Role of tensor force in light nuclei with tensor-optimized shell model

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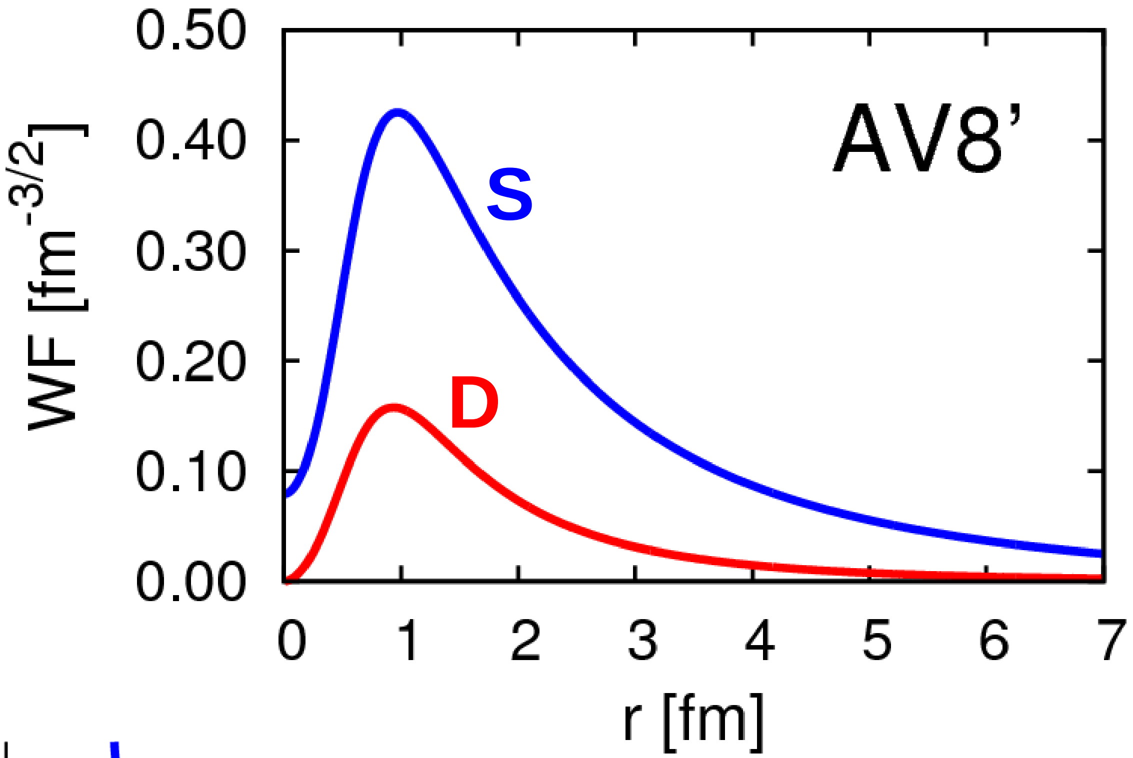
Outline

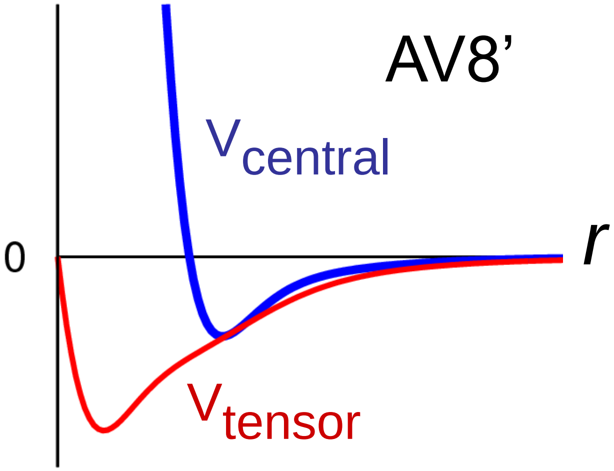
- **Role of V_{tensor}** in nuclei by describing strong tensor correlation explicitly.
- Tensor Optimized Shell Model (**TOSM**) to describe tensor correlation.
- Unitary Correlation Operator Method (**UCOM**) to describe short-range correlation.
- **TOSM+UCOM** to He & Li isotopes with V_{bare}

TM, A. Umeya, H. Toki, K. Ikeda PRC84 (2011) 034315
TM, A. Umeya, H. Toki, K. Ikeda PRC86 (2012) 024318

