
$(0s_{1/2})^4$		91.2 %
$(0s_{1/2})^2_{JT}(\overline{0p}_{1/2})^2_{JT}$	(JT)=(10)	7.4 %
	(JT)=(01)	0.02 %
$(0s_{1/2})^2(\overline{0p}_{3/2})^2$		0.9 %
$(0s_{1/2})^2(\overline{0p}_{1/2})(\overline{0p}_{3/2})$		0.2 %
P[D]		5.6 %
R_m		1.28 fm

• 0^- coupling between $0s_{1/2}$ and $0p_{1/2}$

⇒ pion nature

- Coupling Matrix Element of Tensor force

$$\langle (0s_{1/2})^2_{10} (\overline{0p}_{1/2,3/2})^2_{10} \, |V| (0s)^4 \rangle \quad (b_{0s}=1.2 \text{ [fm]})$$



Coupling from Tensor force is significant with a short $b_{\overline{0p}}$

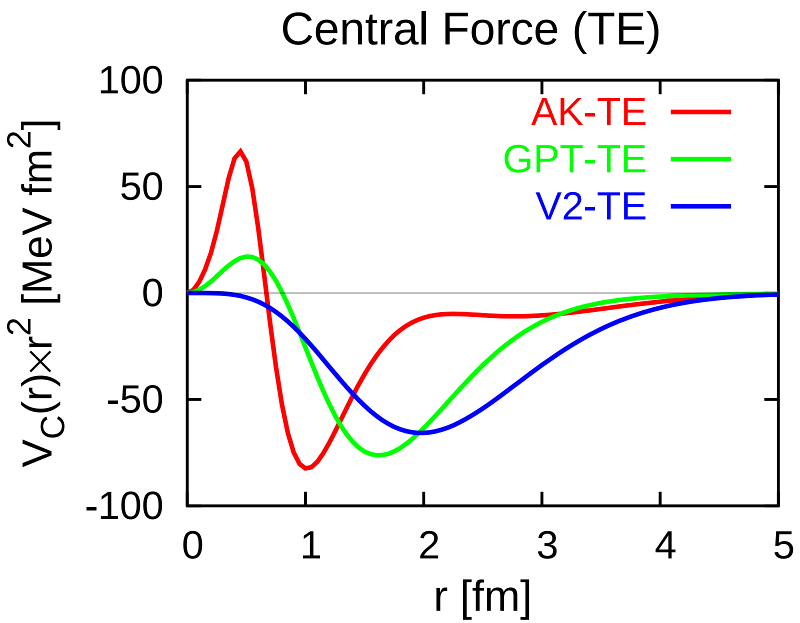
- ^{4}He G.S.(0^+) with Volkov-2+Furutani.+G3RS
  - ^{3}E part of Central force is adjusted to reproduce the B.E. of ^{4}He (28.3 MeV).

