中性子ハロー核におけるテンソル相関の役割とその効果

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Contents

– Tensor correlation (TC) in light nuclei.

– He isotopes

- ○ ^{4}He : Tensor-optimized shell model to describe TC.
- ○ ^{5}He : ^{4}He–n phase shifts, LS splitting.
- ○ ^{6}He : Coupled ^{4}He+n+n model, Tensor suppression in 0^+_2.

– Li isotopes

- ○ ^{9}Li : Tensor(pn) and Pairing(nn) correlations.
- ○ ^{11}Li : Coupled ^{9}Li+n+n model.
  Tensor suppression for the halo formation.

Motivation and purpose of our studies on tensor correlation (TC)

- ○ The tensor force is an essential component in nuclear force and plays a significant role in nuclear structure.

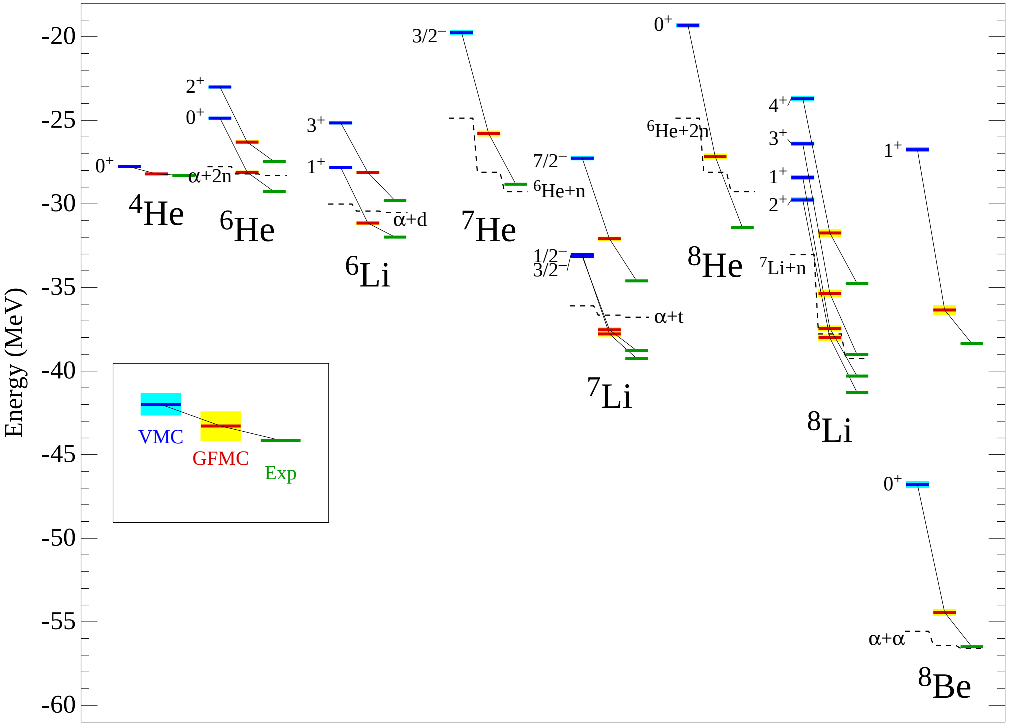
- ○ Physical effect of the tensor force (V_T) is not easy to understand from the various kinds of ab initio calculations in a transparent manner.

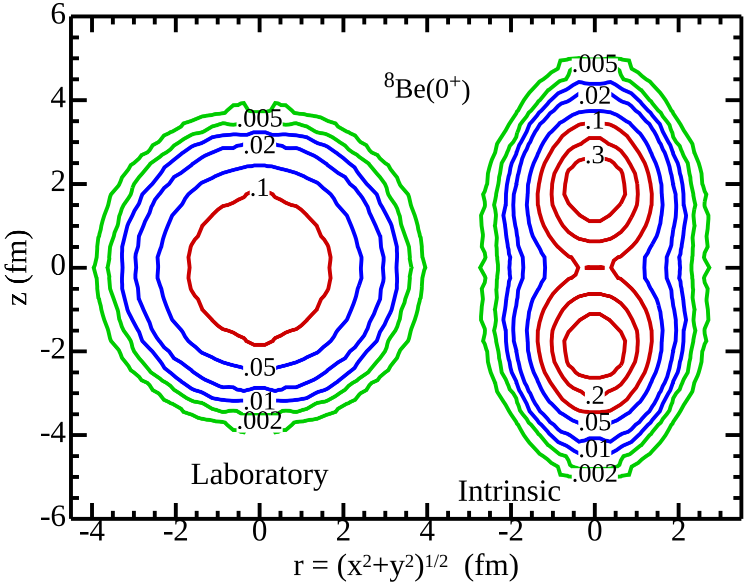
- ○ In the nuclear models such as mean field model and cluster model, V_T has been renomalized into V_C, V_{LS} and V_ρ, based on the Brueckner-Theory.
  - ^{4}He : $(0s)^4 \to \langle V_T \rangle = 0$.

- ○ We would like to understand the physical aspects of the tensor force on the nuclear structure by describing TC explicitly in the model space.

- Recently, various kinds of ab initio calculations are available for light mass nuclei. ($A \simeq$ 10–12)
  - Green's Function Monte Carlo
    R.B.Wiringa,S.C.Pieper,J.Carlson,V.R.Pandharipande, PRC62(2001)
  - No Core Shell Model P.Navrátil, J.P.Vary, B.R.Barrett, PRL84(2000)
  - Faddeev-Yakubovsky A.Nogga, H.Kamada, W.Glöckle,PRL85(2000)
  - Variational method such as...
    - Stochastic variational method Y.Suzuki, K.Varga,PRC52(1995)
    - Gaussian expansion method E.Hiyama,Y.Kino,M.Kamimura,PPNP51(2003)
    - Hyperspherical Harmonics method M.Viviani,A.Kievsky,S.Rosati,FB-S18(1995)
  - ATMS Y.Akaishi et al., Int.Review of Nucl.Phys.4(1986)
  - Unitary operator approach
    - UMOA Fujii-Okamoto-Suzuki,PRC69(2004), UCOM Neff-Feldmeier,NPA713(2003).
  - In ^{4}He, $\langle V_{\rm tensor}\rangle = -68.4$, $\langle V_{\rm central}\rangle = -55.3$, $\langle T\rangle = 102.4$, unit in MeV
    P(D)=13.9%. Kamada et al., PRC64('01)044001.

Variational calculation in real model space: Illinois-Argonne Group





○ C.Pieper, R.B.Wiringa, Annu.Rev.Nucl.Part.Sci.51(2001)

○ R.B.Wilinga,S.C.Pieper,J.Carlson,V.R.Pandaripande, PRC62(2000)014001.

○ $H = T + V_{NN}$, $V_{NN} = V_{\pi} + V^{R}_{ST}$

○ AV18 Potential with three-body force.

○ Variational Monte-Carlo and Green Function Monte-Carlo.

