テンソル最適化殻模型による
軽い核におけるテンソル力の働き

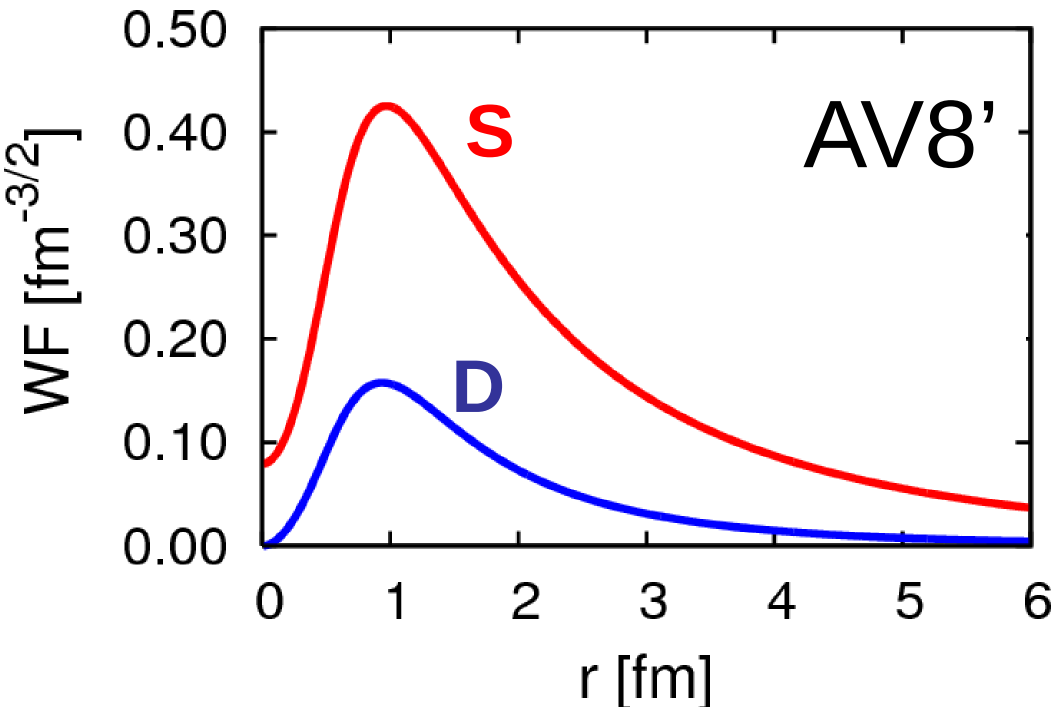
明　孝之　　大阪工業大学

共同研究者　　梅谷　篤史　　日本工業大学
　　　　　　　土岐　博　　　阪大RCNP
　　　　　　　池田　清美　　理研

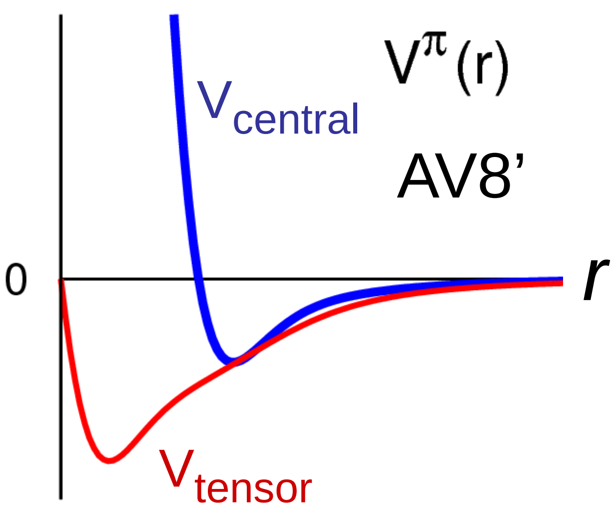
Purpose & Outline

- **Role of V_{tensor}** 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}

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

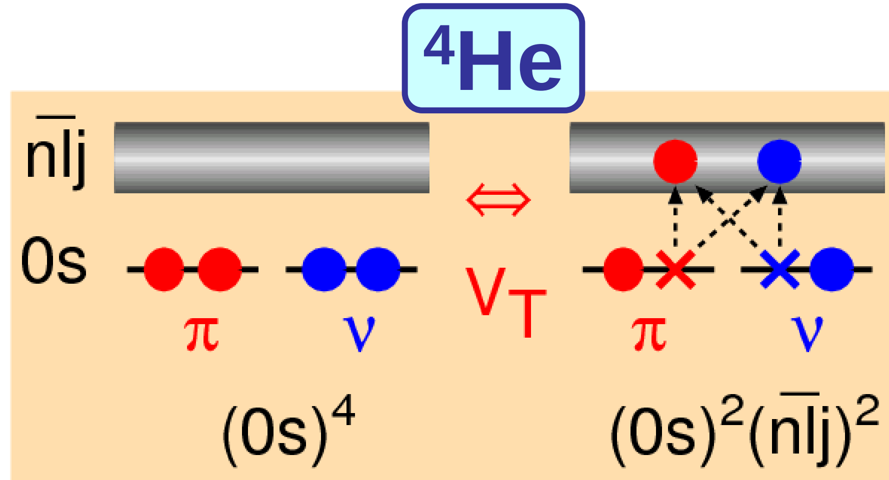
$R_m(d)$=1.22 fm

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

Tensor-optimized shell model (TOSM)

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

- Configuration mixing within 2p2h excitations with high-L orbits.
  - TM et al., PTP113(2005)
  - TM et al., PTP117(2007)



- 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 by Sugimoto et al,(NPA740) / Akaishi (NPA738)
    - RMF by Ogawa et al.(PRC73), AMD by Dote et al.(PTP115)
- Satisfy few-body results with Minnesota central force (^{4,6}He)

Hamiltonian and variational equations in TOSM

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

(0p0h+1p1h+2p2h)