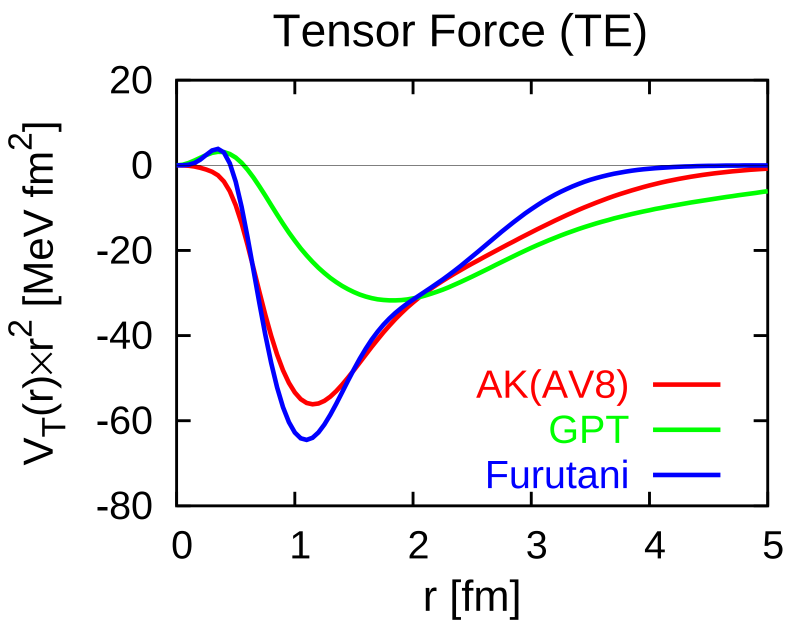
$b_{\overline{0p}}$ [fm]	2.0	1.2 (=b_{0s})	0.8	($V_T \times 1.5$)
⟨Kinetic⟩ [MeV]	61.8	59.6	71.2	78.0
⟨Central⟩	–90.6	–79.5	–75.5	–56.5
⟨Tensor⟩	–0.4	–9.3	–25.6	–51.8
⟨LS⟩	2×10^{-3}	5×10^{-4}	0.6	1.1
R_m [fm]	1.33	1.36	1.29	1.29
2p-2h [%]	2.8	11.6	8.9	16.5
$(\overline{0p}_{1/2})^2_{JT}$ (JT)=(10)	0.5	6.0	7.5	14.6
$(\overline{0p}_{1/2})^2_{JT}$ (JT)=(01)	0.3	0.7	0.2	0.3
$(\overline{0p}_{3/2})^2$	1.5	4.5	1.0	1.3
$(\overline{0p}_{1/2})(\overline{0p}_{3/2})$	0.4	0.3	0.2	0.3
P[D] [%]	0.5	4.6	5.6	11.0

tensor force can be incoroperated

• Effective Interaction

- ◦ Akaishi potential: G-matrix derived from AV8' (Acknowledge to Y. Akaishi)
- ◦ GPT potential: C+LS+T, 3-range Gaussian to fit 2N properties.



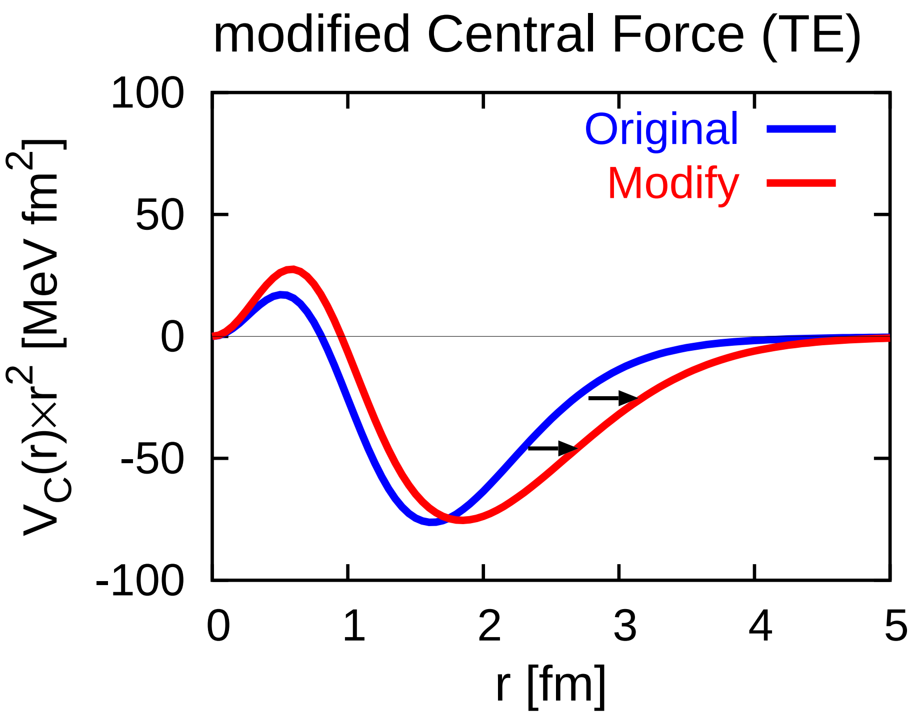


	Int.	E ($\langle V_T \rangle$) [MeV]	2p-2h	R_m [fm]
^{4}He	AK	-19.0 (-30.9)	13 %	1.23
	GPT	-17.4 (-11.2)	8 %	1.45

We use..