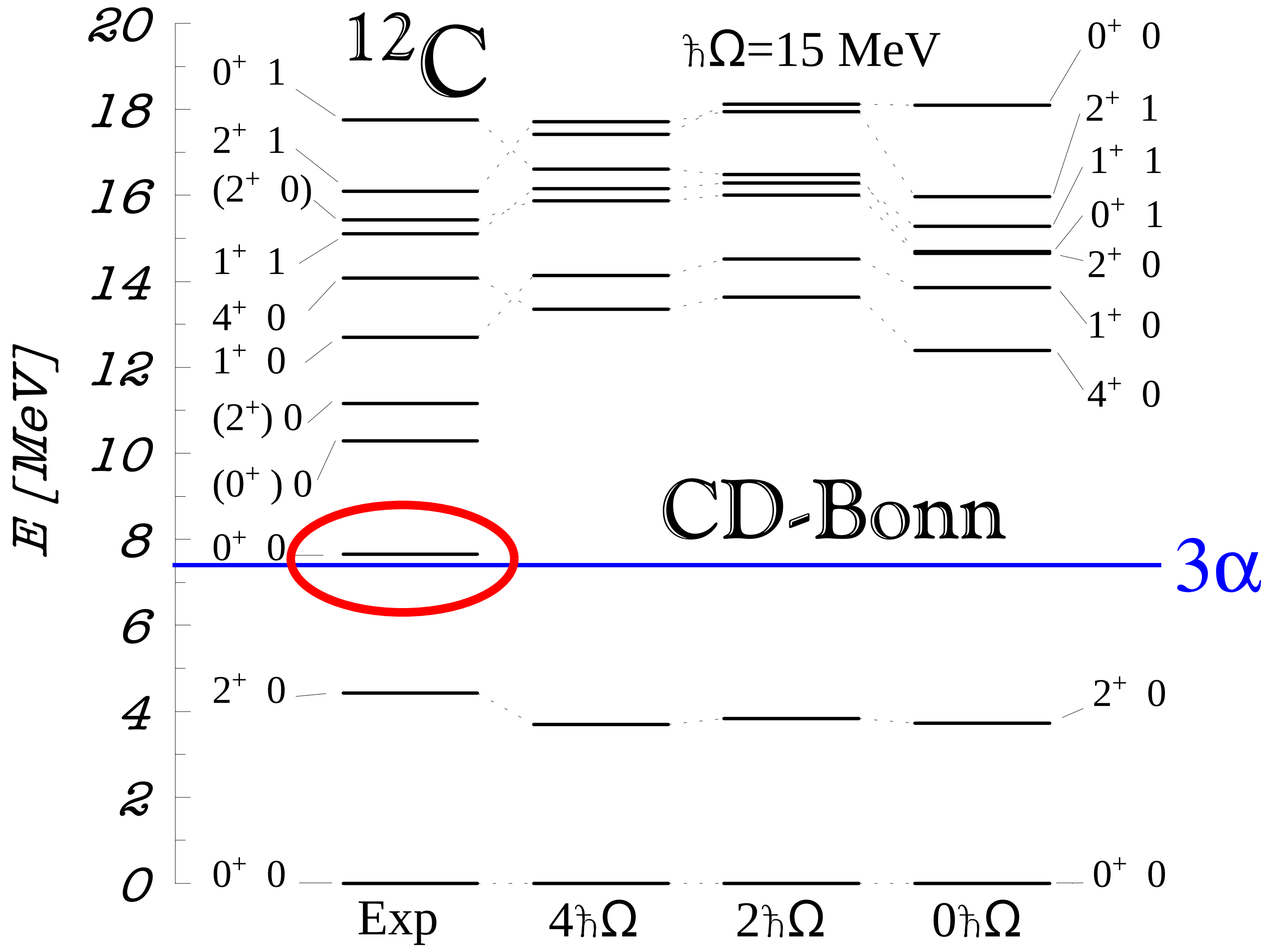
○ Reproduction of binding properties and spectra.

○ V_{π} is 70 – 80 % of the attraction.

○ Cluster structure of ^{8}Be is reproduced.

No core-shell model calculation

P.Navrátil, J.P.Vary, B.R.Barrett, PRL84(2000)

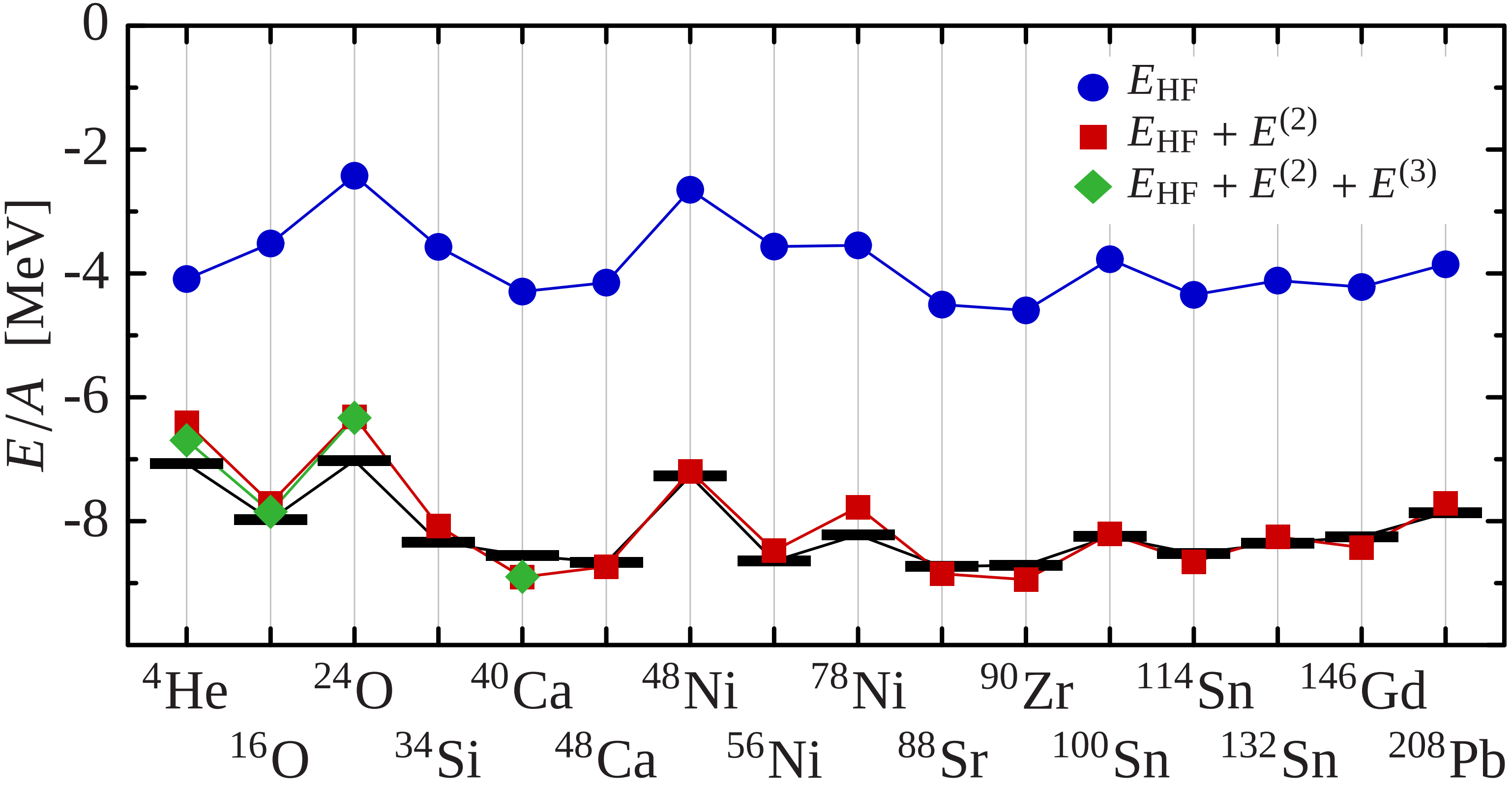


Unitary Correlation Operator Method (UCOM)

- $\Phi_{\text{corr.}} = C_\omega \cdot C_r \cdot \Phi_{\text{uncorr.}} \quad \leftarrow$ HF, FMD, $\cdots$

  tensor and short-range correlator

- $C_r = \exp[-\mathrm{i}\ \Sigma_{(i<j)}\ g_{ij}], \quad g = \frac{1}{2}\left[p_r\ s(r) + s(r)\ p_r\right]$



AV18

R. Roth, P. Papakonstantinou,

N. Paar, H. Hergert, T. Neff,

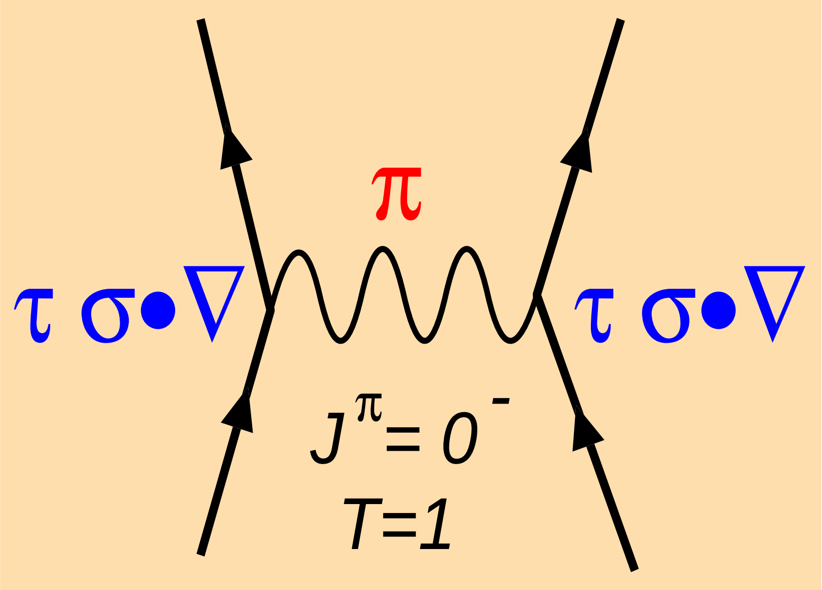
H. Feldmeier, PRC73(2006)

Mean Field approach

Tensor correlation in the mean field theory

by Sugimoto-Toki-Ikeda(NPA740('04))

and Akaishi(NPA738('04)).