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

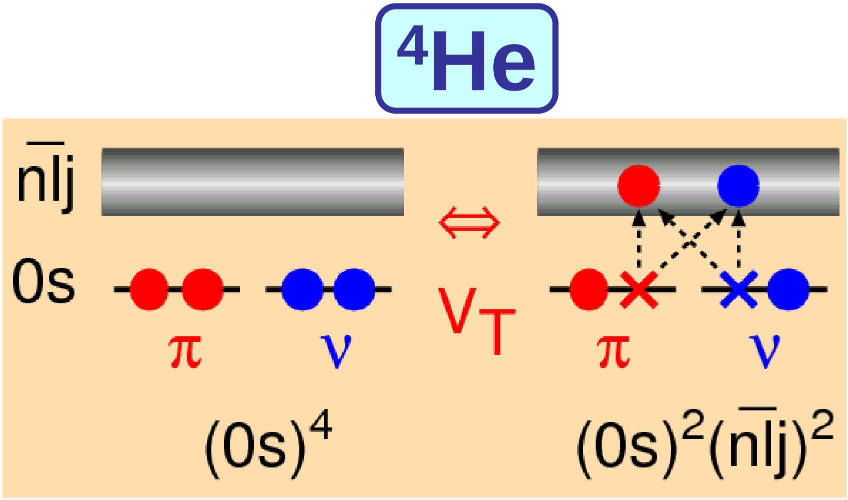
d-wave is
"**spatially compact**"
(high momentum)

Tensor-optimized shell model (TOSM)

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

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

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



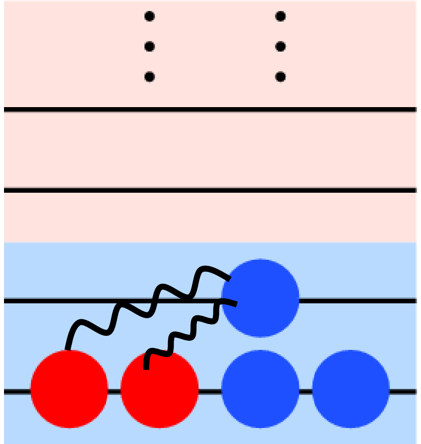
- Length parameters such as b_{0s}, b_{0p}, … are optimized independently, or superposed by many Gaussian bases.
  - Spatial shrinkage of ***D*-wave** as seen in deuteron.

    HF (Sugimoto, NPA740) , RMF (Ogawa, PRC73), AMD (Dote et al., PTP115)
- Satisfy few-body results with Minnesota central force (^{4,6}He)

Tensor force matrix elements

$$M_{SD}(r) = r^2\phi_S(r,b_S)\cdot \mathrm{V}_\mathrm{T}(r)\cdot \phi_D(r,b_D)$$

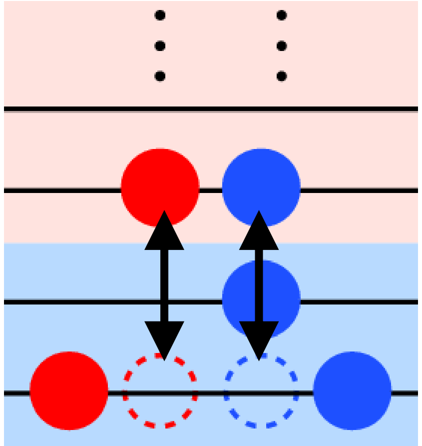
: Integrand of Tensor ME



$b_D = b_S$

$\mathrm{V}_\mathrm{T} = \mathrm{V}_{\text{residual}}$

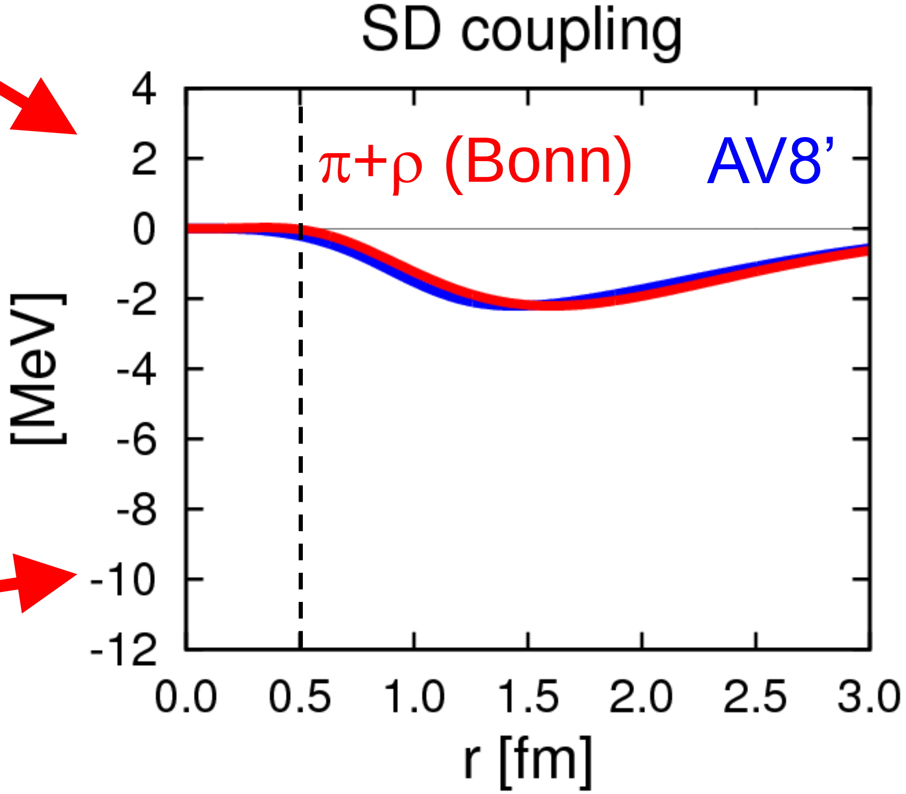
1st order



$b_D = b_S \times 0.5$

$\mathrm{V}_\mathrm{T} \neq \mathrm{V}_{\text{residual}}$

0p0h-2p2h



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

Effect of Tensor force in TOSM

- 1st order treatment of V_T

HF state

  - Spin-saturated nuclei : $\langle 0| V_T |0\rangle=0$
  - For $N \neq Z$ nuclei : $\langle 0| V_T |0\rangle$ ~ few MeV
  - Effect on the energy spectra in unstable nuclei

