# Tensor correlation in neutron halo nuclei

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- Contents
  - Tensor Correlation for s-wave problem in $^{10,11}$Li (cf. pairing).
    - Occurance of Halo structure in $^{11}$Li (N=8).
    - Inversion problem in $^{10}$Li (N=7).
  - Model : $^{9}$Li+n+n with Tensor correlation in $^{9}$Li.

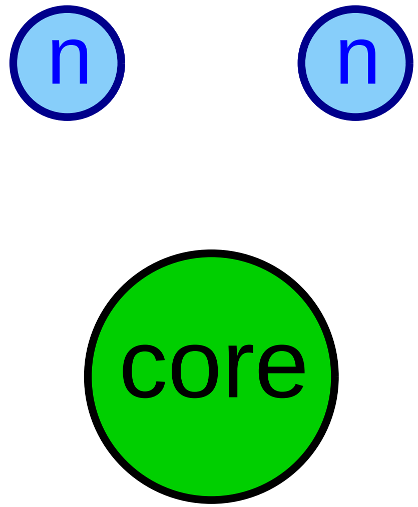
    Analogy : $^{4}$He+n+n of $^{6}$He.
  - Results : 1. $^{4}$He with tensor correlation using Shell Model basis.

    2. $^{5}$He with $^{4}$He+n ($3/2^{-}$–$1/2^{-}$ splitting).

    3. Effective Interaction.

    4. $^{8}$He with tensor and *p*-shell pairing correlations.

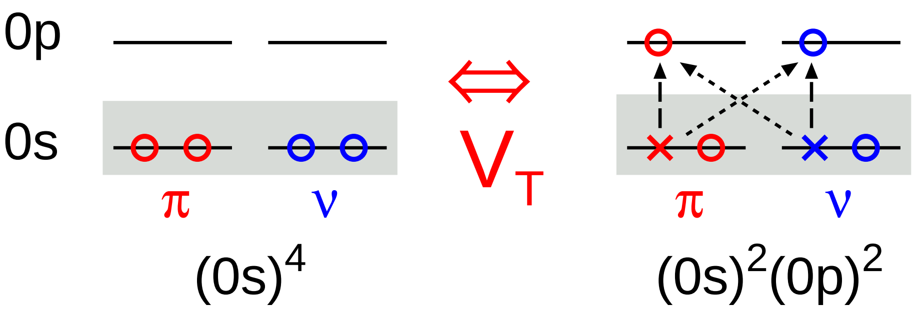
- Description of Halo nuclei based on the "core+n+n" model
  - $^{6}$He : Successful results for G.S. without core excitation.
  - $^{11}$Li : Ambiguity in $^{9}$Li-n interaction.
    - $^{9}$Li : $(0p_{3/2})_{\nu}$ -closed $\longrightarrow$ Underbinding.
    - $^{9}$Li : *p*-shell pairing correlation for neutron
      - ◯ Inversion phenomena in $^{10}$Li.
      - × *p*-shell closed configuration in $^{11}$Li.
  - Effect of tensor correlation
    - $^{9}$Li : pairing corr. + tensor corr.
    - Degeneracy of p- and s-orbitals in both $^{10,11}$Li ?
      - inversion phenomena in N=7, halo production



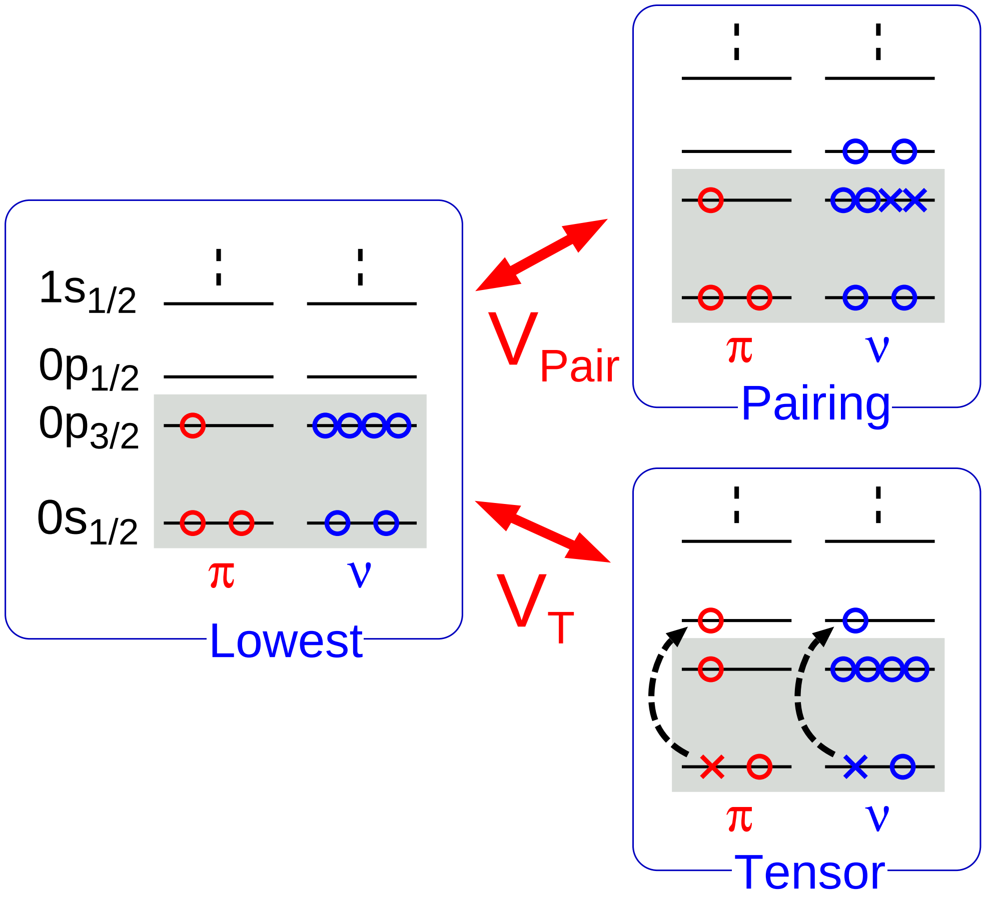

[Ref]: K.Katō, K.Ikeda, PTP89('93)623.
T.Myo, S.Aoyama, K.Katō, K.Ikeda, PTP108('02)133.

