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

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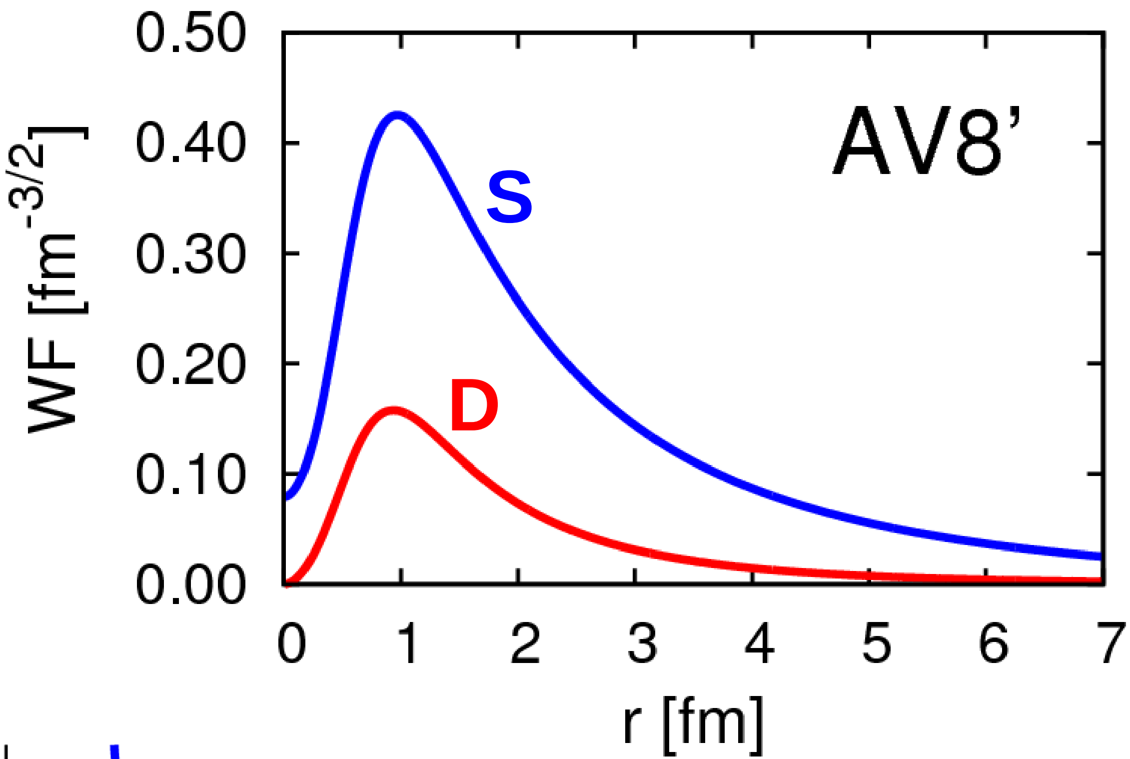
Few-body 20@ Fukuoka, 2012.8

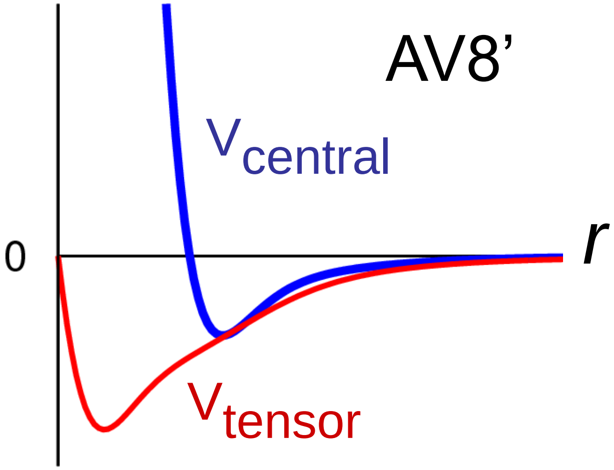
Outline

- **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}
- Halo formation in ^{11}Li (application of TOSM)
  - Coexistence of tensor and pairing correlations