cf. T. Otsuka et al. PRL95(2005)232502.

- In TOSM, 0p0h+1p1h+2p2h
  - In ^{4}He, $\langle V_T\rangle$ ~ –15MeV/A, comparable to GFMC.
  - ***SD*** coupling of 0p0h-2p2h is essential.
  - Describe high momentum (compact *D*-wave)
  - Break N=8 magicity in ^{11}Li. TM et al.PRC76(2007)024305
  - Experiments using (p,d) reaction by Ong-Tanihata @ RCNP, to observe high momentum nucleon.

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

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

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

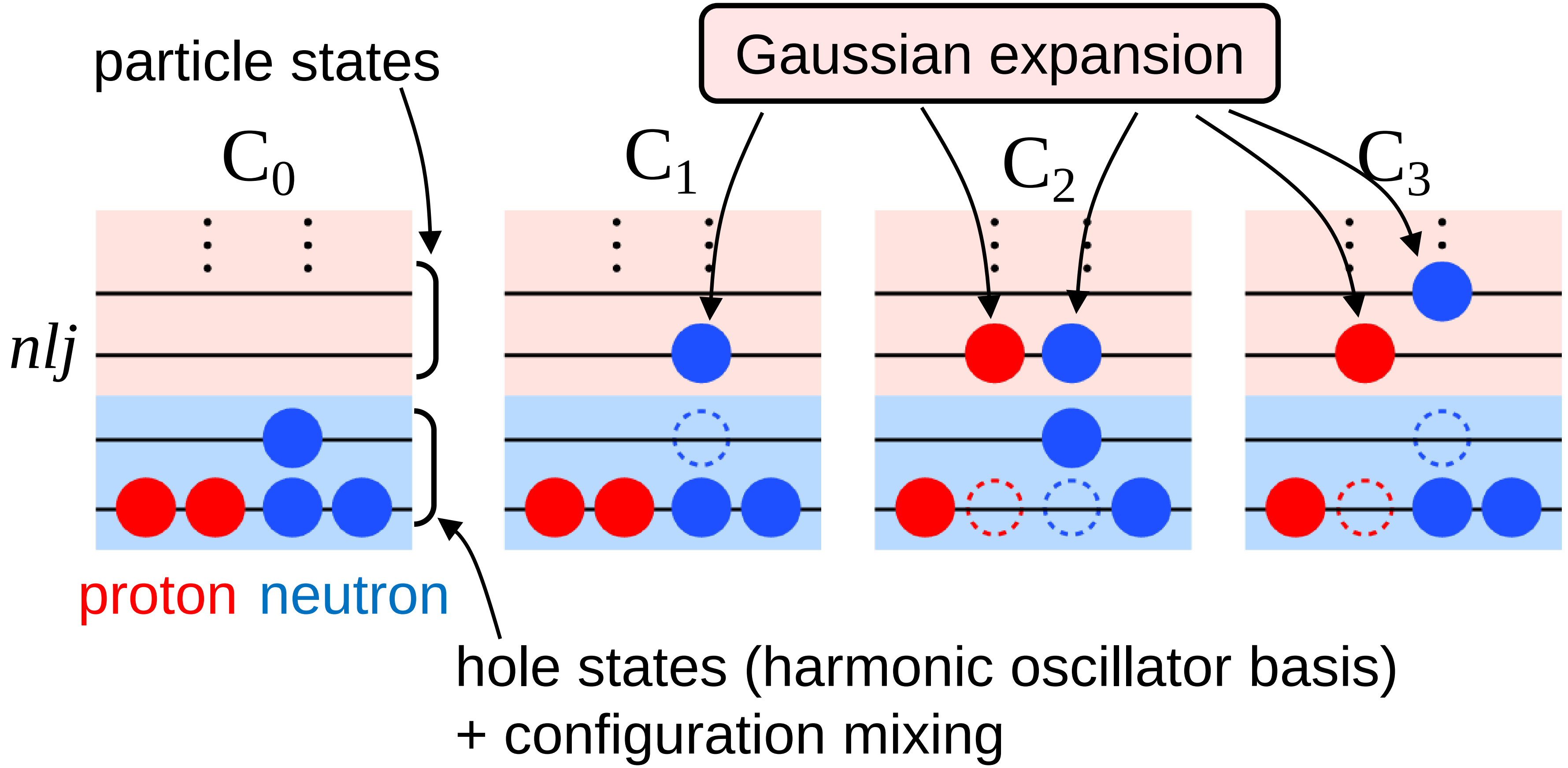
Gaussian basis function

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

Configurations in TOSM



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

Unitary Correlation Operator Method

(short-range part)