- Tensor correlation in $^4$He and $^9$Li core

## – $^4$He –



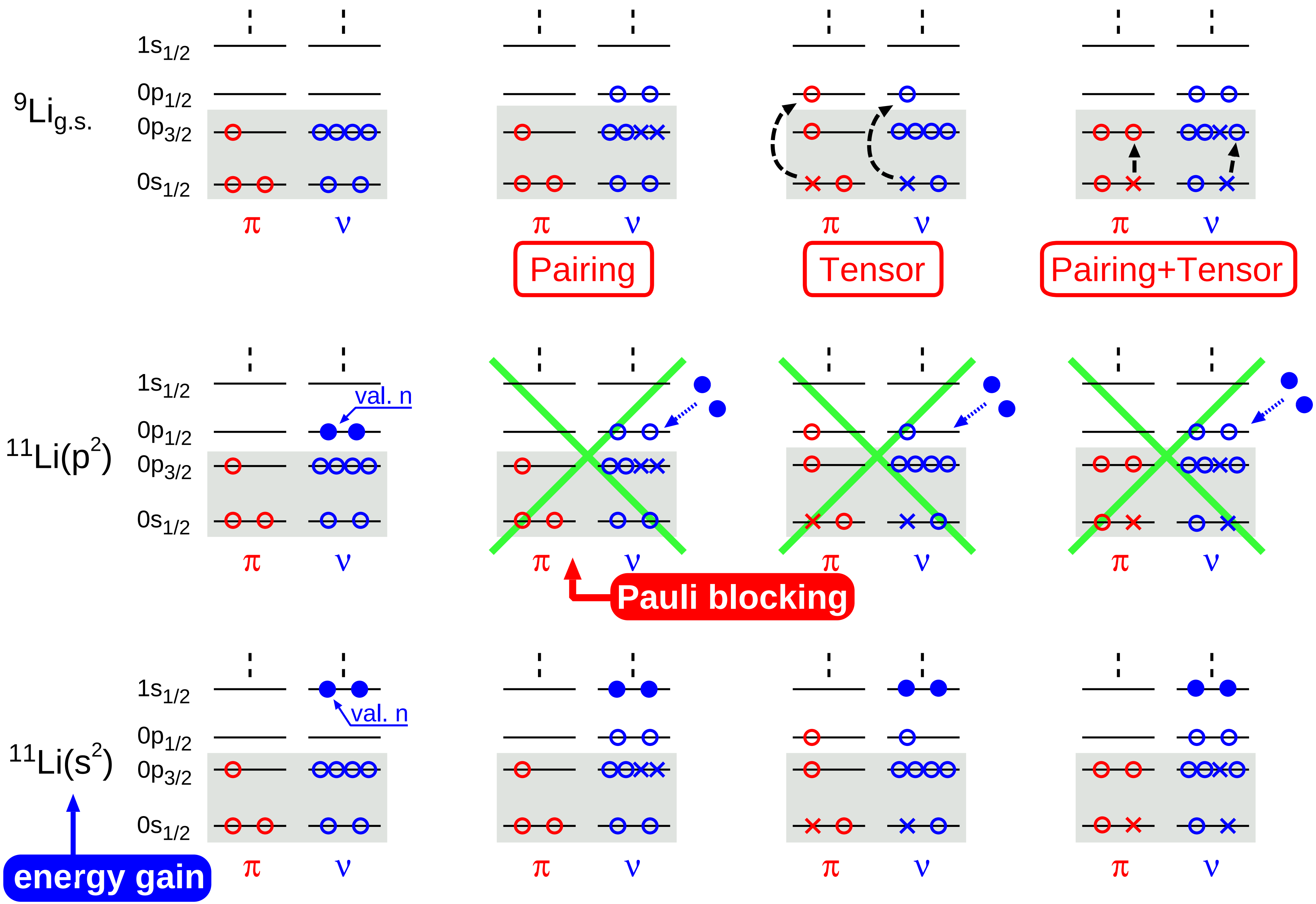

## – $^9$Li –




- $\langle V_T \rangle$ ($^3$E) is large (comparable to $\langle V_C \rangle$)
- 2p-2h excitation from $(0s)^4$
- P[D] ~ 10-13%

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

# • Effect of Tensor Correlation in $^{11}$Li



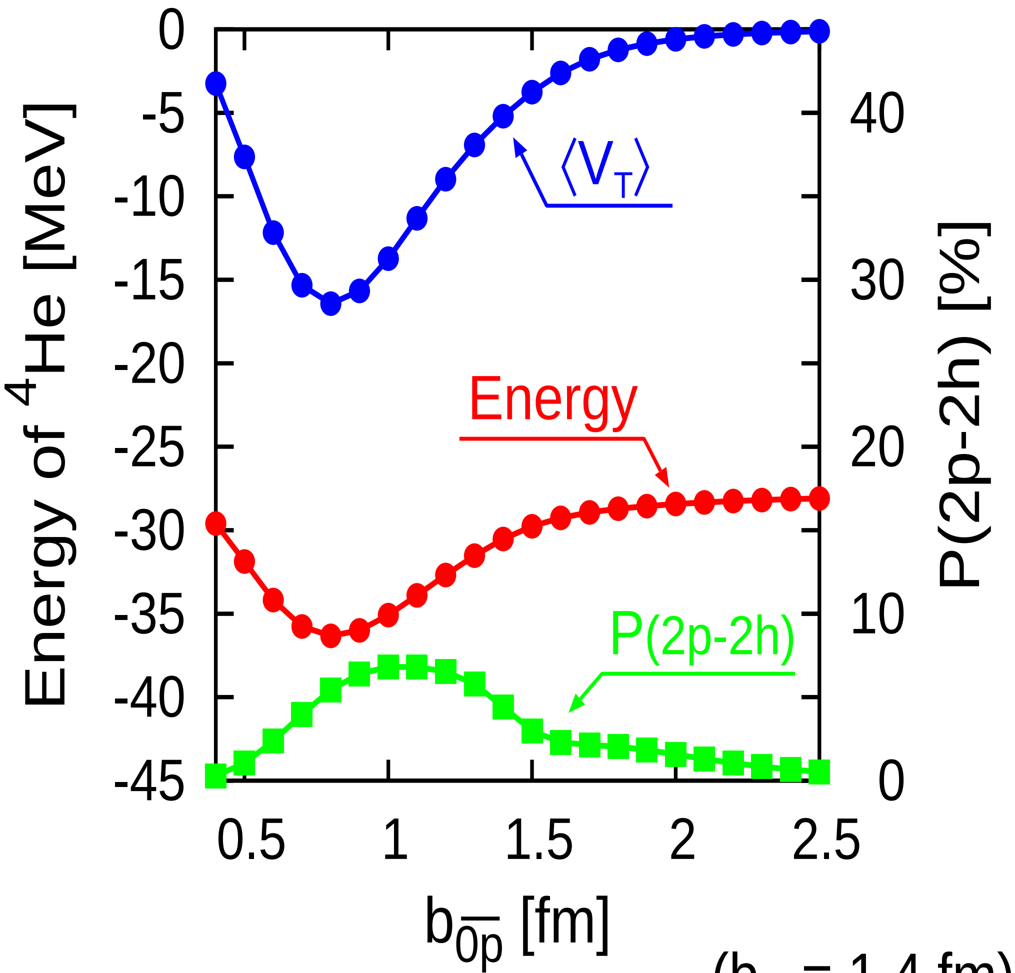
- Model to incorporate the tensor correlation
  - Criterion : $^{4}$He (P[D]∼10-13%)
    - Extension of Terasawa, Nagata's works ($^{5}$He;LS splitting)
    - Application to $^{6}$He=$^{4}$He$^{(*)}$+n+n.

      ⇒ Review of Halo mechanism, Resonance structures.
  - 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.
      - $\Phi(^{4}\mathrm{He}) = \Sigma_\alpha\, C_\alpha\, \psi_\alpha(\{b_i\}) \;= C_1\,(0s)^4 + C_2\,(0s)^2(\overline{0p}_{1/2})^2 + \cdots$
      - $\dfrac{\partial\langle H-E\rangle}{\partial b_i} = 0\ ,\quad \dfrac{\partial\langle H-E\rangle}{\partial C_\alpha} = 0$

- ○ Interaction :
  - Central : Volkov No.2 with M=0.6
  - Tensor : Furutani ($^3$He+p scattering)
  - LS : G3RS

[Ref]: H. Furutani, H. Horiuchi, R.Tamagaki, PTP62('79)981

# • $^4$He G.S.($0^+$) with V2+Furu+G3RS




($b_{0s}$= 1.4 fm)

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

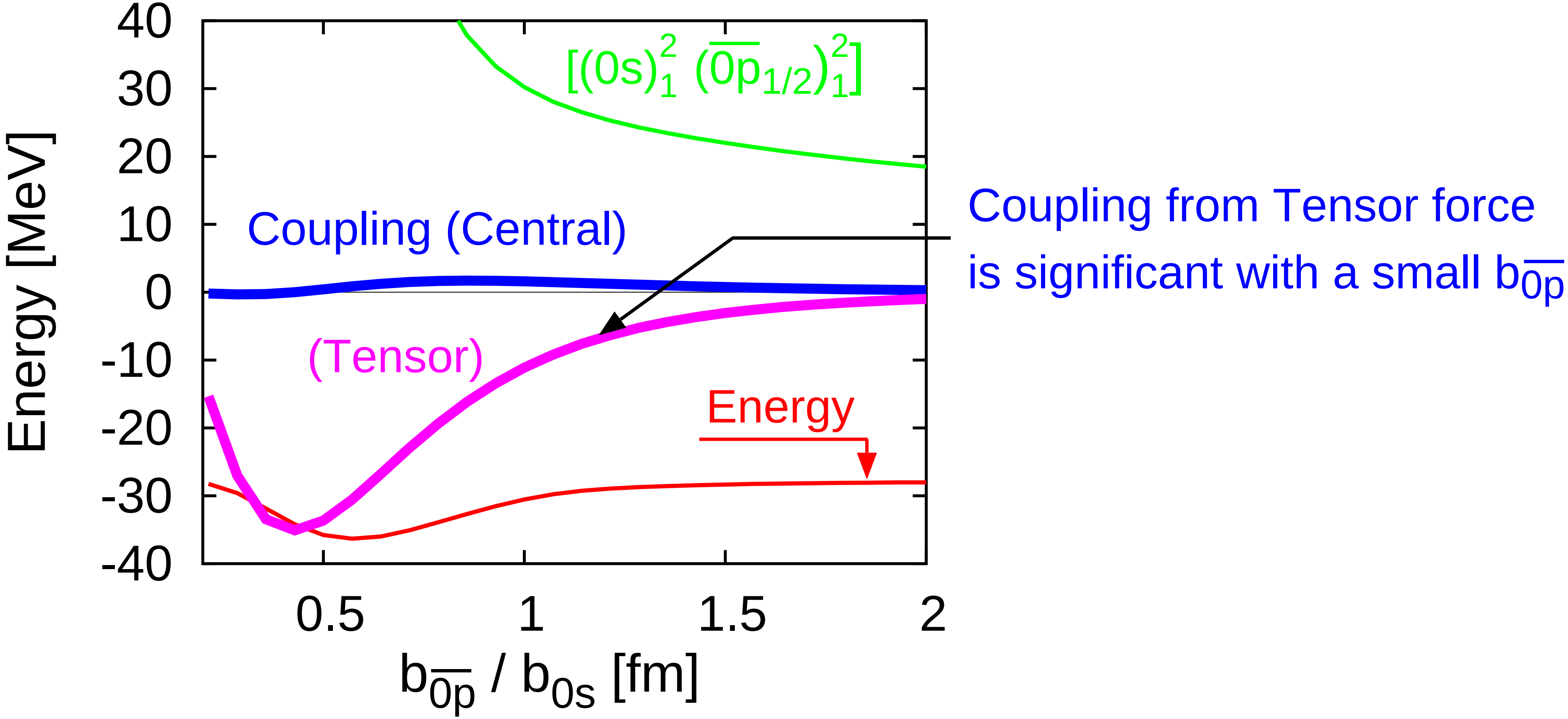
| | | |
|---|---|---|
| $(0s_{1/2})^4$ | | 94.6 % |
| $(0s_{1/2})^2_{JT}(\overline{0p}_{1/2})^2_{JT}$ | (JT)=(10) | 4.5 % |
| | (JT)=(01) | 0.03 % |
| $(0s_{1/2})^2(\overline{0p}_{3/2})^2$ | | 0.3 % |
| $(0s_{1/2})^2(\overline{0p}_{1/2})(\overline{0p}_{3/2})$ | | 0.6 % |
| P[D] | | 3.4 % |

