Tensor-optimized shell model with bare interaction for light nuclei

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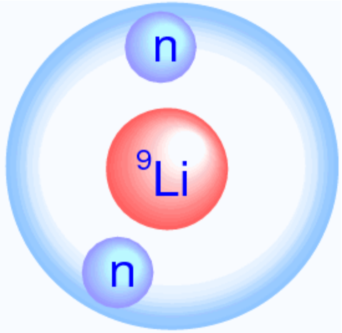
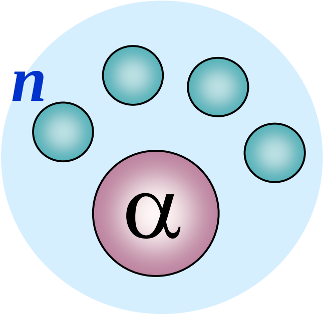
3rd International Symposium on Frontiers in Nuclear Physics -Use of RI beams for study of reaction mechanisms and coupling between bound and continuum states @ Beihang Univ., 2012.11

Scientific activities with Prof. Kiyoshi Kato

- 1996-1998: Master course in Hokkaido Univ.
  - Strength function using complex scaling method (CSM)
- 1999-2002: Doctor course in Hokkaido Univ.
  - Coulomb breakups of halo nuclei, ^{6}He, ^{11}Li, ^{11}Be, ... with CSM
  - Pairing correlation in halo nuclei
- 2003-2007: Researcher in RCNP (Toki, Ikeda)
  - Role of tensor force (pion) in light nuclei with tensor-optimized shell model (TOSM)
  - He isotopes, LS splitting, halo formation in ***^{11}Li***



- 2008- : Osaka Institute of Technology
  - Tensor correlation in nuclei with “TOSM+UCOM using bare *NN* interaction”.
  - Multi particle resonances up to five-body system in unstable nuclei (**^{8}He** as ^{4}He+4n, **^{8}C** as ^{4}He+4p)



Outline

- **Role of V_{tensor}** (V_π) in the nuclear structure 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

Pion exchange interaction vs. V_{tensor}

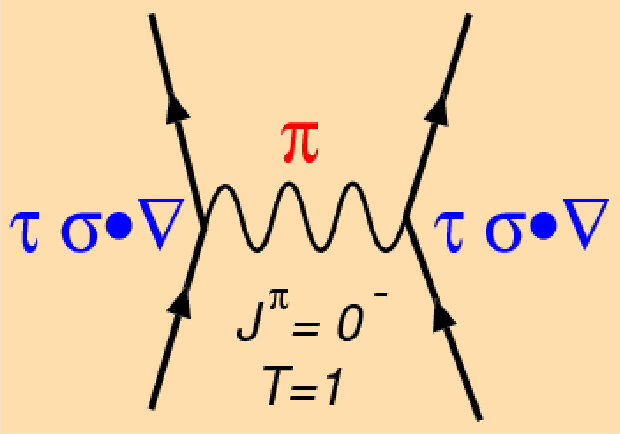
$$3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) \frac{q^2}{m^2+q^2} = (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \frac{q^2}{m^2+q^2} + S_{12} \frac{q^2}{m^2+q^2}$$

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

Delta interaction

Yukawa interaction

Involve large momentum

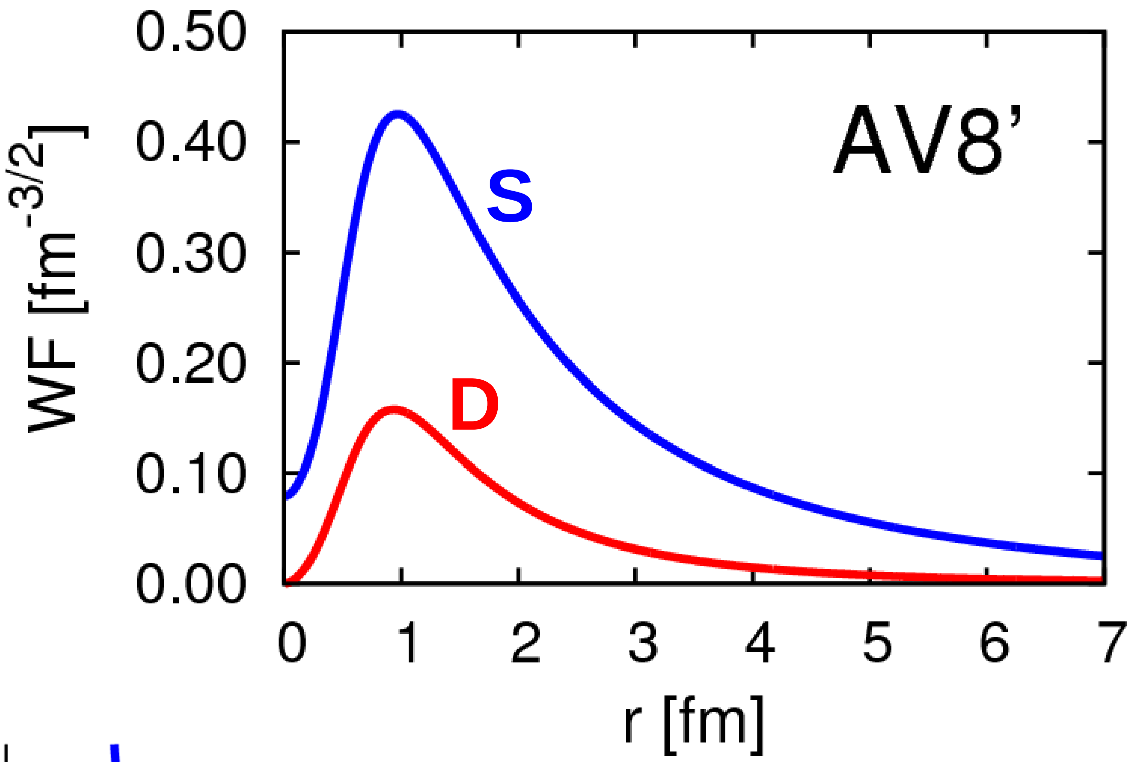


Tensor operator

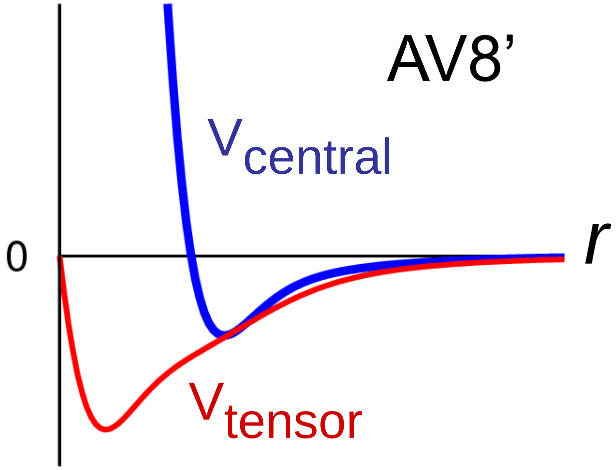
$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

- V_{tensor} produces the high momentum component.