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

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

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

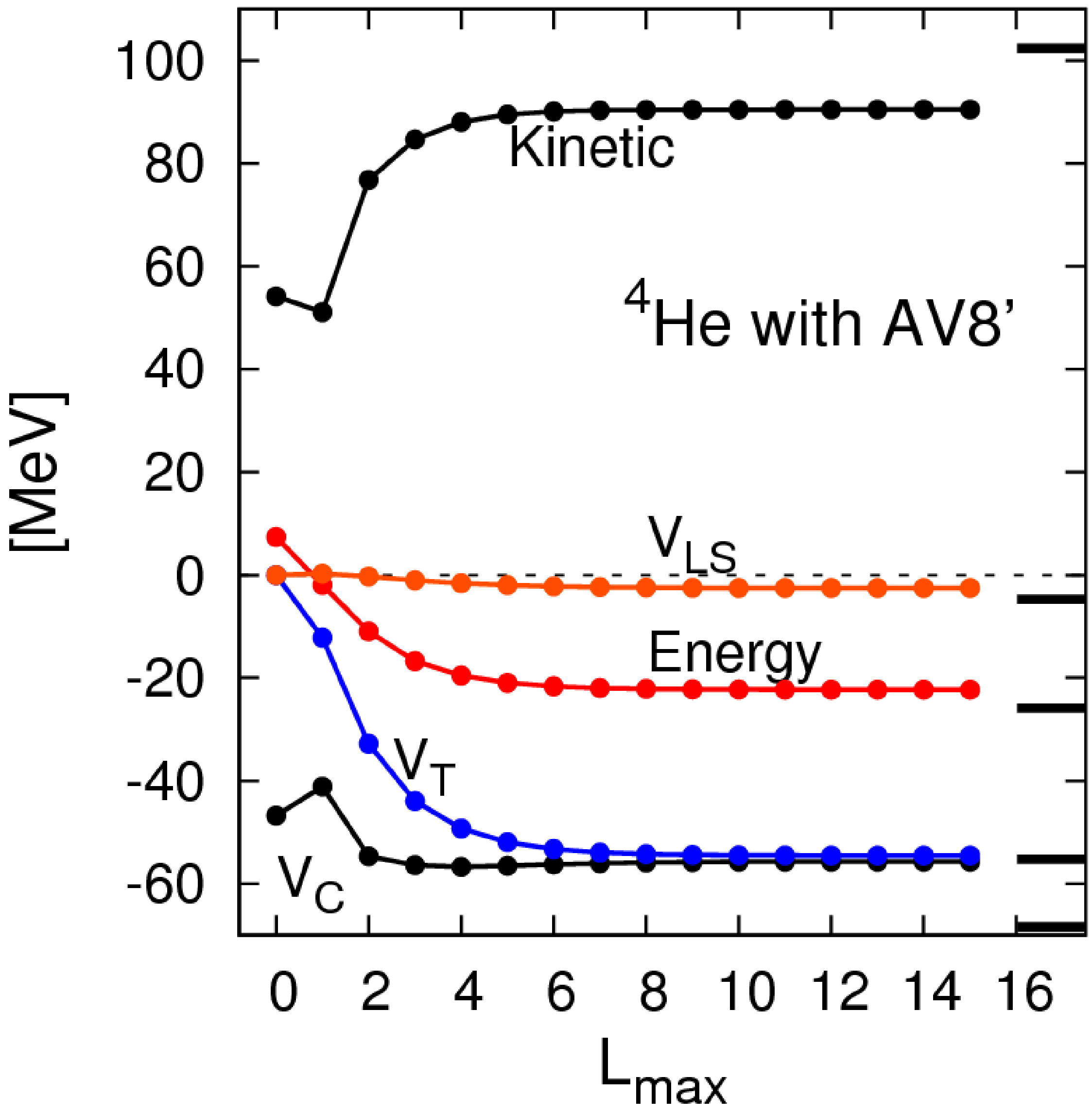
Amount of shift, variationally determined.

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

2-body cluster expansion

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

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



T (exact)

Kamada et al.
PRC64 (Jacobi)