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

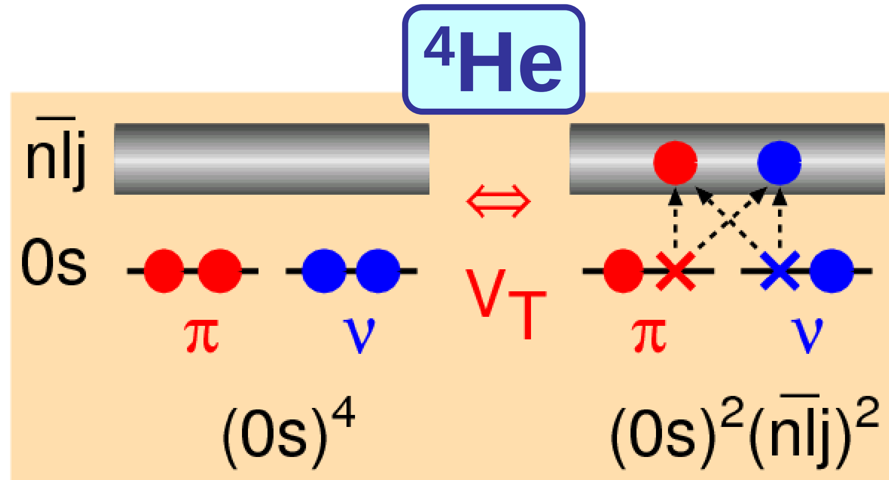
$R_m(d)$=1.22 fm

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

$$\varphi_{lj}^{n'}(\mathbf{r}) = \sum_{n=1}^{N} C_{lj,n}^{n'} \cdot \phi_{lj,n}(\mathbf{r})$$

$$\phi_{lj,n}(\mathbf{r}) \propto r^l \exp\left[-\left(\frac{r}{b_{lj,n}}\right)^2\right]\left[Y_l(\hat{\mathbf{r}}), \chi_{1/2}^{\sigma}\right]_j$$