Deuteron & 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



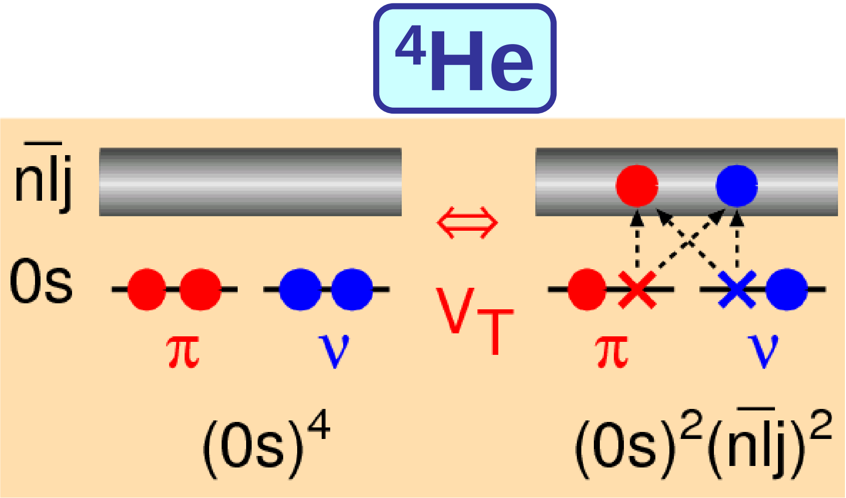
R_m(s)=2.00 fm

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



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

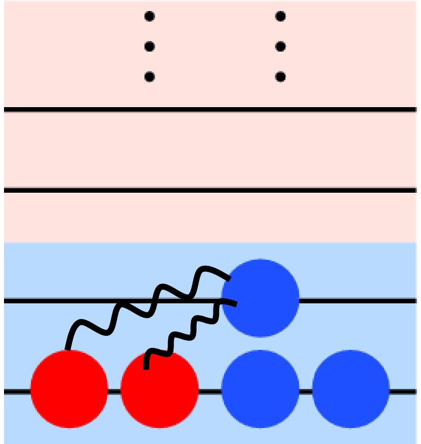
cf. $\frac{V_\pi}{V_{NN}} \sim 80\%$ in GFMC

- Length parameters such as $b_{0s}, b_{0p}, \ldots$ 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

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

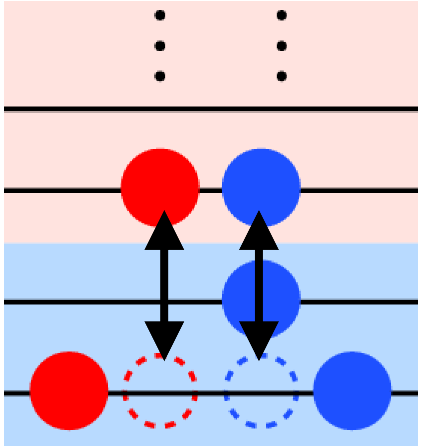
: Integrand of Tensor ME



$b_D = b_S$

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

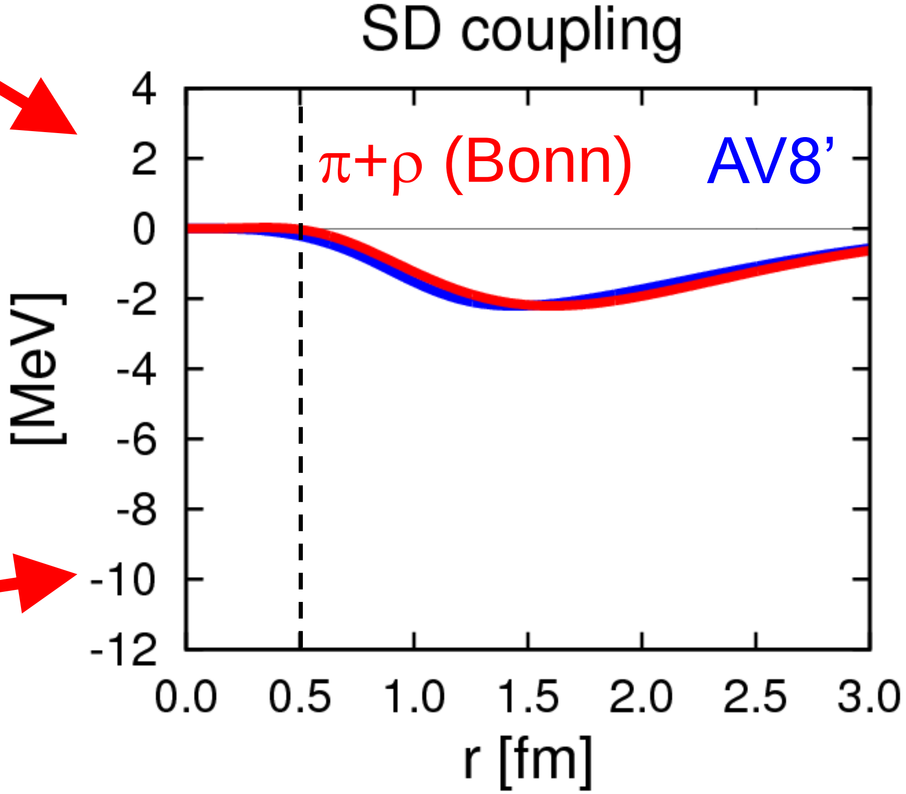
1st order



$b_D = b_S \times 0.5$

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

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 between 0p0h & 2p2h is essential
  - Describe high momentum (compact *D*-wave)
  - Break N=8 magic in ^{11}Li. TM et al.PRC76(2007)024305
  - Experiments using (p,d) reaction by Ong-Tanihata Group @ 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