- Central : GPT
- Tensor , LS : Aakaishi

◦ GPT+AK with modification to reproduce ^{4}He properties



◦ 2nd range of GPT central is extended to reproduce R_m of ^{4}He

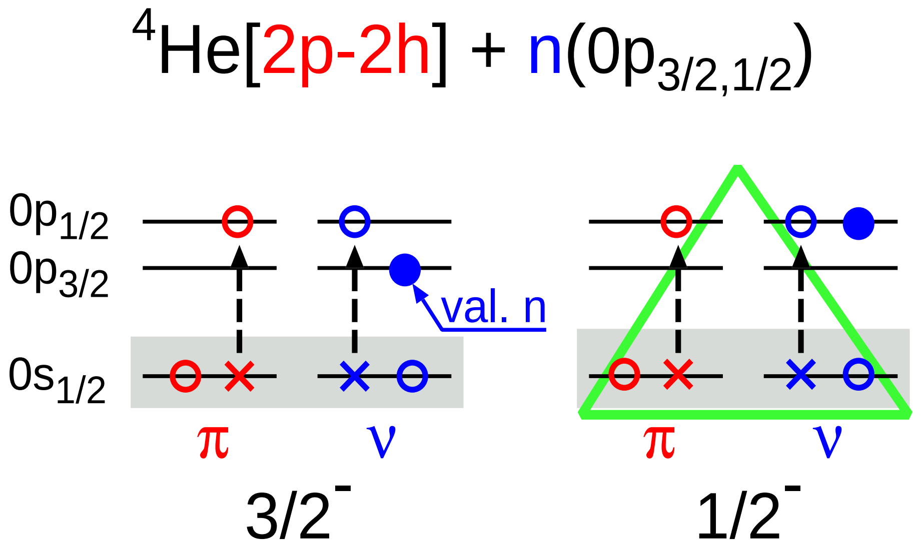
$$V_2 = v_2 \cdot e^{-(r/R_2)^2}$$

$$R_2 \rightarrow R_2 + \Delta R \quad (\Delta R{=}0.25 \text{ fm})$$

$$v_2 \rightarrow v_2 + \Delta v$$

E ($\langle V_T \rangle$) [MeV]	P[2p-2h]	R_m[fm]	
-28.3 (-17.0)	9.3 %	1.48	$V_T \times 1.0$
-28.3 (-29.9)	12.5 %	1.48	$V_T \times 1.5$

