テンソル最適化殻模型による軽い核での核力の役割

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Outline

- **Role of V_{tensor}** in light nuclei
  - He & Li isotopes, ^{8}Be with V_{bare}
- Tensor Optimized Shell Model (**TOSM**) to describe tensor correlation.
- Unitary Correlation Operator Method (**UCOM**) to describe short-range correlation.

He and Li isotopes

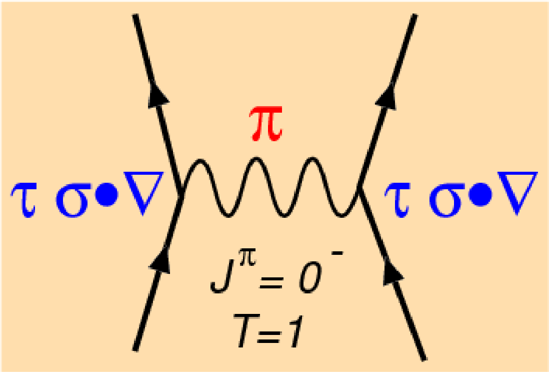
TM, A. Umeya, H. Toki, K. Ikeda PRC84 (2011) 034315

TM, A. Umeya, H. Toki, K. Ikeda PRC86 (2012) 024318

Pion exchange interaction vs. V_{tensor}

$$3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) \frac{q^2}{m^2+q^2} = (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \frac{q^2}{m^2+q^2} + S_{12} \frac{q^2}{m^2+q^2}$$

$$= (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \left[\frac{m^2+q^2}{m^2+q^2} - \frac{m^2}{m^2+q^2} \right] + S_{12} \frac{q^2}{m^2+q^2}$$



δ interaction

Yukawa interaction

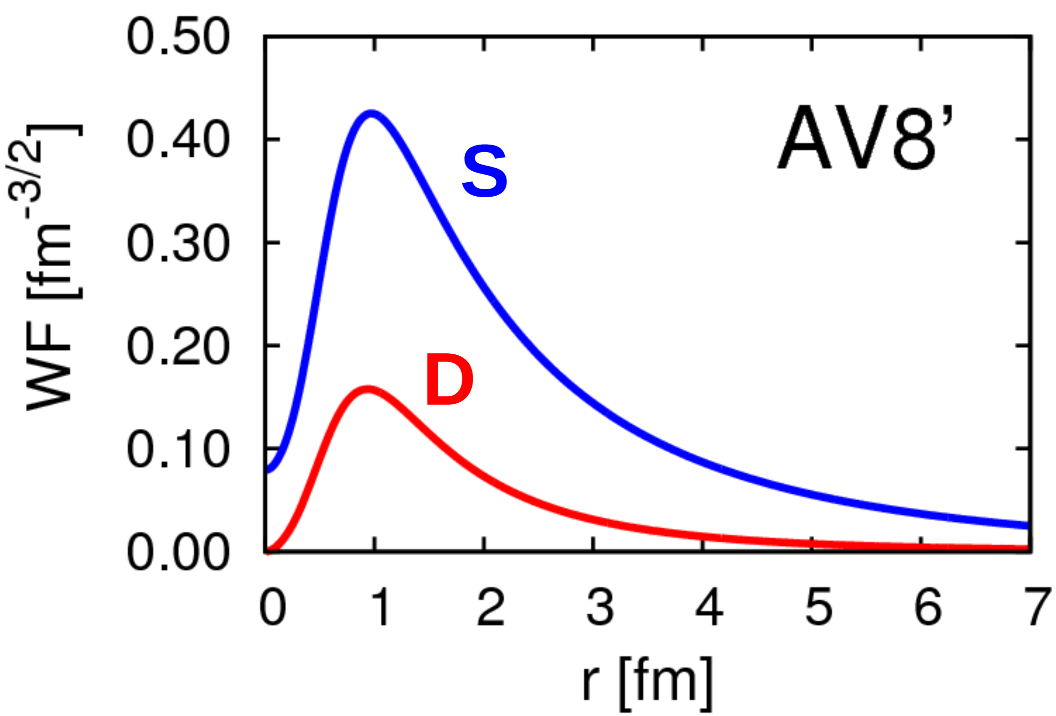
Involve large momentum

Tensor operator

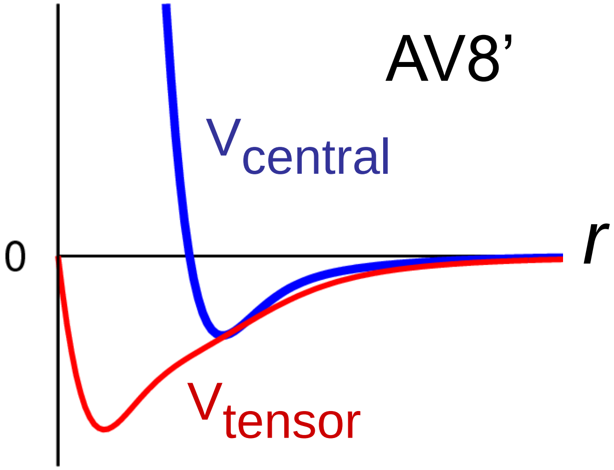
$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

- V_{tensor} produces the high momentum component.

Deuteron properties & tensor force



Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P(L=2)	5.77%
Radius	1.96 fm



$R_m(s)$=2.00 fm

$R_m(d)$=1.22 fm

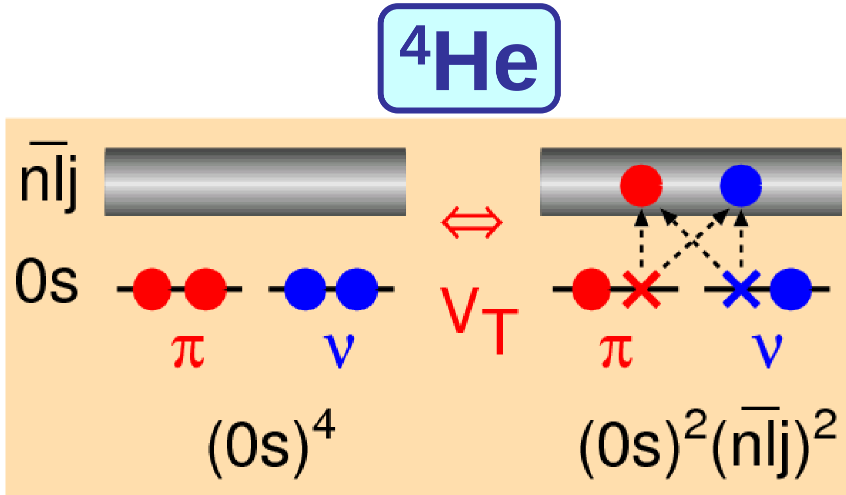
d-wave is
"**spatially compact**"
(high momentum)

Tensor-optimized shell model (TOSM)

TM, Sugimoto, Kato, Toki, Ikeda PTP117(2007)257

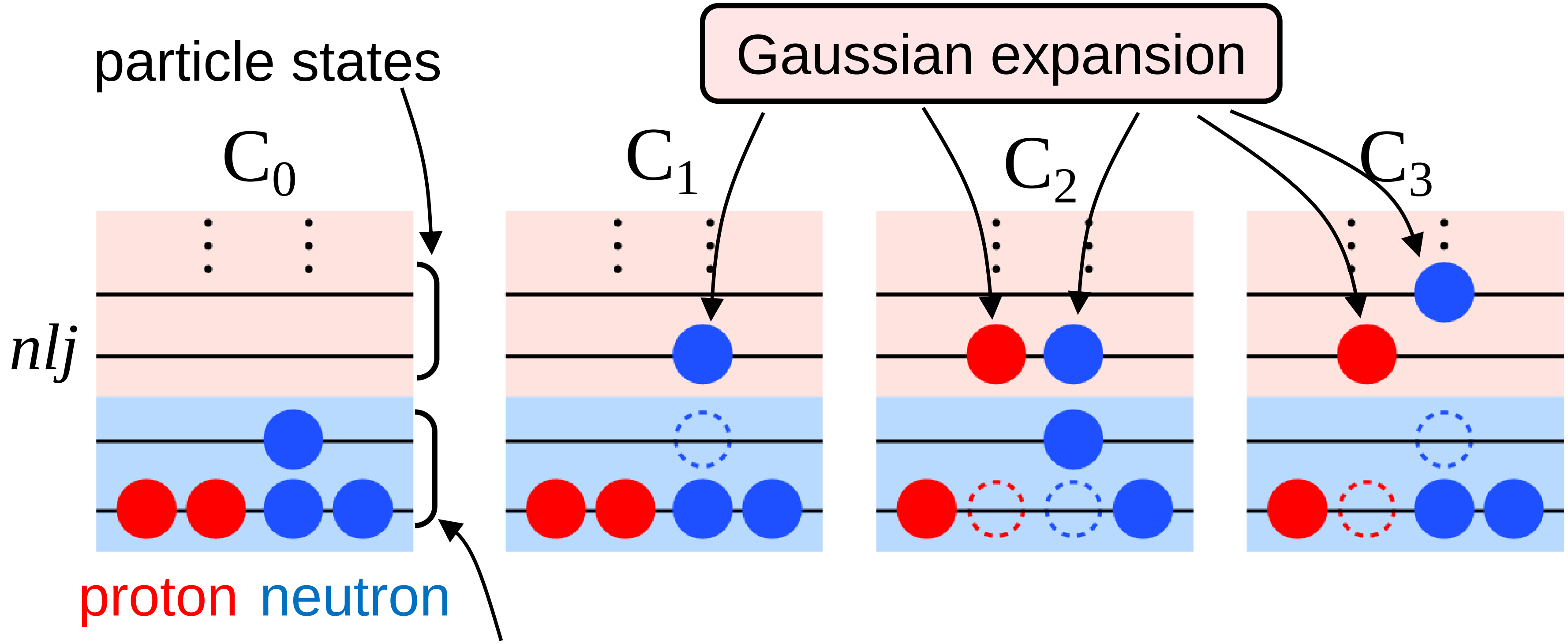
- 2p2h excitations with high-L orbits.
- V_{tensor} is **NOT** treated as residual interactions

  cf. $\frac{V_{\pi}}{V_{NN}}$ ~ 80% in GFMC



- Length parameters such as b_{0s}, b_{0p}, … are optimized independently, or superposed by many Gaussian bases.
  - Spatial shrinkage of ***D*-wave** as seen in deuteron.
    HF (Sugimoto, NPA740) , RMF (Ogawa, PRC73), AMD (Dote et al., PTP115)
- Satisfy few-body results with Minnesota central force (^{4,6}He)

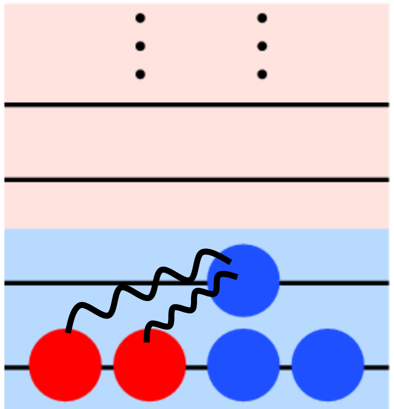
Configurations in TOSM



hole states (harmonic oscillator basis)
+ configuration mixing (0s→0p)

Application to Hypernuclei to investigate ΛN-ΣN coupling
by **Umeya** (NIT), **Hiyama** (RIKEN)

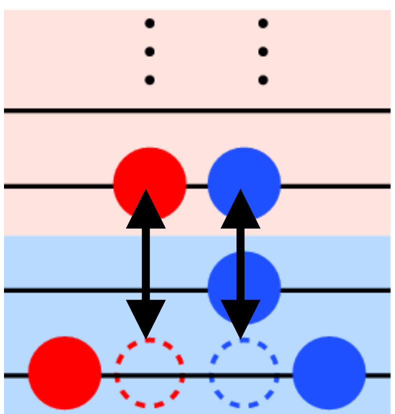
Tensor force matrix elements



$b_D \sim b_S$

$V_T = V_{\text{residual}}$

1st order



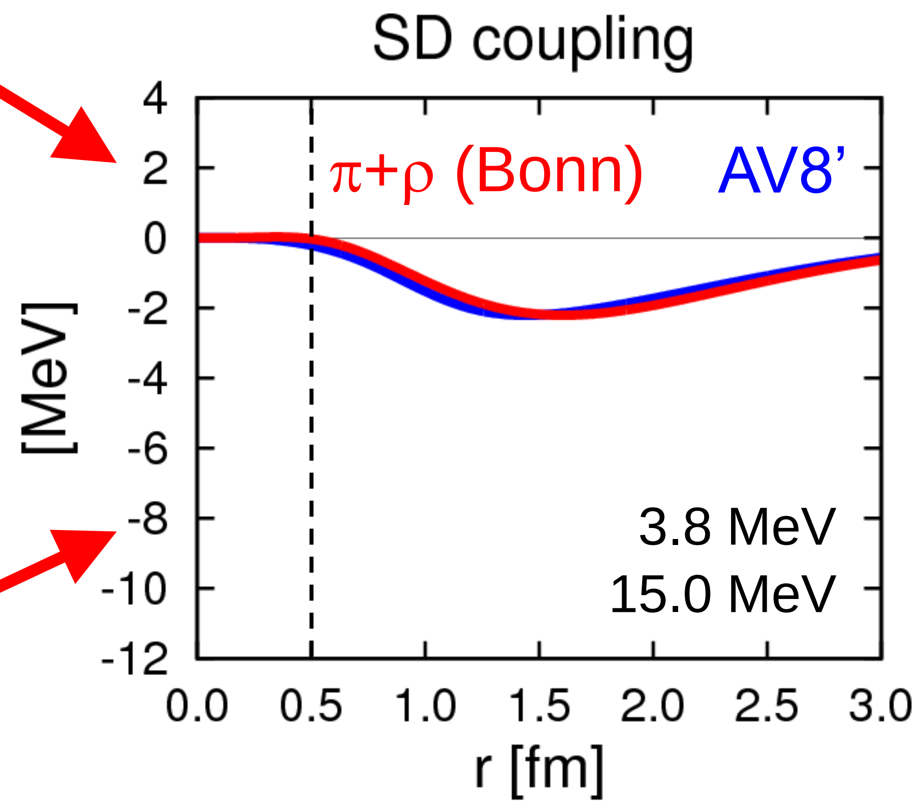
$b_D \sim b_S \times 0.5$

$V_T \neq V_{\text{residual}}$

0p0h-2p2h

$$M_{SD}(r) = r^2 \phi_S(r, b_S) \cdot V_T \cdot \phi_D(r, b_D)$$

: Integrand of Tensor ME



- Centrifugal potential (1GeV@0.5fm) pushes away D-wave.