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

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

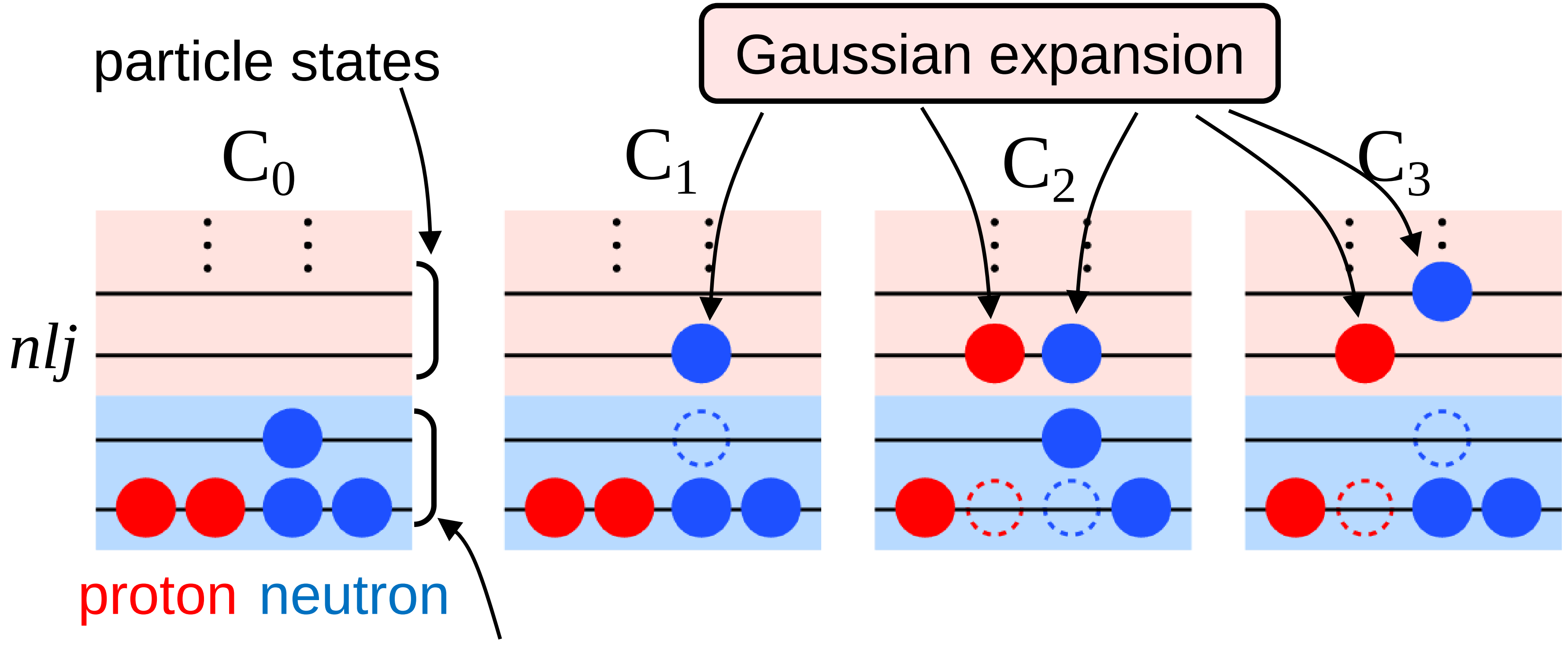
Gaussian basis function

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



hole states (harmonic oscillator basis)
+ configuration mixing

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

Unitary Correlation Operator Method

(short-range part)

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

TOSM

short-range correlator

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

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

Bare Hamiltonian

Shift operator depending on the relative distance

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

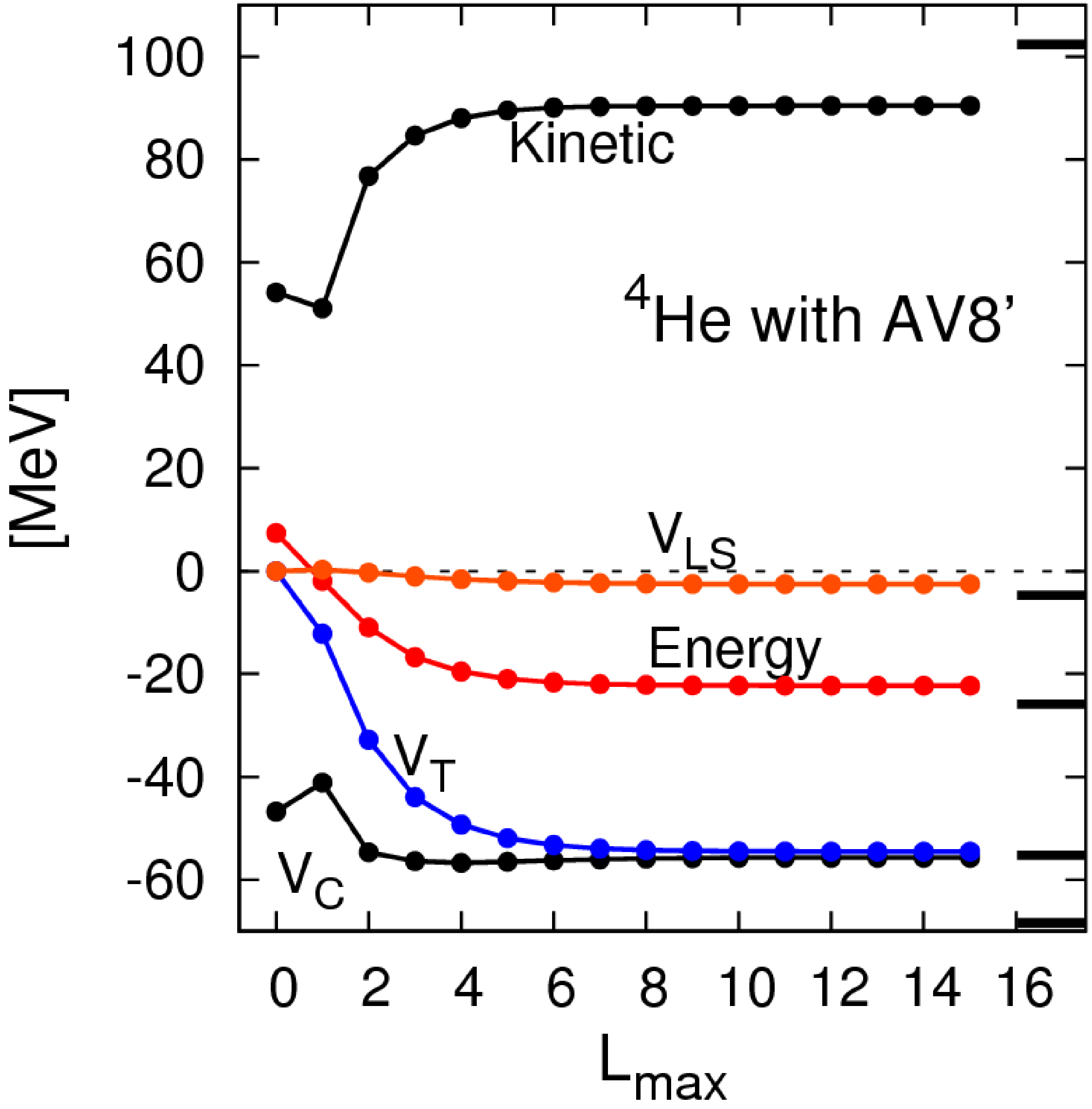
Amount of shift, variationally determined.