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

Gaussian basis function

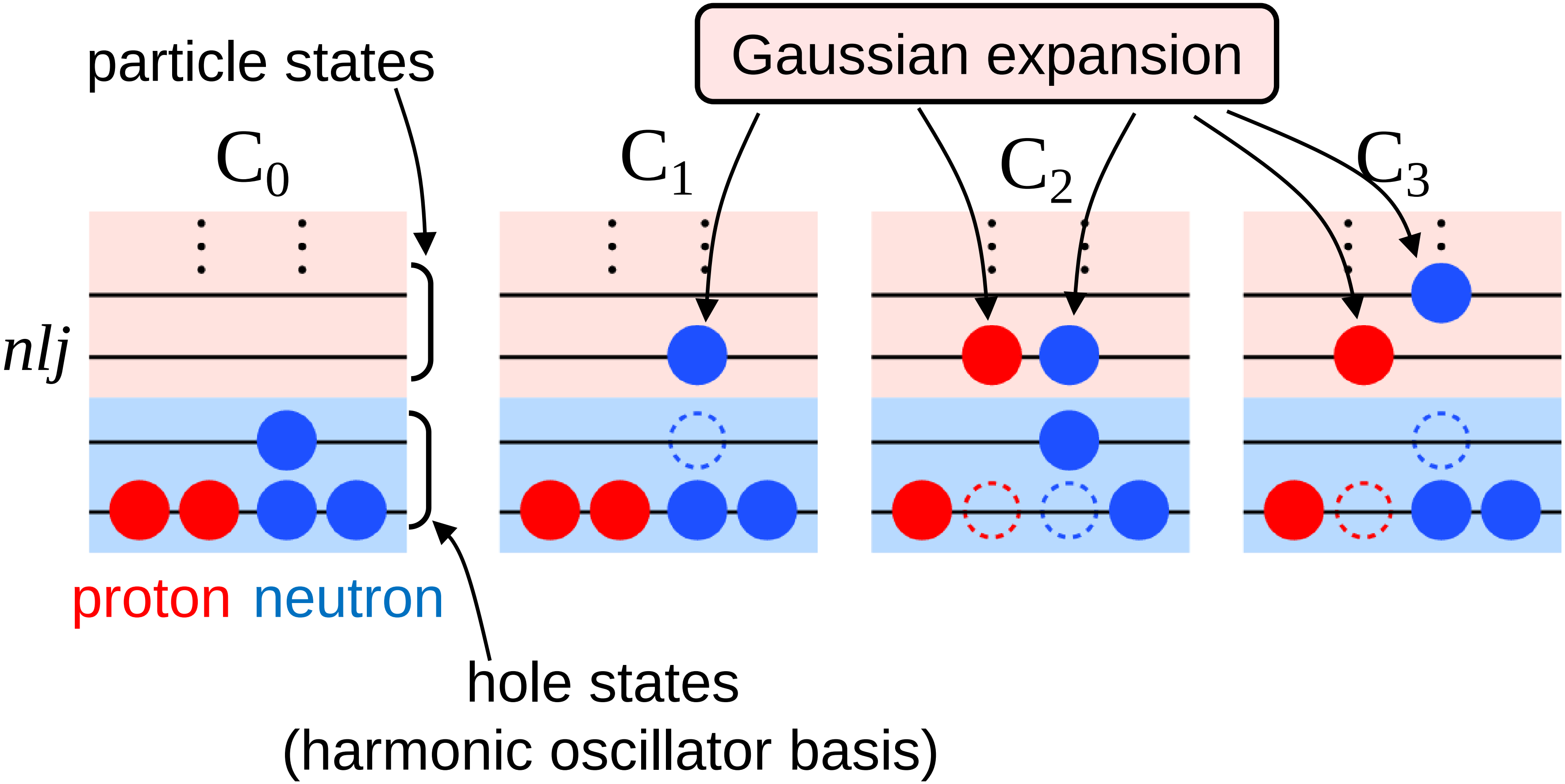
Hiyama, Kino, Kamimura
PPNP51(2003)223

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

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

TOSM code : *p*-shell region

Configurations in TOSM



Application to Hypernuclei by **A. Umeya**
to investigate ΛN-ΣN coupling

21st Tue.
III-a

Unitary Correlation Operator Method

(short-range part)