V_{LS}

E

V_C

V_T

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

- variational calculation

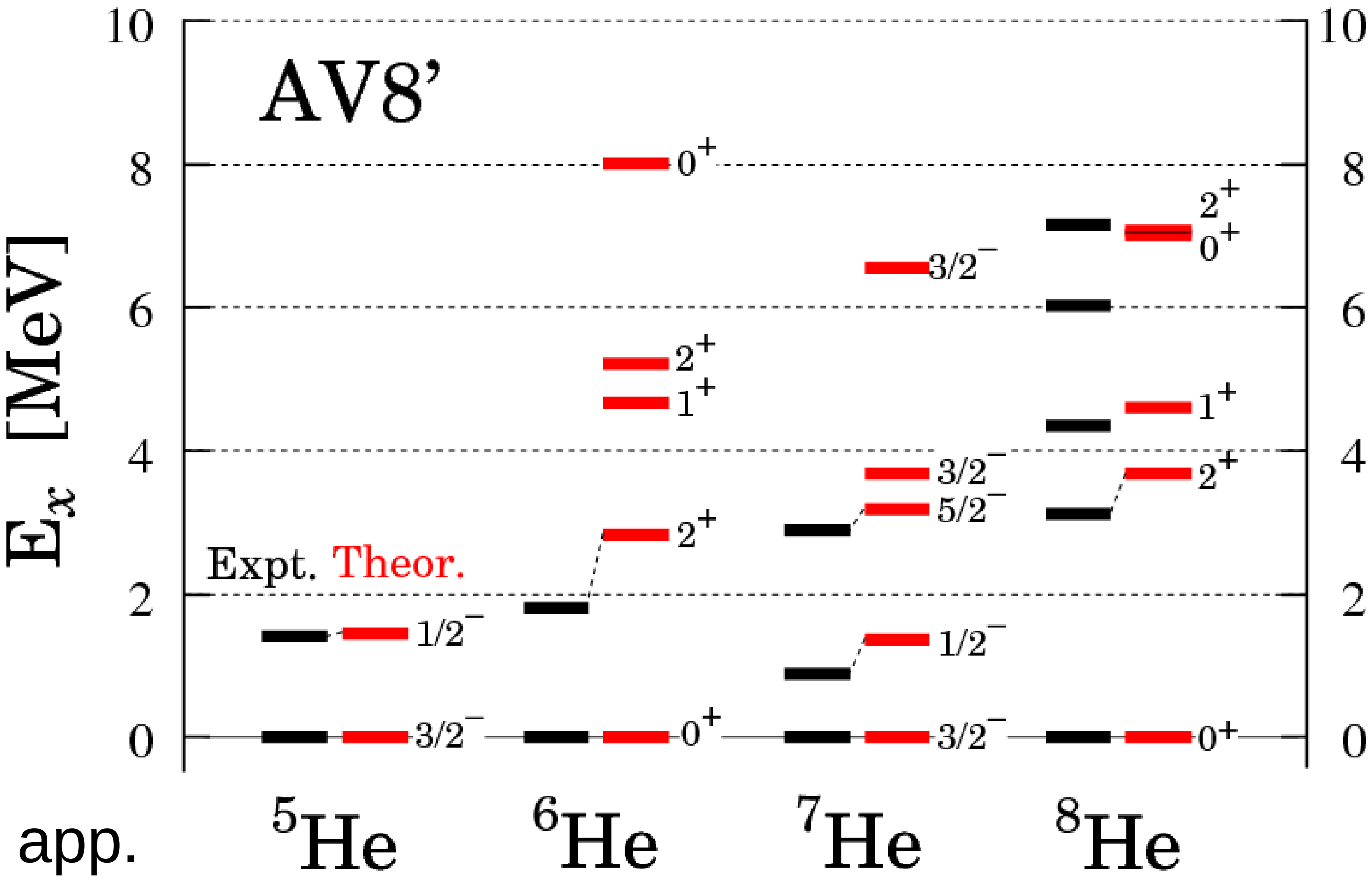
- Gaussian expansion with 9 bases

good convergence