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

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)

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

V_{LS}

E

V_C

V_T

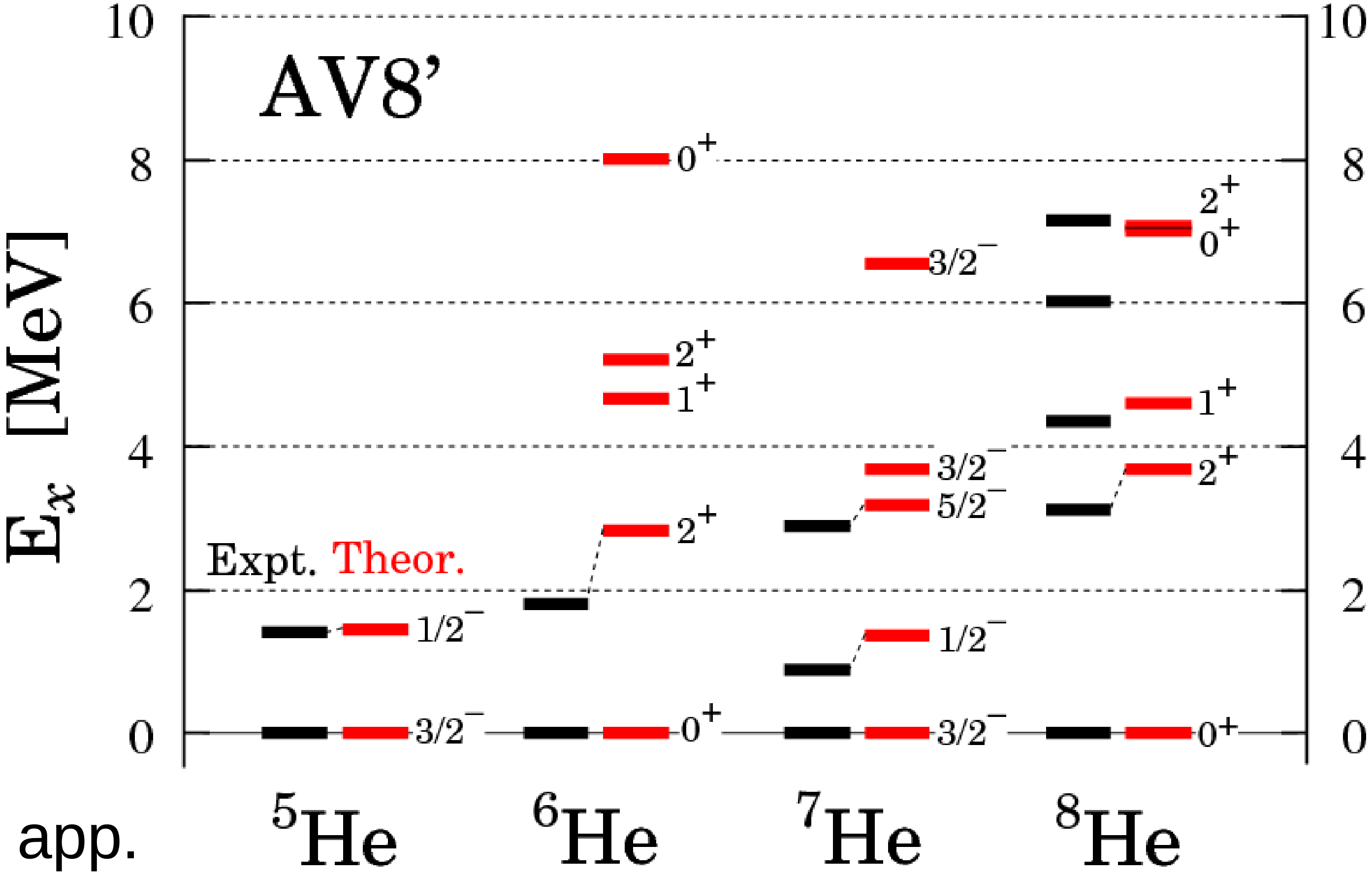
- variational calculation
- Gaussian expansion with 9 bases

good convergence

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

- Excitation energies in MeV

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



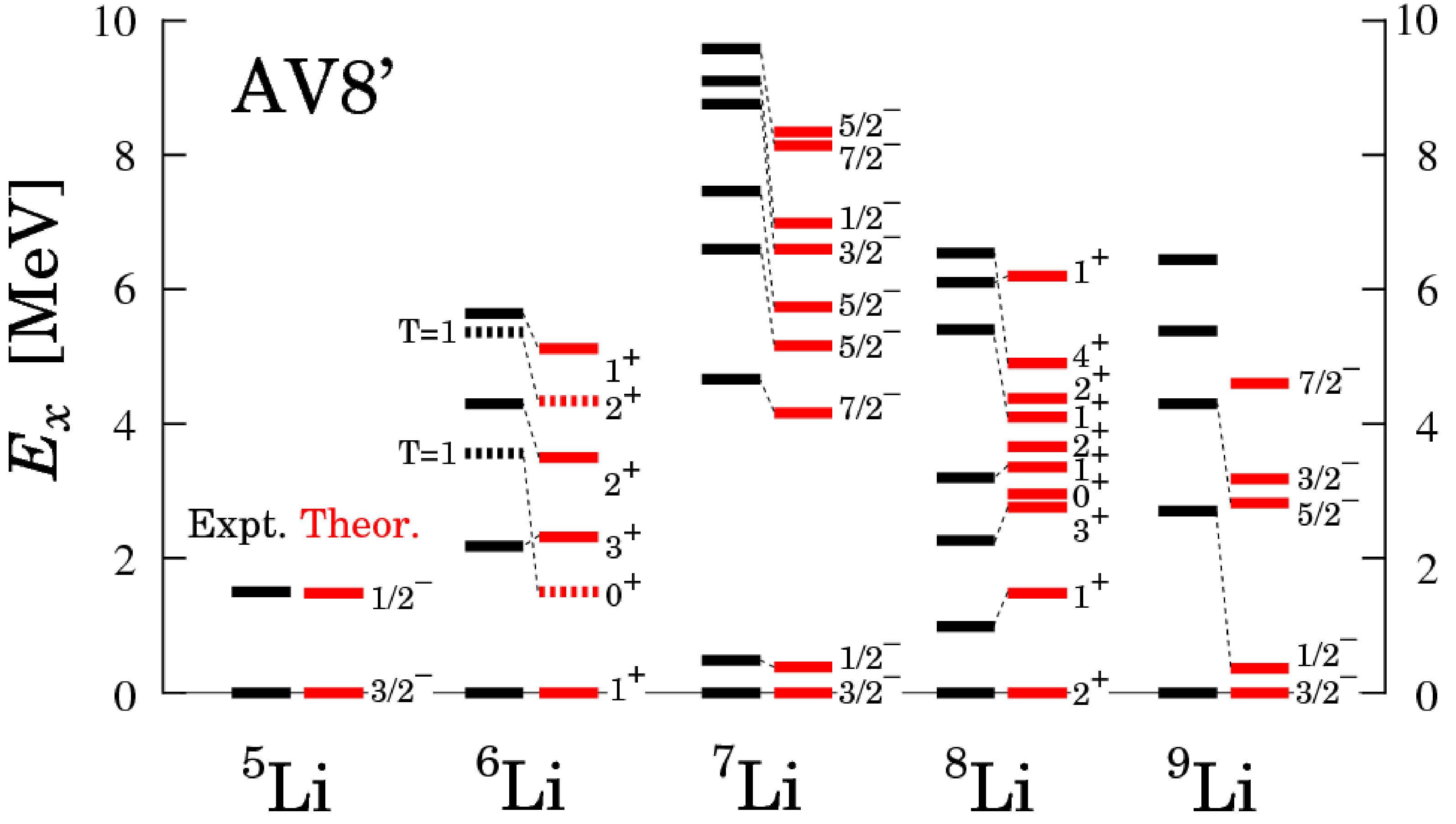
- Bound state app.
- No continuum
- No V_{NNN}