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

$\Rightarrow$ pion nature

- Coupling Matrix Element of Tensor force

$$\langle (0s_{1/2})^2_1 (\overline{0p}_{1/2})^2_1 \,|V|\, (0s)^4 \rangle \quad (b_{0s}=1.4\ [\mathrm{fm}])$$



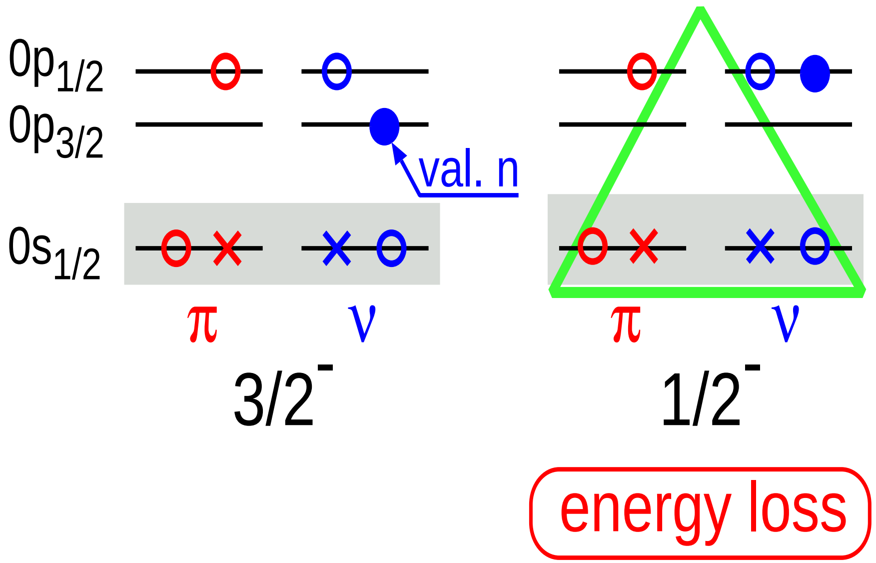
- $^4$He G.S.($0^+$) with V2+Furu.+G3RS
  - $^3$E part of Central force is adjusted to reproduce the B.E. of $^4$He (28.3 MeV).

| $b_{\overline{0p}}$ [fm] | | 2.0 | 1.4 ($=b_{0s}$) | 0.8 | ($V_T \times 1.5$) |
|---|---|---|---|---|---|
| $\langle$Kinetic$\rangle$ [MeV] | | 45.8 | 49.5 | 52.7 | 58.0 |
| $\langle$Central$\rangle$ | | –74.3 | –73.4 | –66.0 | –53.8 |
| $\langle$Tensor$\rangle$ | | –0.6 | –5.2 | –16.4 | –34.3 |
| $\langle$LS$\rangle$ | | $2\times10^{-3}$ | $1\times10^{-4}$ | 0.5 | 1.0 |
| $R_m$ [fm] | | 1.52 | 1.48 | 1.48 | 1.48 |
| 2p-2h [%] | | 1.6 | 4.1 | 5.4 | 11.0 |
| $(\overline{0p}_{1/2})^2_{JT}$ | (JT)=(10) | 0.6 | 2.9 | 4.5 | 9.6 |
| | (JT)=(01) | 0.1 | 0.1 | $3\times10^{-2}$ | 0.1 |
| $(\overline{0p}_{3/2})^2$ | | 0.8 | 0.2 | 0.3 | 0.6 |
| $(\overline{0p}_{1/2})(\overline{0p}_{3/2})$ | | $6\times10^{-2}$ | 0.9 | 0.5 | 0.6 |
| P[D] [%] | | 0.5 | 2.3 | 3.4 | 7.2 |

tensor force can be incoroperated

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

$^4$He[2p-2h] + n($p_{3/2,1/2}$)



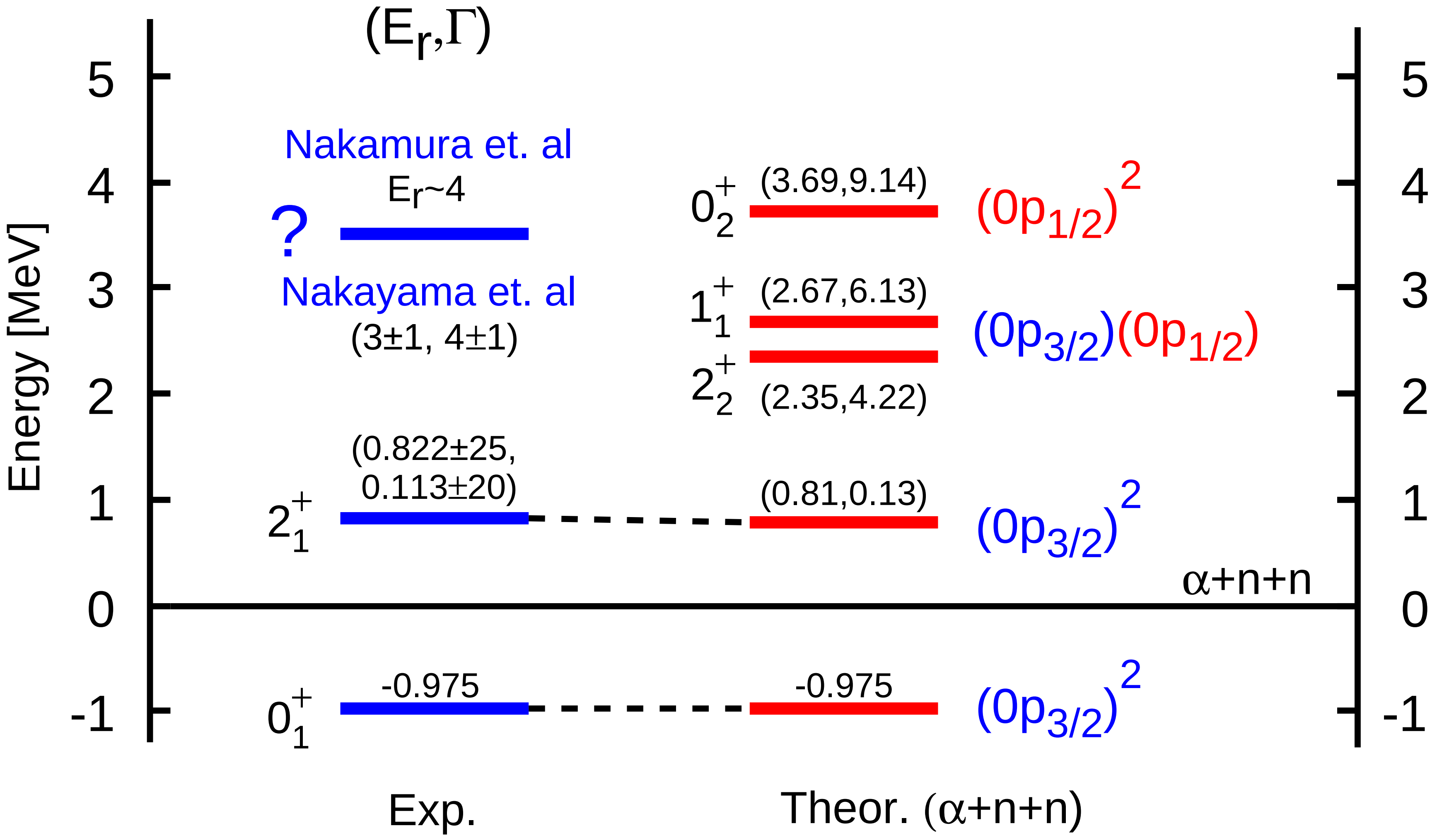

- $^4$He: $0s_{1/2}+\overline{0p}_{1/2}$
  - ($b_{0s}$=1.4 fm, $b_{\overline{0p}}$=0.8 fm)
- $^4$He+n interaction (OCM)
  - Central: Folding potential with Volkov No.2
  - No LS part.
- $H(^5\mathrm{He}) = H(^4\mathrm{He}) + H_{rel}$
- $\Phi(^5\mathrm{He}) = (0s)^4 \cdot \psi^1_{rel} + (0s)^2(\overline{0p}_{1/2})^2 \cdot \psi^2_{rel}$