Hamiltonian and variational equations in TOSM

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

(0p0h+1p1h+2p2h)

$$\Phi(A) = \sum_k C_k \cdot \psi_k(A)$$

Shell model type configuration with mass number A

Particle state : Gaussian expansion for each orbit

$$\varphi_{lj}^{n'}(\mathbf{r}) = \sum_{n=1}^{N} C_{lj,n}^{n'} \cdot \phi_{lj,n}(\mathbf{r}) \qquad \phi_{lj,n}(\mathbf{r}) \propto r^l \exp\left[-\frac{1}{2}\left(\frac{r}{b_{lj,n}}\right)^2\right]\left[Y_l(\hat{\mathbf{r}}), \chi_{1/2}^{\sigma}\right]_j$$

$$\left\langle \varphi_{lj}^{n'} \middle| \varphi_{lj}^{n''} \right\rangle = \delta_{n',n''}$$

Gaussian basis function

Hiyama, Kino, Kamimura
PPNP51(2003)223

$$\frac{\partial\langle H-E\rangle}{\partial C_k} = 0, \quad \frac{\partial\langle H-E\rangle}{\partial b_{lj,n}} = 0$$

c.m. excitation is excluded by Lawson's method

Unitary Correlation Operator Method

(short-range part)

$$\Psi_{\text{corr.}} = C \cdot \Phi_{\text{uncorr.}}$$

TOSM

short-range correlator

$$C^{\dagger} = C^{-1} \quad \text{(Unitary trans.)}$$

$$H\Psi = E\Psi \;\rightarrow\; C^{\dagger}HC\Phi \equiv \hat{H}\Phi = E\Phi$$

Bare Hamiltonian

Shift operator depending on the relative distance

$$C = \exp(-i\sum_{i<j} g_{ij}), \qquad g_{ij} = \tfrac{1}{2}\left\{ p_r s(r_{ij}) + s(r_{ij}) p_r \right\} \qquad \vec{p} = \vec{p}_r + \vec{p}_{\Omega}$$

Amount of shift, variationally determined.

$$C^{\dagger} r C \simeq r + s(r) + \tfrac{1}{2} s(r) s'(r) \cdots$$

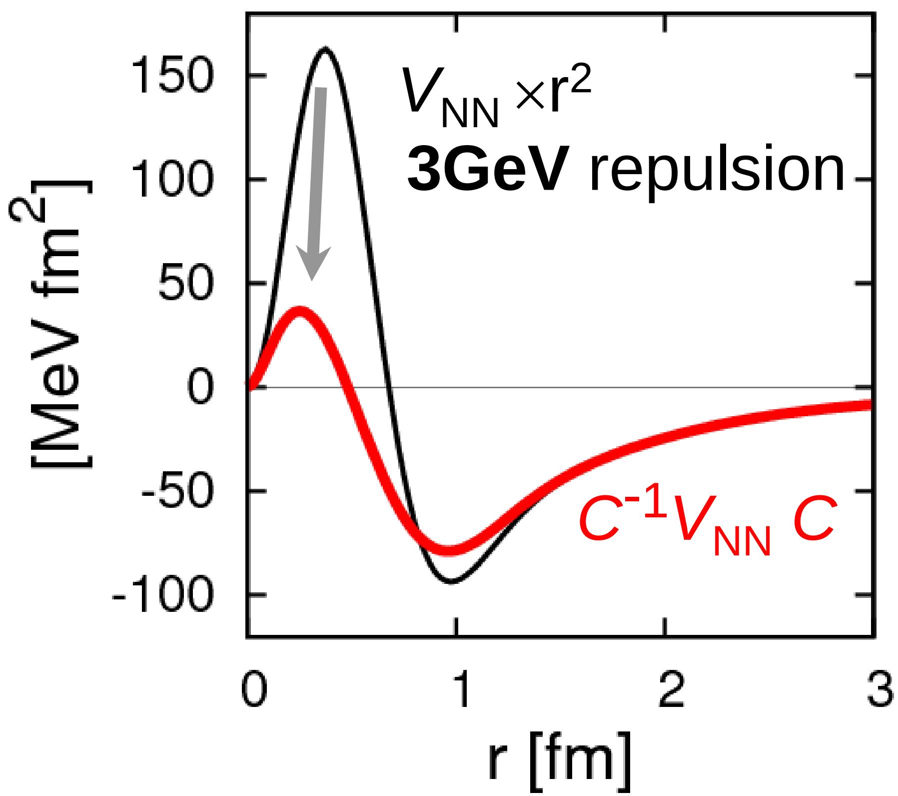
2-body cluster expansion

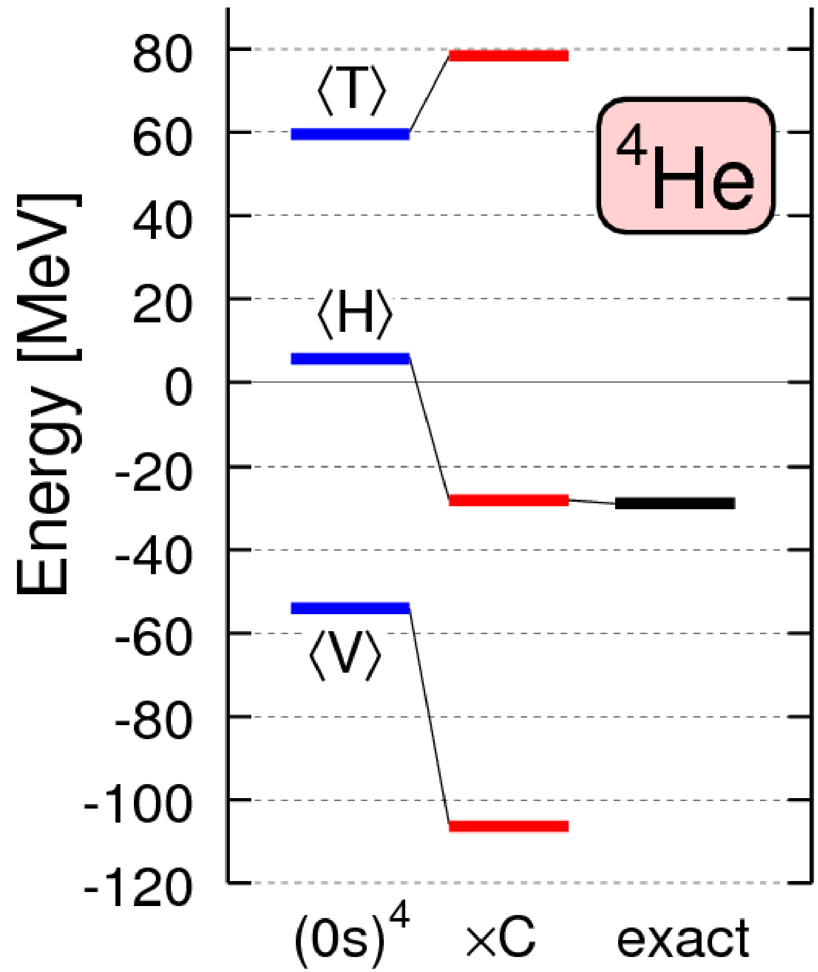
H. Feldmeier, T. Neff, R. Roth, J. Schnack, NPA632(1998)61

Unitary Correlation Operator Method

(short-range part)

C : UCOM operator

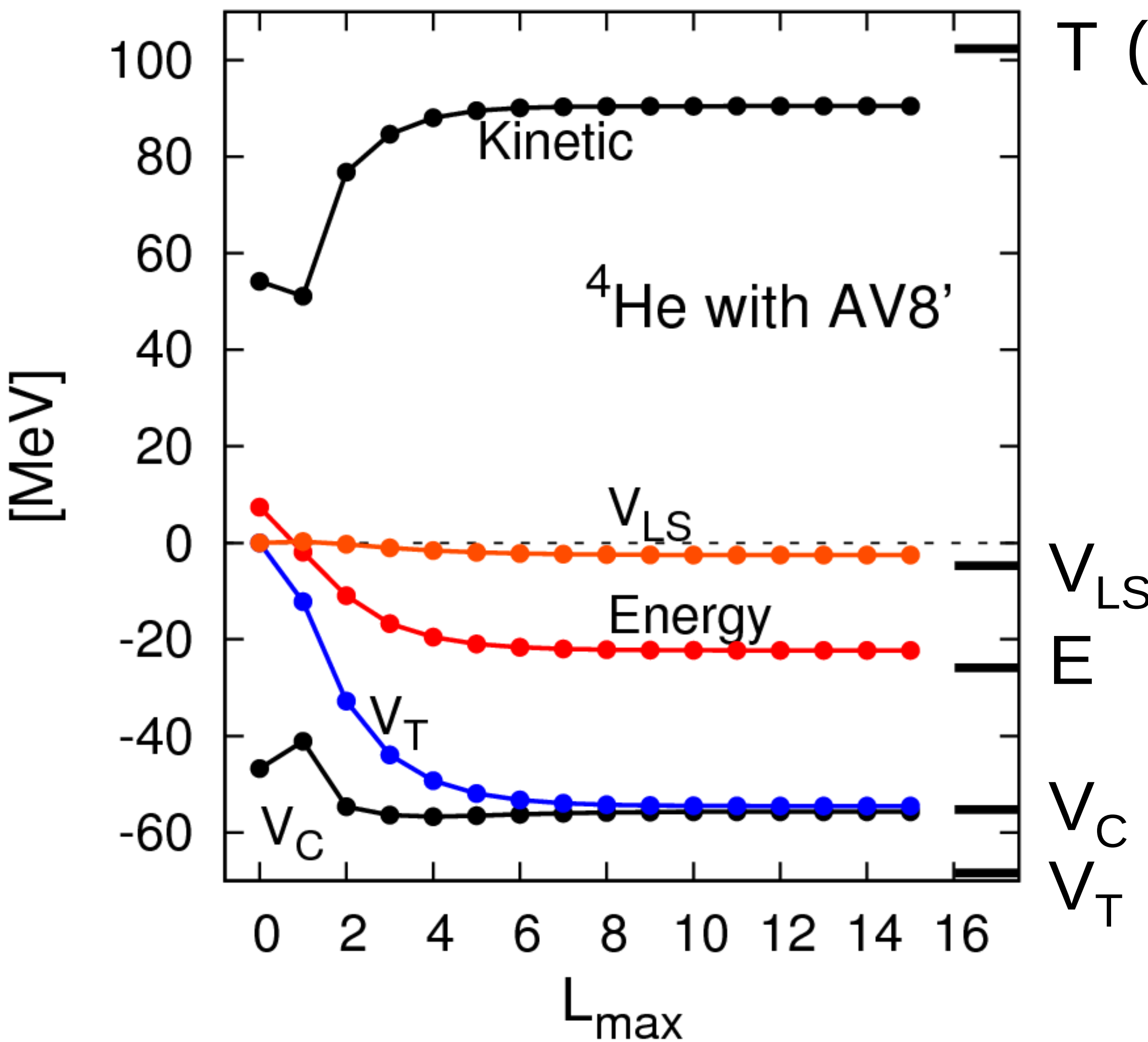




^{4}He in UCOM (Afnan-Tang, Central only)