- **CPPHF** : Charge- and Parity-Projected Hartree-Fock method
- Single particle orbit breaks the parity and charge.
  - $\phi_{\mathrm{i}} = \phi_{\mathrm{i}}^{p} + \phi_{\mathrm{i}}^{n}$ (p: proton, n: neutron),
  - $\phi^{p}_{\mathrm{j}=1/2} = \phi^{p}_{0\mathrm{s}1/2} + (\boldsymbol{\sigma}\cdot\boldsymbol{r})\,\phi^{p}_{0\mathrm{s}1/2} = \phi^{p}_{0\mathrm{s}1/2} + \phi^{p}_{0\mathrm{p}1/2}$.

cf. Ogawa et al., CPP-RMF, PRC73(2006), Doté et al., CPP-AMD, PTP115(2006),
Isshiki-Naito-Ohnishi, AMD with coherent pion, PTP114(2005)

Our approach based on the exteded shell model

– T.Myo, K.Katō, K. Ikeda, PTP113(2005) –

- We use the extended shell model approach to take into account TC explicitly, "Tensor-optimzed shell model", referring to the results of CPPHF.
  - 1p1h + 2p2h excitations: Configuration mixing beyond the major shell.

$$\boxed{\Phi({}^4\mathrm{He}) = \Sigma_i\, C_i\, \psi_i(\{b_\alpha\}) \;=\; C_1\,(0s)^4 + C_2\,(0s)^2(\overline{0p}_{1/2})^2 + \cdots}$$

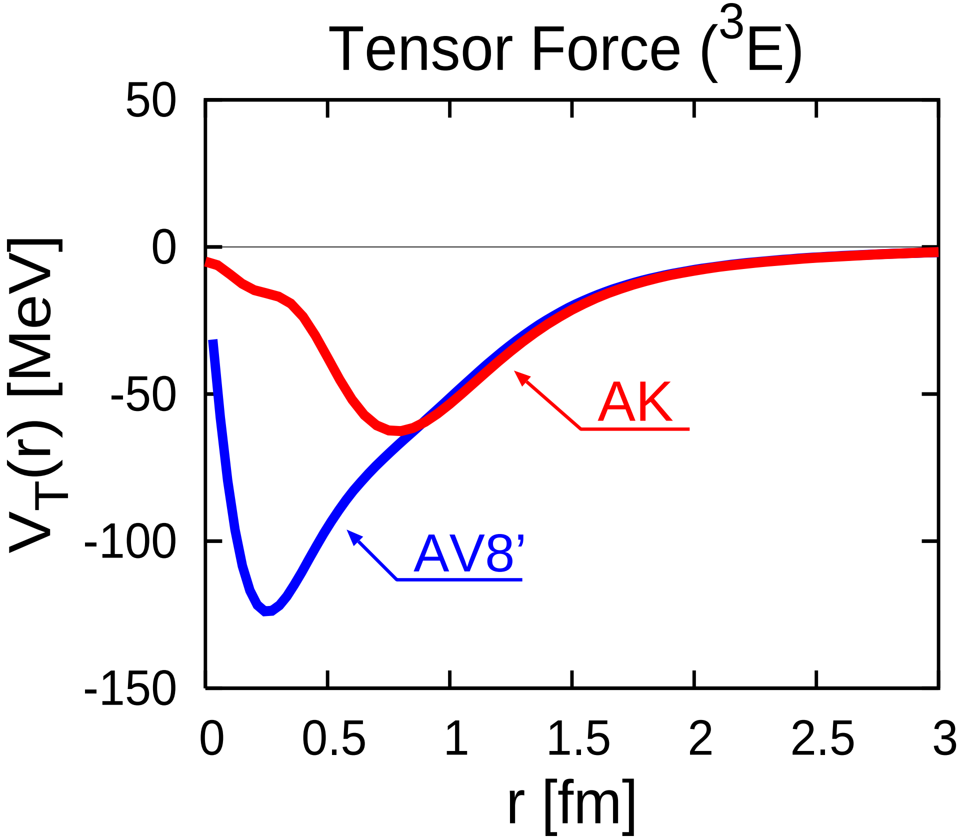
- HO basis with independent length parameters $\{b_\alpha\}$, such as $b_{0s} \neq b_{\overline{0p}}$, . . . to represent the high momentum components. (cf. works by Sugimoto et al./ Akaishi)

$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij}, \qquad v_{ij} = v_{ij}^{C} + v_{ij}^{T} + v_{ij}^{LS} + v_{ij}^{Clmb},$$

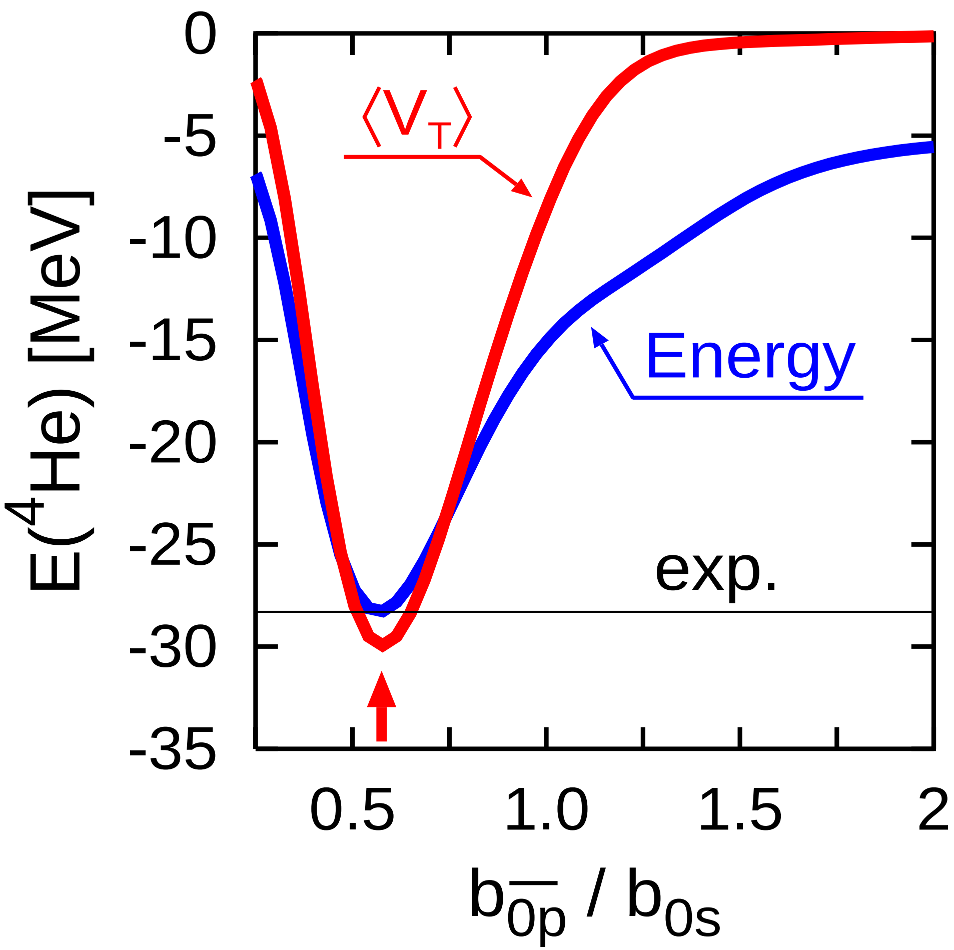
$$\delta \frac{\langle \Phi |\, H \,| \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0 \quad \Rightarrow \quad \frac{\partial \langle H - E \rangle}{\partial b_\alpha} = 0\,, \quad \frac{\partial \langle H - E \rangle}{\partial C_i} = 0.$$

- ○ Interaction : Akaishi force (AK) (NPA738)
  - G-matrix using AV8' with $k_Q = 2.8\ \text{fm}^{-1}$ ($> k_F = 1.4\ \text{fm}^{-1}$)

    $\Rightarrow$ Long and intermidiate ranges of the tensor force survive.
  - Central part : We adjust the intermediate range to fit B.E. and R_m of ^{4}He.