∘ $E_R$=($E_r$,$\Gamma$) [MeV] of $^5$He using $^4$He with V2+Furu.+G3RS

| | Exp.(KKNN) | Present ($V_T \times 1.0$) | Present ($V_T \times 1.5$) |
|---|---|---|---|
| $3/2^-$ | (0.74, 0.60) | (0.74, 0.65) | (0.74, 0.65) |
| $1/2^-$ | (2.13, 5.84) | (1.01, 1.05) | (1.37, 1.85) |
| $\Delta E$ | 1.47 | 0.27 | 0.63 |

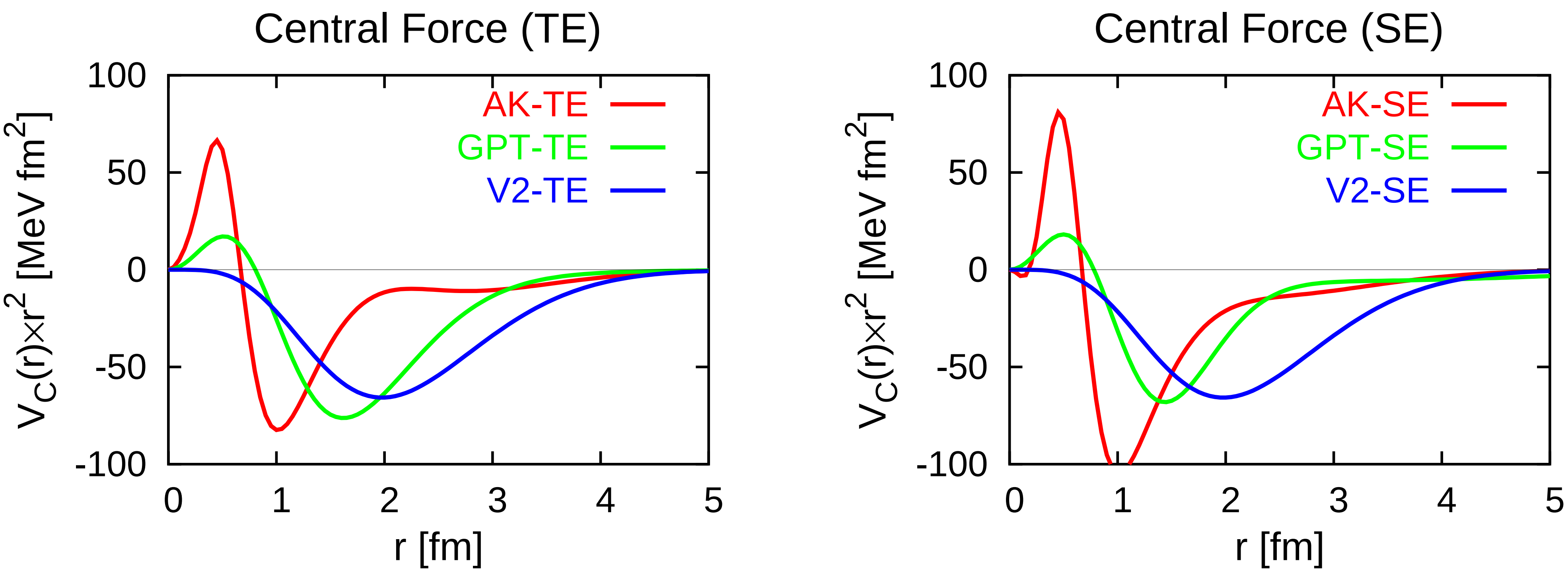
$\Rightarrow$ Visible contribution of tensor correlation

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

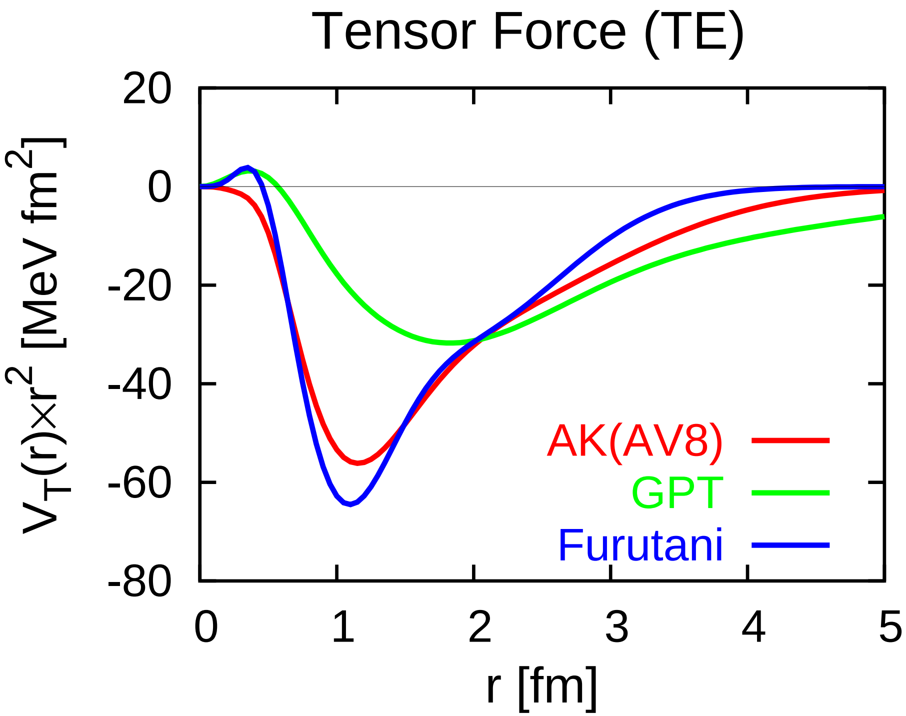


# • Effective Interaction

- ◦ Akaishi potential : G-matrix derived from AV8' (Acknowledge to Prof.Akaishi)
- ◦ GPT potential (Gogny-Pires-Tourreil).
  - – C+LS+T, 3-range Gaussian to fit *d*'s prperties, and NN phase shifts.




[Ref]: D. Gogny, P. Pires and R. De Tourreil, Phys. Lett. B32('70)591



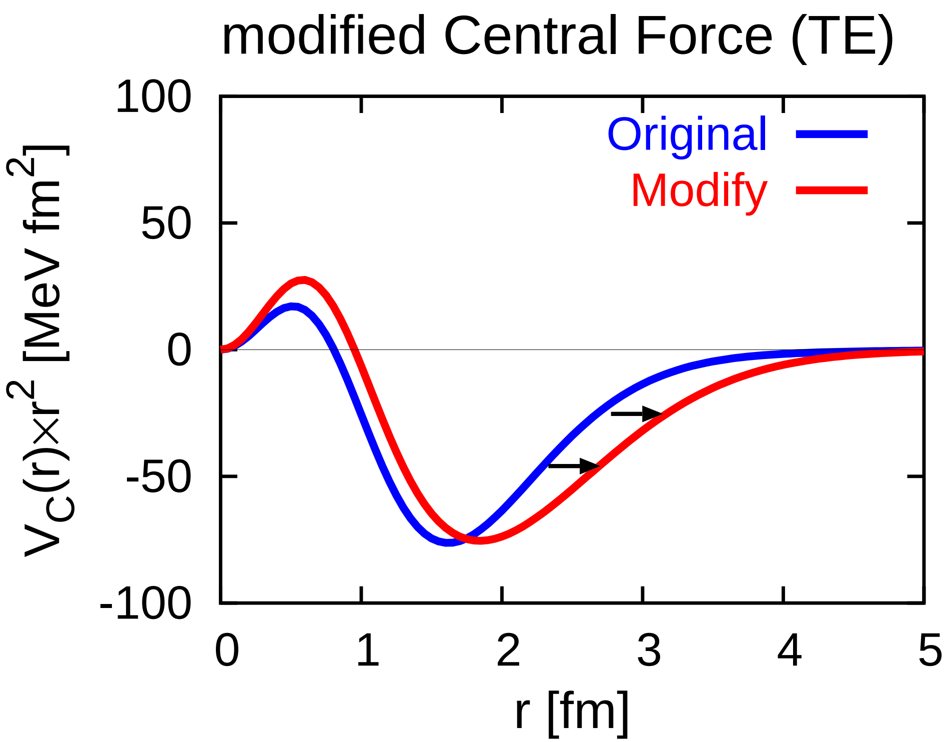

○ Properties of $^4$He with 0s+0p up to 2p-2h.