H. Feldmeier, T. Neff, R. Roth, J. Schnack, NPA632(1998)61

^{4}He in TOSM + short-range UCOM



Kamada et al.
PRC64 (Jacobi)

TM, H. Toki, K. Ikeda
PTP121(2009)511

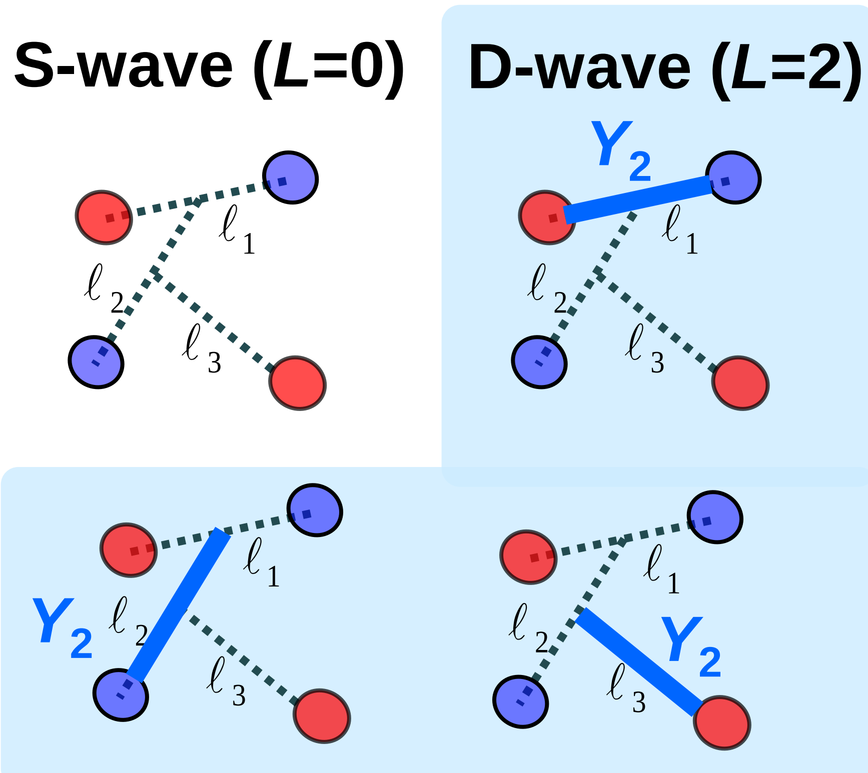
- variational calculation

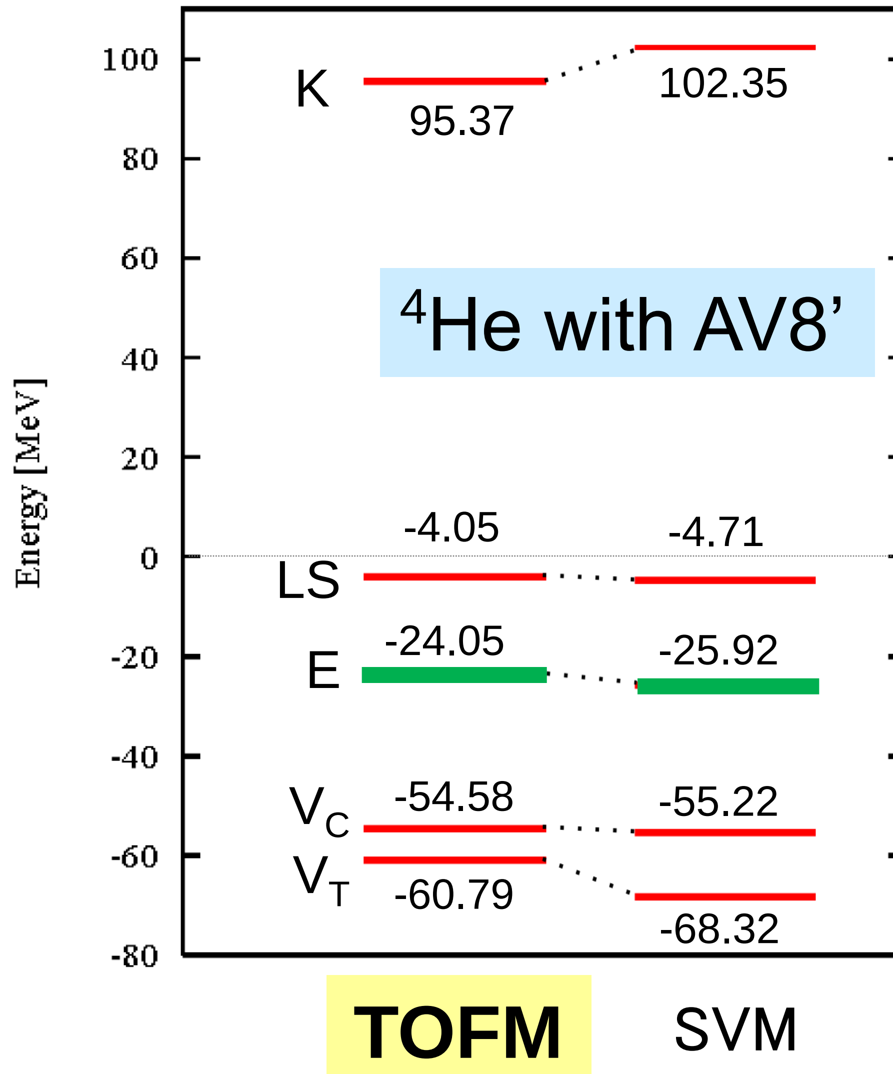
- Gaussian expansion with 9 bases

good convergence

Tensor Optimized Few-body Model (TOFM)

- Same as TOSM concept
- No use of UCOM
- Correlated Gaussian basis
  + Global vector in SVM



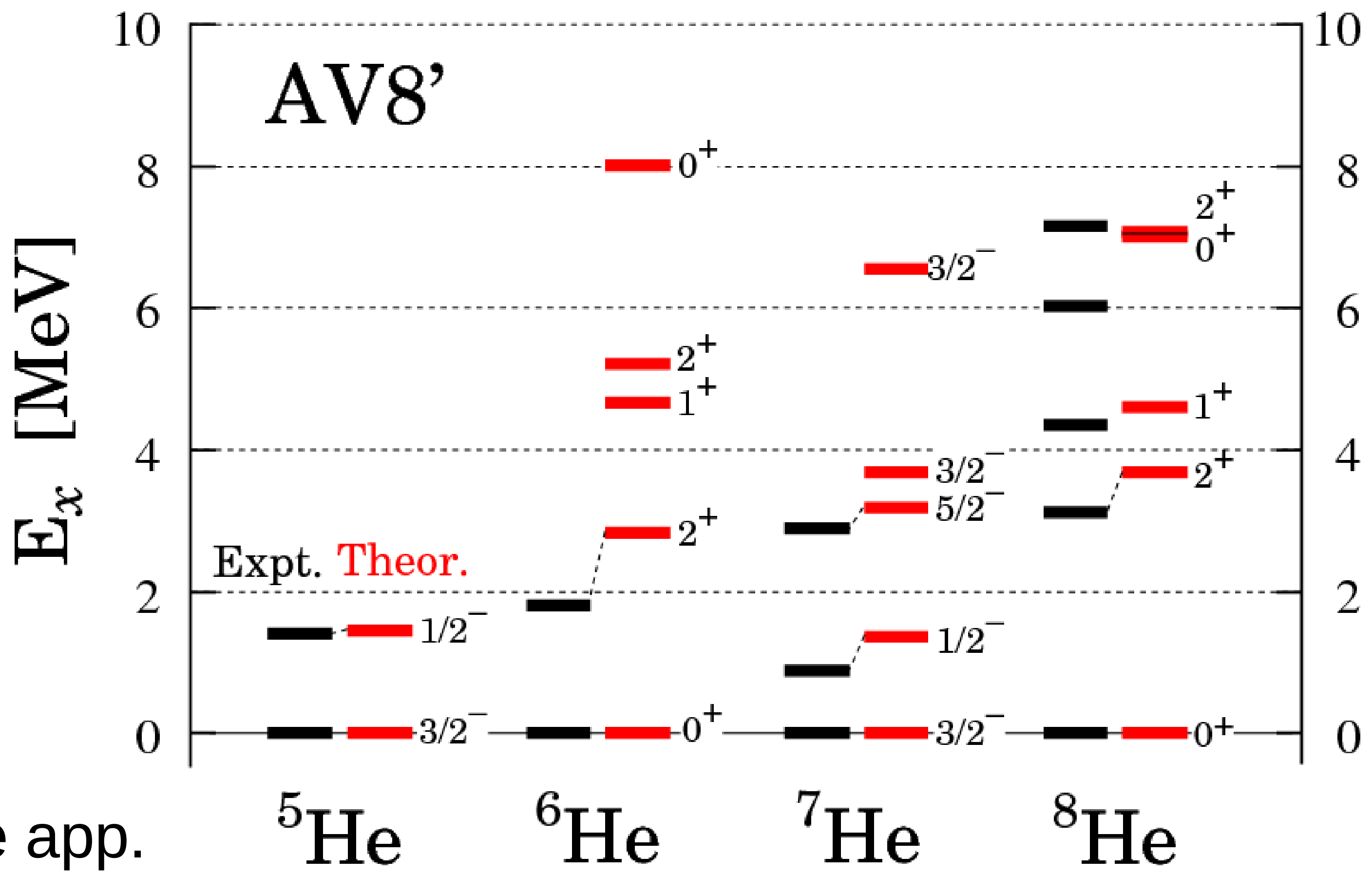


Horii, Toki, Myo, Ikeda PTP127(2012)1019

$^{5\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV

TM, A. Umeya, H. Toki, K. Ikeda
PRC84 (2011) 034315



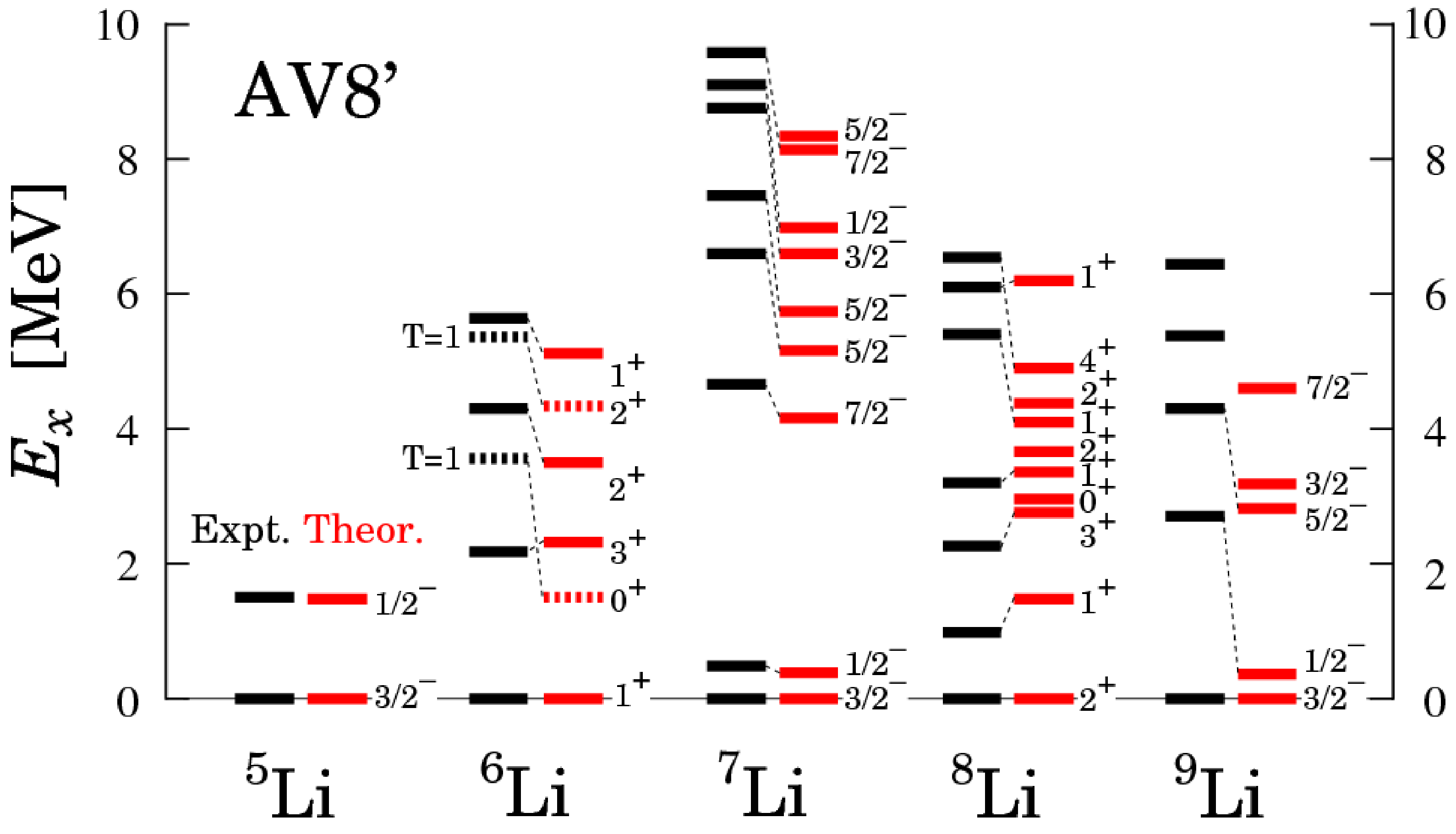
- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