• 3/2$^-$-1/2$^-$ splitting in ^{5}He with ^{4}He$^{(*)}$+n model



energy loss in ^{4}He

Tensor correlation is suppressed

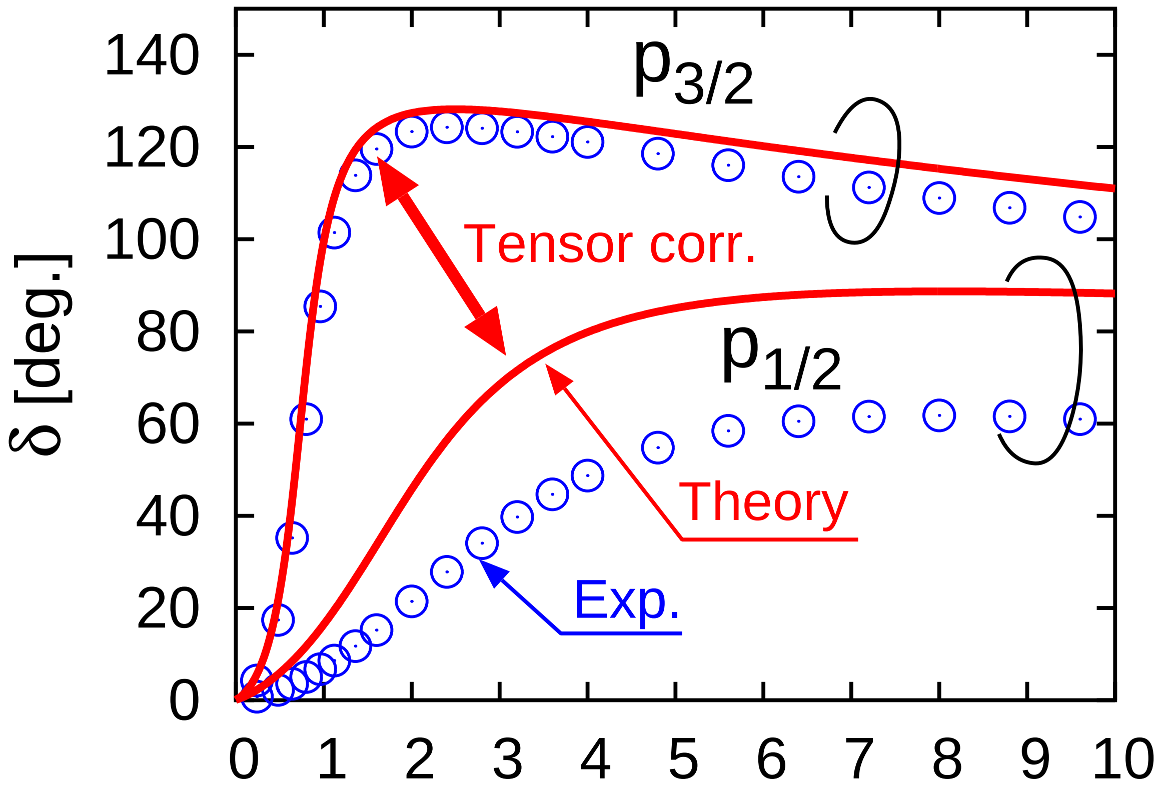
⇒ LS splitting appears

- ○ ^{4}He+n interaction (OCM)
  - – one-range Gaussian without LS
- ○ $H(^5\mathrm{He}) = H(^4\mathrm{He}) + H_{\mathrm{rel}}$
- ○ $\Phi(^5\mathrm{He}) = (0s)^4 \cdot \psi^1_{\mathrm{rel},j} + (0s)^2(\overline{0p_{1/2}})^2 \cdot \psi^2_{\mathrm{rel},j}$
- ○ $\psi^i_{\mathrm{rel},j} = (\overline{0p_j}) + \Sigma_{n=1}(\overline{np_j})$.