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

$\Rightarrow$ • Central, LS : GPT

• Tensor : Aakaishi

## ◦ GPT+AK with modification to reproduce $^4$He properties




◦ Central part of GPT(2nd range)

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

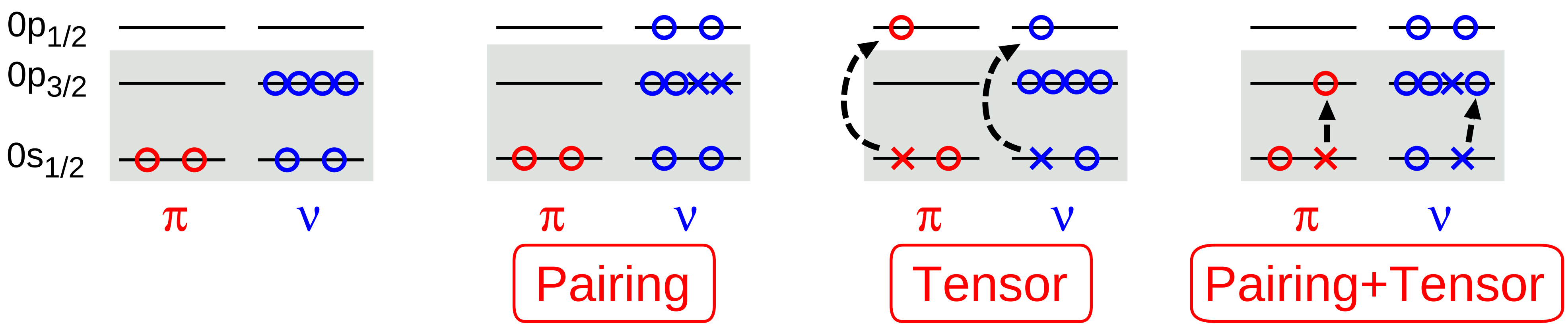
$$R_2 \rightarrow R_2 + \Delta R \quad (\Delta R{=}0.27 \text{ fm})$$

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

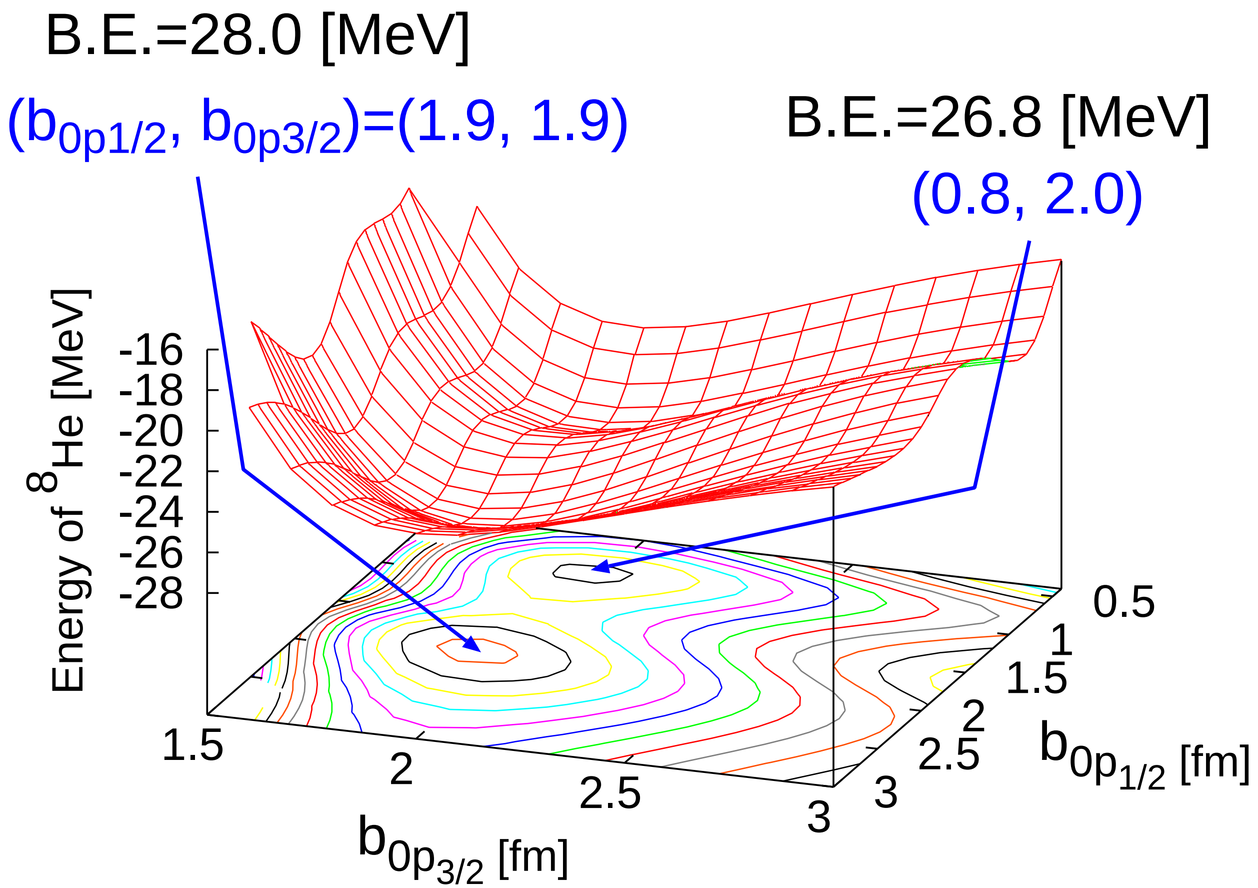
◦ Properties of $^4$He using mod.GPT+AK

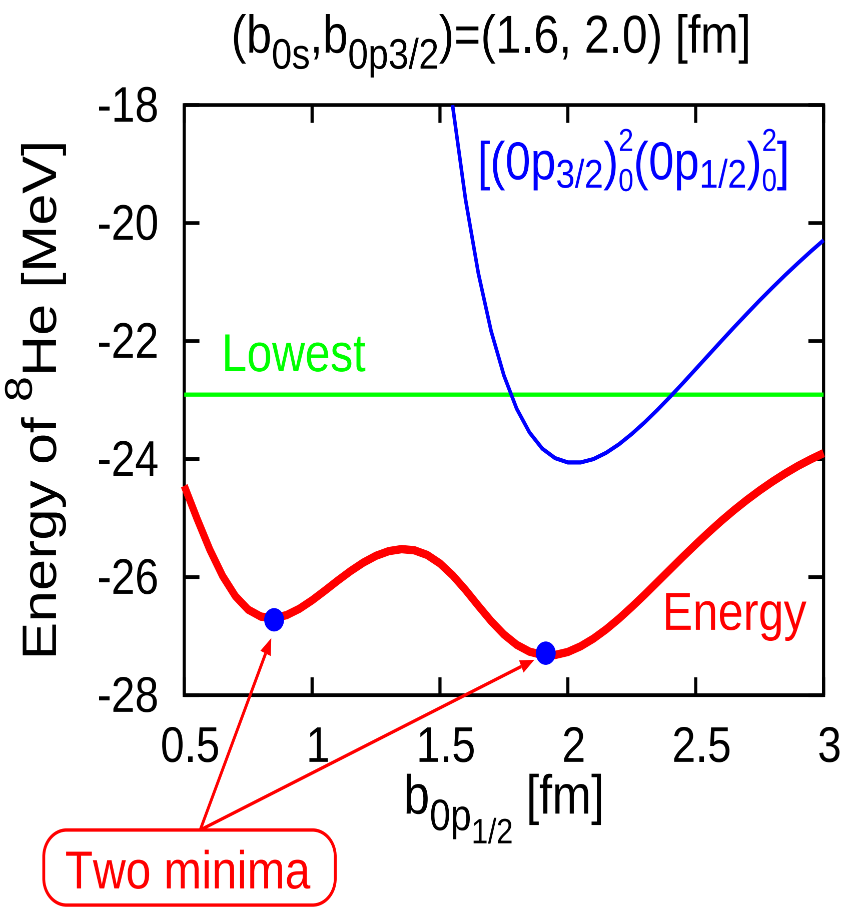
| E ($\langle V_T \rangle$) [MeV] | P[2p-2h] | $R_m$ [fm] |
|---|---|---|
| −28.3 (−16.9) | 10 % | 1.49 |

- $^8$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,LS : GPT with strengthening $v_2$ by 4%
    - – Tensor : Akaishi