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

$\psi_k(A)$: shell model type configuration with mass number A

Particle state : Gaussian expansion for each orbit

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

Gaussian basis function

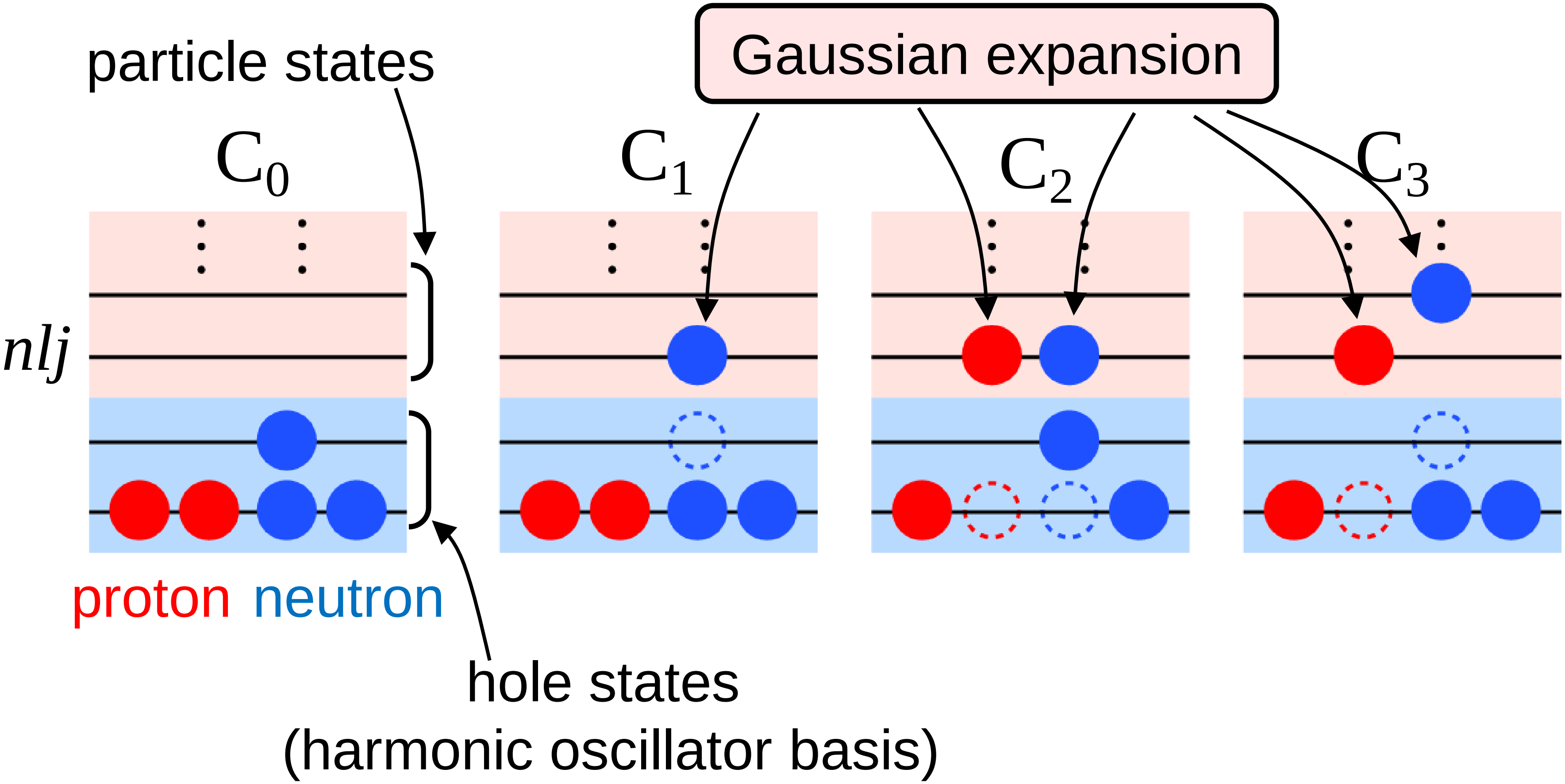
$$\left\langle \varphi_{lj}^n \middle| \varphi_{lj}^{n'} \right\rangle = \delta_{n,n'}$$

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

TOSM code : *p*-shell region

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

Configurations in TOSM



Application to Hypernuclei by Umeya (NIT) to investigate ΛN-ΣN coupling

Unitary Correlation Operator Method

(short-range part)

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

TOSM

short-range correlator

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

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

Bare Hamiltonian

Shift operator depending on the relative distance

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

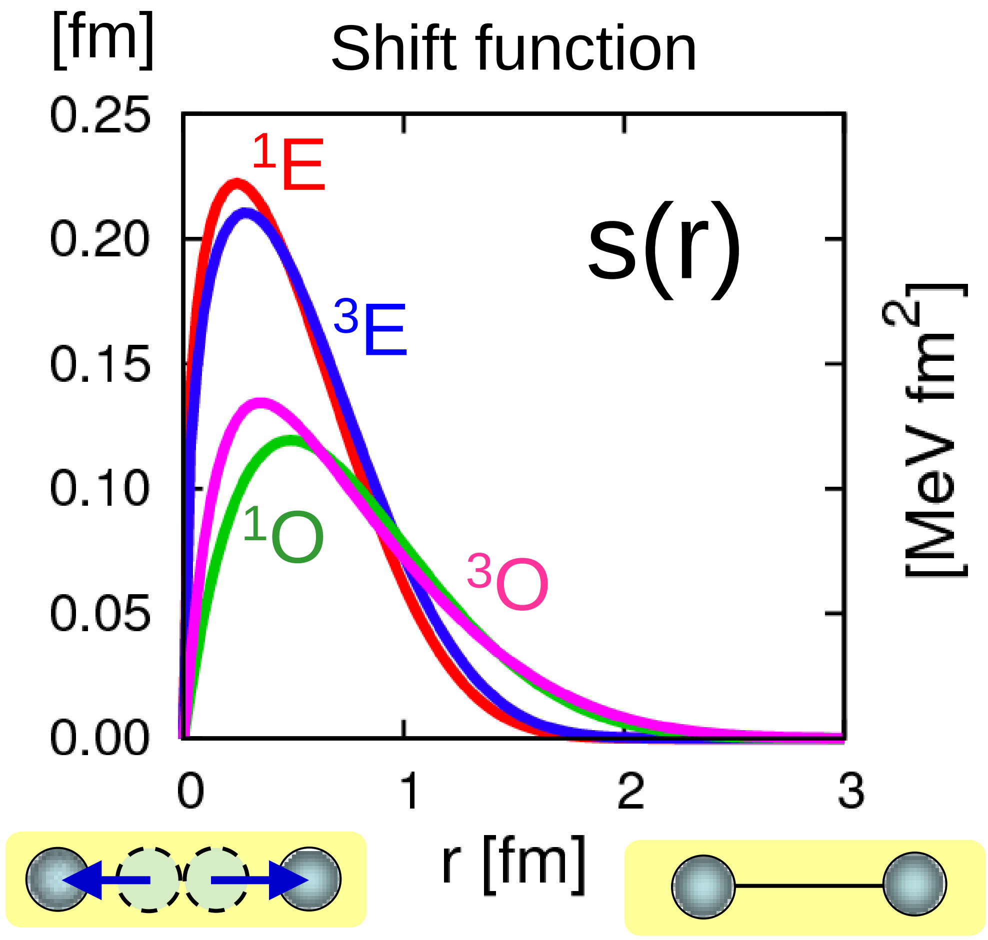
Amount of shift, variationally determined.

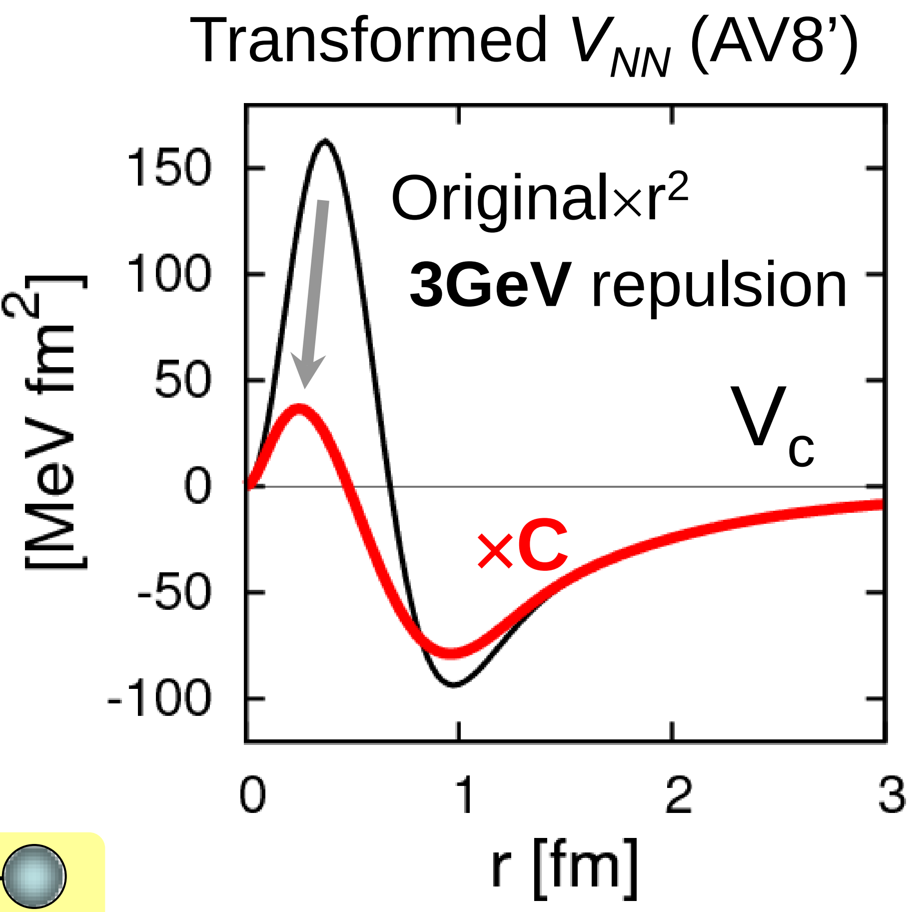
$$C^{\dagger} r C \simeq r + s(r) + \tfrac{1}{2} s(r) s'(r) \cdots$$