○ $E_R=(E_r,\Gamma)$ [MeV] of ^{5}He resonant poles

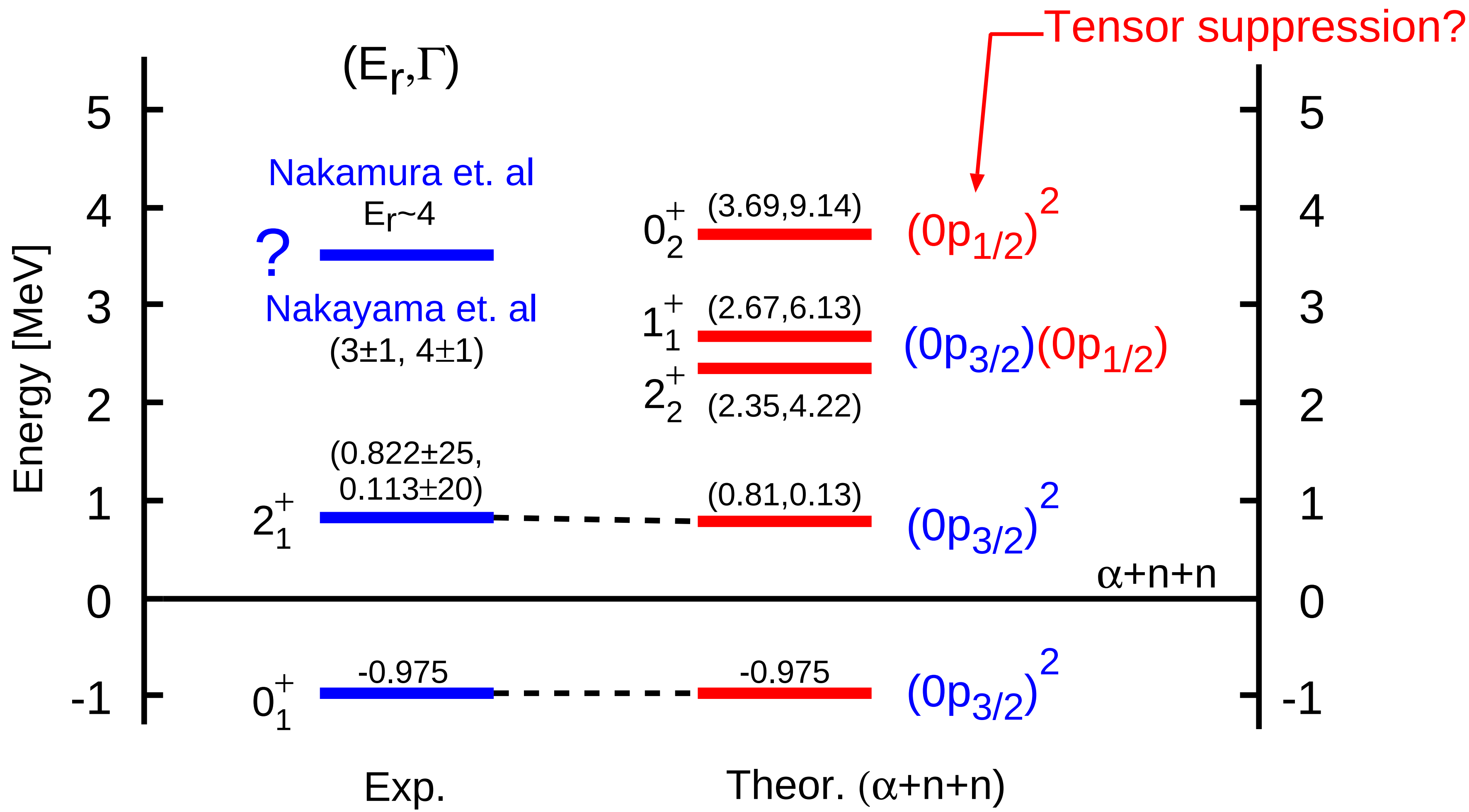
	Exp.(KKNN)	Present ($V_T\times1.0$)	Present ($V_T\times1.5$)
$3/2^-$	(0.74, 0.60)	(0.74, 0.60)	(0.74, 0.59)
$1/2^-$	(2.13, 5.84)	(1.10, 1.45)	(1.47, 3.10)
ΔE	1.47	0.36	0.73

Phase shifts of ^{4}He+n system



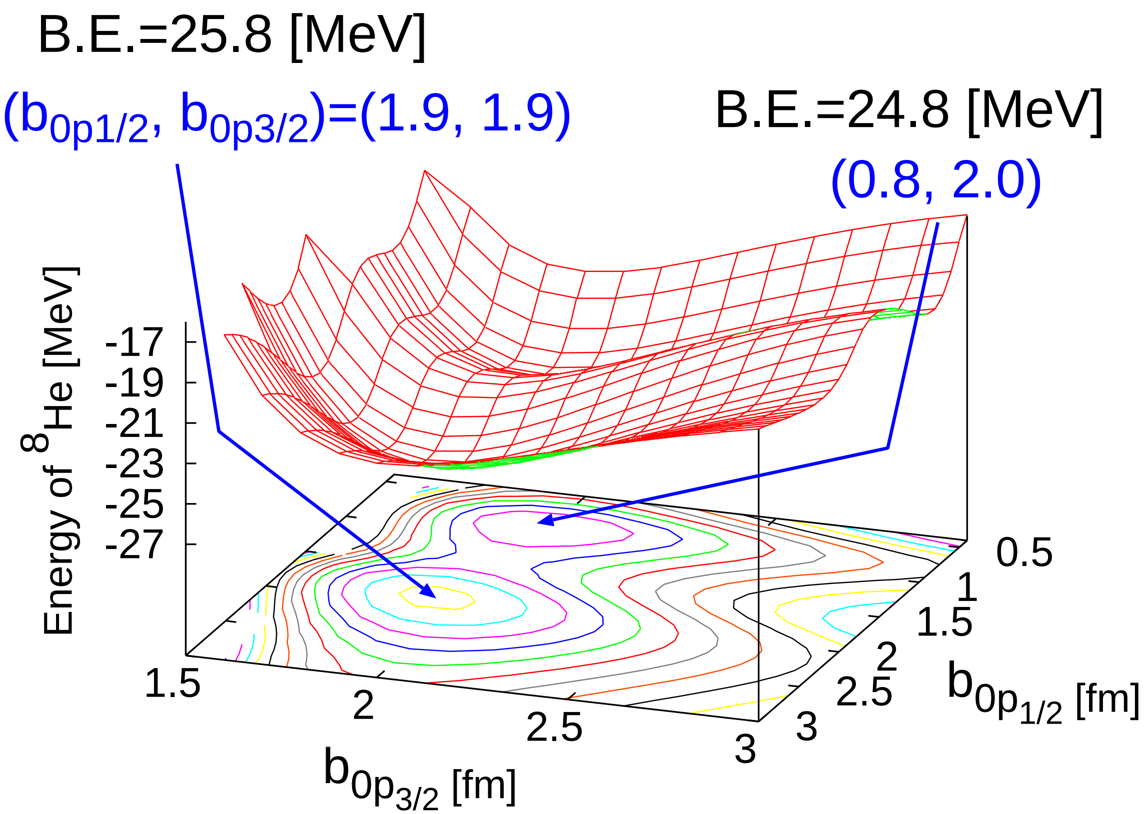
acknowledge to R. Suzuki (Hokkaido Univ.)