Previous results : ^{4}He with 0S+0P of HO bases, $V_T\times1.5$



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

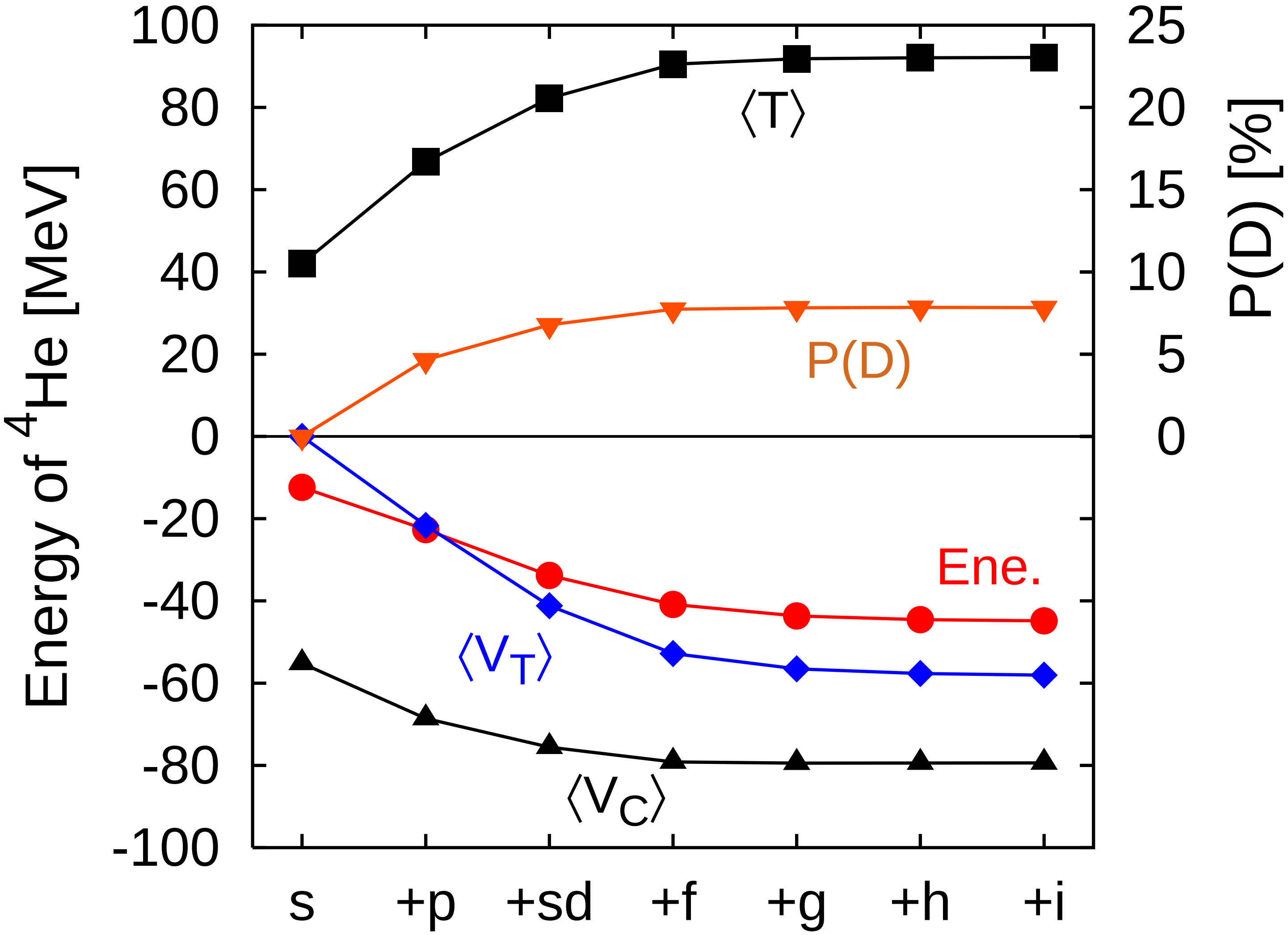
$(0s_{1/2})^4$		87.5 %
$(0s_{1/2})^2_{JT}(\overline{0p}_{1/2})^2_{JT}$	(JT)=(10)	7.7 %
	(JT)=(01)	1.3 %
$(0s_{1/2})^2(\overline{0p}_{3/2})^2$		3.4 %
$(0s_{1/2})^2(\overline{0p}_{1/2})(\overline{0p}_{3/2})$		0.06 %
P[D]		6.9 %
R_m		1.48 fm

○ narrow p-orbit ⇒ higher shell effect

○ 0^- coupling of $0s_{1/2}-0p_{1/2}$
⇒ pion nature

○ (J,T)=(1,0) ⇒ deuteron correlation

^{4}He with HO basis by adding high angular momentum states.



- ○ Length parameters

orbit	$\overline{b}_{nlj} / b_{0s}$
$\overline{0p_{1/2}}$	0.65
$\overline{0p_{3/2}}$	0.58
$\overline{1s_{1/2}}$	0.63
$\overline{0d_{3/2}}$	0.58
$\overline{0d_{5/2}}$	0.53
$\overline{0f_{5/2}}$	0.66
$\overline{0f_{7/2}}$	0.55

- ○ The solutions show a good convergence.

$\Rightarrow$ higher shell effect $\sim 16\,\hbar\omega$

^{4}He with 0S+0P+SD+F+G,   4 Gaussians

Energy [MeV]	-28.0
$\langle V_T \rangle$ [MeV]	-51.0

$(0s_{1/2})^4$		85.0 %
$(0s_{1/2})^2_{JT}(\overline{0p}_{1/2})^2_{JT}$	(JT)=(10)	5.0 %
	(JT)=(01)	0.3 %
$(0s_{1/2})^2[(\overline{1s}_{1/2})(\overline{0d}_{3/2})]_{10}$		2.4 %
$(0s_{1/2})^2[(\overline{0p}_{3/2})(\overline{0f}_{5/2})]_{10}$		2.0 %
$(0s_{1/2})^2[(\overline{0p}_{1/2})(\overline{0p}_{3/2})]_{10}$		0.9 %
P[D]		9.6 %

$\langle T \rangle = \quad 71.2$ [MeV]

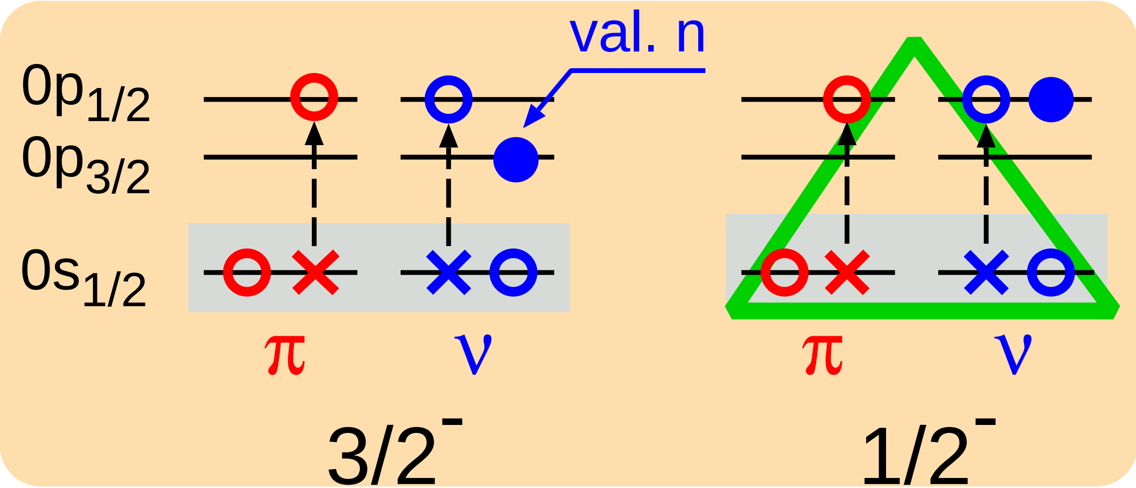
$\langle V_C \rangle = -48.6$ [MeV]

c.m. excitation ~ 0.6 MeV.

⇐ Three cases are selectively mixed.

- one shows 0^- pion nature
- deuteron correlation with JT=(01)
- $(\Delta L = \Delta S = 2)$ properties of V_T.