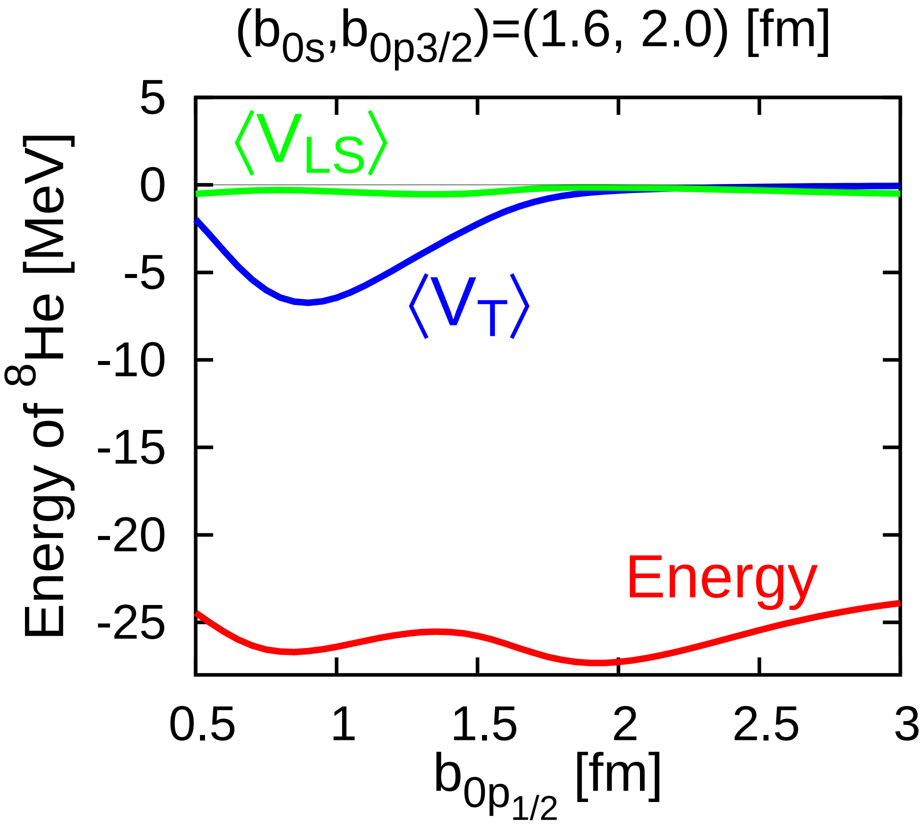


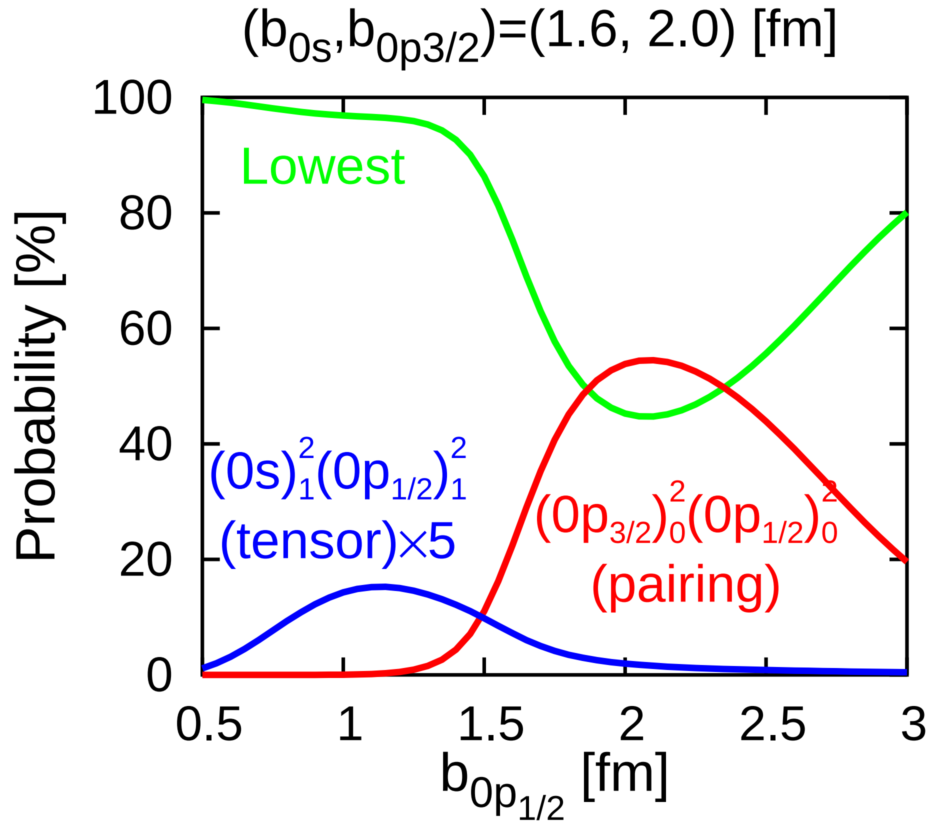
- Energy of $^8$He ($0^+$) with mod.GPT+AK ($b_{0s}$= 1.6 [fm])



## ○ Properties of two minima in $^8$He ($0^+$)




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

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

# Summary

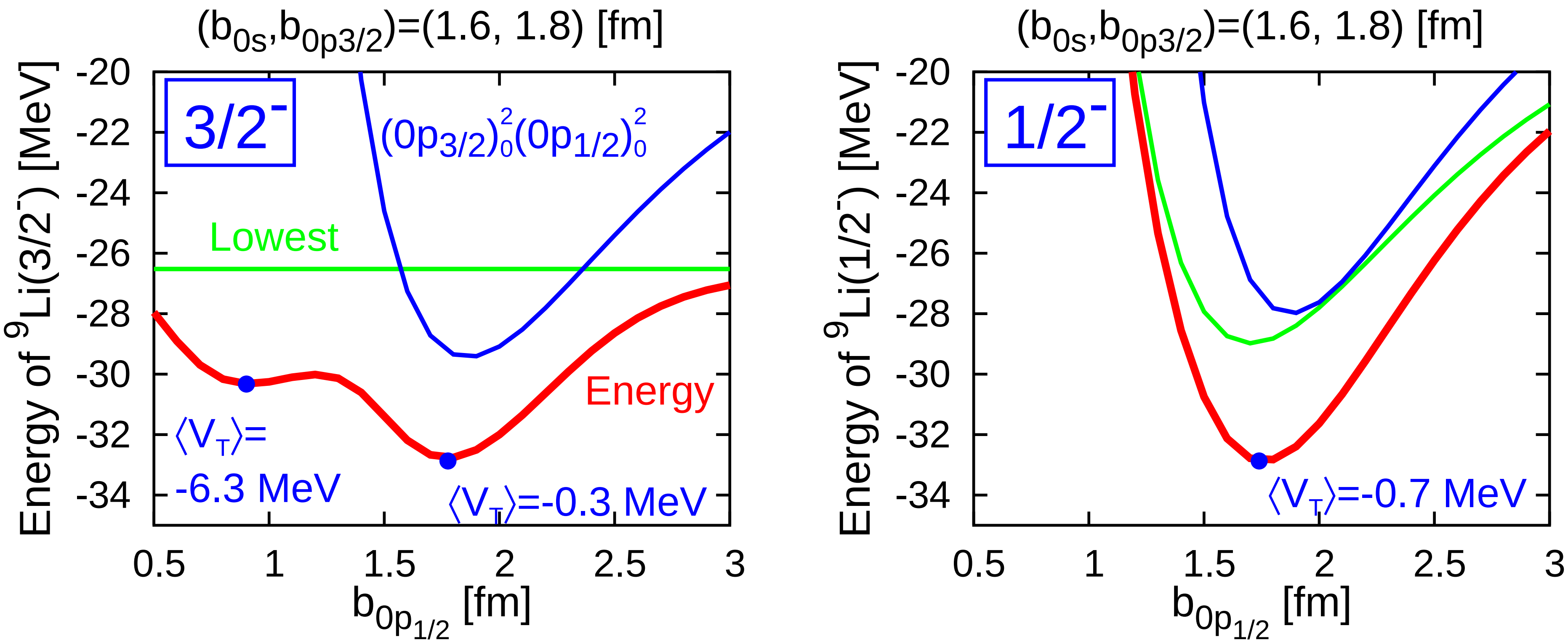
1. Tensor correlation is expected to give a contribution to lower the 1s-orbit in neutron drip line nuclei.