2-body cluster expansion

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

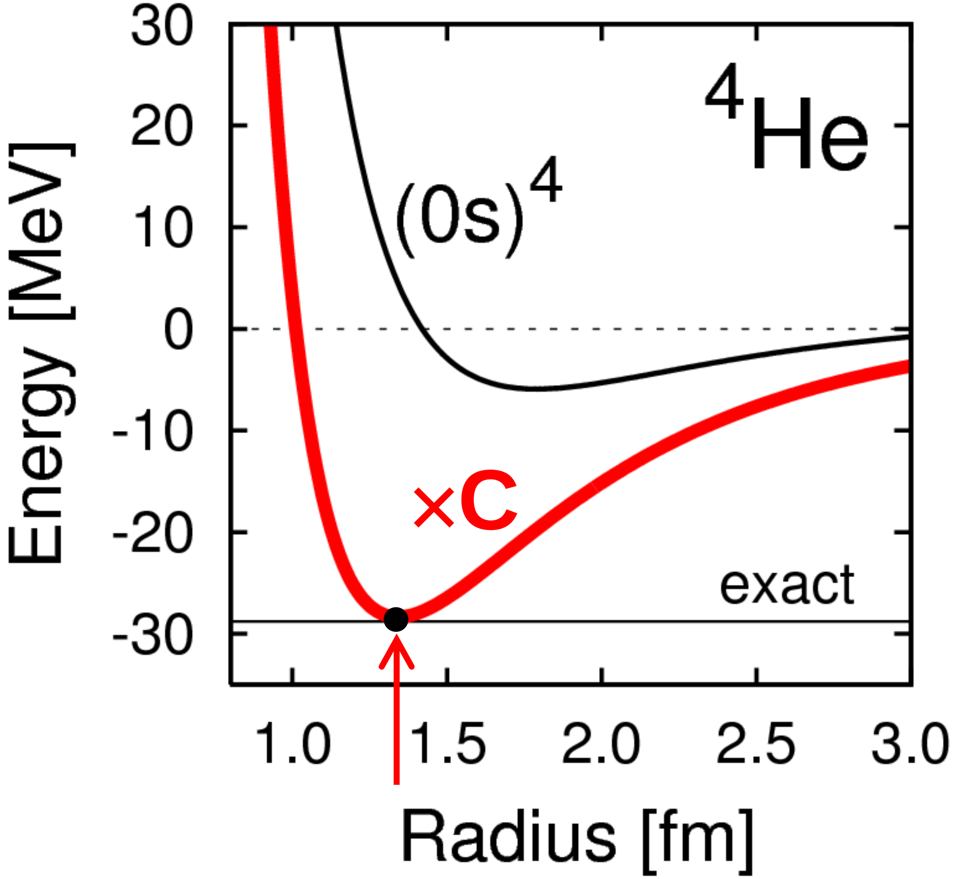
Short-range correlator : **C** (or **C_r**)