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

- Excitation energies in MeV

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



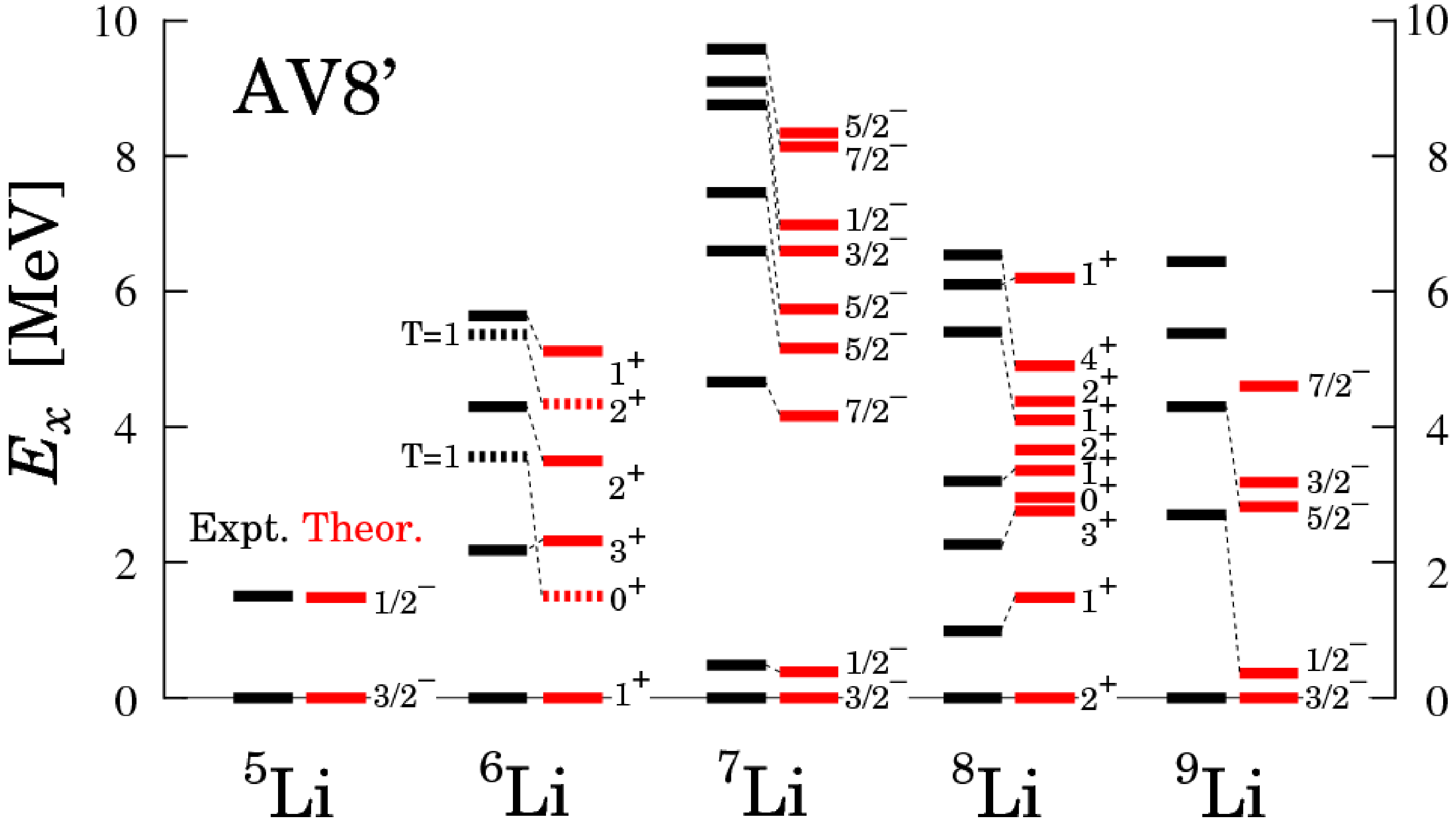
- Bound state app.
- No continuum
- No V_{NNN}