LS splitting in ^{5}He in a coupled ^{4}He+n model



Tensor correlation is suppressed in 1/2$^-$ due to the Pauli-blocking

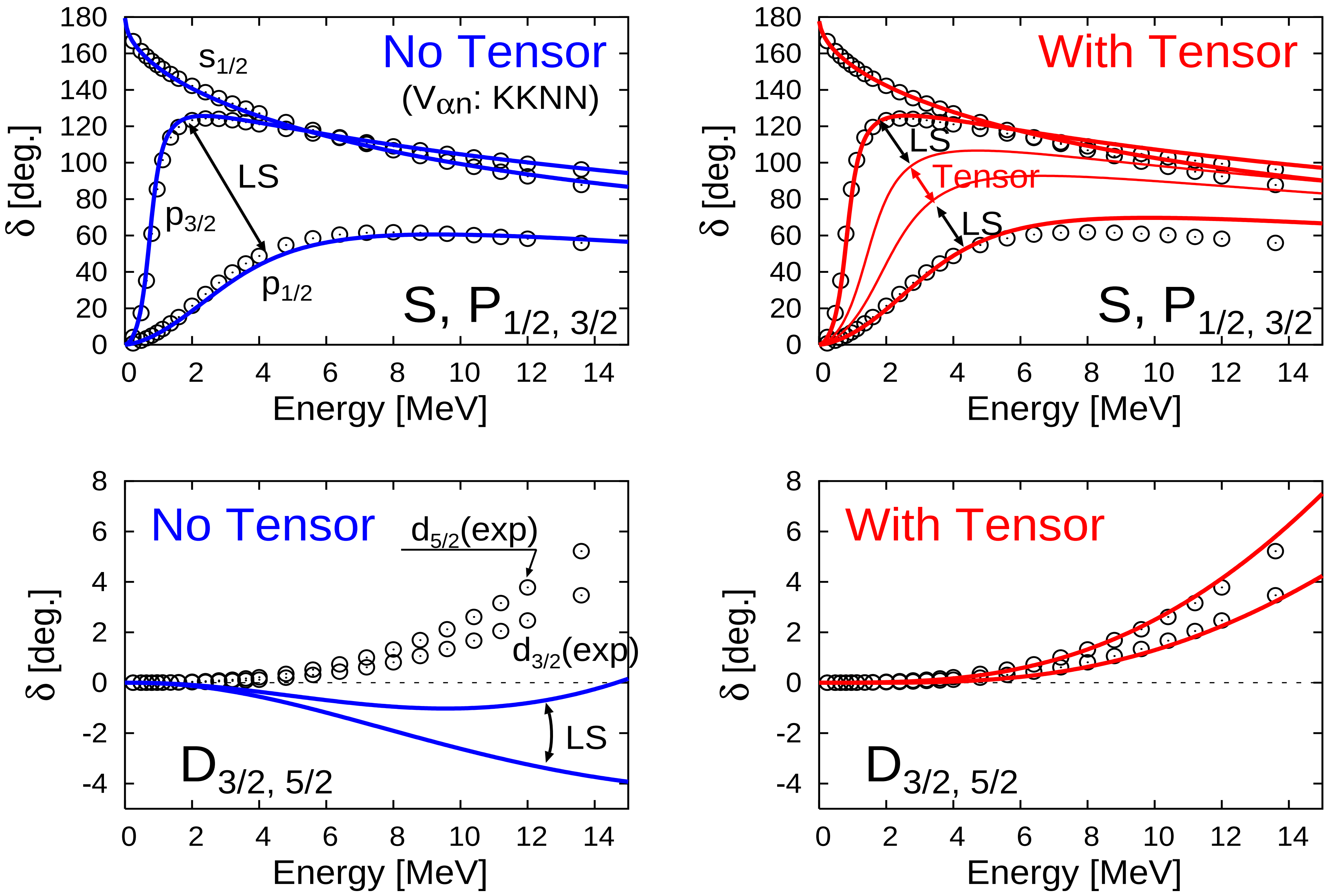
An appreciable contribution to the doublet (LS) splitting

[Ref] T. Terasawa, PTP22('59), S. Nagata, T. Sasakawa, T. Sawada and R. Tamagaki, PTP22('59)
K. Ando and H. Bando PTP66('81)

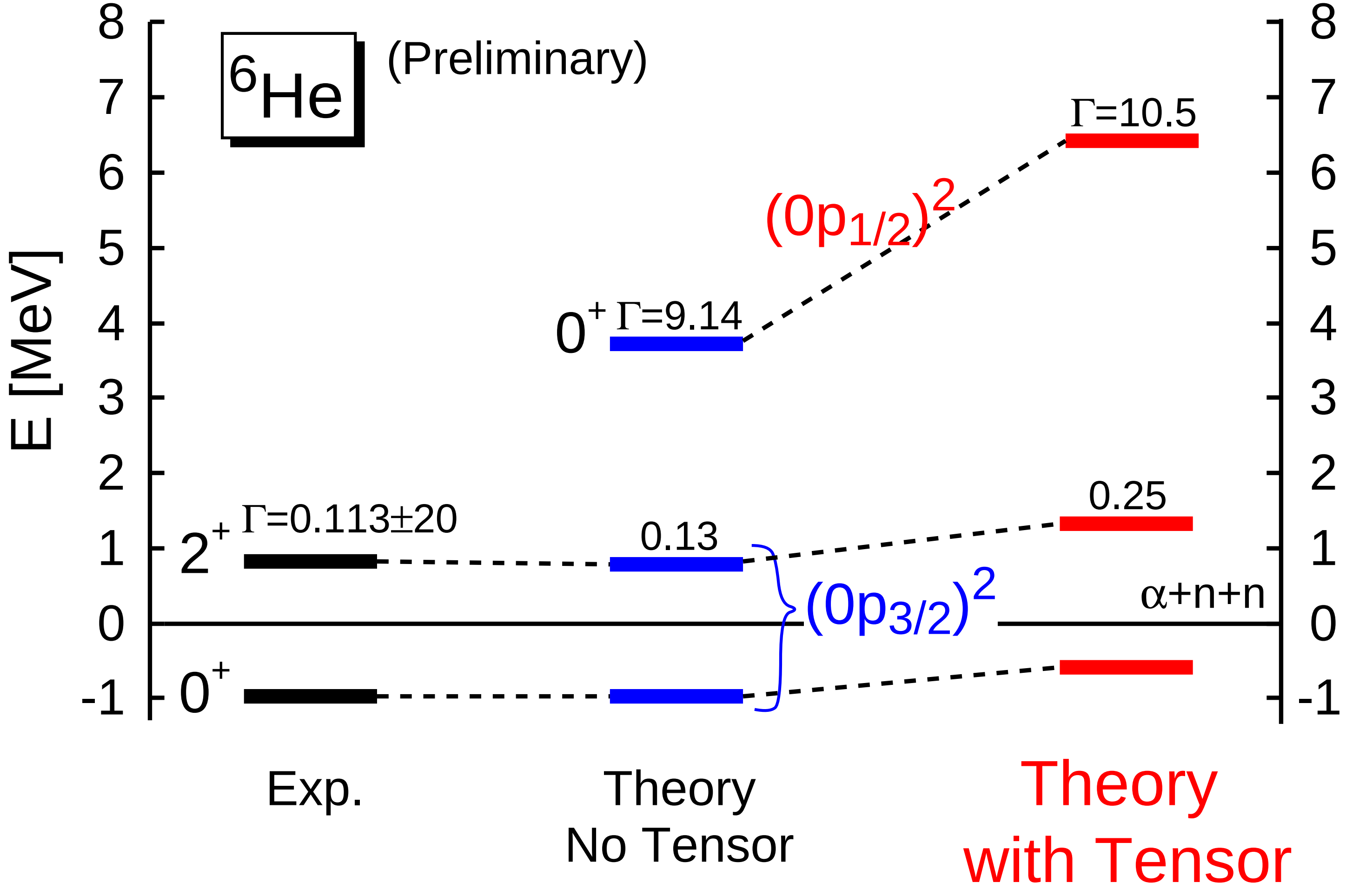
- The system is solved by OCM equation.
  - $H(^5\mathrm{He}) = H(^4\mathrm{He}) + H_{\mathrm{rel}}, \qquad \Phi^J(^5\mathrm{He}) = \mathcal{A}\{\sum_{i=1}^{N} \psi_i(^4\mathrm{He}) \cdot \chi_i^J(r)\}$
  - $\sum_{i=1}^{N} [\, h_{ij}(^4\mathrm{He}) + (T_r + V_{\alpha n} + \Lambda_i)\ \delta_{ij}\,]\, \chi_j^J(r) = E\, \chi_i^J(r)$

$$\Lambda_i = \lambda \cdot \Sigma_{\alpha \in {}^4\mathrm{He}} \,|\phi_\alpha\rangle\langle\phi_\alpha|, \qquad \text{for } j=1,\cdots,N.$$

Phase shifts of ^{4}He-n with TC



^{6}He in a coupled 3-body ^{4}He+n+n model



- ○ $(0p_{3/2})^2$ does not change the energy ⇒ Naive ^{4}He+n+n model is applicable.
- ○ $(0p_{1/2})^2$ loses the energy ⇒ Tensor suppression in 0^+_2

⇒ Contribute to Level inversion in N=7,8 isotones.