$^{5\text{-}9}$Li with TOSM+UCOM

- Excitation energies in MeV

TM, A. Umeya, H. Toki, K. Ikeda
PRC86(2012) 024318

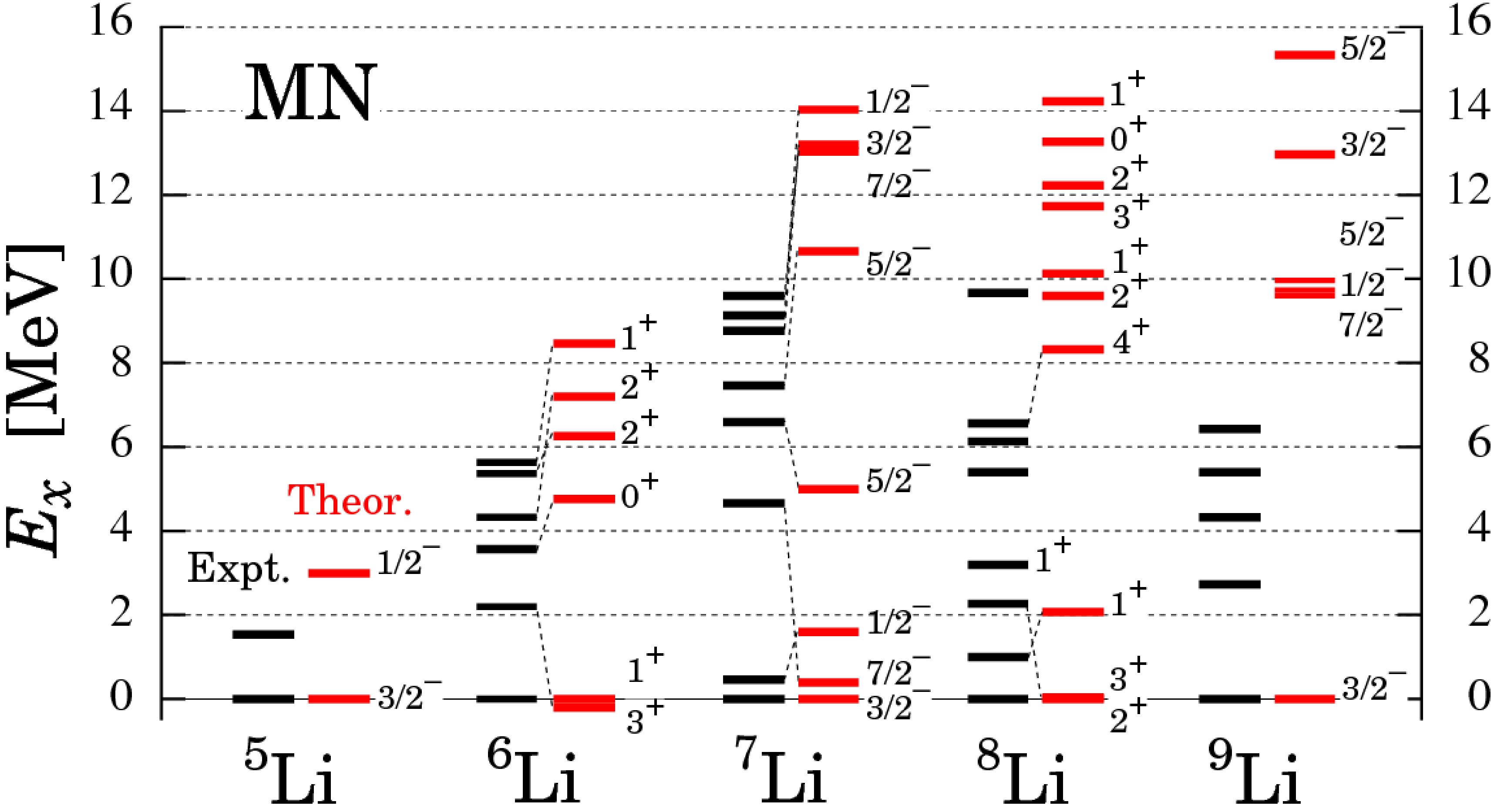


- Excitation energy spectra are reproduced well

$^{5\text{-}9}$Li with TOSM

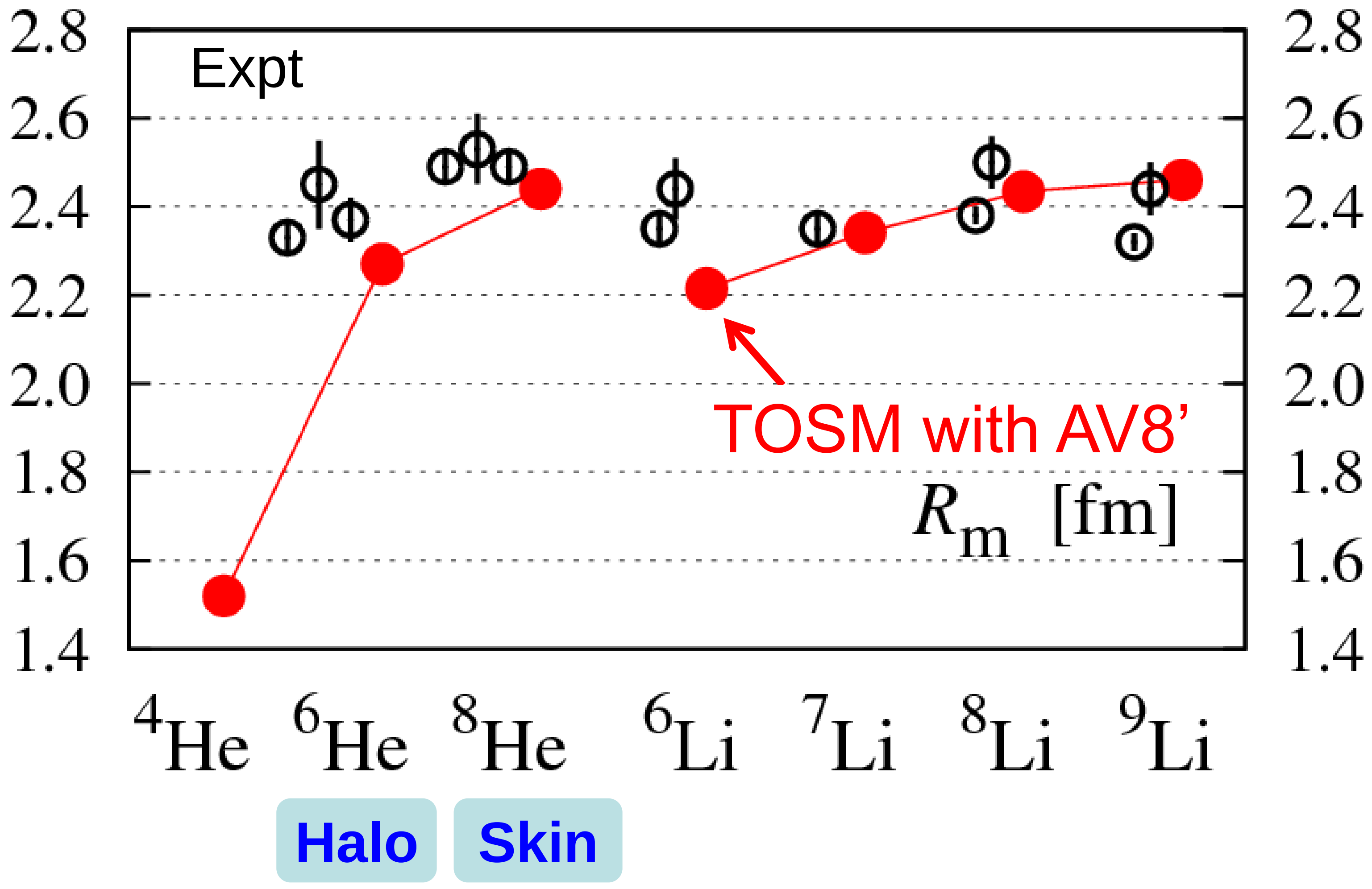
Minnesota force
NO tensor

- Excitation energies in MeV



- Too large excitation energy

Matter radius of He & Li isotopes



I. Tanihata et al., PLB289(‘92)261
O. A. Kiselev et al., EPJA 25, Suppl. 1(‘05)215.
A. Dobrovolsky, NPA 766(2006)1
G. D. Alkhazov et al., PRL78(‘97)2313
P. Mueller et al., PRL99(2007)252501

Configurations of ^{4}He with AV8'

TM, H. Toki, K. Ikeda
PTP121(2009)511

$(0s_{1/2})^4$	83.0 %
$(0s_{1/2})^{-2}{}_{JT}(p_{1/2})^2{}_{JT}$ ***JT*=10**	2.6
JT=01	0.1
$(0s_{1/2})^{-2}{}_{10}(1s_{1/2})(d_{3/2})_{10}$	2.3
$(0s_{1/2})^{-2}{}_{10}(p_{3/2})(f_{5/2})_{10}$	1.9
Radius [fm]	1.54

- deuteron correlation with $(J,T)=(1,0)$

Cf. R.Schiavilla et al. (VMC) PRL98(2007)132501
R. Subedi et al. (JLab) Science320(2008)1476

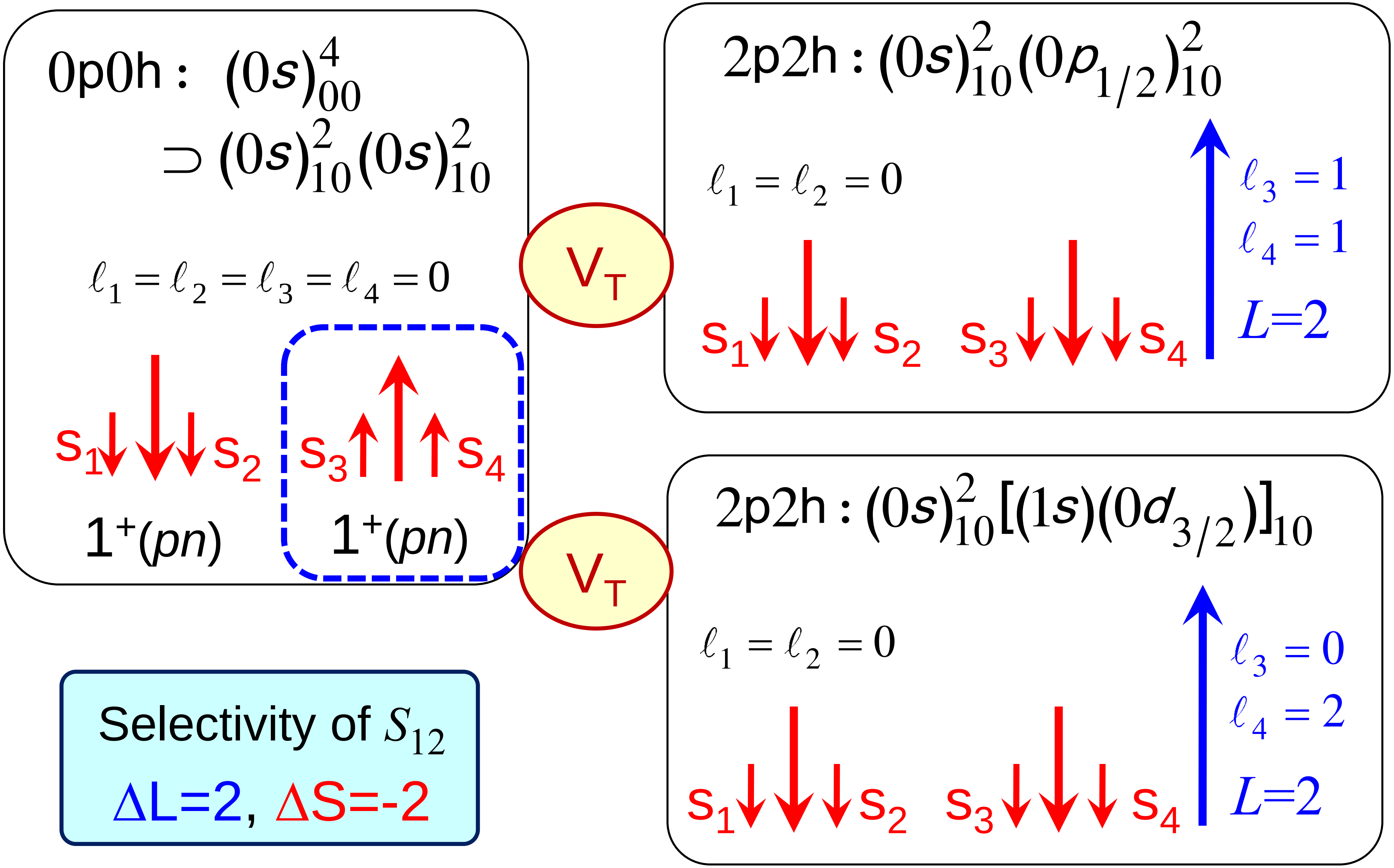
$^{12}C(e,e'pN)$

S.C.Simpson, J.A.Tostevin PRC83(2011)014605

$^{12}C \rightarrow {}^{10}B+pn$

- ^{4}He contains $p_{1/2}$ of "*pn*-pair"
  - Same feature in ^{5}He-^{8}He ground state