- 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

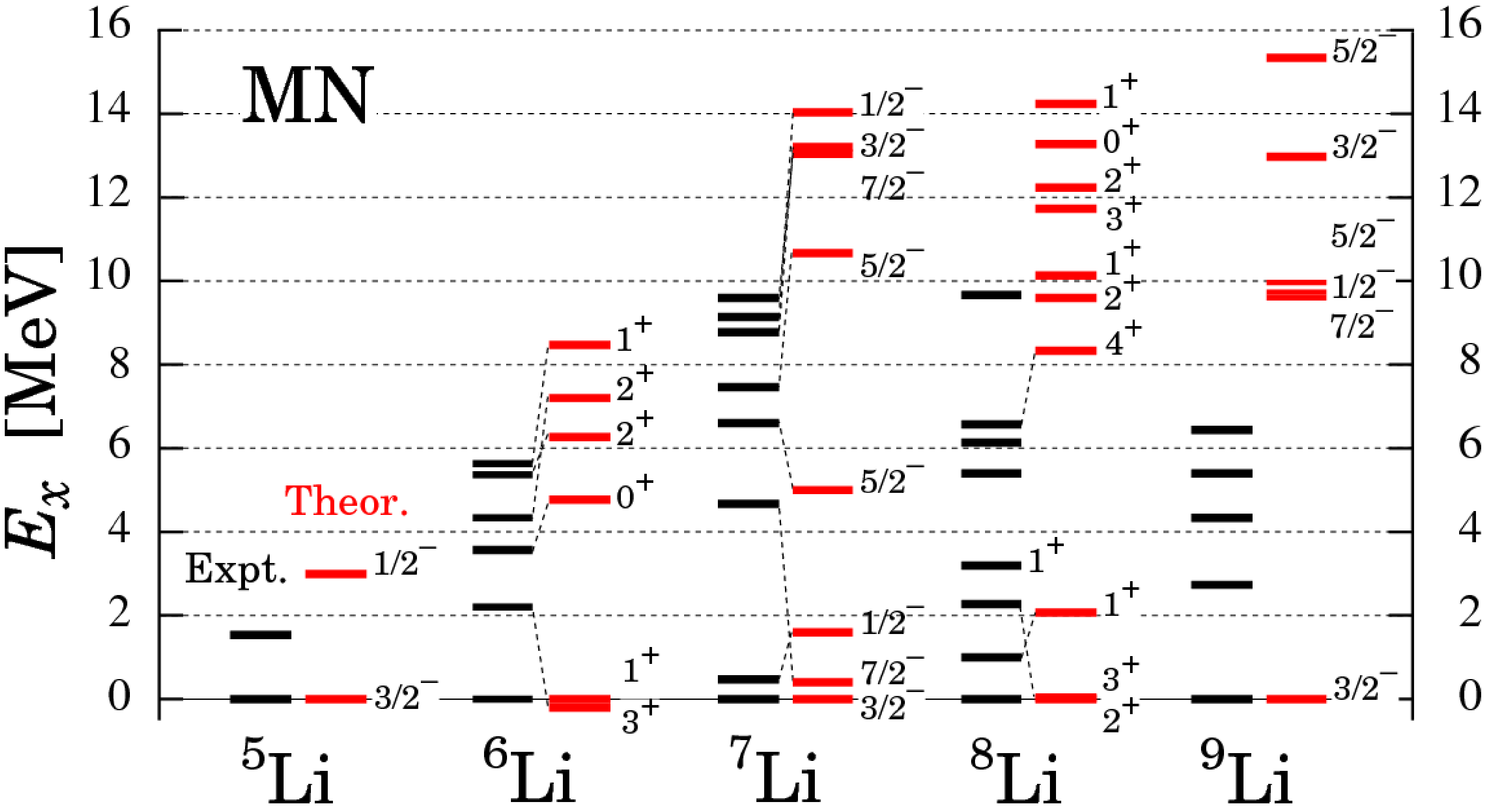


- Excitation energy spectra are reproduced well

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

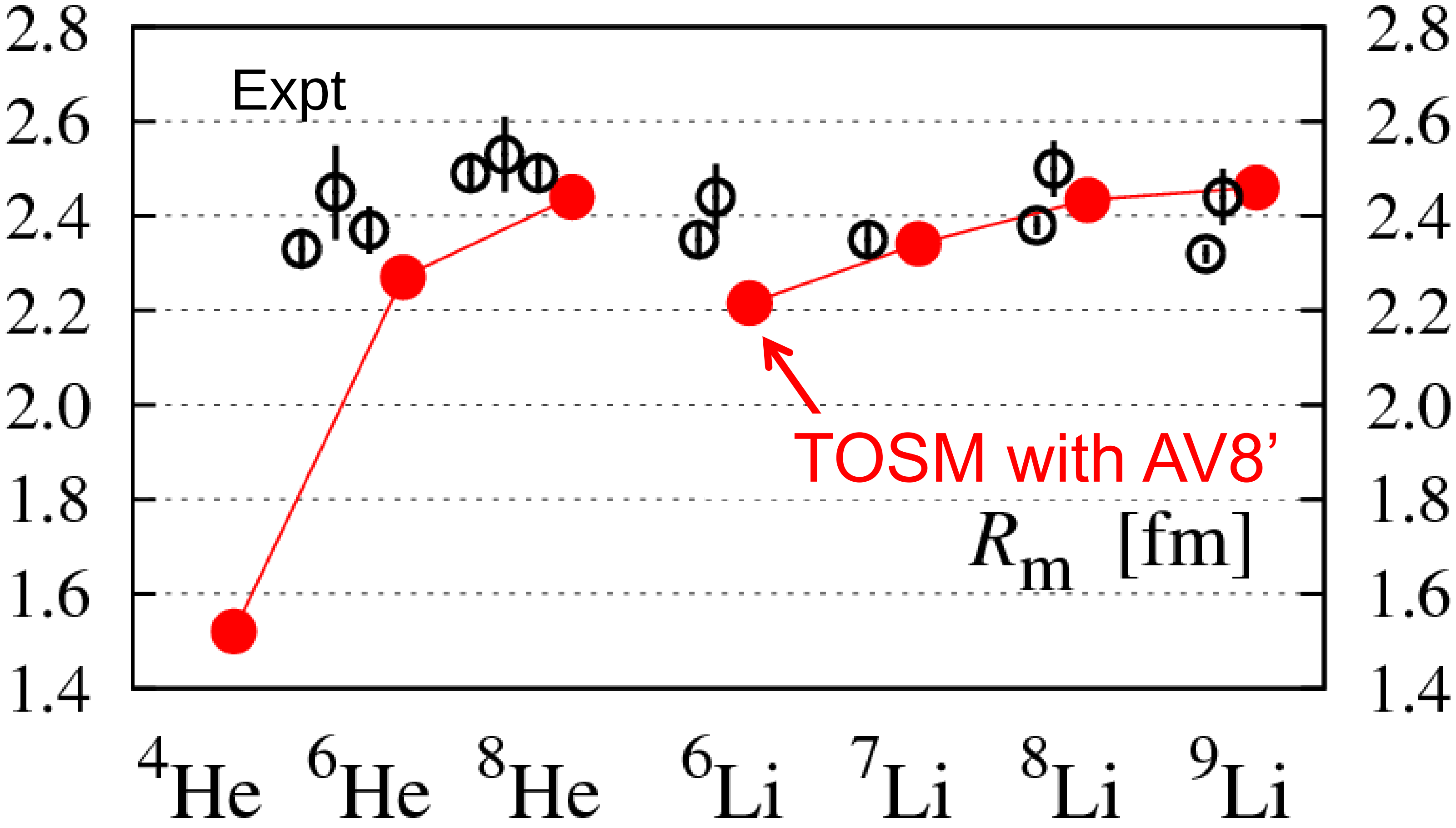
Minnesota force
(Central+LS)