Structures of ^{11}Li

- Expt. : S_{2n}=0.31 MeV, R_m=3.12±0.16 / 3.53±0.06 fm (^{9}Li: 2.32 fm).

- Breaking of magic number N=8, halo structure in G.S.
  - Simon et al.(PRL83, expt) : $(1s)^2 \sim 50\%$, Mechanism is unclear.

- Virtual s-state in ^{10}Li :
  - Expt. : Invariant mass spectrum of ^{9}Li-n.
  - Many theories assume a deep s-wave ^{9}Li-n potential.
    - Thompson-Zhukov(PRC49) / Garrido-Fedorov-Jensen(NPA700).
    - Halo structure is reproduced for G.S., and soft dipole resonances appear.

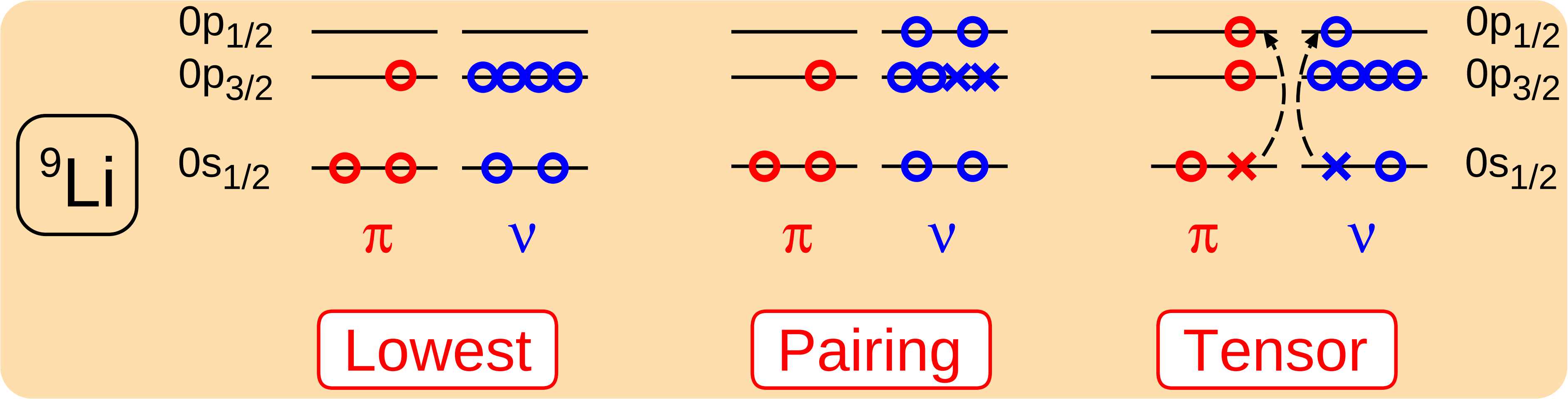
- Our group performs the extended three-body model analysis with configuration mixing for ^{9}Li (PTP101, PTP108, PLB576, pairing).

Explicit tensor and pairing correlations in ^{9}Li for analysis of ^{11}Li

○ Configuration mixing with H.O. basis function (TM, K.Katō, K. Ikeda, PTP113)

(S. Sugimoto et al for ^{12}C, ^{16}O)

- $0s + \overline{0p} + \overline{1s0d}$ within 2p2h excitations.
- Length parameters $\{b_\alpha\}$ are determined independently and variationally. This is useful to represent the high momentum component.



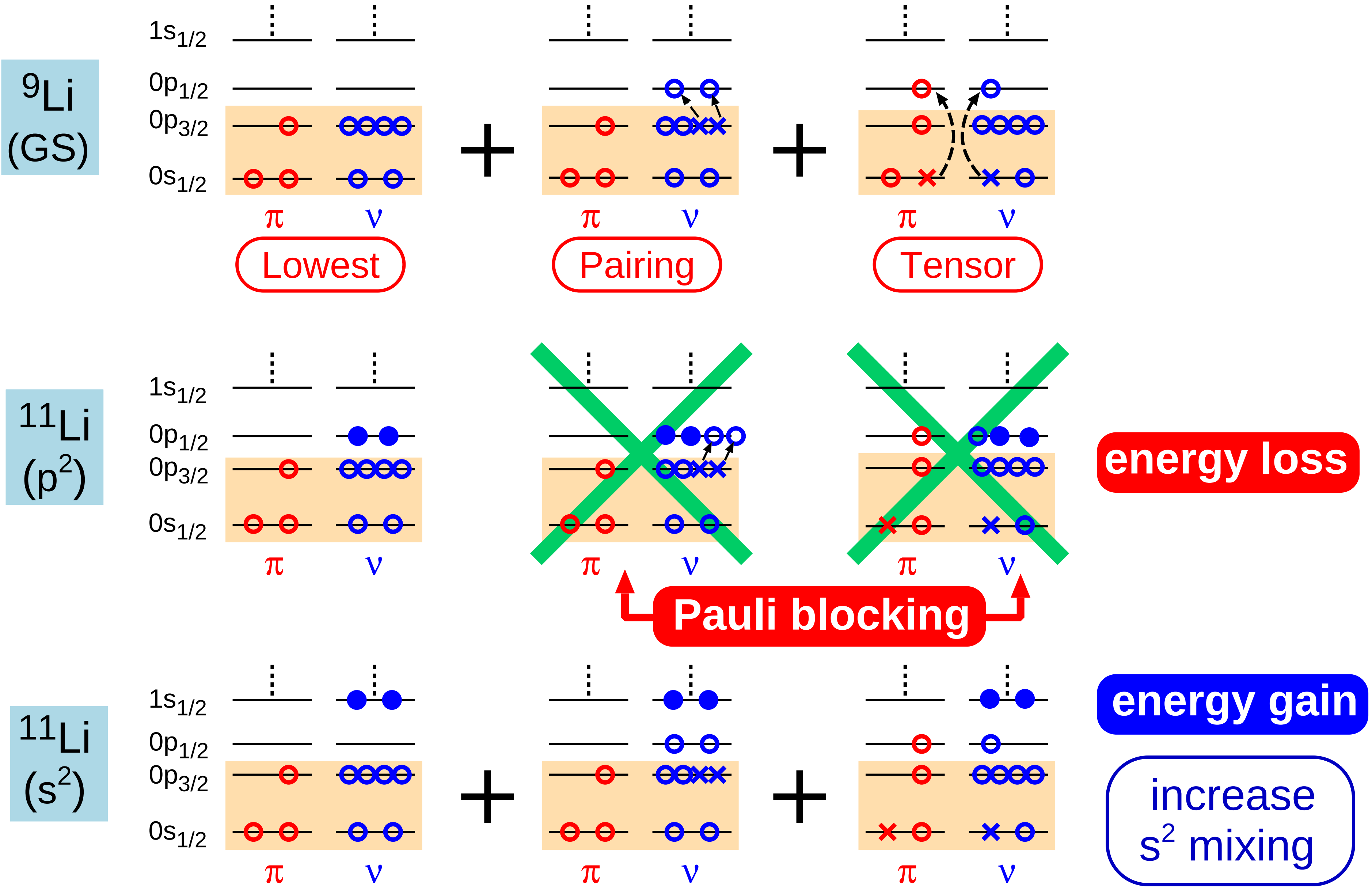
Superposition of the tensor and pairing correlations in ^{9}Li

Energy [MeV]	−44.3
$\langle V_T \rangle$ [MeV]	−31.9
R_m [fm]	2.30

0p0h		78.5 %
$(0p_{3/2})^{-2}_{01}(\overline{0p}_{1/2})^{2}_{01}$		8.8 %
$(0s_{1/2})^{-2}_{JT}(\overline{0p}_{1/2})^{2}_{JT}$	(JT)=(10)	6.8 %
	(JT)=(01)	0.2 %
$(0s_{1/2})^{-2}_{10}[(\overline{1s}_{1/2})(\overline{0d}_{3/2})]_{10}$		1.9 %
$(0s_{1/2})^{-2}_{10}(\overline{0d}_{3/2})^{2}_{10}$		1.2 %

- Tensor correlation:
  - ○ 0^- coupling of $0s_{1/2}-0p_{1/2}$
    ⇒ pion nature of V_T
  - ○ (J,T)=(1,0)
    ⇒ deuteron correlation