- 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

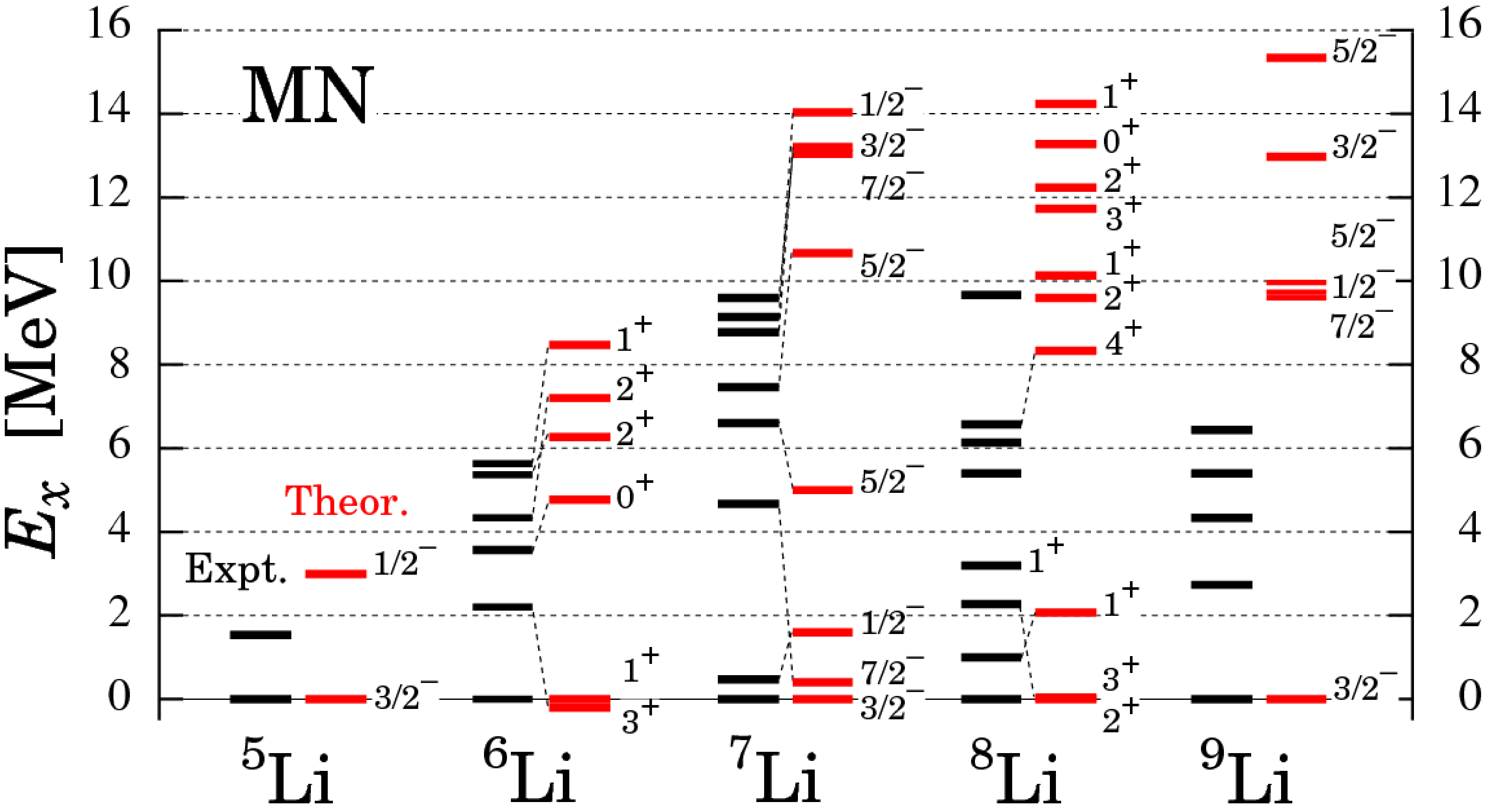


- Excitation energy spectra are reproduced well

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

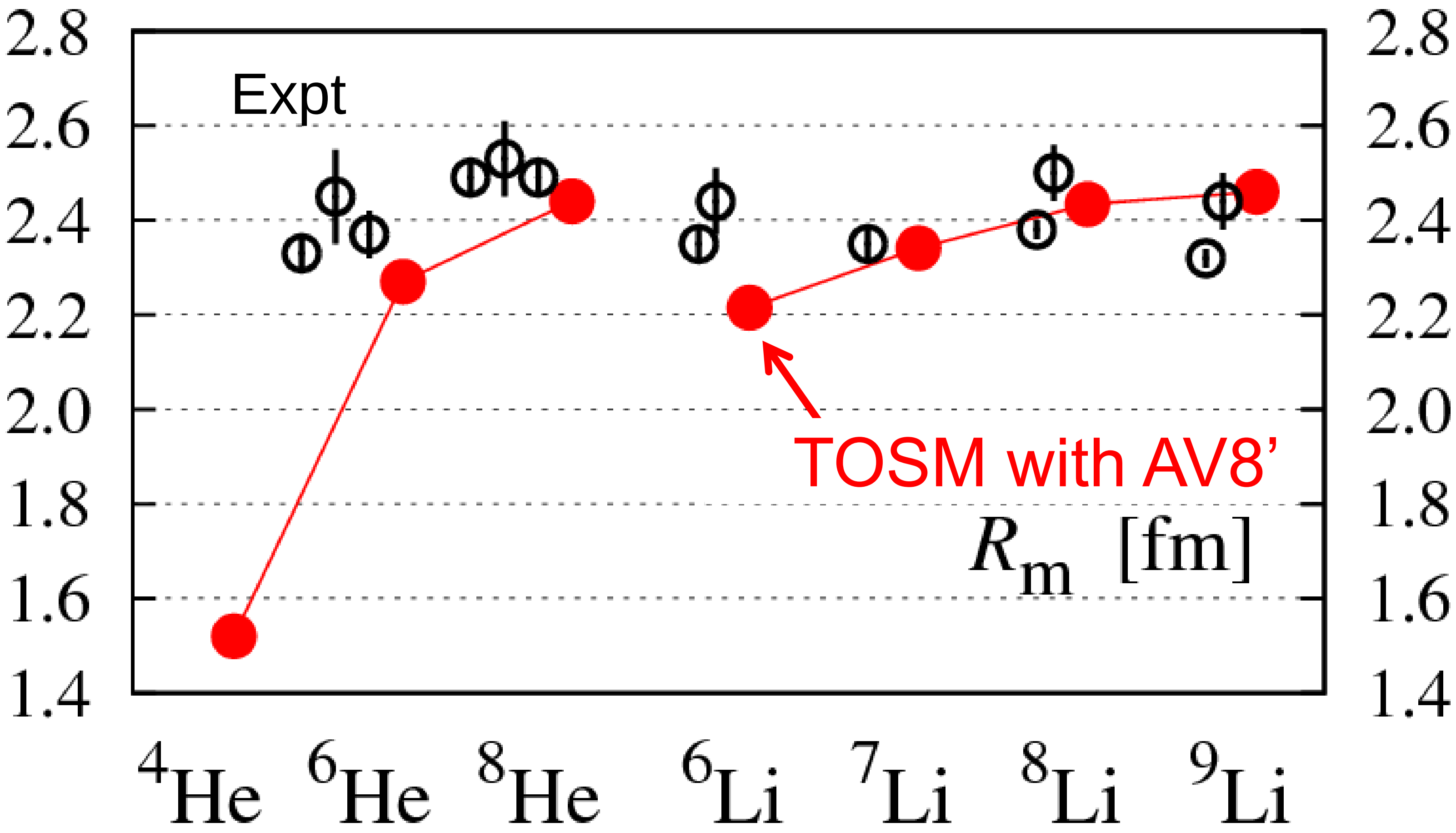
Minnesota force
(Central+LS)

- Excitation energies in MeV



- Too large excitation energy