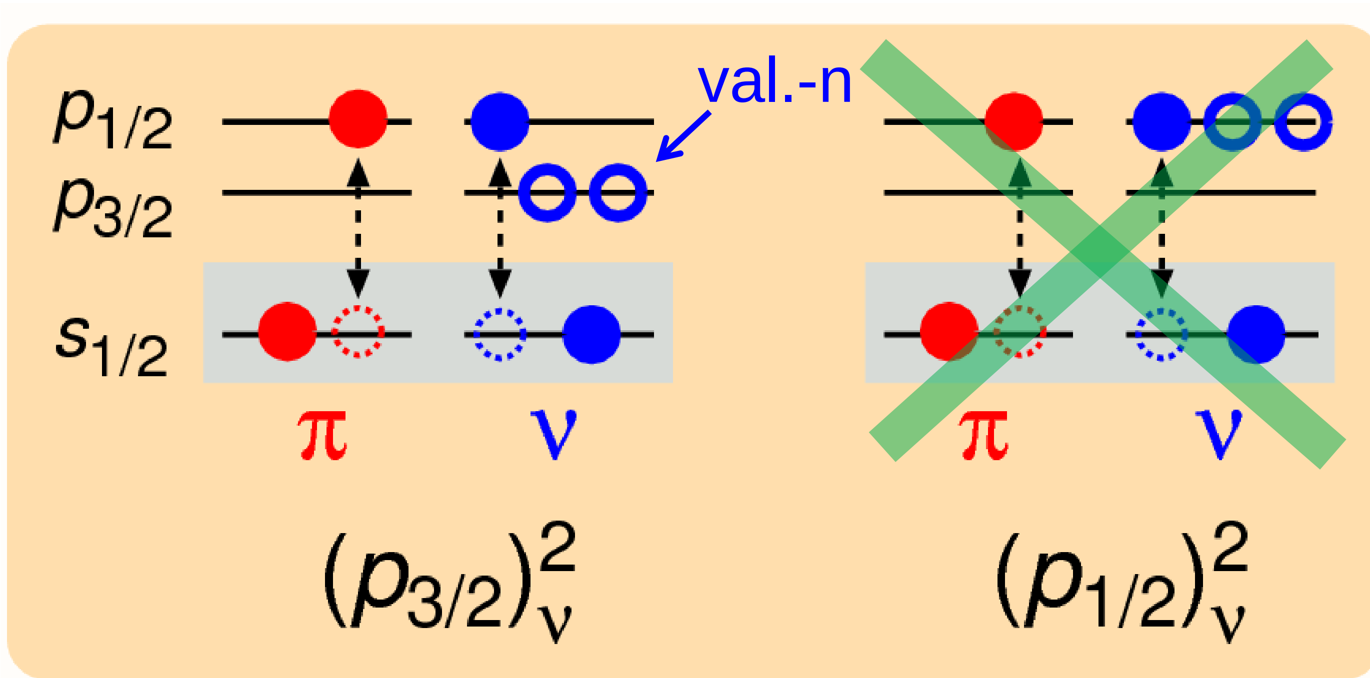
Selectivity of the tensor coupling in ^{4}He



Selectivity of S_{12}

$\Delta L=2$, $\Delta S=-2$

Tensor correlation in ^{6}He



Ground state

Excited state

halo state (0$^+$)

Tensor correlation is **suppressed**
due to Pauli-Blocking

TM, K. Kato, K. Ikeda, J. Phys. G31 (2005) S1681

^{6}He : Hamiltonian components

- Difference from ^{4}He in MeV

^{6}**He**	0^+_1	0^+_2
n^2 **config**	$(p_{3/2})^2$	$(p_{1/2})^2$
ΔKin.	**53.0**	**34.3**
ΔCentral	**–27.8**	**–14.1**
ΔTensor	**–12.0**	**–0.2**
ΔLS	**–4.0**	**2.1**

b_{hole}=1.5 fm

$\hbar\omega$=18.4 MeV

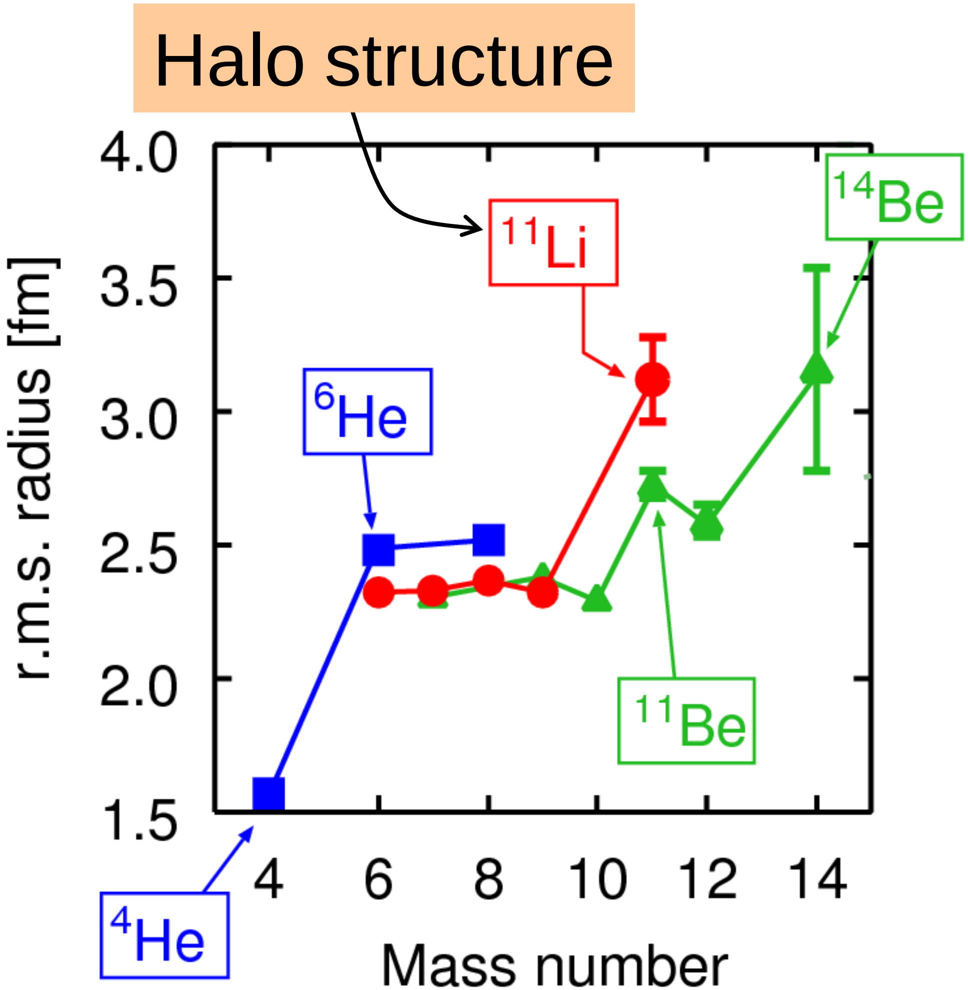
LS splitting energy in ^{6}He

same trend in $^{5-8}$He, ^{10,11}Li

Halo formation with large *s*-wave in ^{11}Li

Ikeda, Myo, Kato, Toki
Lecture Notes in Physics 818 (2010) "Clusters in Nuclei" Vol.1

Characteristics of Li-isotopes

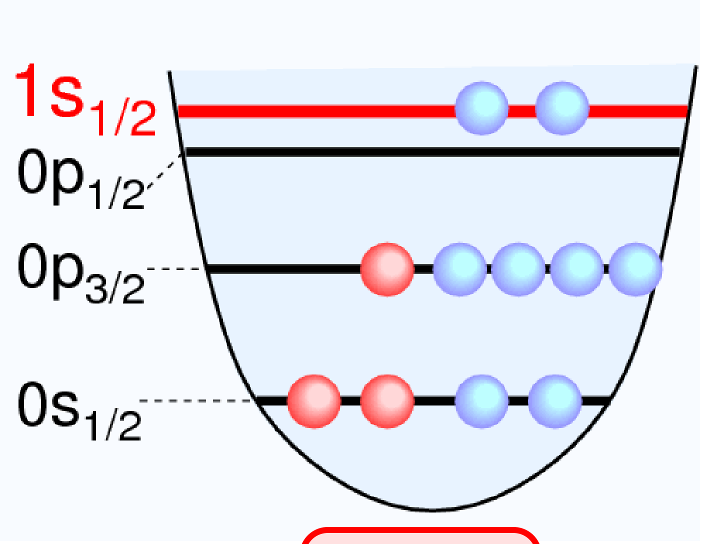


Tanihata et al., PRL55(1985)2676.
PLB206(1998)592.

✓ Breaking of magicity N=8

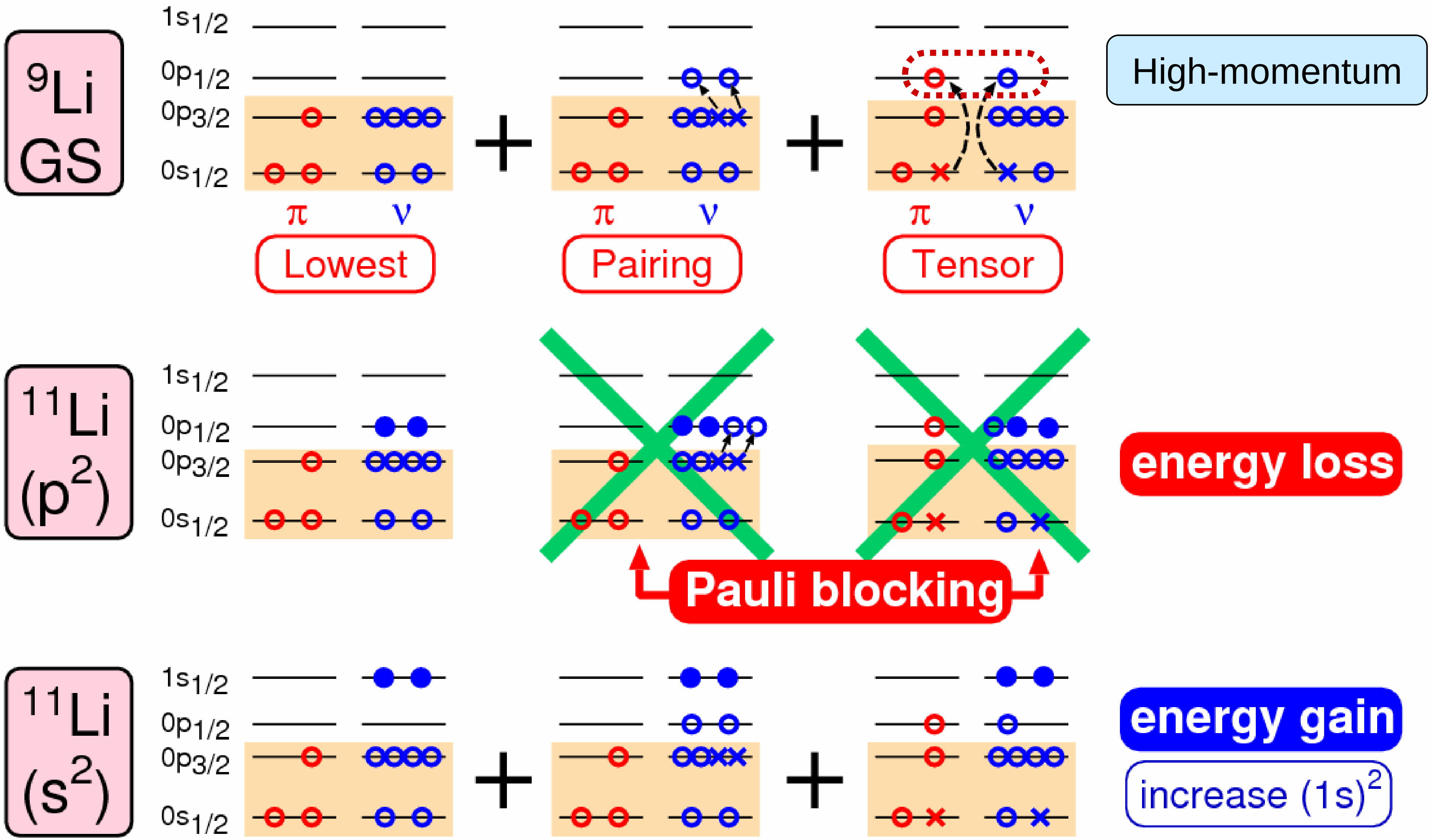
- $^{10-11}$Li, $^{11-12}$Be
- ^{11}Li … $(1s)^2$ ~ 50%.