- Excitation energies in MeV



- Too large excitation energy

Matter radius of He & Li isotopes



Halo **Skin**

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

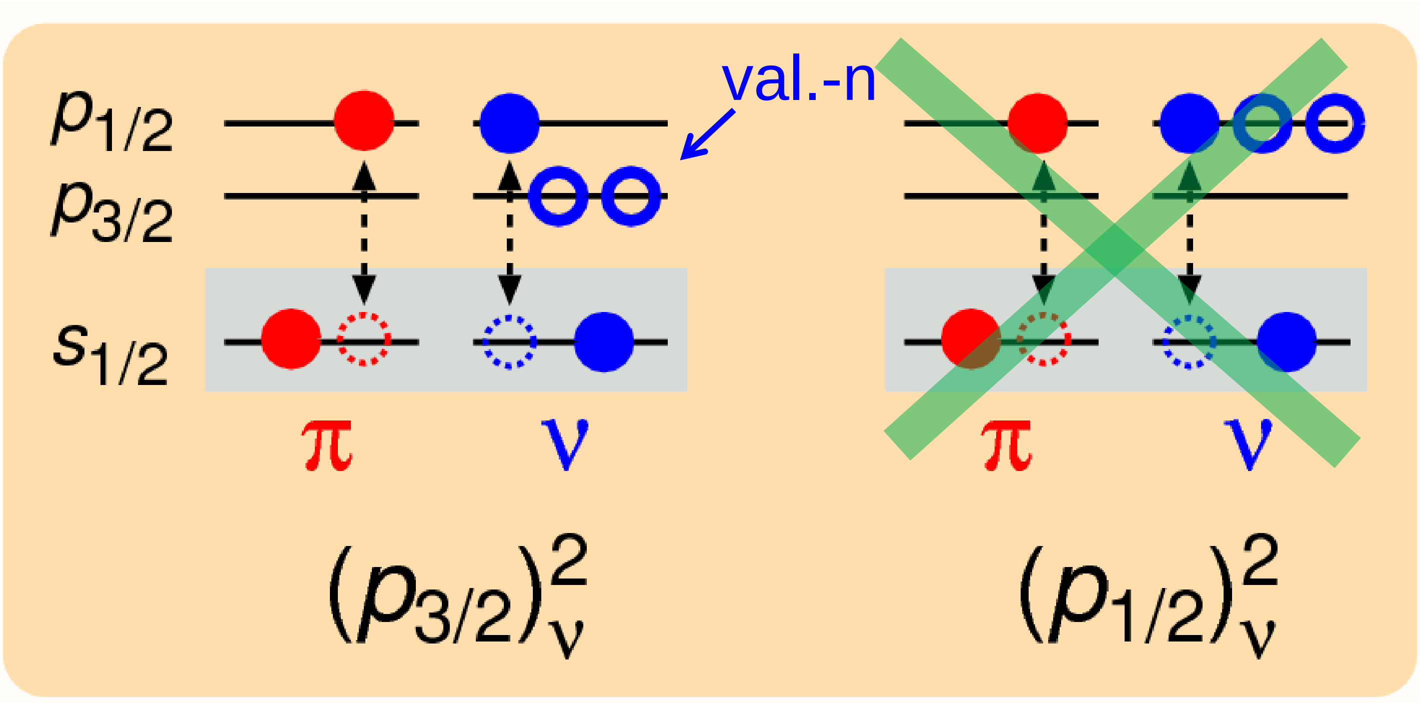
$^{12}\mathrm{C}(\mathrm{e,e'}pN)$

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

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

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

Tensor correlation in ^{6}He



$\Delta E \sim 3$MeV
as a net

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

Li isotopes: Ground state configurations

		***p-shell* Config.**	**Weight**	
LS	**^{6}Li (1^{+},T=0)**	$(0p_{1/2})(0p_{3/2})$	43%	S=1
jj	**^{6}Li (0^{+},T=1)**	$(0p_{3/2})^{2}$	72%	IAS of ^{6}He
jj	**^{7}Li ($3/2^{-}$)**	$(0p_{3/2})^{3}$	48%	
jj	**^{8}Li (2^{+})**	$(0p_{3/2})^{4}$	41%	
jj	**^{9}Li ($3/2^{-}$)**	$(0p_{3/2})^{5}$	46%	

- $^{6}\mathrm{Li}_{gs}$ … *LS* coupling → Indication of α+d clustering
- $^{7\text{-}9}$Li … *jj* coupling

Summary

- **TOSM+UCOM** using V_{bare}.
  - Strong tensor correlation from 0p0h-2p2h.
- Reproduce the excitation energy spectra.
- ^{4}He contains **"*pn*-pair of $p_{1/2}$"** than $p_{3/2}$.
  - **He isotopes with $p_{3/2}$** has large contributions of V_{tensor} & Kinetic energy.
- $^6\mathrm{Li}_{\mathrm{gs}}$: ***LS* coupling**, $\alpha+d$ clustering (T=0).
- $^{7\text{-}9}$Li : ***jj* coupling**

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