Matter radius of He & Li isotopes



Halo **Skin**

A. Dobrovolsky, NPA 766(2006)1

I. Tanihata et al., PLB289(‘92)261

G. D. Alkhazov et al., PRL78(‘97)2313

O. A. Kiselev et al., EPJA 25, Suppl. 1(‘05)215.

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

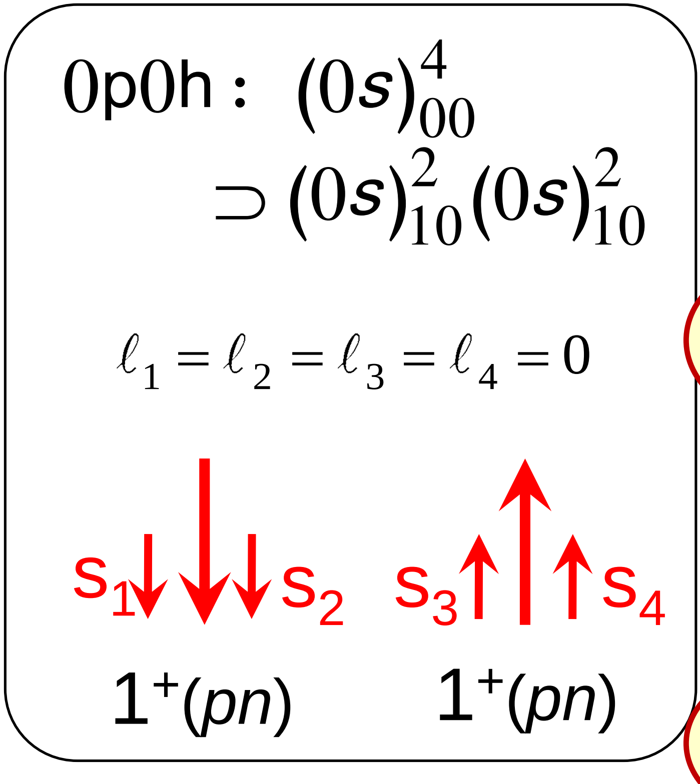
^{12}C(e,e'*pN*)