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

TOSM

short-range correlator

$C^\dagger = C^{-1}$ (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

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

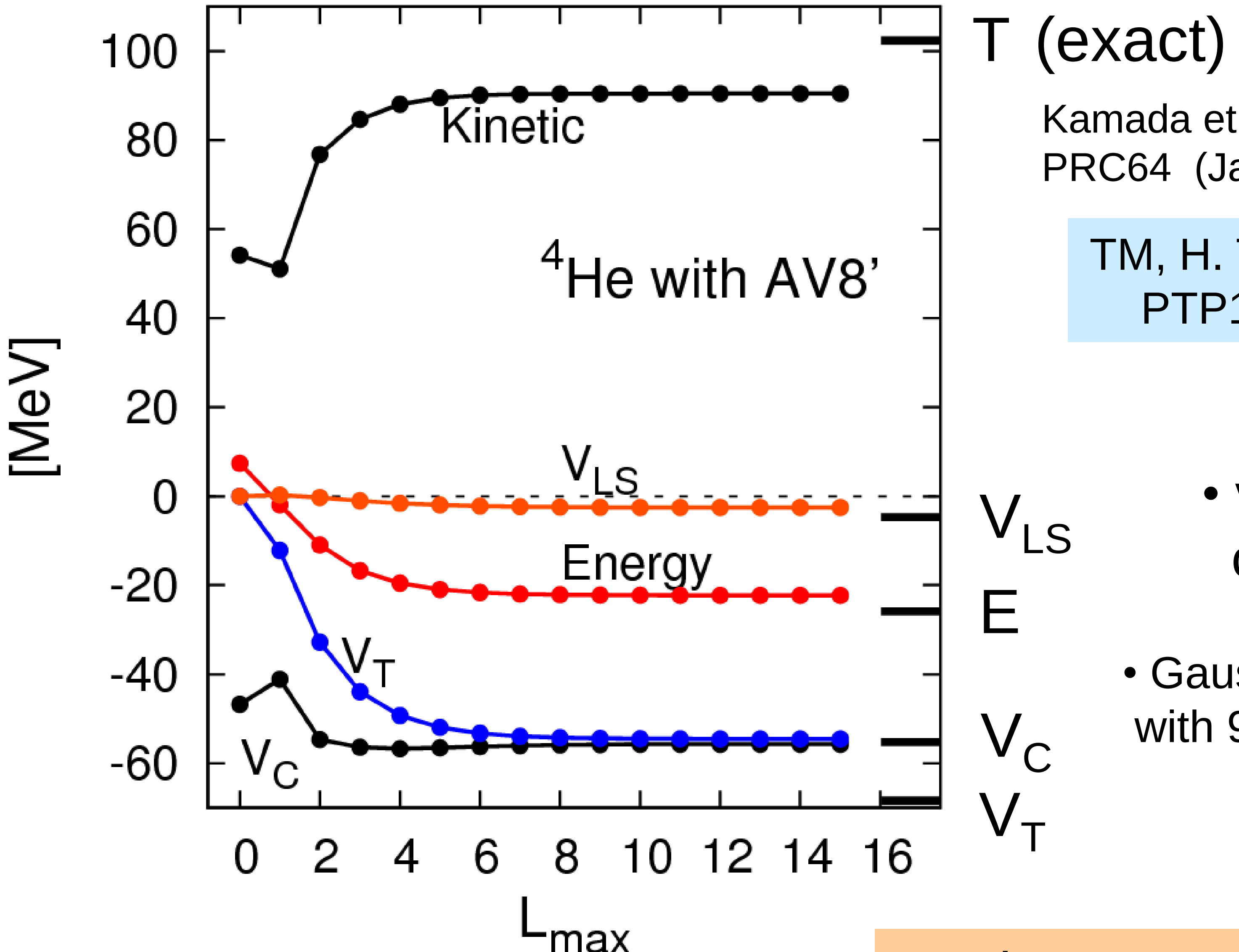
Amount of shift, variationally determined.

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

2-body cluster expansion

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

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



Kamada et al.
PRC64 (Jacobi)