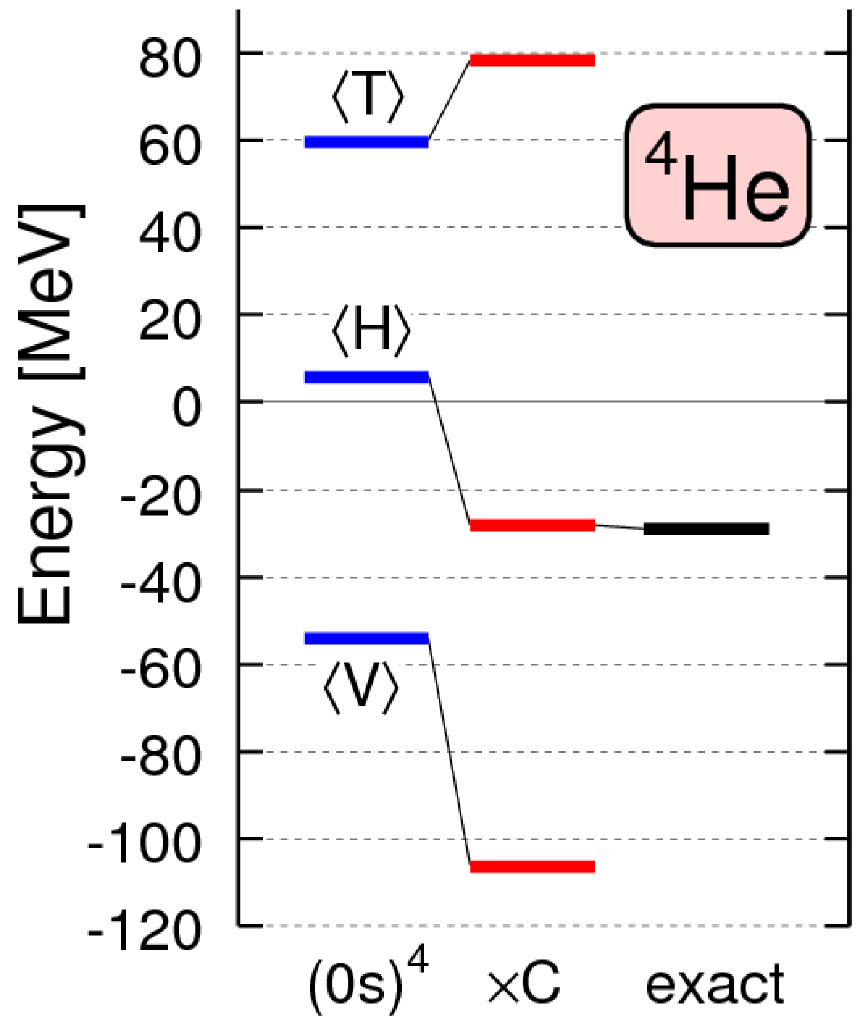




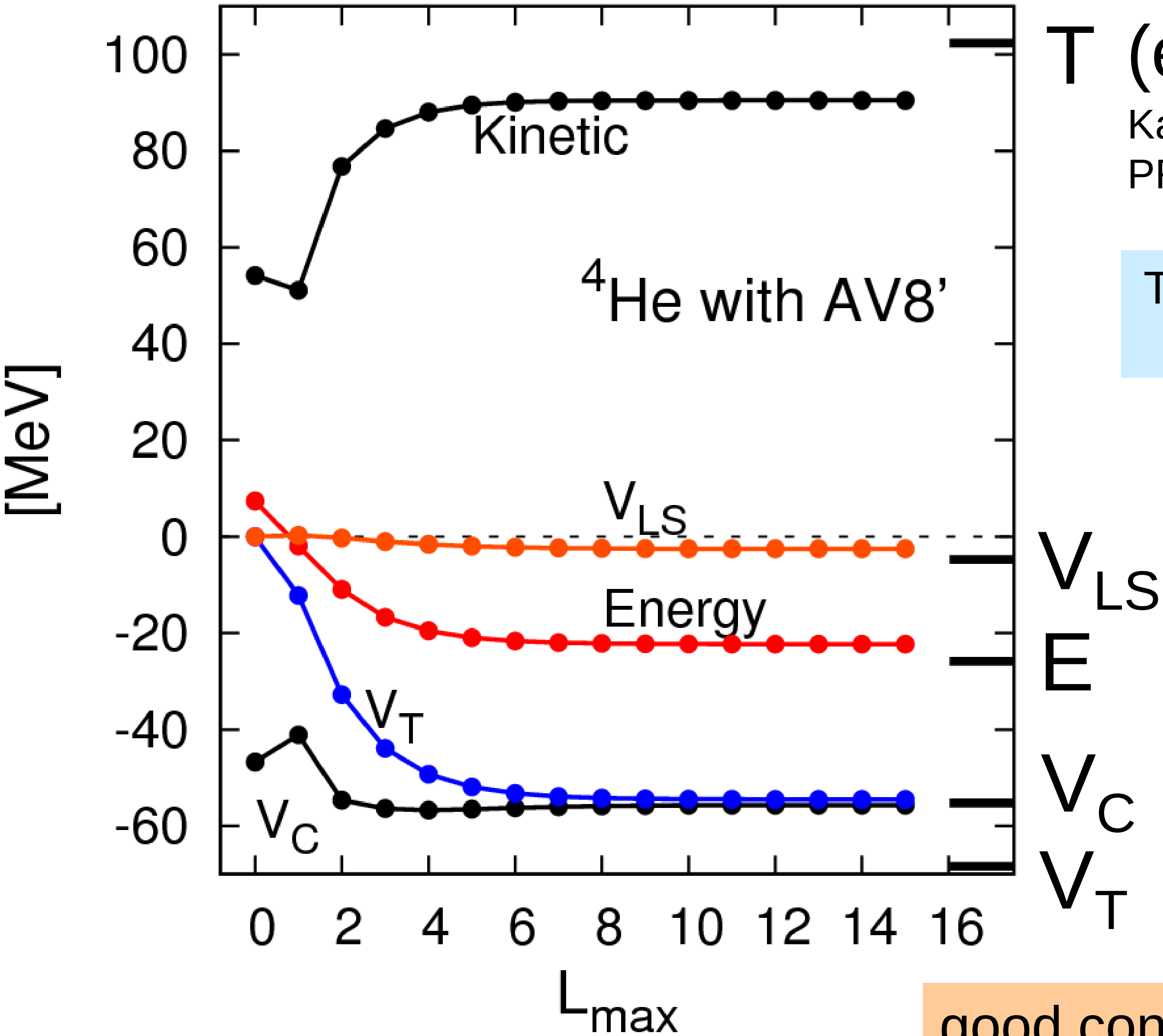
We further introduce partial-wave dependence in "s(r)" of UCOM → ***S*-wave UCOM**

^{4}He in UCOM (Afnan-Tang, $V_{central}$ only)





^{4}He in TOSM + *S*-wave UCOM



Kamada et al.
PRC64 (Jacobi)

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

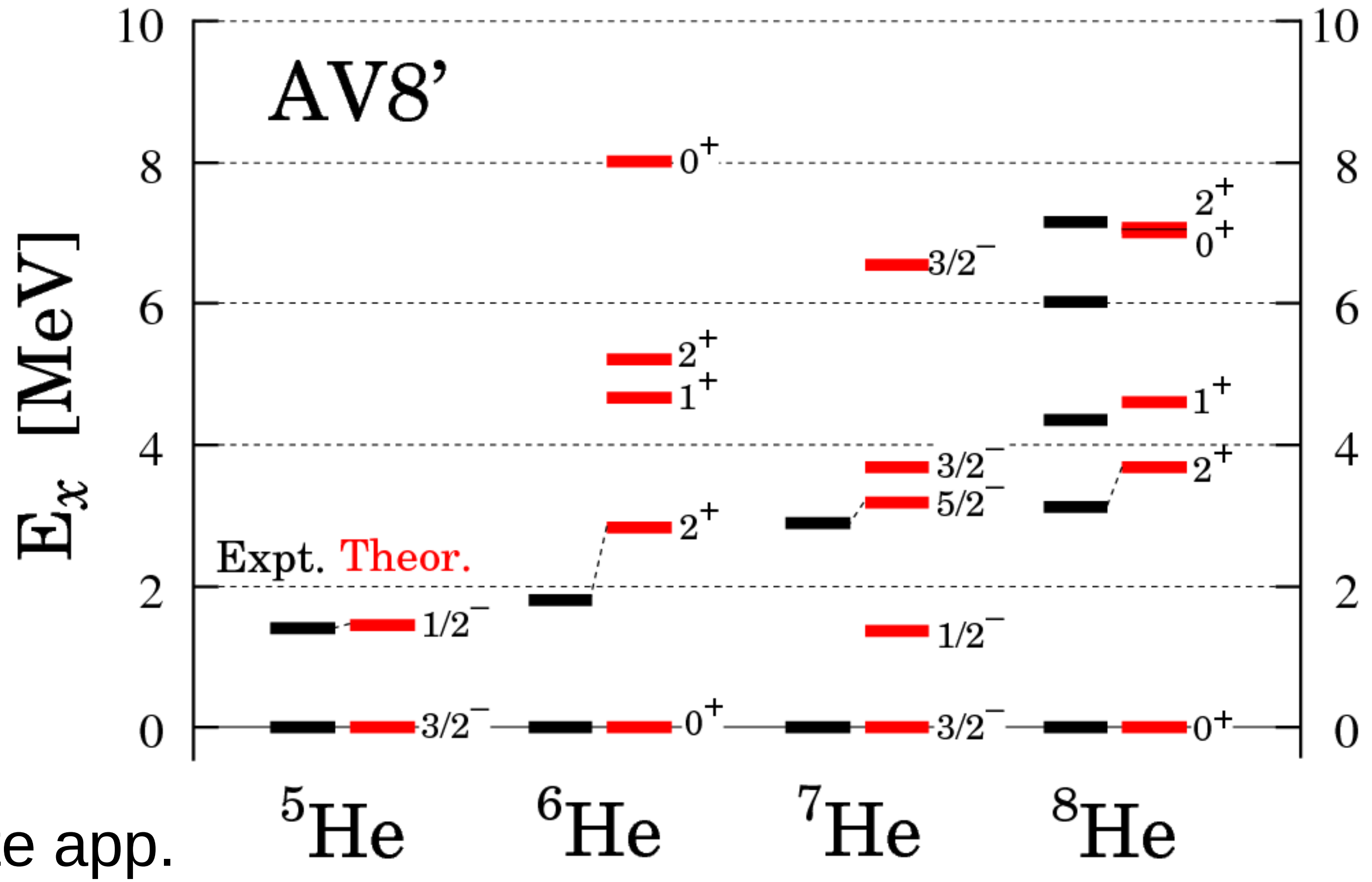
- variational calculation
- Gaussian expansion with 9 Gaussians