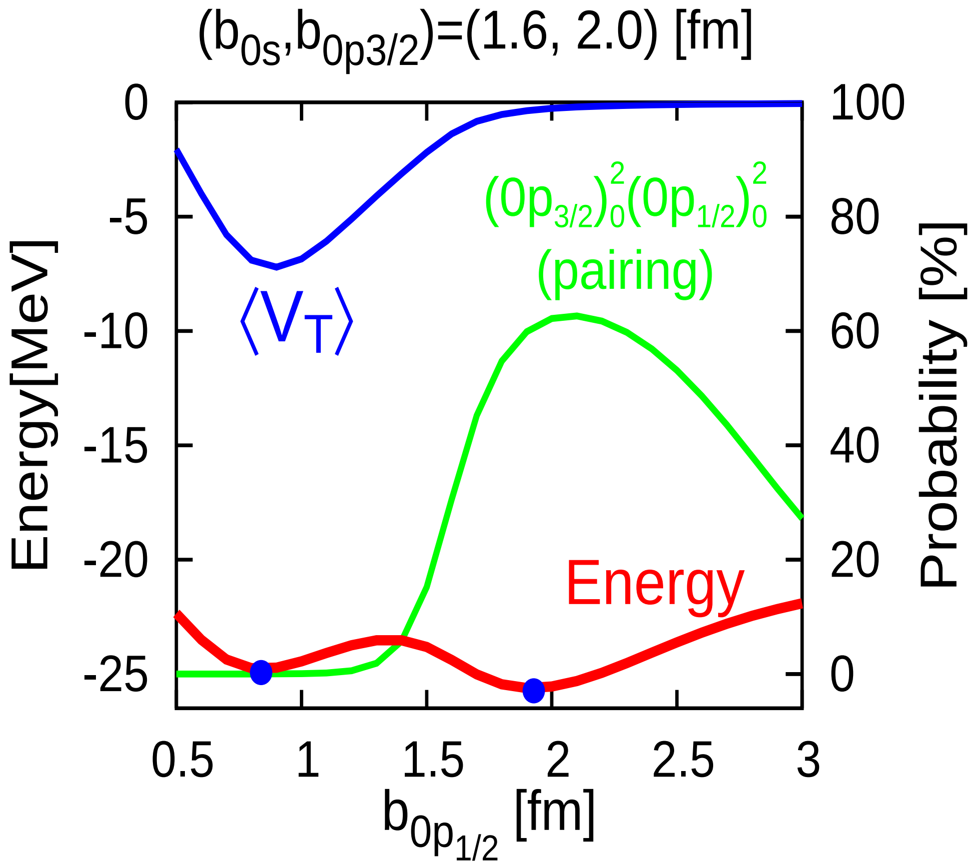
- Energy Levels of ^{6}He without tensor correlation



- ^{8}He (0^{+}) : same neutron number as ^{9}Li (b_{0s}= 1.6 [fm])

  ○ 2p-2h : tensor ($0s \rightarrow 0p$) + pairing($0p_{3/2} \rightarrow 0p_{1/2}$) correlations





○ two minima: Tensor correlation with short $b_{0p1/2}$ ($\sim b_{0s}/2$) .