Effect of pairing and tensor correlation in ^{11}Li



energy loss

Pauli blocking

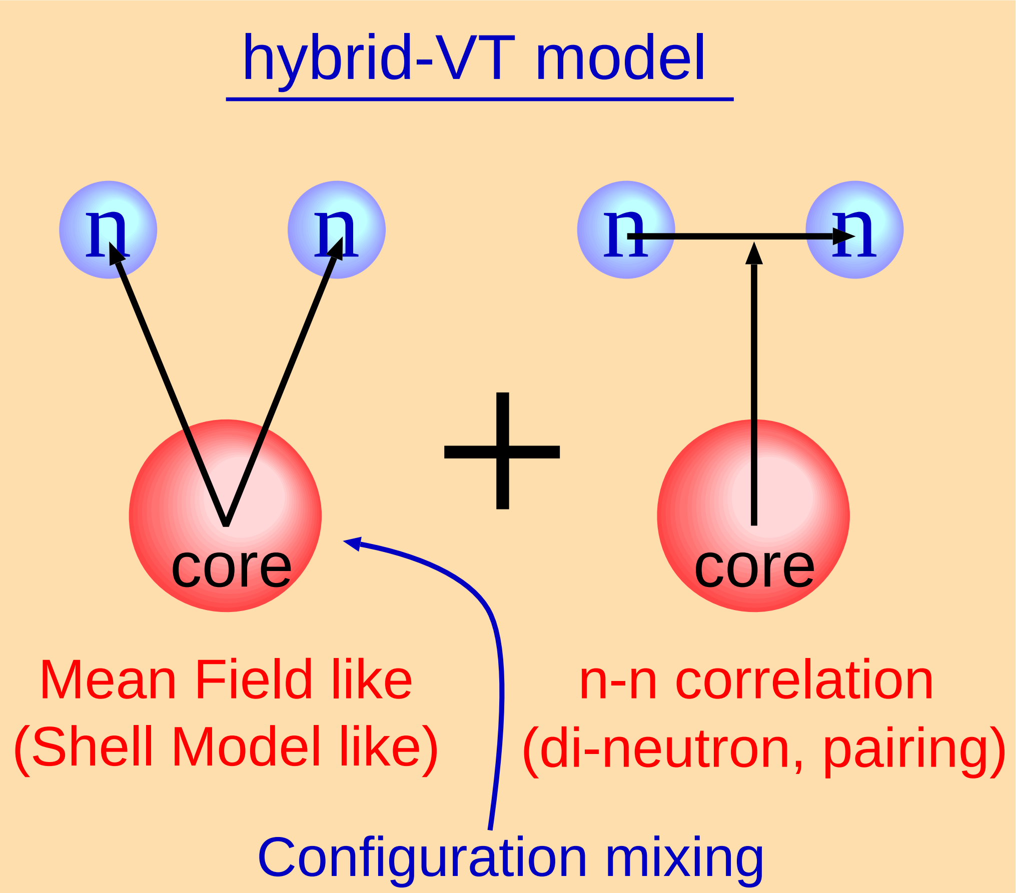
energy gain

increase s^2 mixing

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

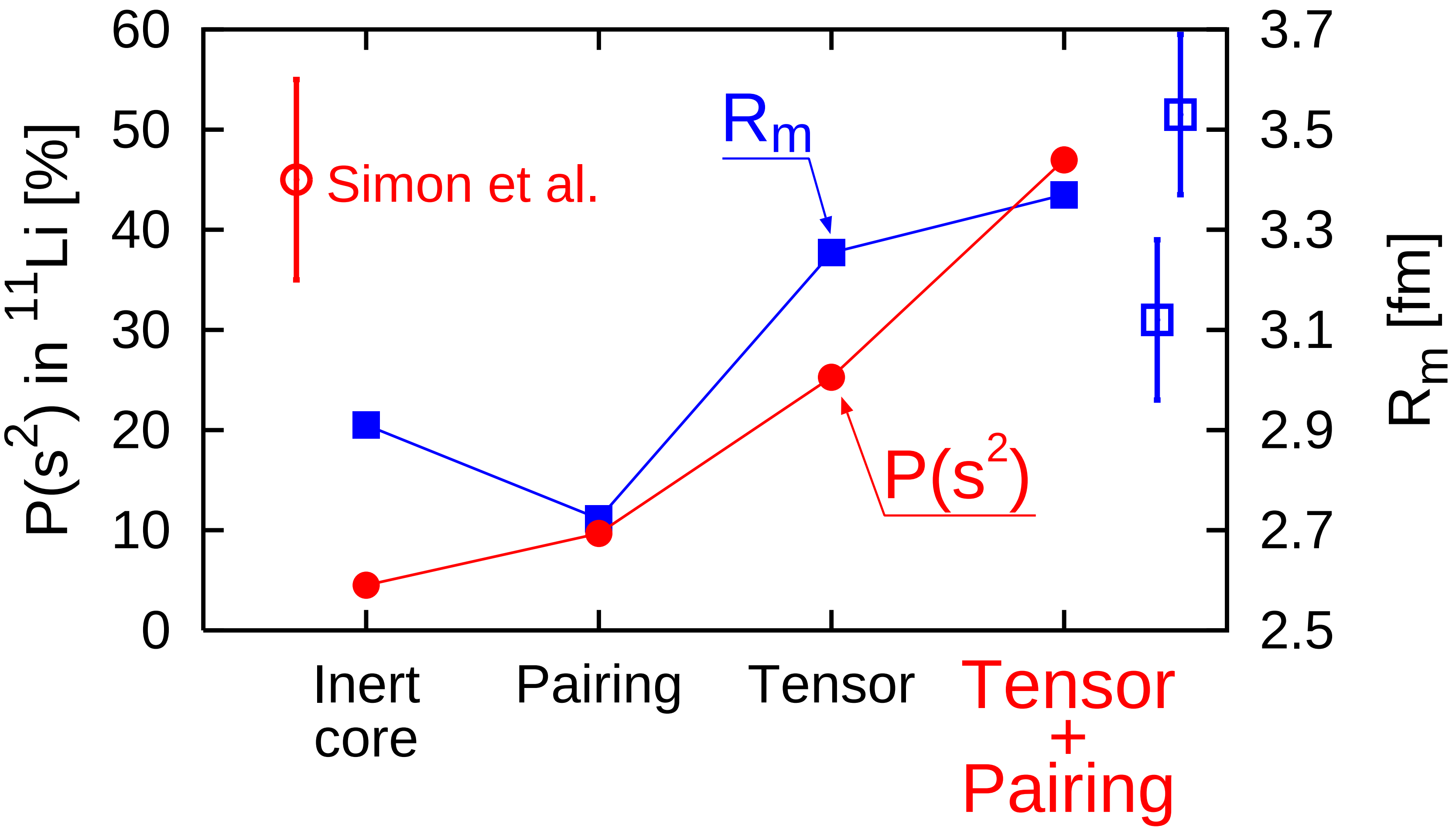
Hamiltonian for ^{11}Li in the orthogonarity condition mdoel

- Folding potential with MHN(G-matrix)
  - Same strength for s- and p-waves.
  - Adjust to reproduce $S_{2n}=0.31$ MeV.
- Argonne potential (AV8') for last 2n.