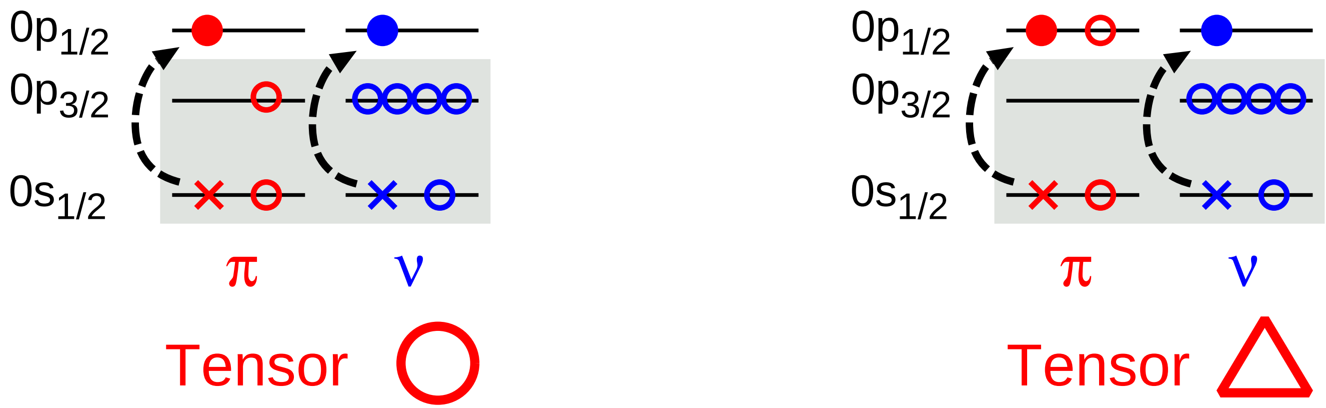
2. Effects of Tensor correlation in $^4$He and $^5$He.
   - $^4$He : p-wave is favored to shrink, Coupling between $0s_{1/2}$ and $0p_{1/2}$.
     (cf. Akaishi(HF), Sugimoto(HF), Doté(AMD) )
   - $^5$He : Visible contribution to the $3/2^-$-$1/2^-$ splitting.

3. Effective interaction
   - modified GPT+AK tensor : Properties of $^4$He is reproduced.
   - Adequate interaction should be found such as for LS part.

4. For $^8$He and $^9$Li
   - Tensor and Pairing correlations produce the energy minima.
     (different $b_{0p1/2}$ values) $\Longrightarrow$ superpose.

• $^9$Li ($3/2^-$, $1/2^-$) with 0s+0p, $^8$He($0^+$)+p



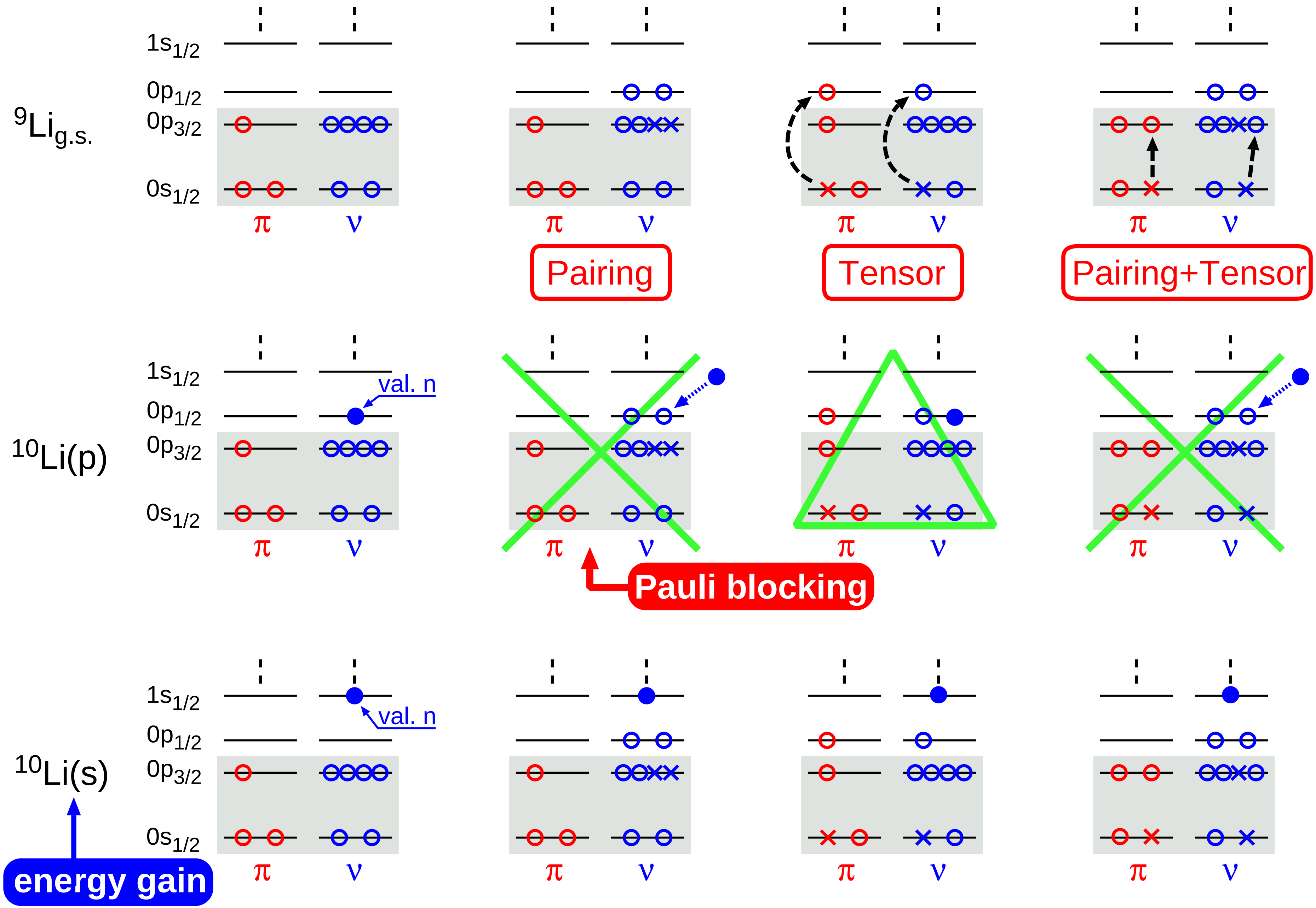
- Tensor correlation (TC) in $^9$Li($3/2^-$) for $^{11}$Li

$$|0\rangle = (0s_{1/2})^4\,(0p_{3/2})_\pi\,(0p_{3/2})^4_\nu\ ,$$
$$|^9\text{Li}\rangle = |0\rangle + |\text{TC}\rangle.$$

  - Nagata's Method (PTP22(1959)274)
    - Direct inclusion of D-state component in the relative motion.

$$|\text{TC}\rangle = \mathcal{F}_\text{T}\,|0\rangle$$
$$\mathcal{F}_\text{T} = \Sigma_{i<j}\,\mathcal{F}_{ij}$$
$$\mathcal{F}_{ij} = f(\boldsymbol{r}_{ij})\cdot\widehat{a}^r_{ij}, \qquad \boldsymbol{r}_{ij} = \boldsymbol{r}_i - \boldsymbol{r}_j$$
$$f(\boldsymbol{r}_{ij}) = f(r_{ij})\cdot\left[\,Y_2(\boldsymbol{r}_{ij})\otimes S_{2,ij}\,\right]_0$$
$$S_{2,ij} = \left[\boldsymbol{s}_i\otimes\boldsymbol{s}_j\right]_2$$
$$f(r) = \Sigma_{n=1}^N\,C_n\cdot\phi_n(r)$$

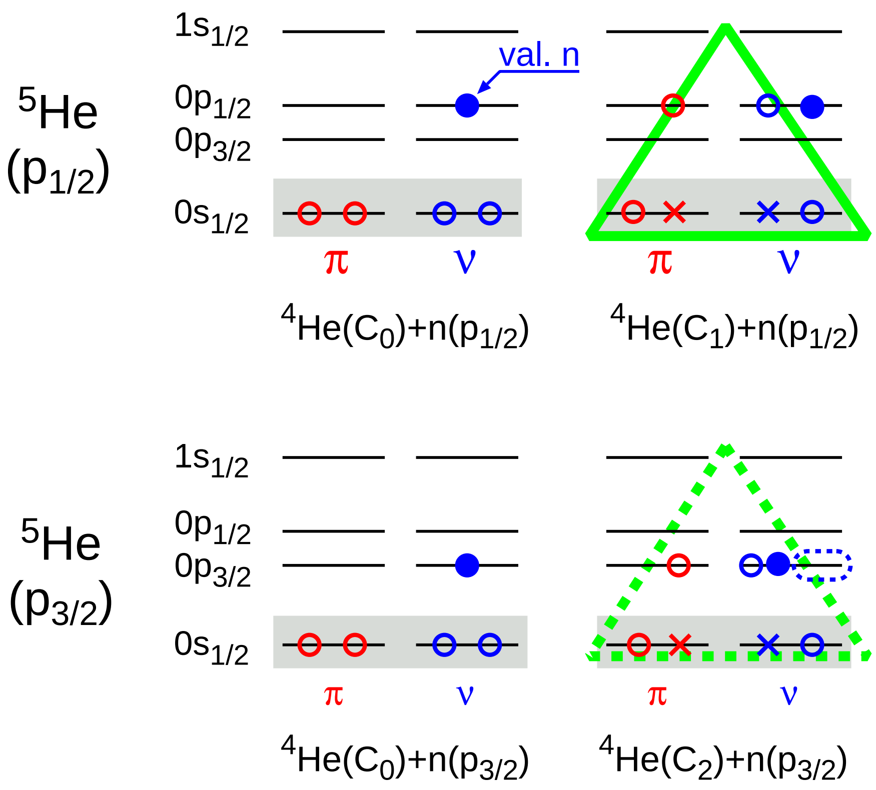
# • Effect of Tensor Correlation in $^{10}$Li