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

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

- ^{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



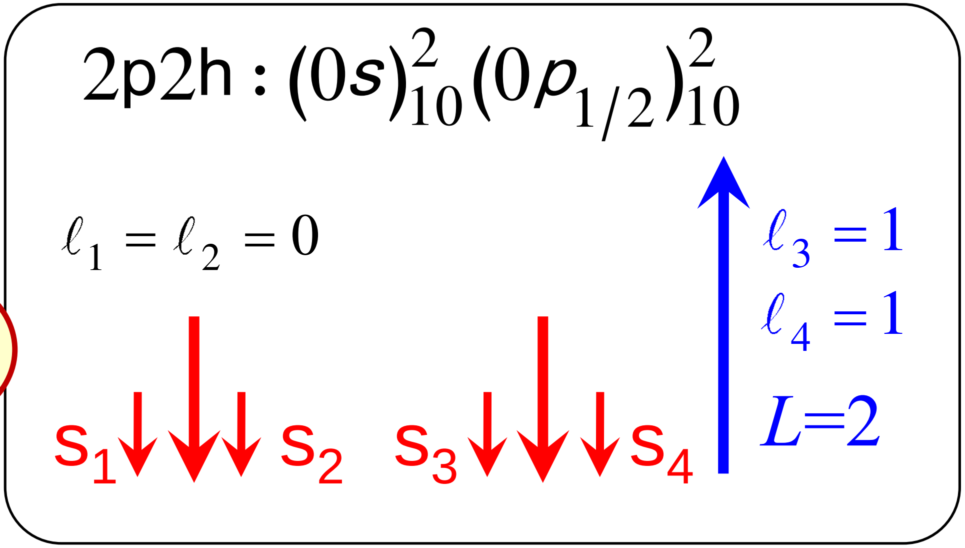
0p0h : $(0s)^4_{00}$

$\supset (0s)^2_{10}(0s)^2_{10}$

$\ell_1 = \ell_2 = \ell_3 = \ell_4 = 0$

$1^+(pn)$ $1^+(pn)$

V_T



2p2h : $(0s)^2_{10}(0p_{1/2})^2_{10}$

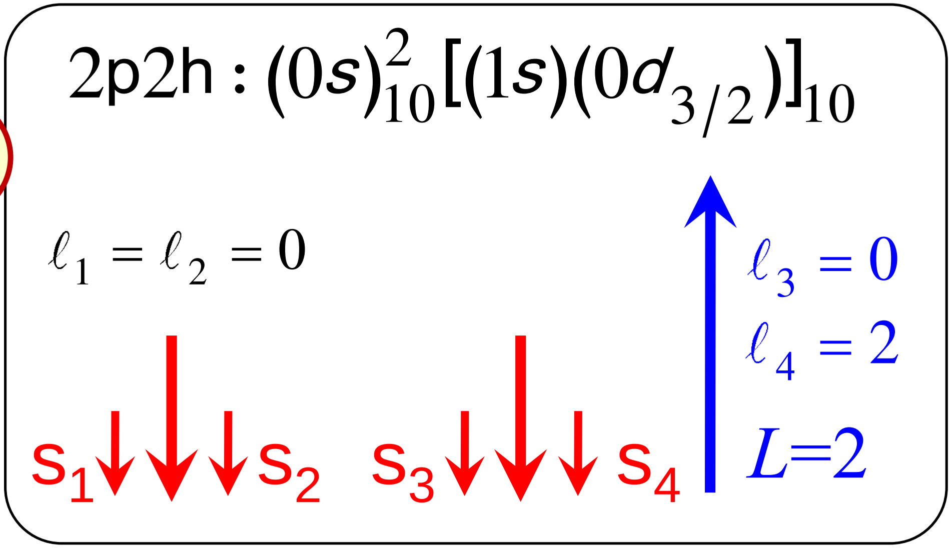
$\ell_1 = \ell_2 = 0$

$\ell_3 = 1$

$\ell_4 = 1$

$L=2$

V_T



2p2h : $(0s)^2_{10}[(1s)(0d_{3/2})]_{10}$

$\ell_1 = \ell_2 = 0$

$\ell_3 = 0$

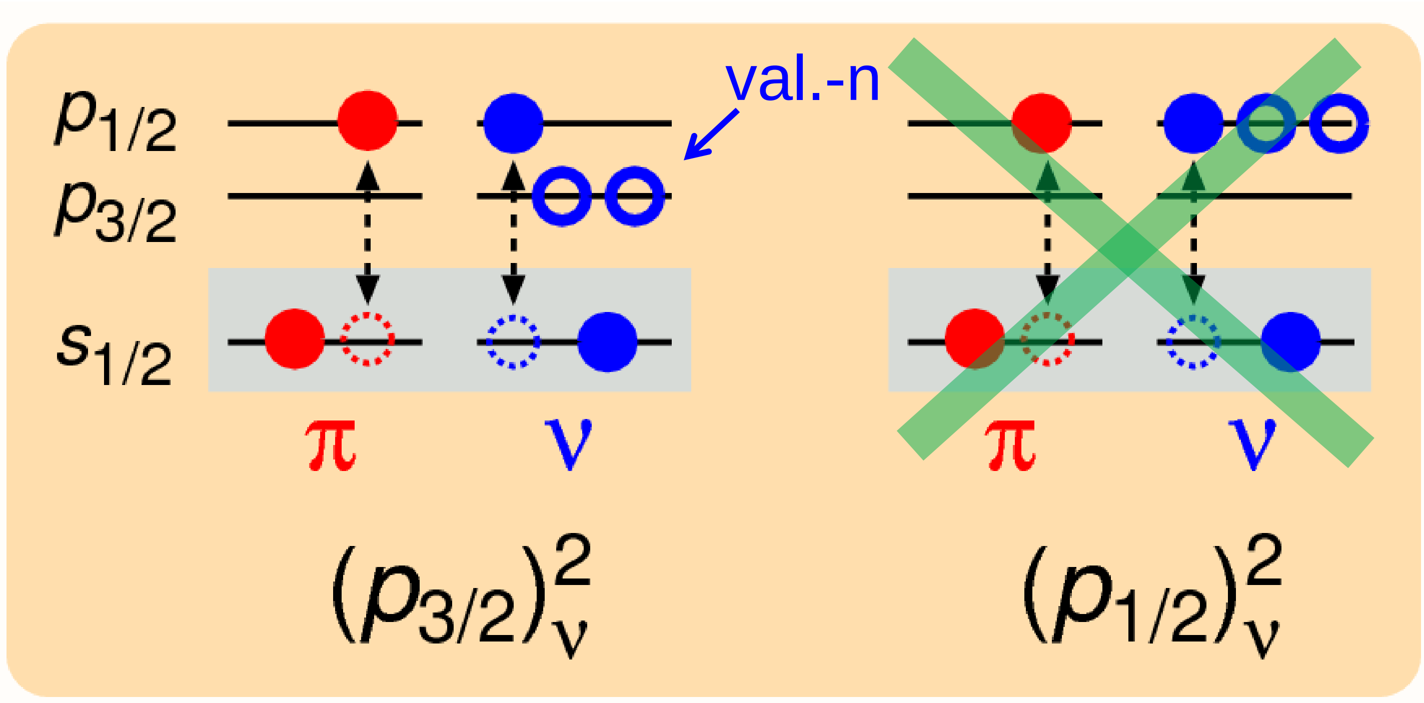
$\ell_4 = 2$

$L=2$

Selectivity of tensor operator

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

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 component in TOSM

- 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