good convergence

$^{4\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV

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

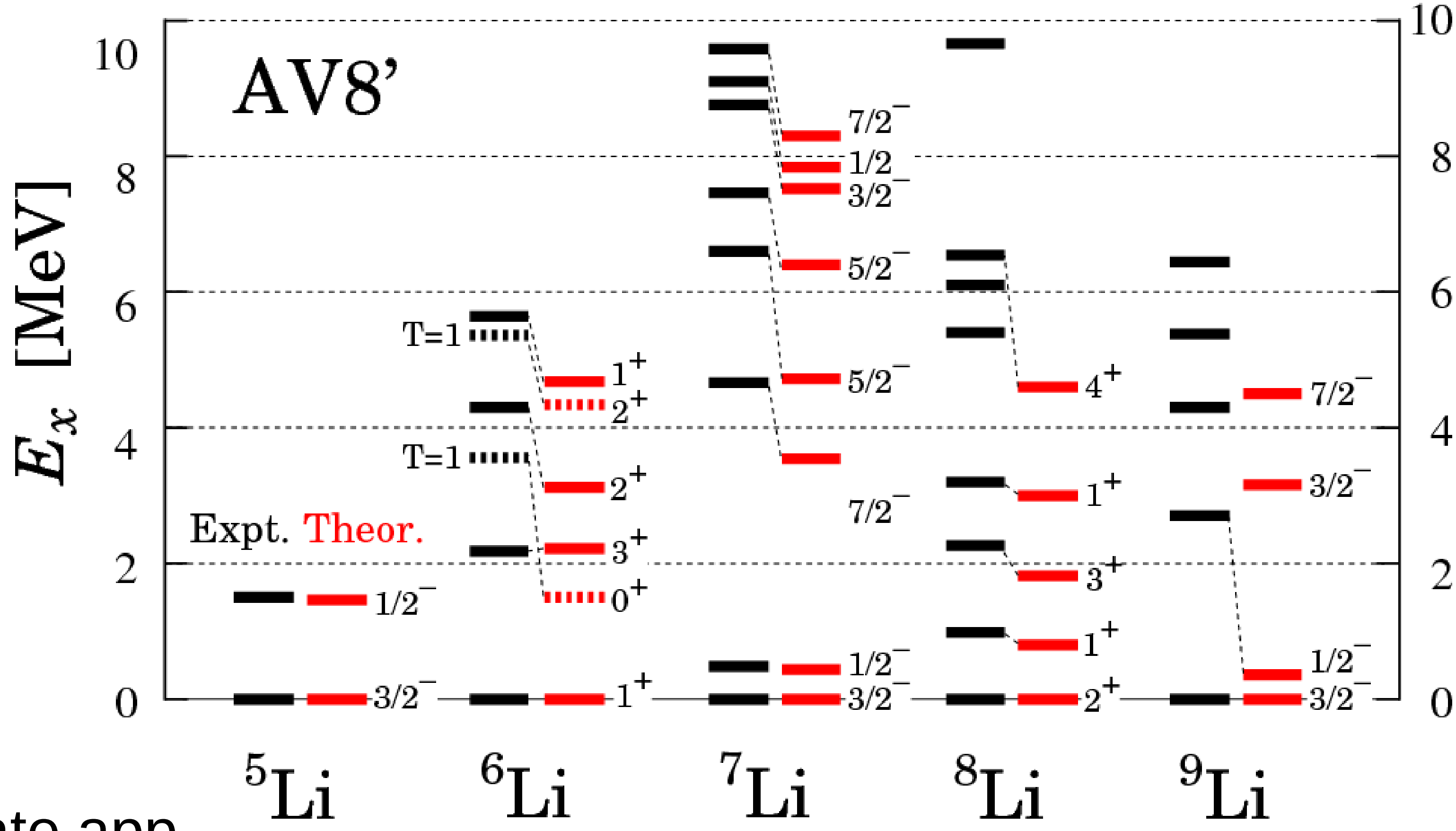


- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

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

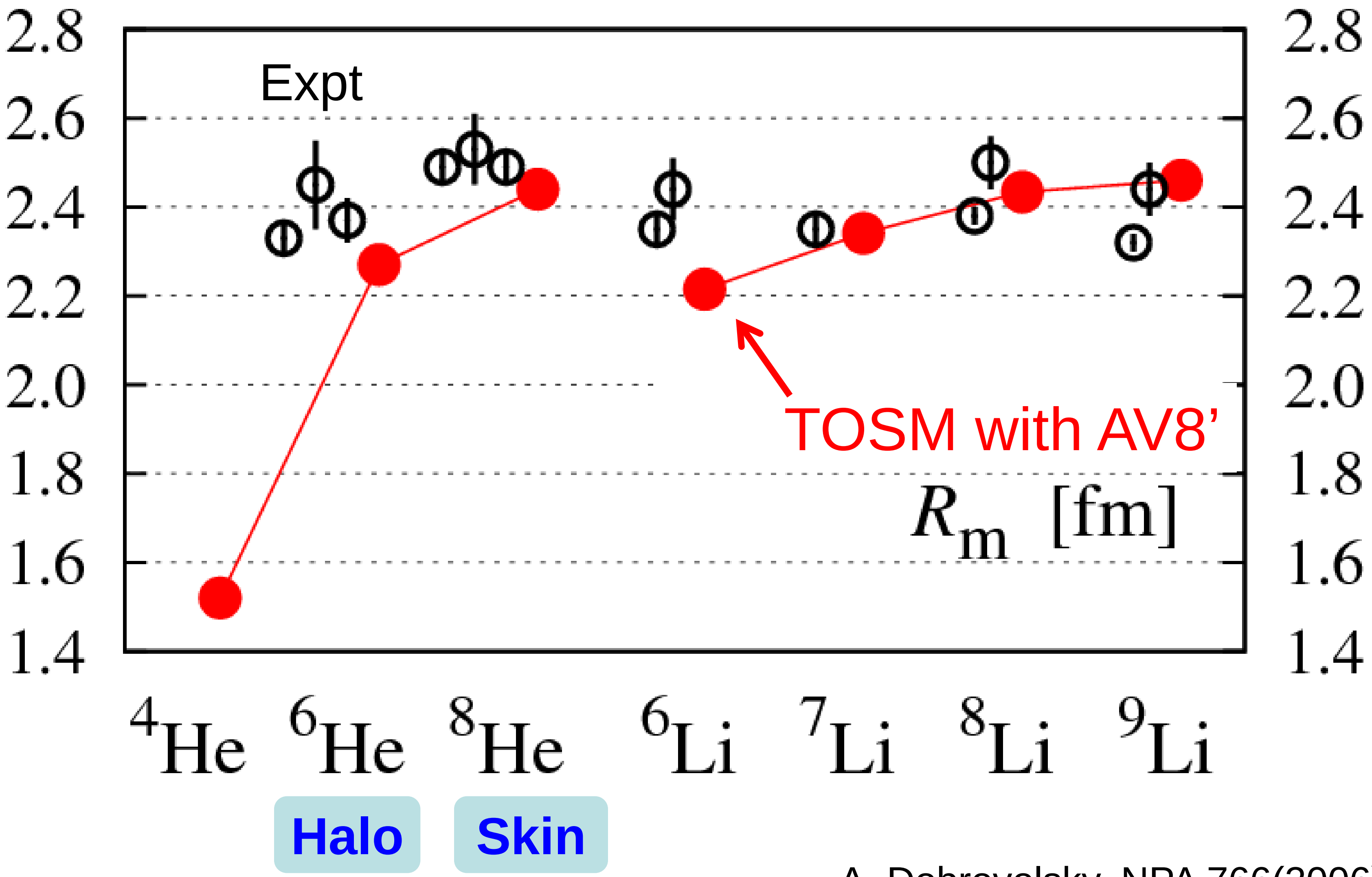
- Excitation energies in MeV



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

- Excitation energy spectra are reproduced well

Matter radius of He & Li isotopes