  (Expt by Simon et al.,PRL83)
- Mechanism is unclear



^{11}Li

Expected effects of pairing and tensor correlations in ^{11}Li



Pairing-blocking :

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

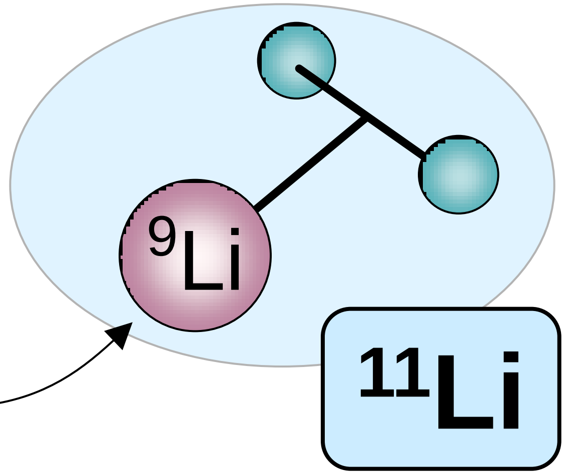
^{11}Li with ^{9}Li$_{\text{TOSM}}$+n+n cluster model

- System is solved based on RGM

$$H(^{11}\text{Li}) = H(^{9}\text{Li}) + H_{\text{rel}}(^{9}\text{Li-n-n})$$

$$\Phi(^{11}\text{Li}) = \mathcal{A}\left\{\sum_{i=1}^{N} \underline{\psi_i(^{9}\text{Li})} \cdot \chi_i(nn)\right\}$$

TOSM basis



- Orthogonality Condition Model (OCM) is applied.

$$\sum_{i=1}^{N}\left[H_{ij}(^{9}\text{Li}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12}) \cdot \delta_{ij}\right]\chi_j(nn) = E\chi_i(nn)$$

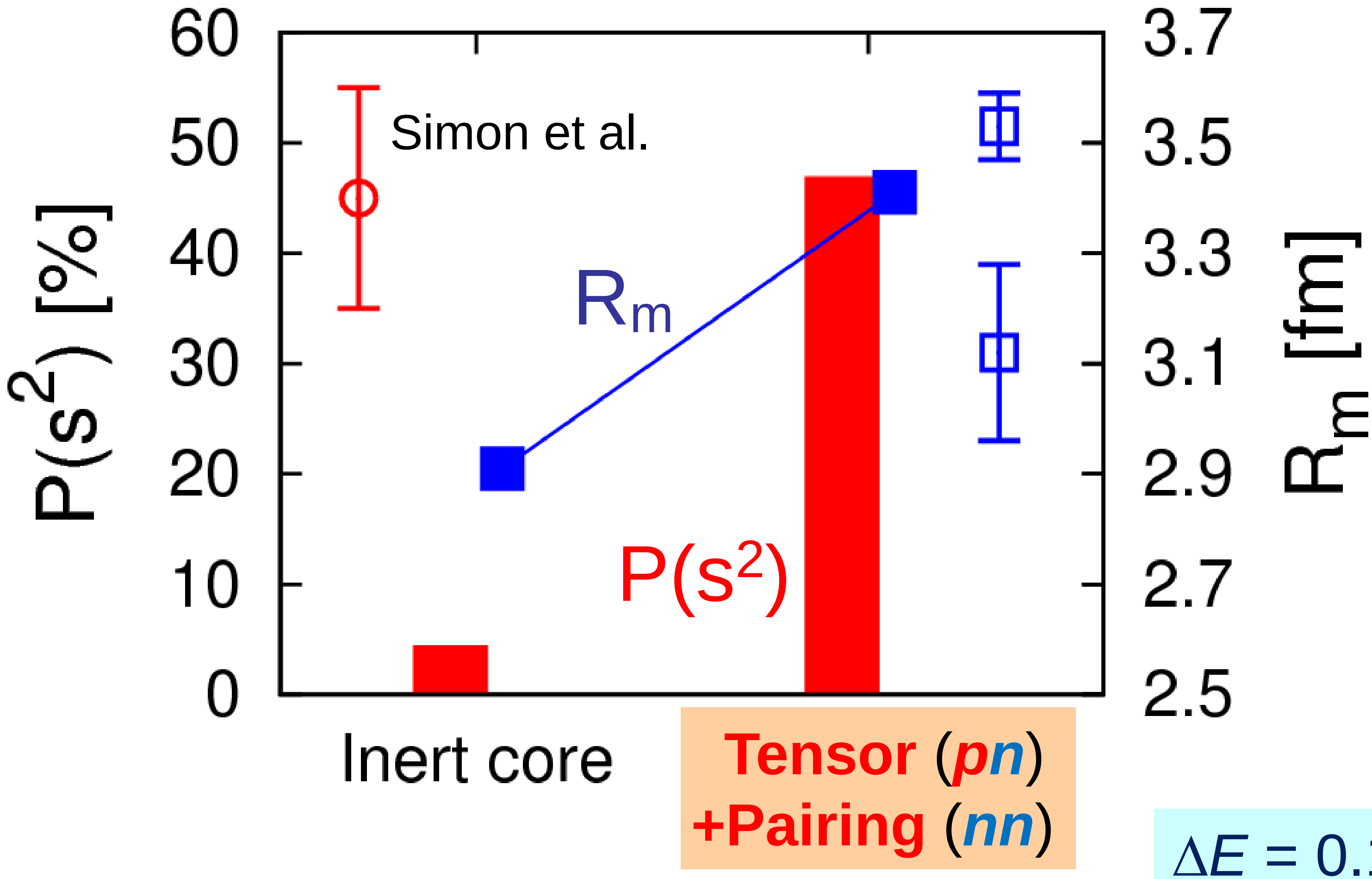
$H_{ij}(^{9}\text{Li}) = \langle \psi_i | H(^{9}\text{Li}) | \psi_j \rangle$: Hamiltonian for ^{9}Li with TOSM

$\chi(nn) = \mathcal{A}\{\varphi_1\varphi_2\}$: few-body method with Gaussian expansion

$\langle \varphi_i | \phi_\alpha \rangle = 0, \ \{\phi_\alpha \in {}^{9}\text{Li}\}$: Orthogonality to the Pauli-forbidden states

TM, K.Kato, H.Toki, K.Ikeda PRC76(2007)024305

^{11}Li properties (S_{2n}=0.31 MeV)



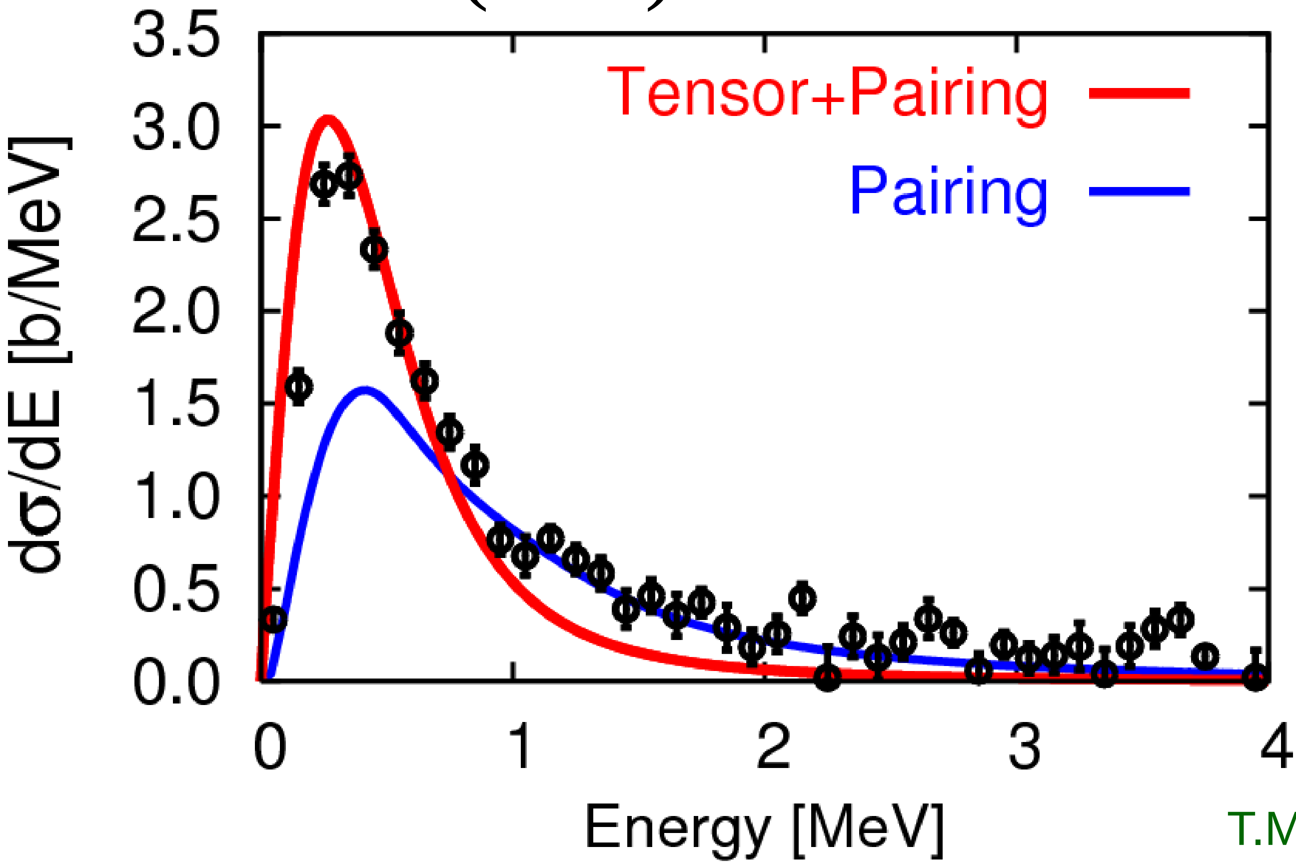
ΔE = 0.1MeV

Pairing correlation between halo neutrons couples $(0p)^2$ and $(1s)^2$

TM, K.Kato, H.Toki, K.Ikeda, PRC76(2007)024305
TM, Y.Kikuchi, K.Kato, H.Toki, K.Ikeda, PTP119(2008)561