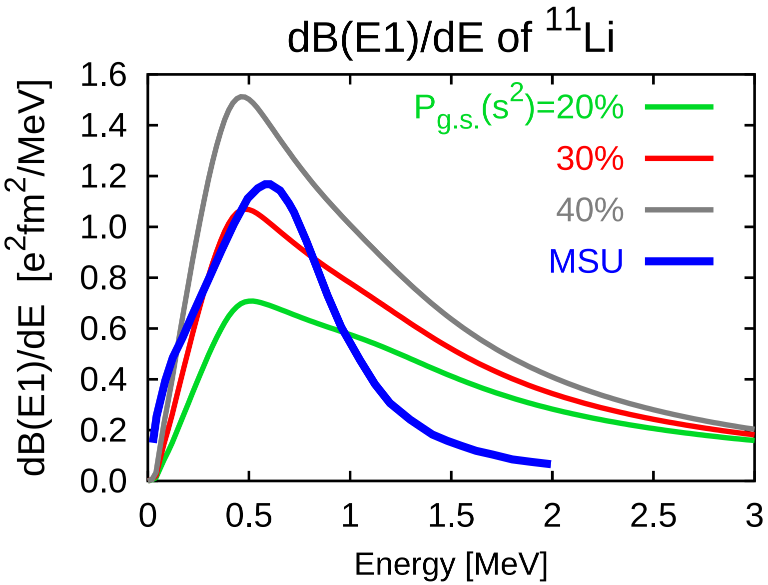
Pairing correlation with $b_{0p1/2}=b_{0p3/2}$.

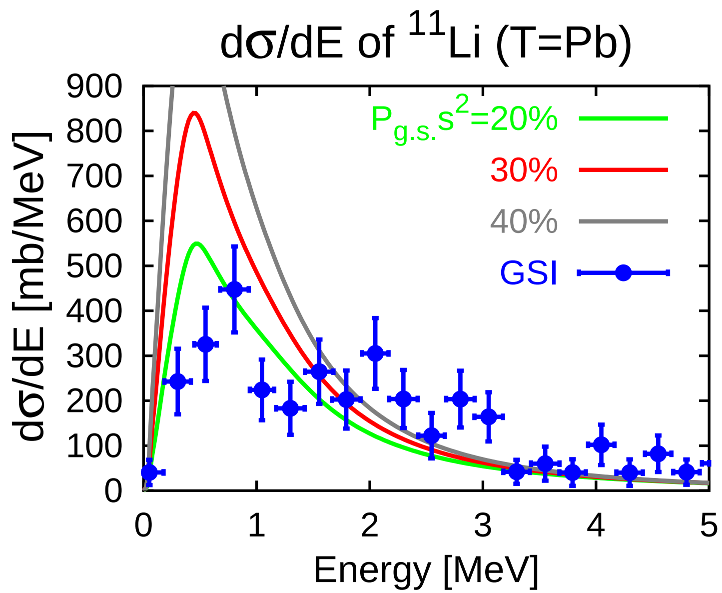
Summary

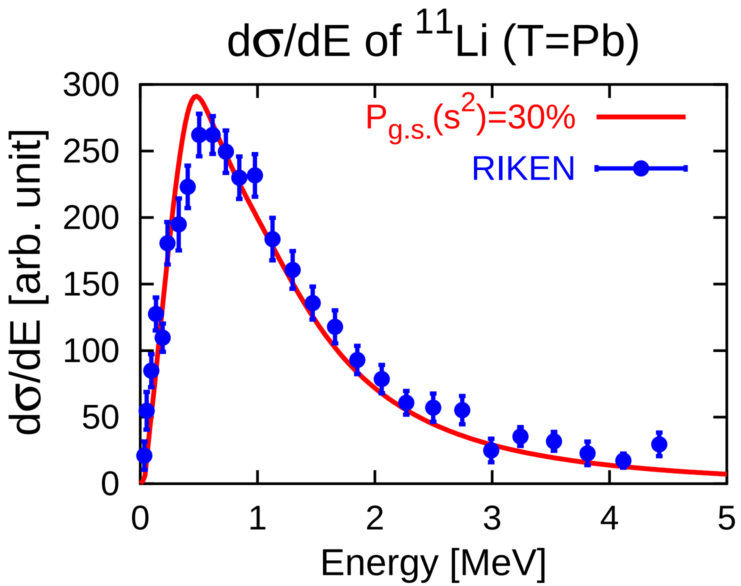
1. Pairing correlation contributes to the formation of the weak-binding state.
2. Pairing-blocking can reproduce the ^{10}Li's properties, but not ^{11}Li.
3. Tensor correlation is expected to contribute to the inversion problem.
4. Effects of Tensor correlation in ^{4,5}He.
   - ^{4}He : p-wave is shrunk, Coupling between $0s_{1/2}$ and $0p_{1/2}$.