A. Dobrovolsky, NPA 766(2006)1

I. Tanihata et al., PLB289('92)261

G. D. Alkhazov et al., PRL78('97)2313

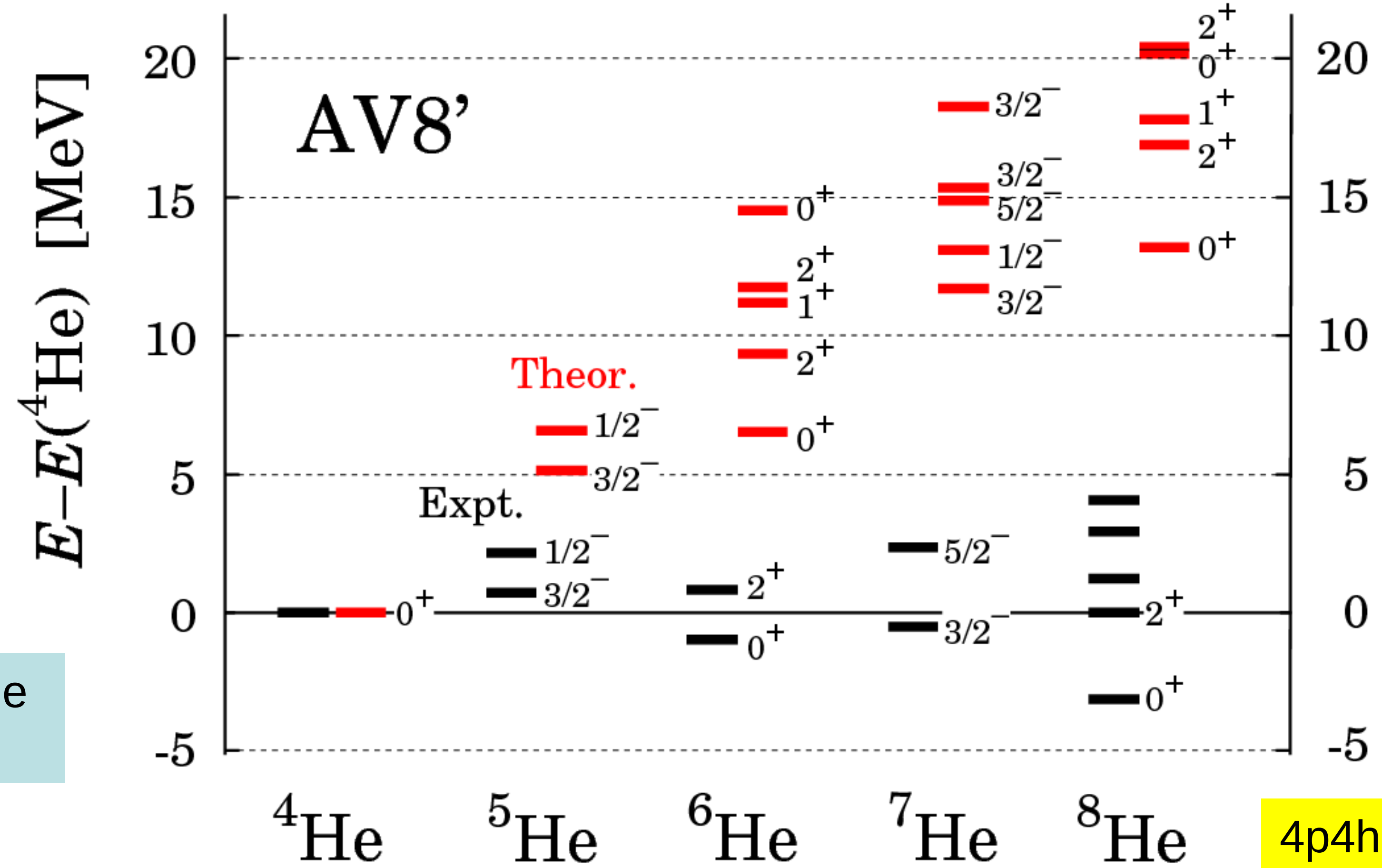
O. A. Kiselev et al., EPJA 25, Suppl. 1('05)215.

P. Mueller et al., PRL99(2007)252501

$^{4-8}$He with TOSM+UCOM

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

- Difference from ^{4}He in MeV



~6 MeV in ^{8}He using GFMC

- No V_{NNN}
- No continuum

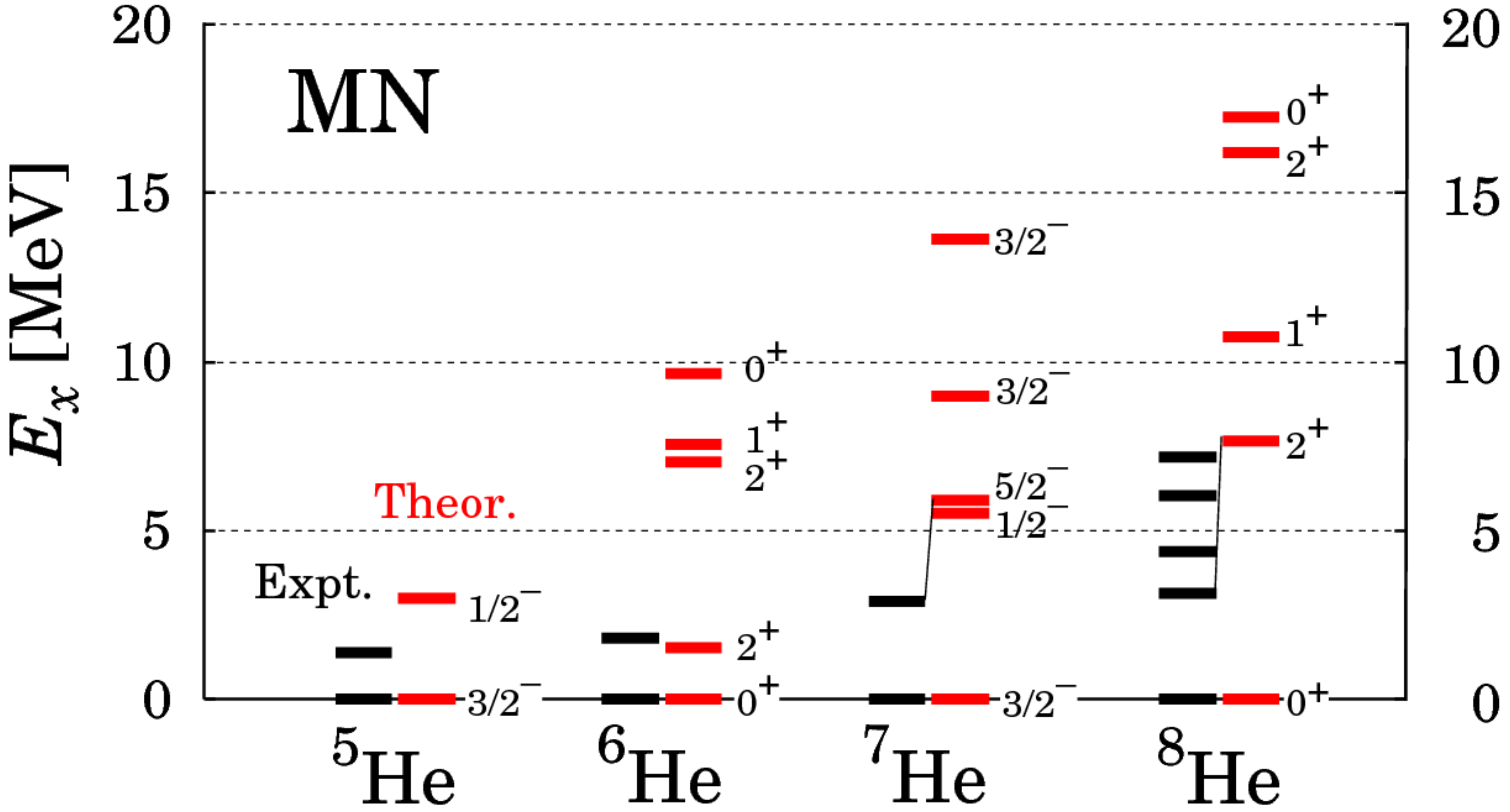
4p4h in TOSM

~7 MeV in ^{8}He using Cluster model (PLB691(2010)150 , TM et al.)