Coulomb breakup strength of ^{11}Li

$$^{11}\mathrm{Li\,(G.S.)} \rightarrow {}^{9}\mathrm{Li} + n + n$$



No three-body resonance

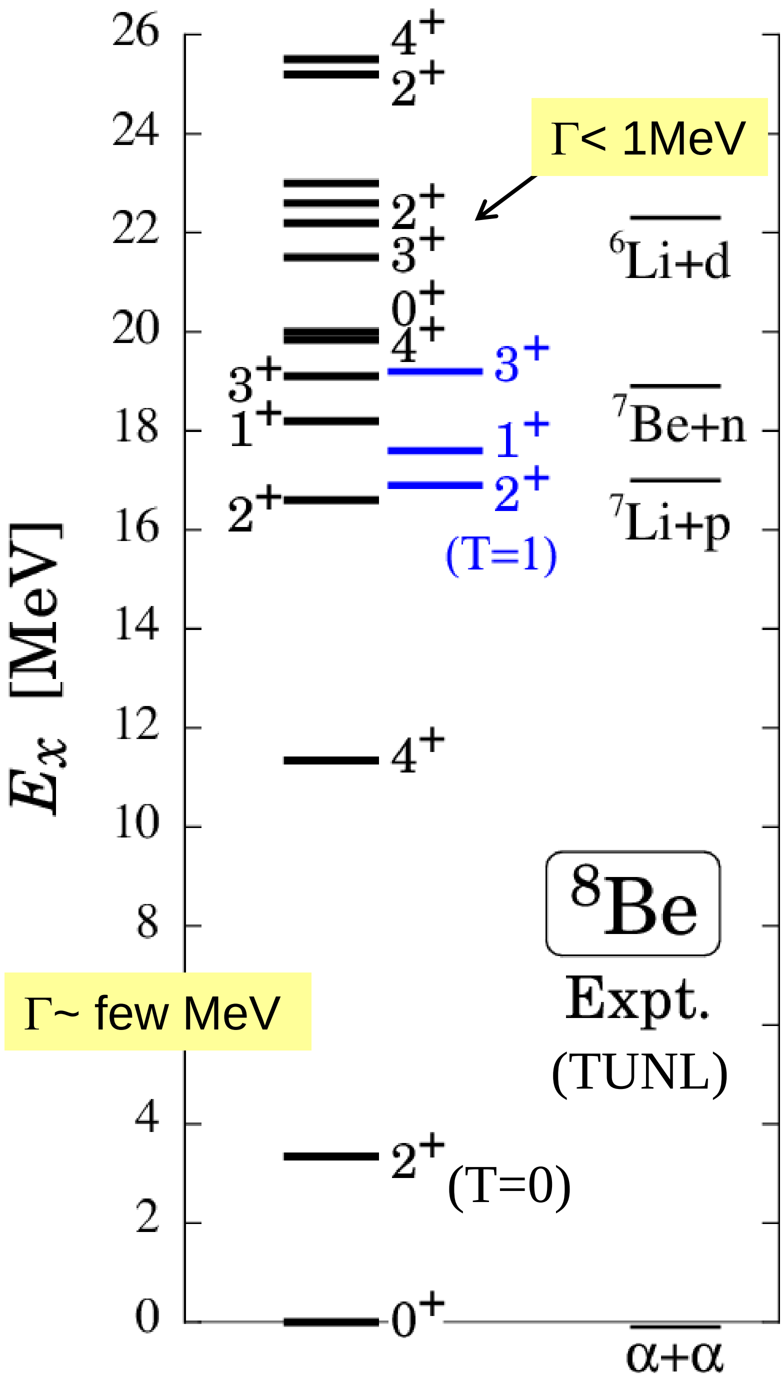
E1 strength by using the Green's function method

+Complex scaling method

+Equivalent photon method (TM et al., PRC63('01))

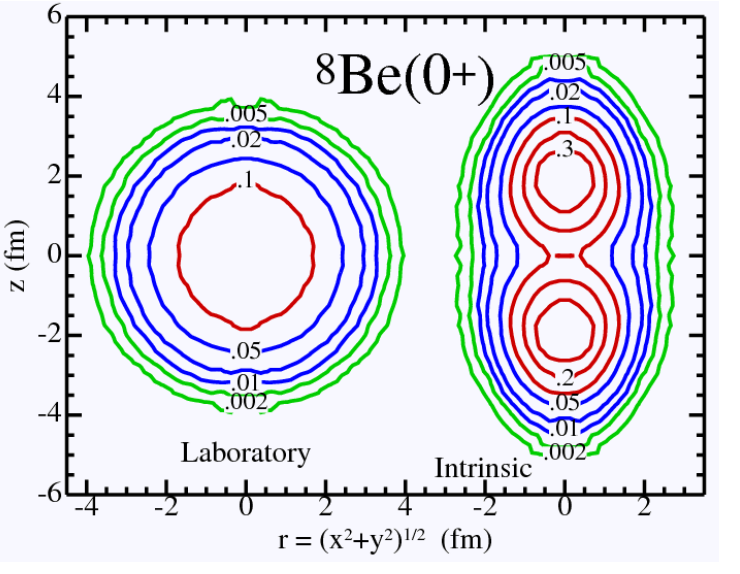
T.Myo, K.Kato, H.Toki, K.Ikeda PRC76(2007)024305

- Expt: T. Nakamura et al. , PRL96,252502(2006)
- Energy resolution with $\sqrt{E}$ =0.17 MeV.

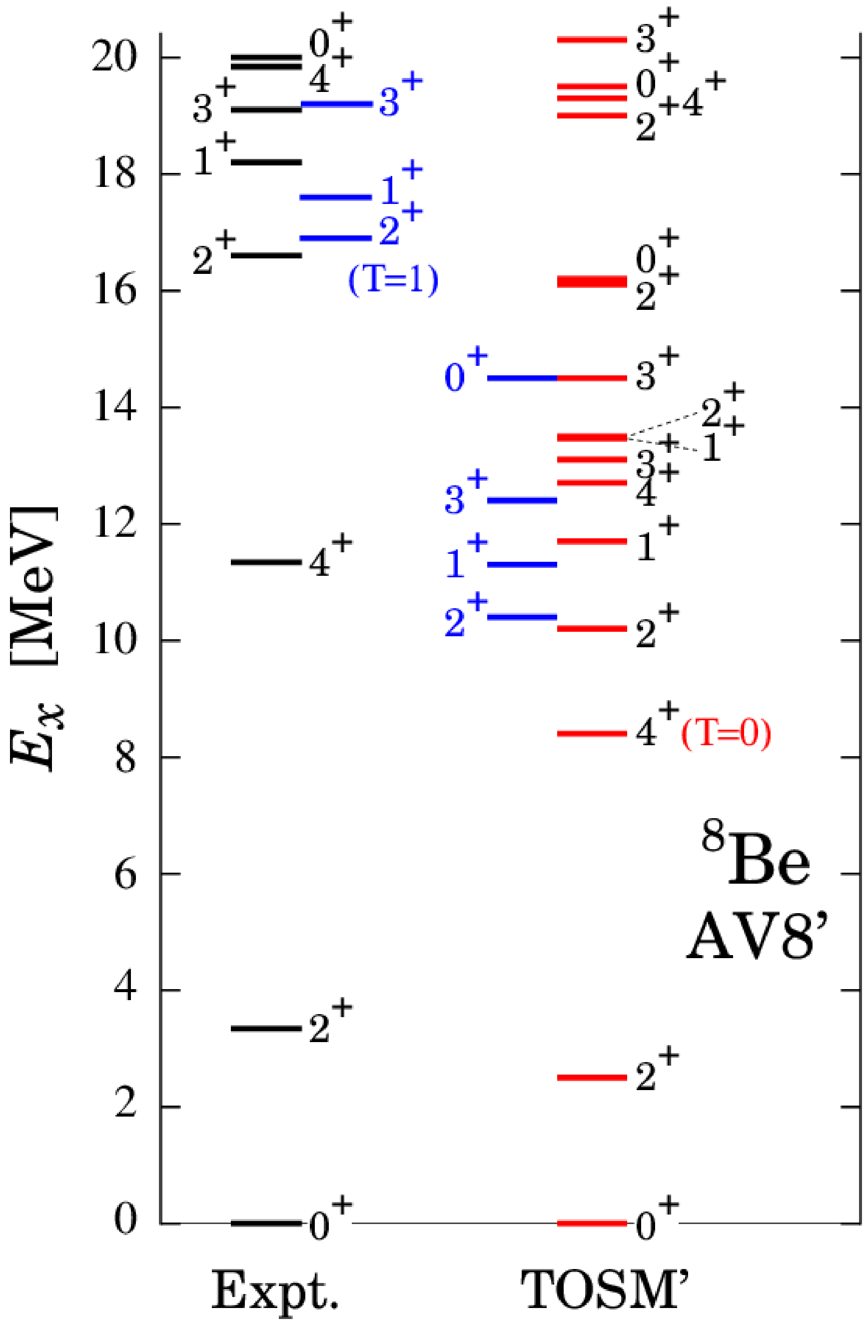


^{8}Be spectrum

- Argonne Group
  - Green's function Monte Carlo
    C.Pieper, R.B.Wiringa, Annu.Rev.Nucl.Part.Sci.51 (2001)

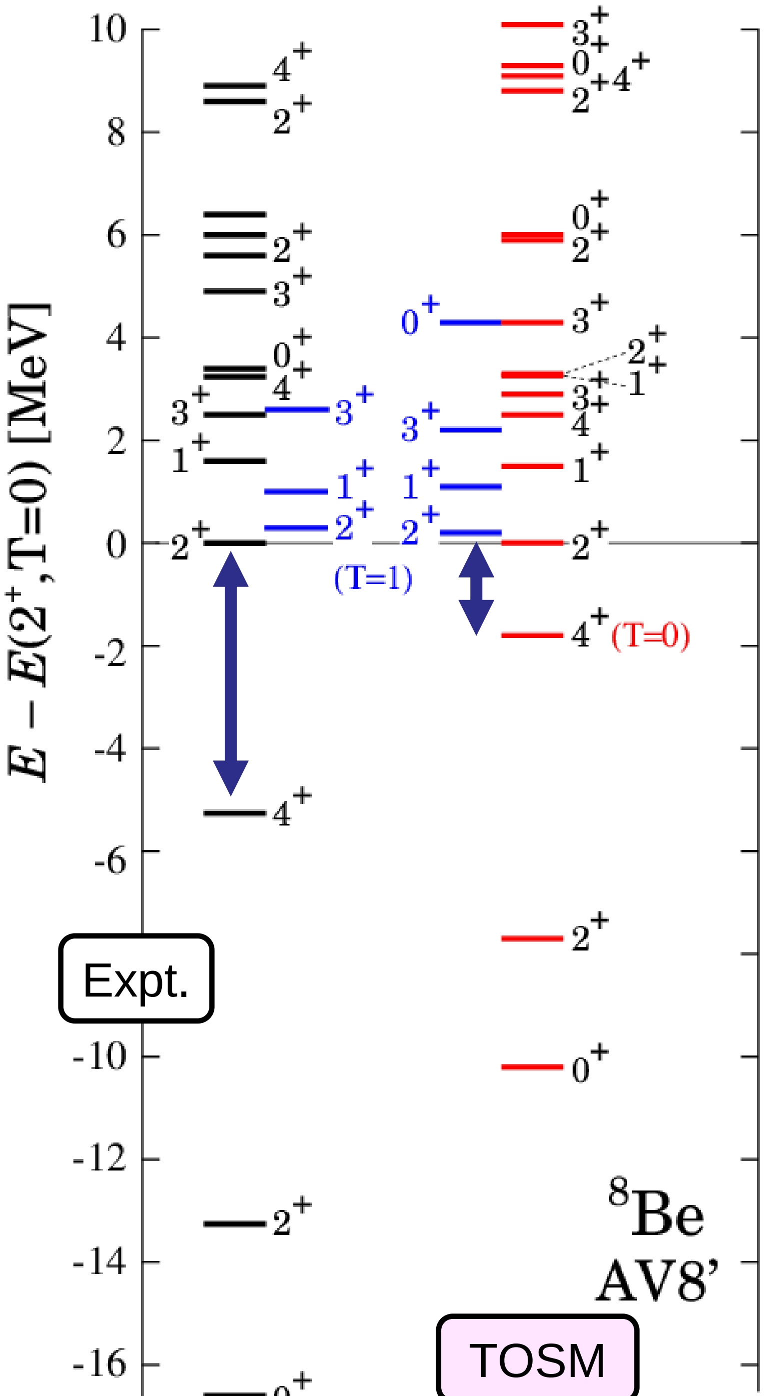


α-α structure



^{8}Be in TOSM – AV8' –

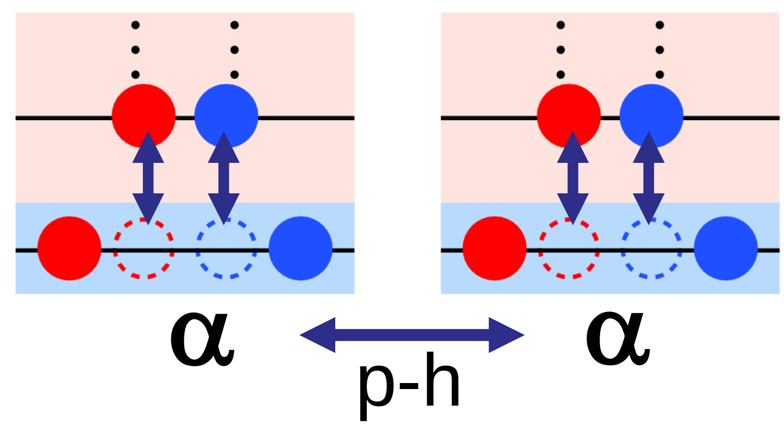
- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)
- ground band
- highly excited states
  - small E_X
  - correct level order (T=0,1)
- $R_m(^8Be)$=2.21 fm
  - Brink 2α model: 2.48 fm
  - ^{4}He :1.52 fm
  - ^{12}C :2.35 fm



^{8}Be in TOSM – AV8' –

- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)