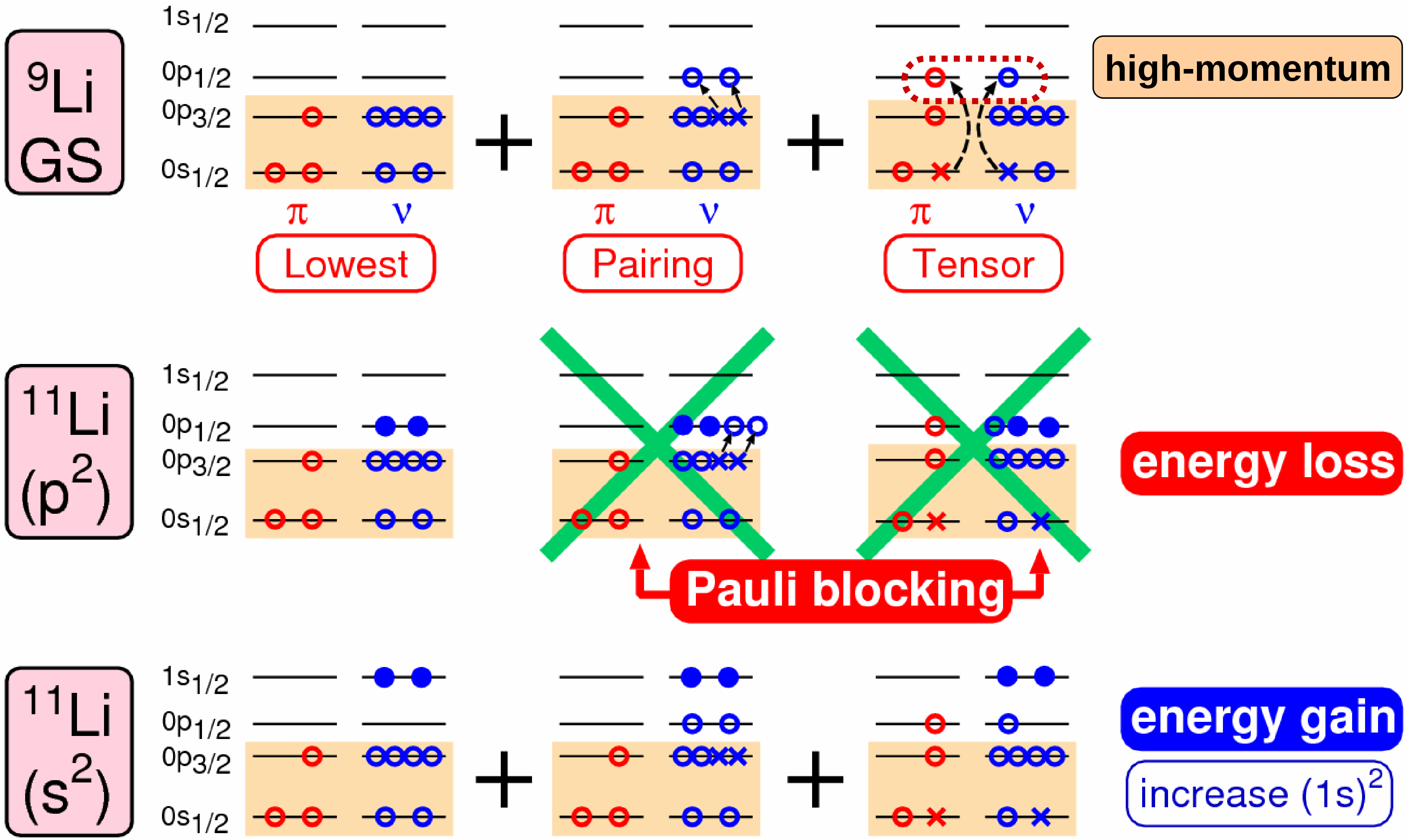
LS splitting energy in ^{6}He

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

Halo formation with large 1*s*-wave in ^{11}Li

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

Effects of tensor & pairing correlations in ^{11}Li

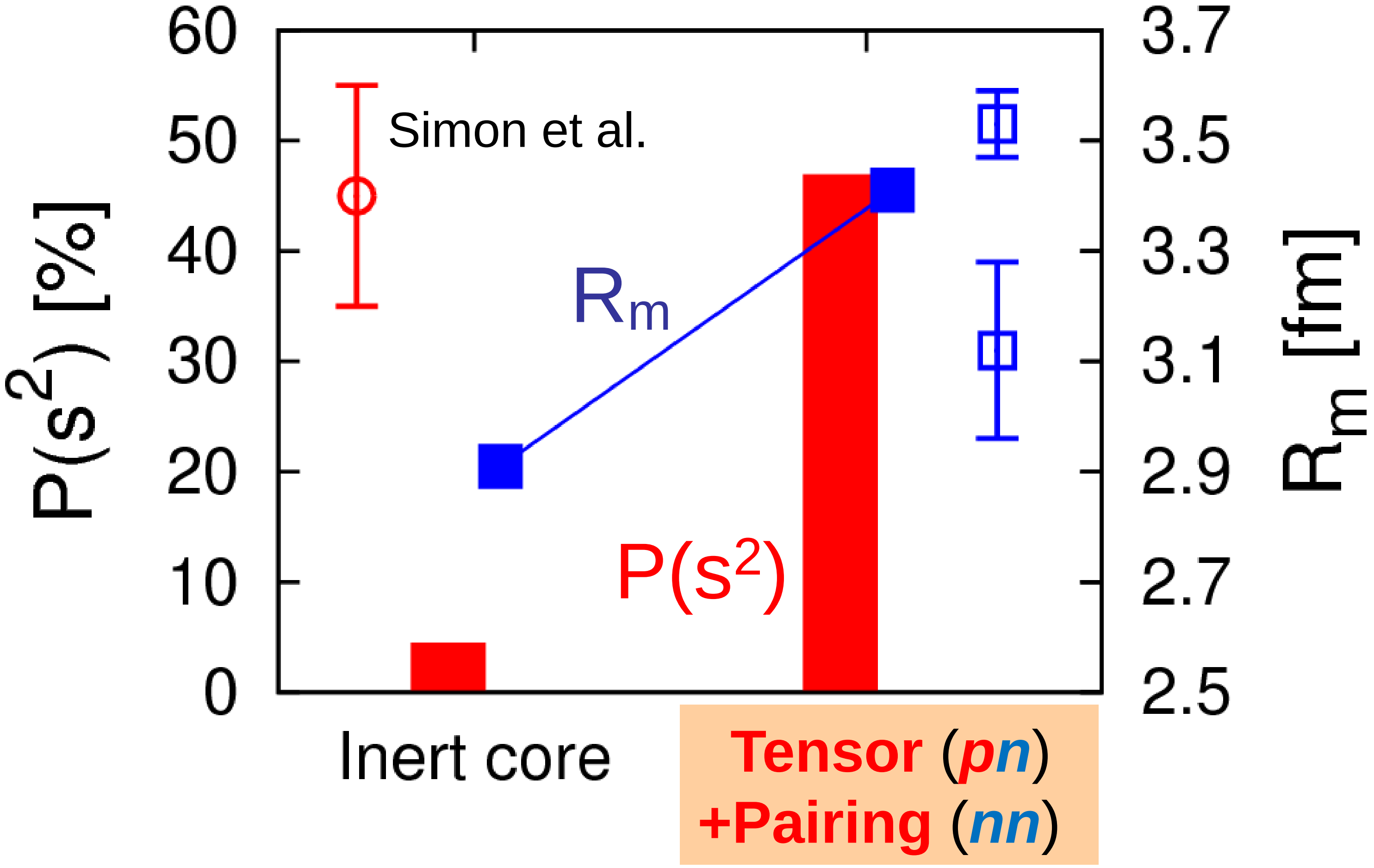


Exp ~ 50%

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 properties (S_{2n}=0.31 MeV)



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

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

Summary

- **TOSM+UCOM** using V_{bare}.
- 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}Li$_{\mathrm{gs}}$: ***LS* coupling**, indication of $\alpha+d$ cluster.
- $^{7\text{-}9}$Li : ***jj* coupling**

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