[Ref] TM, S. Aoyama, K.Kato, K.Ikeda, PTP108(2002)

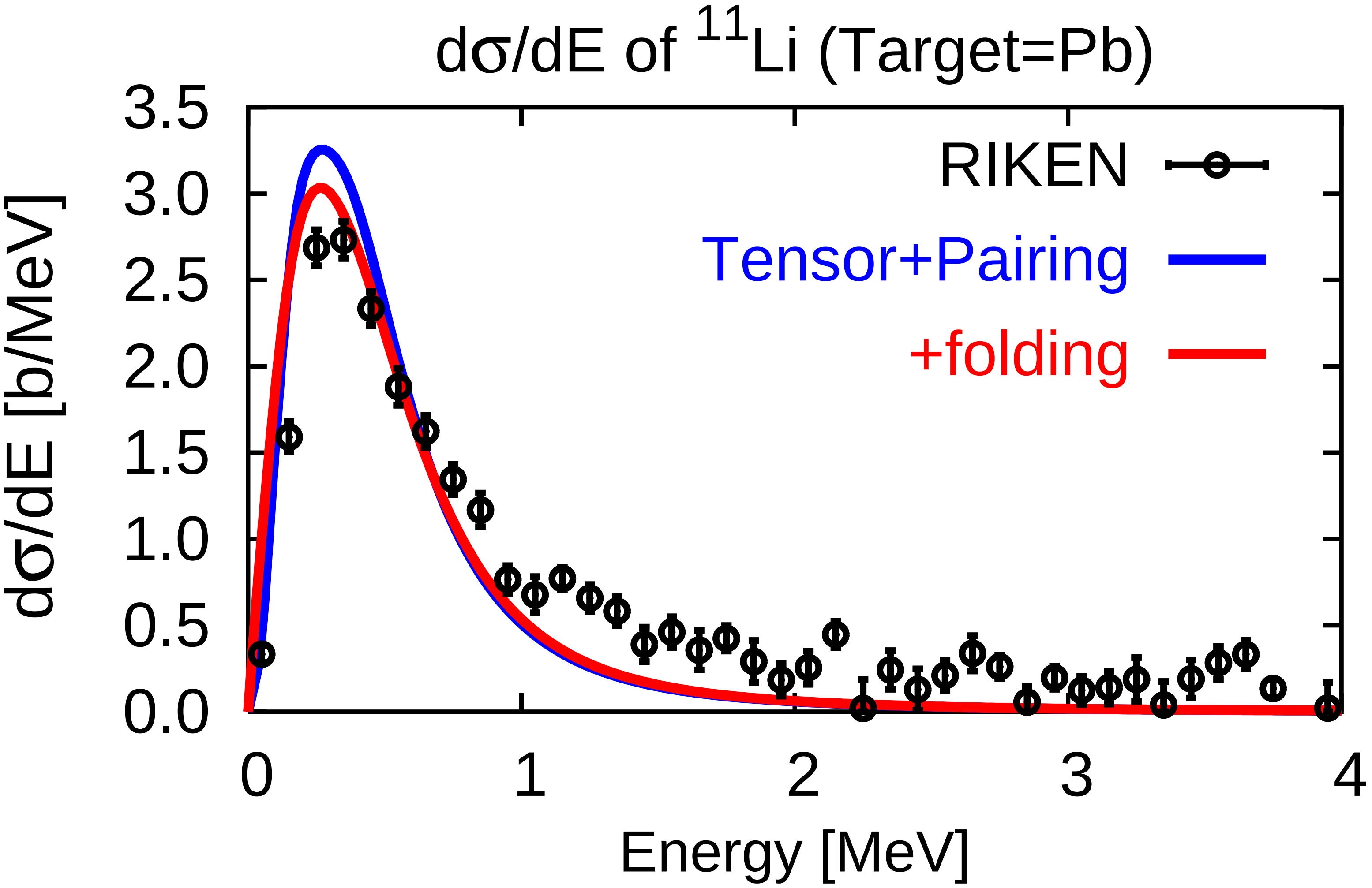
^{11}Li G.S. properties with tensor and pairing correlations



$E(s^2)$-$E(p^2)$	2.1	1.4	0.5	–0.1	[MeV]

pairing correlation couples $(0p)^2$ with $(1s)^2$ for last 2n

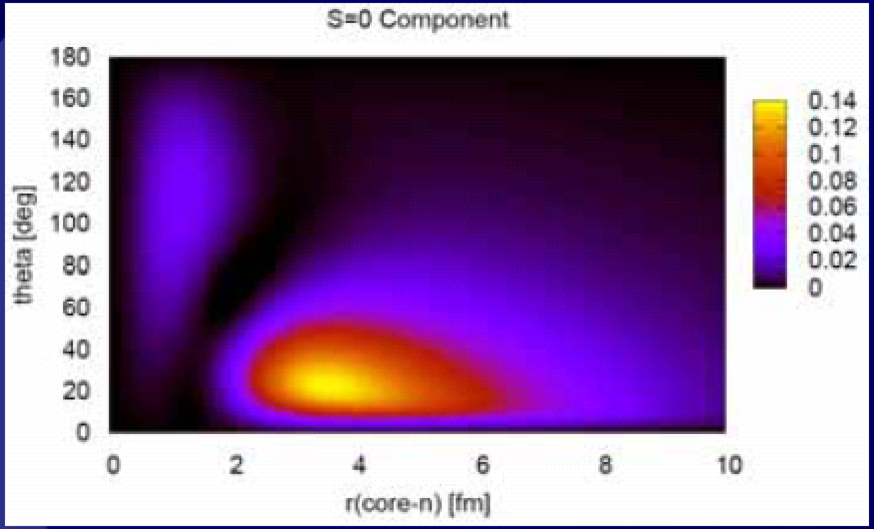
Coulomb breakup strength into ^{9}Li+n+n system

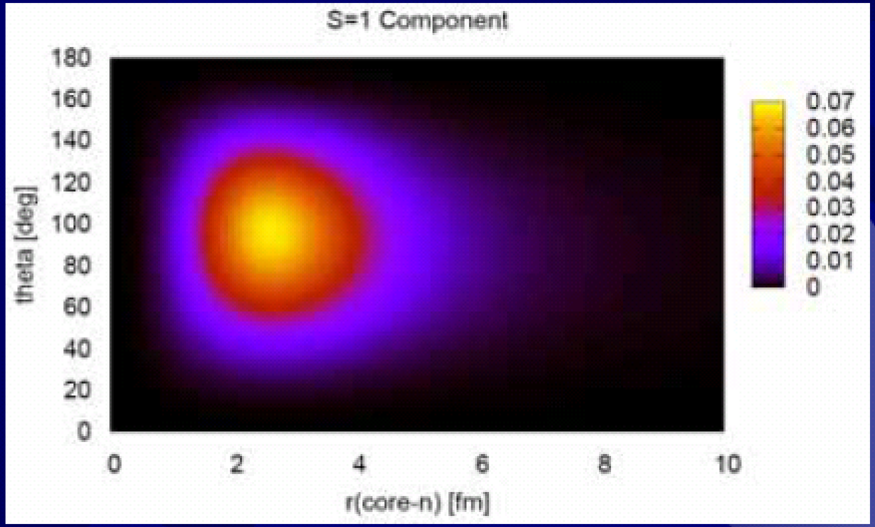


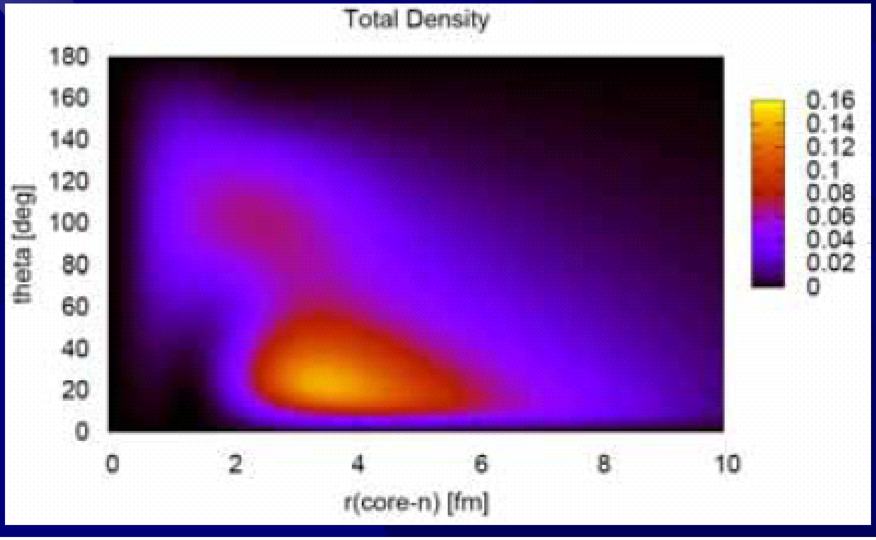
- ○ No three-body resonances.
- ○ Exp. : Nakamura et al., RIKEN Accel.Prog.Rep.38.

コア励起を含む場合の確率密度分布

4. Core(3 config.) & Tensor+Pairing ⇒ s^2=46.9%







Summary

1. Explicit effects of the tensor correlation (TC) are investigated in light nuclei.
2. ^{4}He : i) Three specific 2p2h configurations are favored to describe TC.
   ii) spatial shrinkage of the particle states is important to describe TC.
3. ^{5}He : Contribute to LS splitting / ^{6}He : Tensor suppression in 0^+_2.
   - $0p_{1/2}$-orbit neutrons cause the strong Pauli-blocking.
4. ^{11}Li : Tensor suppression leads to the large admixture of $(1s)^2$ in G.S.
   - "Tensor+Pairing" naturally explains 50 % of $(1s)^2$.
5. Future problem : How to treat the short-range correlation.