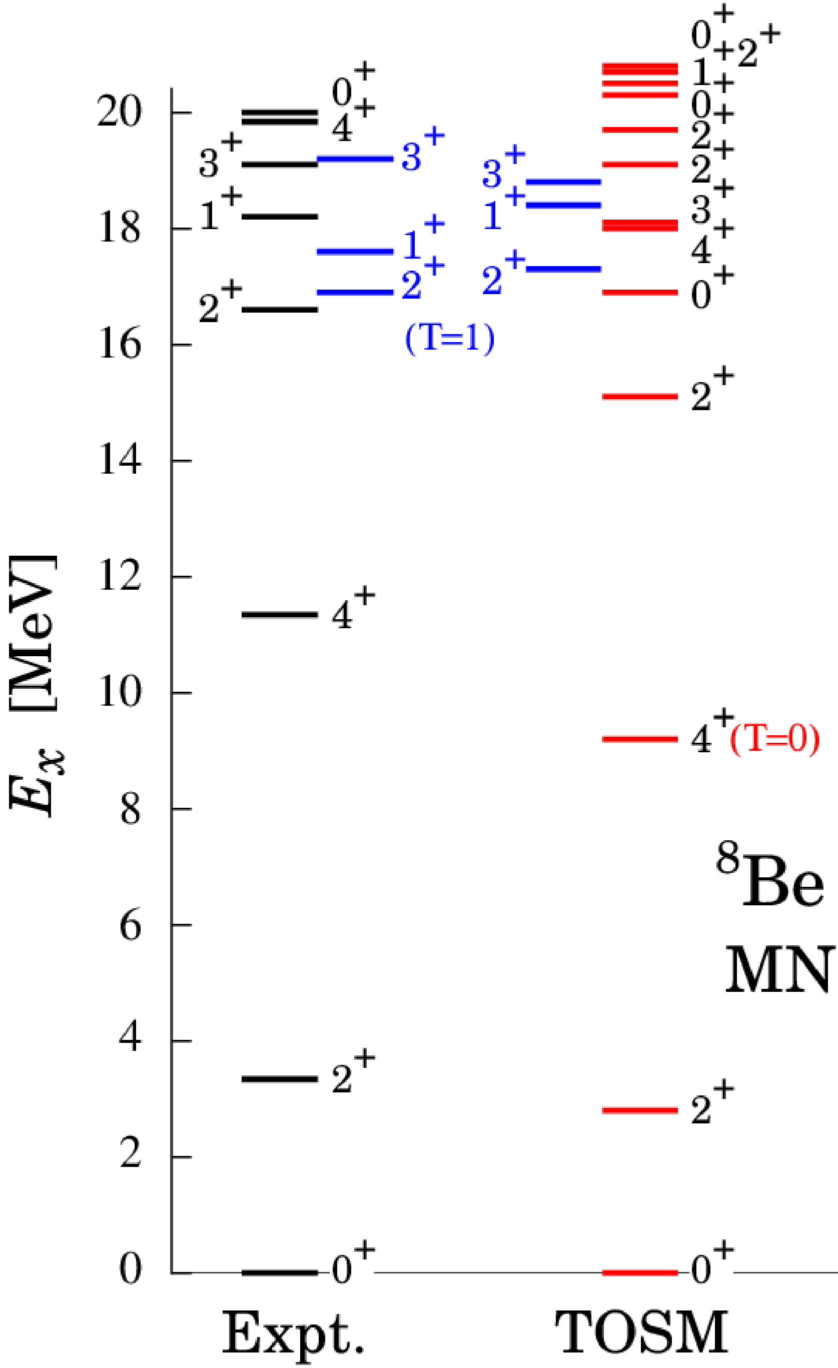
- **α** : 0p0h+2p2h with high-*k*
  → naively 2α needs 4p4h.



Hamiltonian components in ^{8}Be

State		Kinetic	Central	Tensor
^{4}He		**95**	**–56**	**–62**
^{8}Be	0^{+}_{1}	**192**	**–115**	**–97**
	2^{+}_{1}	191	–112	–95
	2^{+}_{2}	185	–98	–92
	$2^{+}_{T=1}$	168	–94	–82

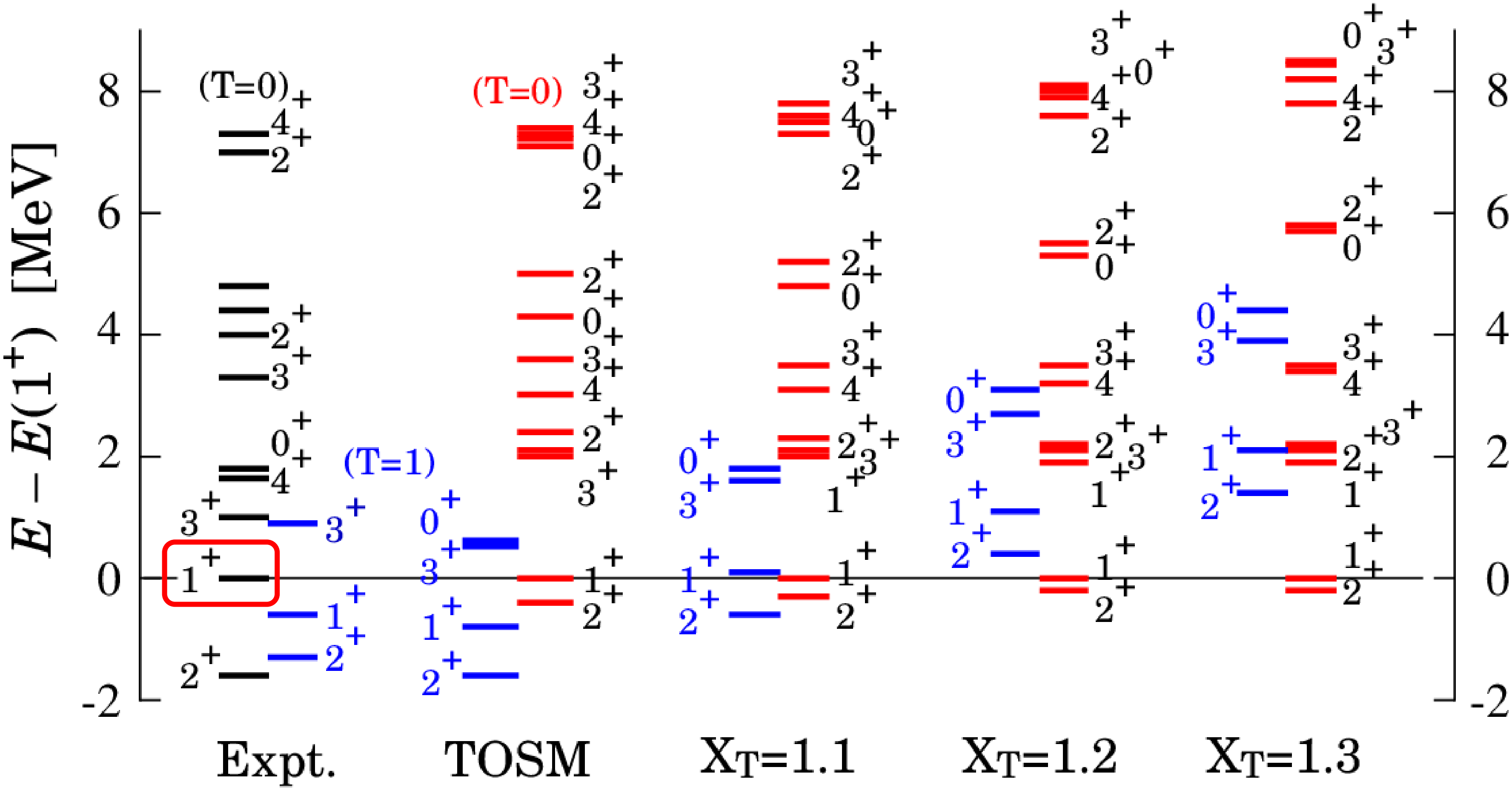
- Grand state
  - Kinetic & Central ~ twice of ^{4}He
  - Tensor ~ 1.6 of ^{4}He
  - larger ⟨H⟩ components than highly excited states.
- Kinetic & Tensor
  - *T*=0 states > *T*=1 states



^{8}Be in TOSM – Minnesota –

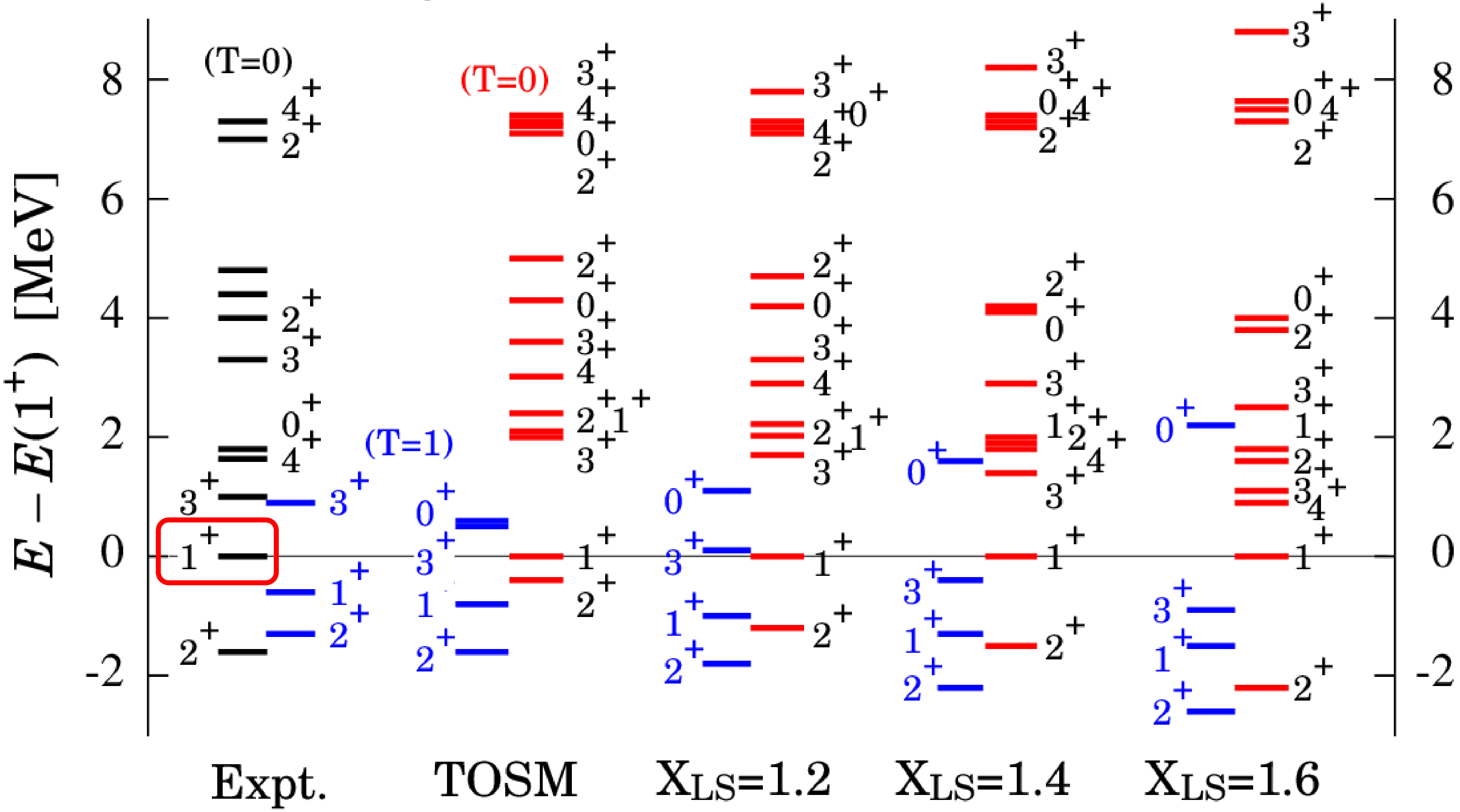
- ground band
- highly excited states
  - good E_X
  - incorrect level order (0^+,1^+,3^+)
  - E_X(T=0) < E_X(T=1)
- Radius (R_m) is small
  - ^{4}He 1.39 fm
  - ^{8}Be 1.89 fm
  - ^{12}C   1.85 fm

V_{tensor} dependence of ^{8}Be



- *S*-wave UCOM can be simulated with X_T~1.1 (PTP121)
- Stronger tensor correlation in **<u>T=0 states</u>** than T=1 states.

V_{LS} dependence of ^{8}Be



- UCOM underestimates ⟨LS⟩ due to the lack of three-body term.
- Spectrum gets wider (2^+,1^+,3^+), same trend in T=0 & T=1.

Summary

- **TOSM+UCOM** using V_{bare}.
  - Strong tensor correlation from 0p0h-2p2h.
- He & Li isotopes
  - Energy spectra, Radius
  - ^{4}He contains **"*pn*-pair of $p_{1/2}$"** due to V_T.
- ^{8}Be, T=0 & T=1.
  - Two aspects : Grand band states & highly excited states.
  - Indication of more configurations such as 4p4h to describe 2α structure in the grand band states.