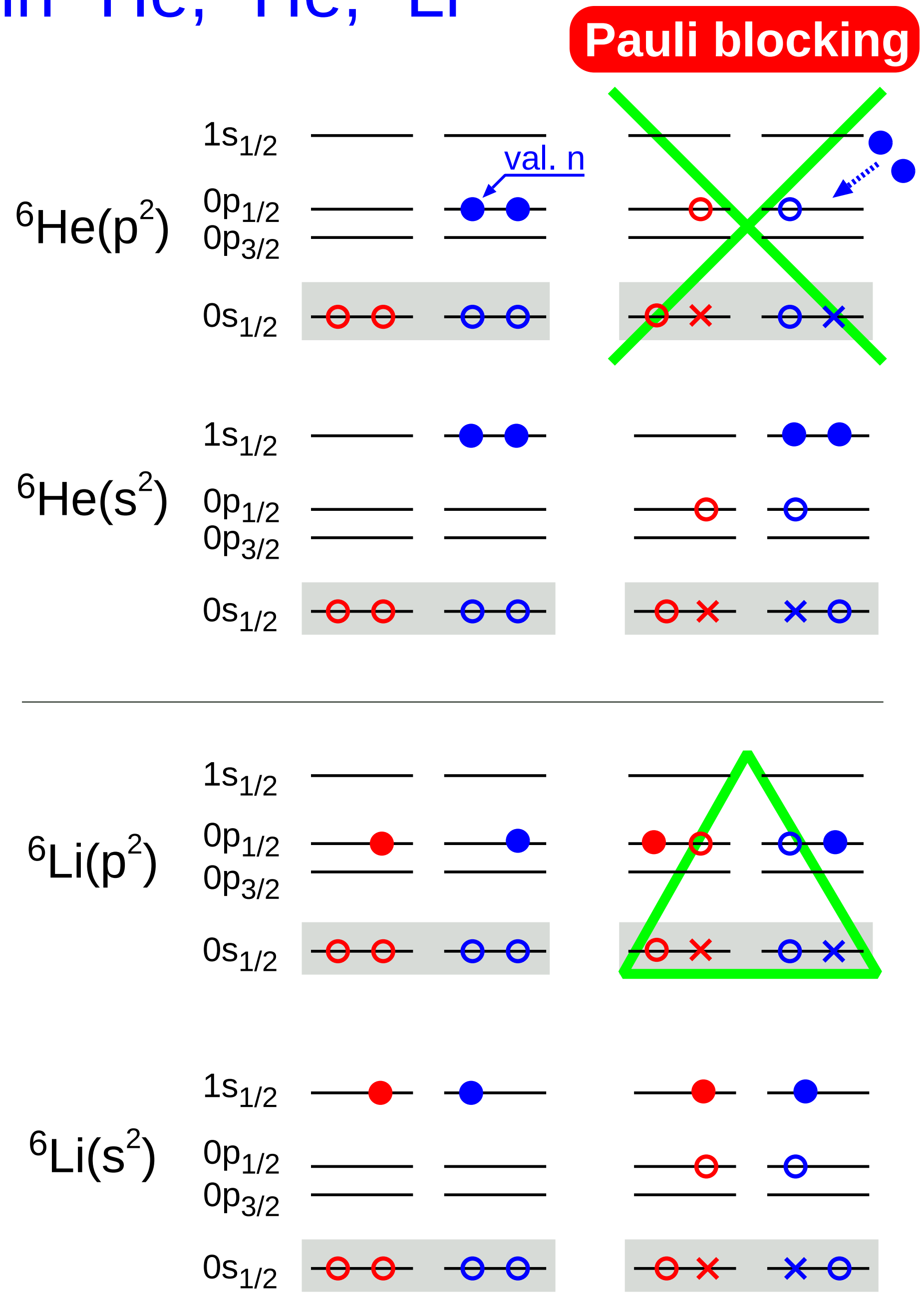


# • Effect of Tensor Correlation in $^5$He, $^6$He, $^6$Li

cf. T. Terasawa, PTP23(1960)87.

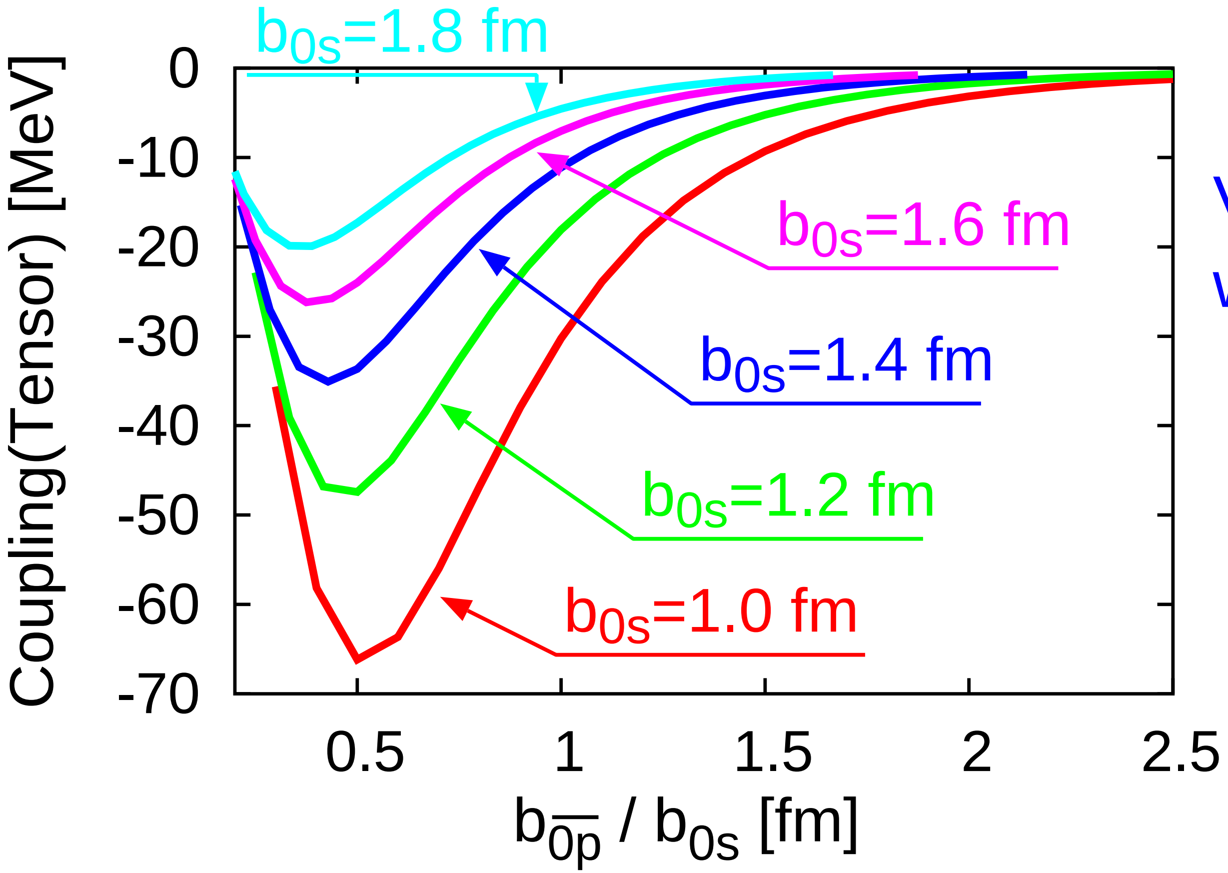
- $3/2^- - 1/2^-$ splitting in $^5$He



- Coupling Matrix Element of Tensor force

$\langle (0s_{1/2})^2_1 (\overline{0p}_{1/2})^2_1 |V_T| (0s)^4 \rangle$ ($b_{0s}$=1.4 [fm])




$V_T$ becomes large with narrow 0s-wave

○ Effect of tensor force on the energy surface of $^8$He ($0^+$)