     (cf. Akaishi(HF), Sugimoto(HF), Doté(AMD))
   - ^{5}He : contribute to LS splitting.
   - Effective interaction ; strength of tensor force, ρ-dependent part,..
5. For ^{8}He, ^{9}Li
   - Tensor and Pairing correlations produce the energy minima.
     (different $b_{0p1/2}$ values) $\Longrightarrow$ We should superpose them.

• Dipole transition of ^{11}Li (PC(^{9}Li)=15%, No dipole resonances)

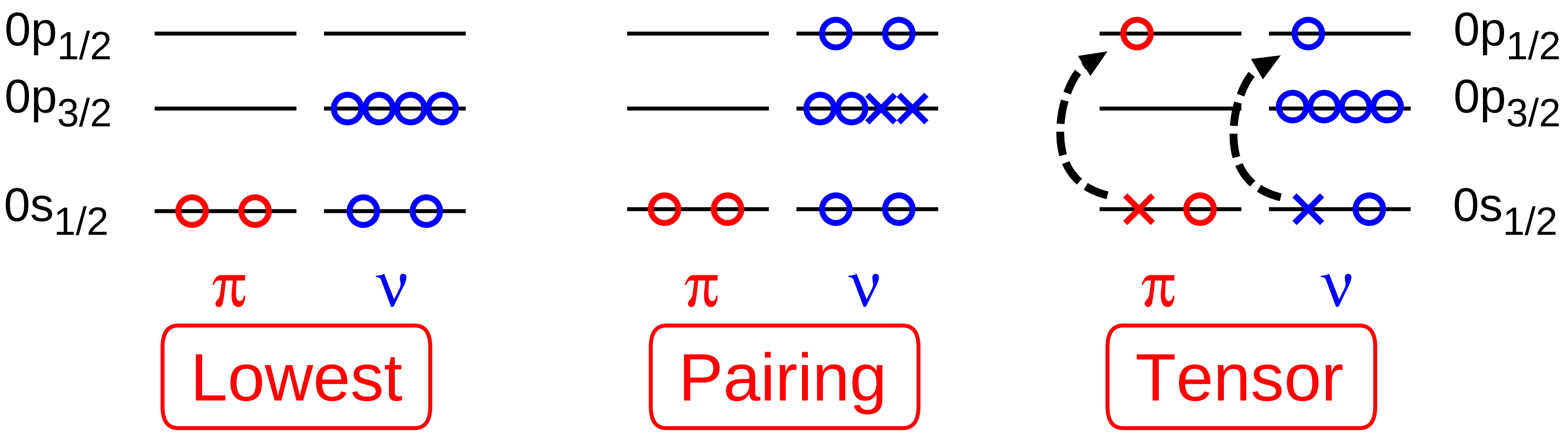






[Ref]: T. Myo, S.Aoyama,K.Katō, K.Ikeda, PLB576('03)281.

- ^{8}He (0^{+}) : same neutron number as ^{9}Li
  - Configuration with H.O. basis function:
    - $0s_{1/2}+\overline{0p}_{1/2}+\overline{0p}_{3/2}$ up to 2p-2h.
    - Length parameters $\{b_i\}$ are determined variationally.
  - Interaction :
    - Central : GPT with strengthening v_2 by 3%
    - Tensor, LS : Akaishi



• ^{9}Li ($3/2^-$) with 0s+0p, ^{8}He(0^+)+$p_{3/2}$