$^{4\text{-}8}$He with TOSM

Minnesota force (Central+LS)

- Excitation energies in MeV



Configurations of ^{4}He in TOSM 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

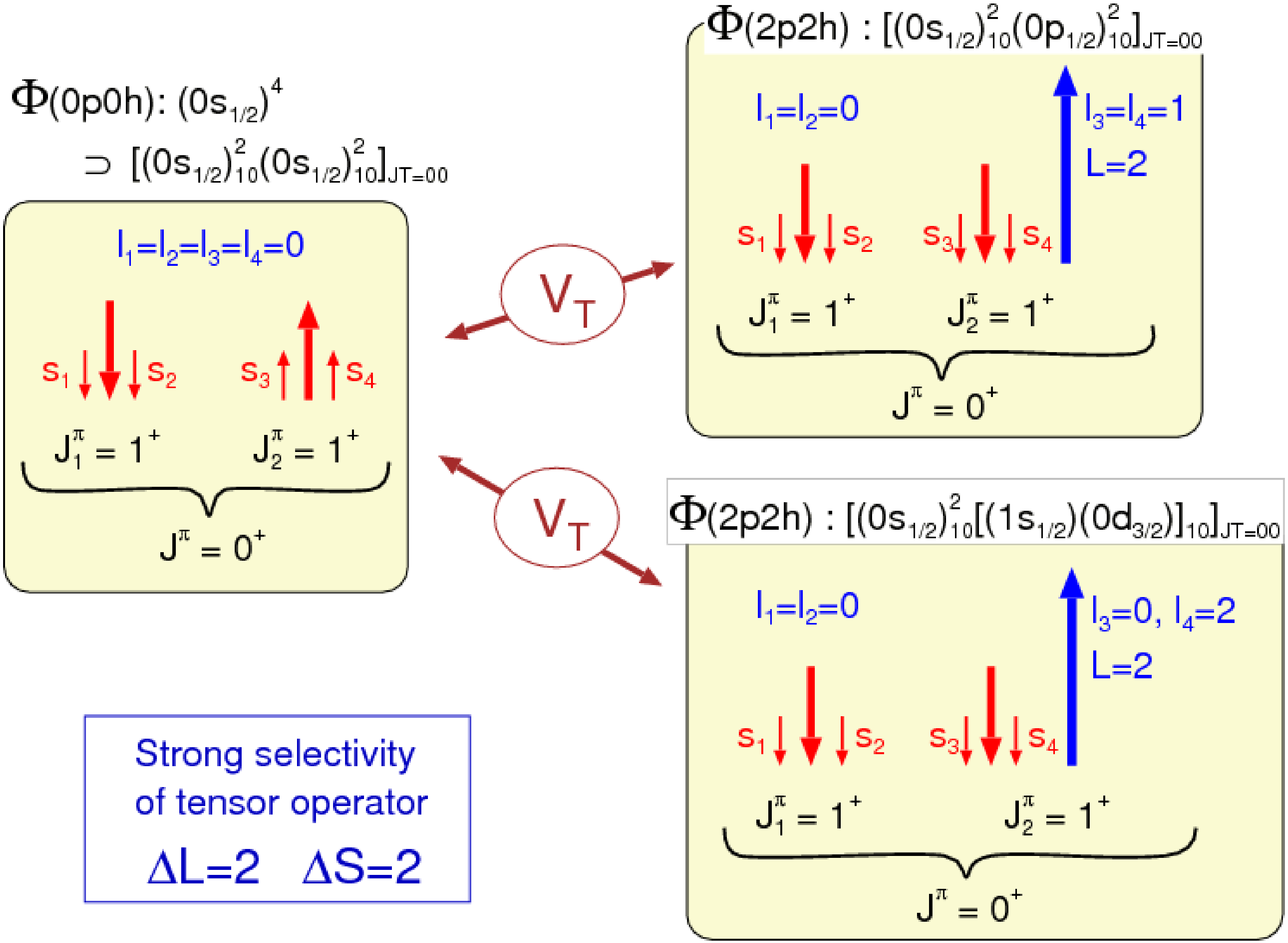
^{12}C(e,e'*pN*)

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



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

PHYSICAL REVIEW C **83**, 014605 (2011)

Two-nucleon correlation effects in knockout reactions from ^{12}C

E. C. Simpson and J. A. Tostevin (Surrey, UK)

Reactions that involve the direct and sudden removal of a pair of like or unlike nucleons from a fast projectile beam by a light target nucleus are considered. Specifically, we study the three two-nucleon removal channels from ^{12}C that populate final states in the ^{10}Be, ^{10}B, and ^{10}C reaction residues. The calculated two-nucleon removal cross sections and the residue momentum distributions are compared with available high-energy data at 250, 1050, and 2010 MeV per nucleon, i.e., data that are inclusive with respect to the bound final states of the residues. The measured *np* removal cross sections only are significantly greater than the values calculated, suggesting that the reaction mechanism observes enhanced *np* spatial correlations compared to those present in the shell-model wave functions.

Expt: ^{12}C+^{12}C (1983,1988)

^{12}C $\xrightarrow{-2N}$ ^{10}Be, ^{10}B, ^{10}C

TABLE III. Theoretical and experimental cross sections for two-nucleon knockout from ^{12}C,
2100 MeV per nucleon. All cross sections are in mb. The TNAs used were calculated using the WBP

Energy	^{10}Be **-2*p***			^{10}C **-2*n***		
MeV/u	σ_{th}	σ_{exp}	σ_{exp}/σ_{th}	σ_{th}	σ_{exp}	σ_{exp}/σ_{th}
250 [12]	7.48	5.88 ± 9.70	0.79 ± 1.30	5.80	5.33 ± 0.81	0.92 ± 0.14
1050 [13]	6.62	5.30 ± 0.30	0.80 ± 0.05	5.13	4.44 ± 0.24	0.87 ± 0.05
2100 [13]	6.52	5.81 ± 0.29	0.89 ± 0.04	5.04	4.11 ± 0.22	0.82 ± 0.04

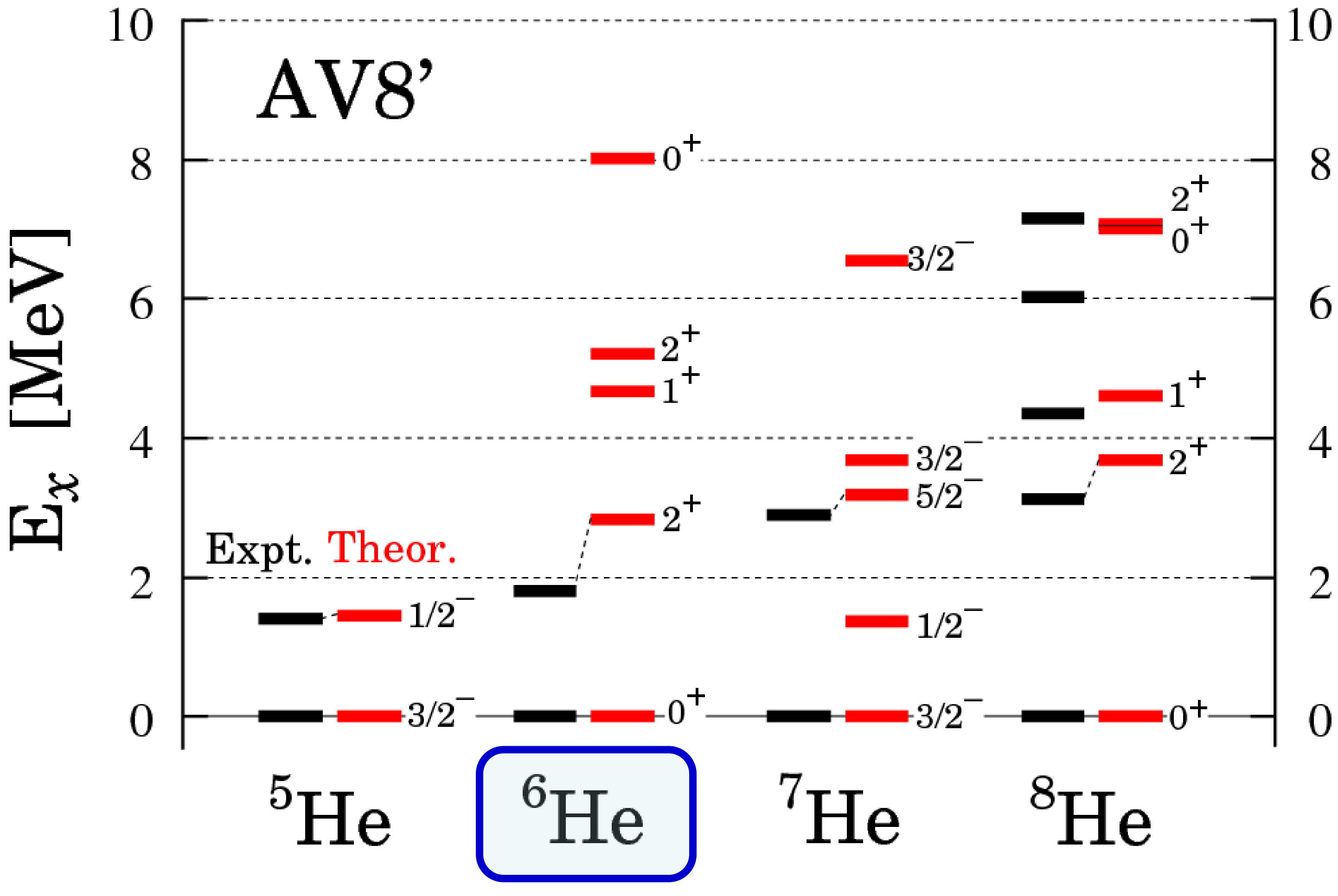
for projectile energies of 250, 1050, and
P interaction.

^{10}B **-*pn***		
σ_{th}	σ_{exp}	σ_{exp}/σ_{th}
21.57	47.50 ± 2.42	2.20 ± 0.11
19.27	27.90 ± 2.20	1.45 ± 0.11
19.02	35.10 ± 3.40	1.84 ± 0.18

- OXBASH shell model with WBP interaction
- Eikonal reaction model with optical limit of Glauber theory

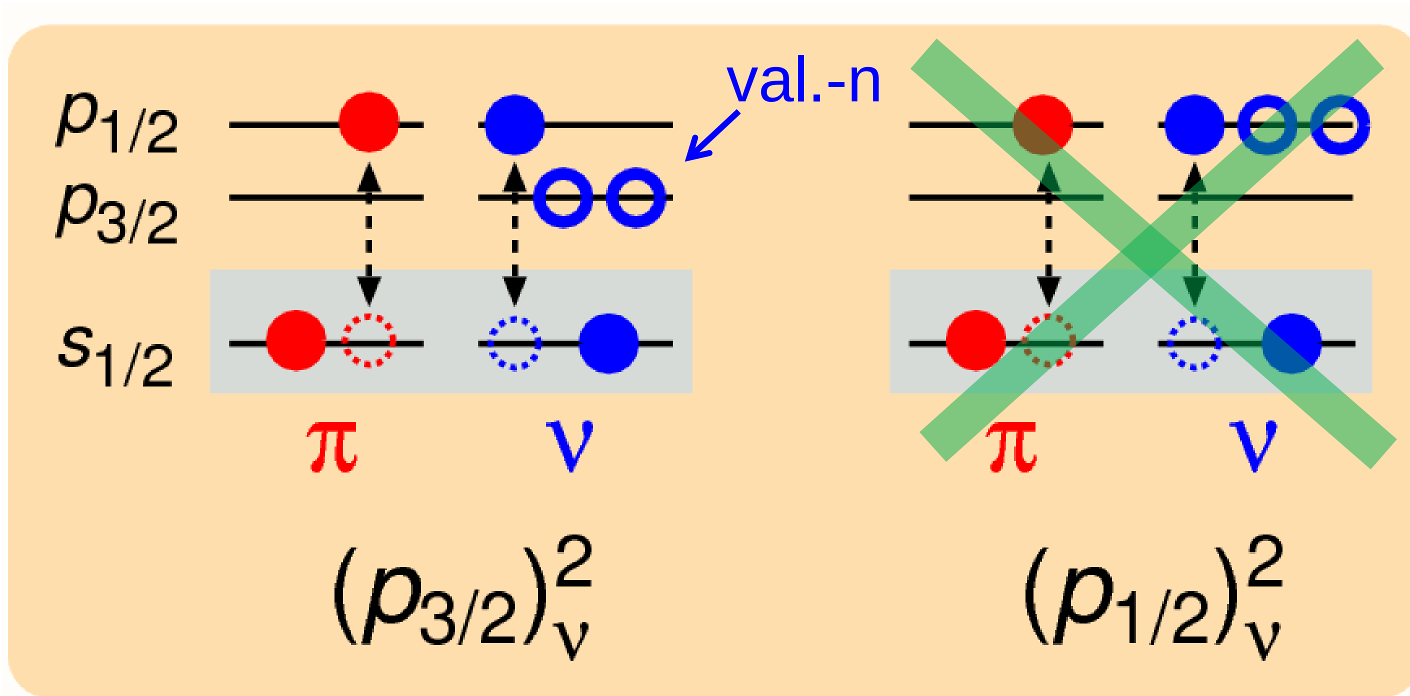
$^{4\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV



- No V_{NNN}
- No continuum
- Excitation energy spectra are reproduced well

Tensor correlation in ^{6}He



Ground state

halo state (0^+)

Excited state

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**	$(p_{3/2})^2$	$(p_{1/2})^2$

b_{hole}=1.5 fm

$\hbar\omega$=18.4 MeV (hole)

same trend in $^{5-8}$He

LS splitting energy in ^{5}He

•Terasawa, Arima PTP23 ('60)
•Nagata, Sasakawa, Sawada, Tamagaki, PTP22('59)
•Myo, Kato, Ikeda, PTP113 ('05)

Configurations of “*pn* in $^6Li_{gs}$”

$^6Li(1^+)$	AV8’	Minnesota
$(0p_{1/2})(0p_{3/2})$	43%	29%
$(0p_{3/2})^2$	38%	56%

	S=0	S=1
$(0p_{1/2})(0p_{3/2})$	11%	89%
$(0p_{3/2})^2$	56%	44%

Summary

- **TOSM+UCOM** with bare nuclear force.
- ^{4}He contains much **"*pn*-pair of $p_{1/2}$"**.
- He isotopes with $p_{3/2}$ has large contributions of V_{tensor} & Kinetic energy.
- ^{6}Li with S=1 component.

Review **Di-neutron clustering and deuteron-like tensor correlation in nuclear structure focusing on ^{11}Li**

K. Ikeda, T. Myo, K. Kato and H. Toki
Springer, Lecture Notes in Physics 818 (2010)
"Clusters in Nuclei" Vol.1, 165-221.