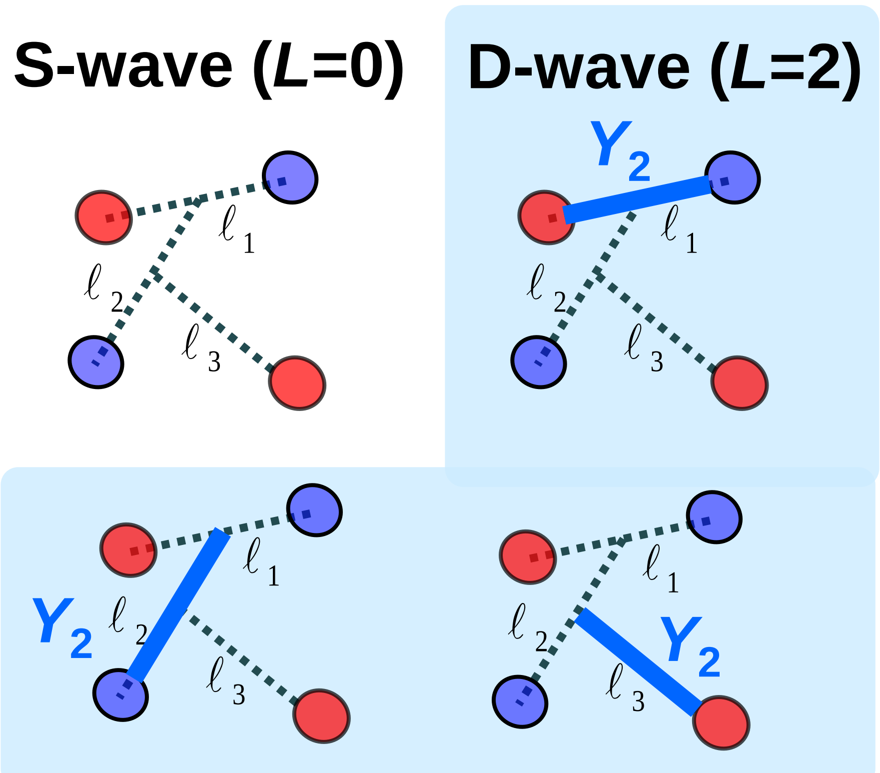
TM, H. Toki, K. Ikeda
PTP121(2009)511

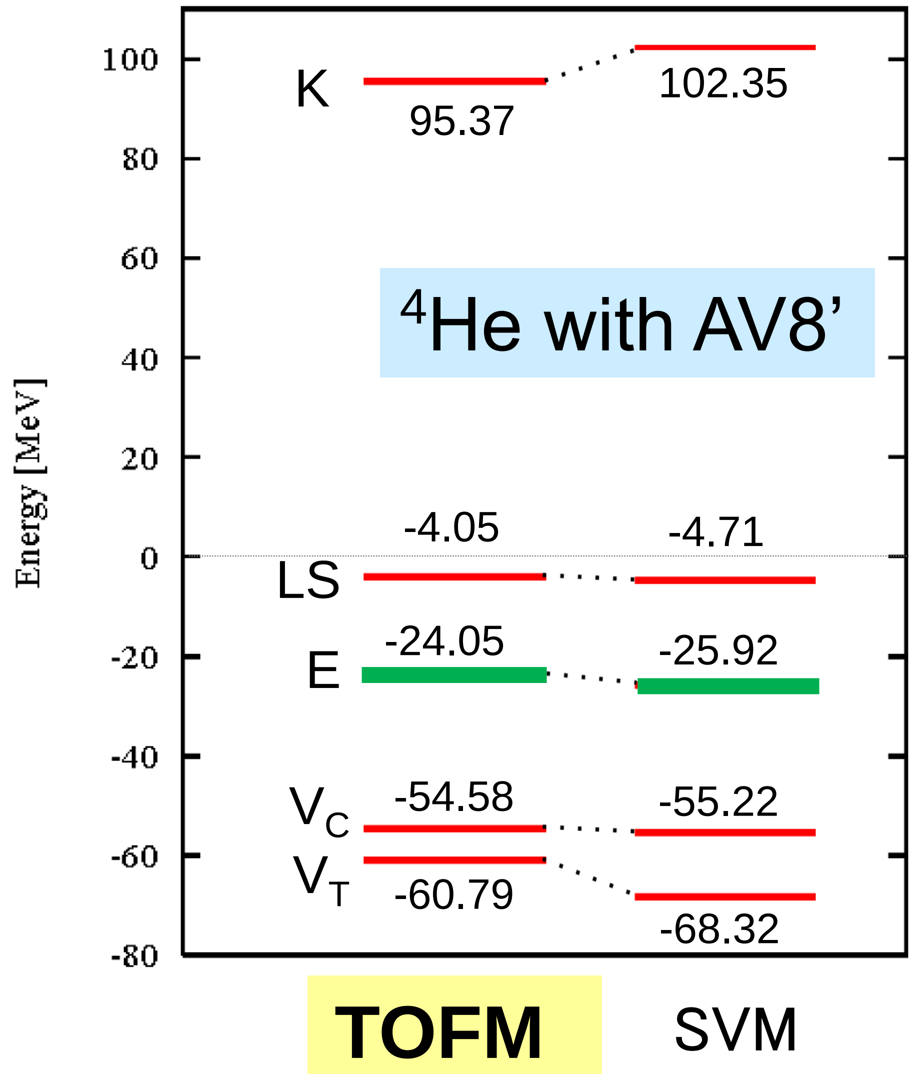
- variational calculation
- Gaussian expansion with 9 Gaussians

good convergence

Tensor Optimized Few-body Model (TOFM)

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





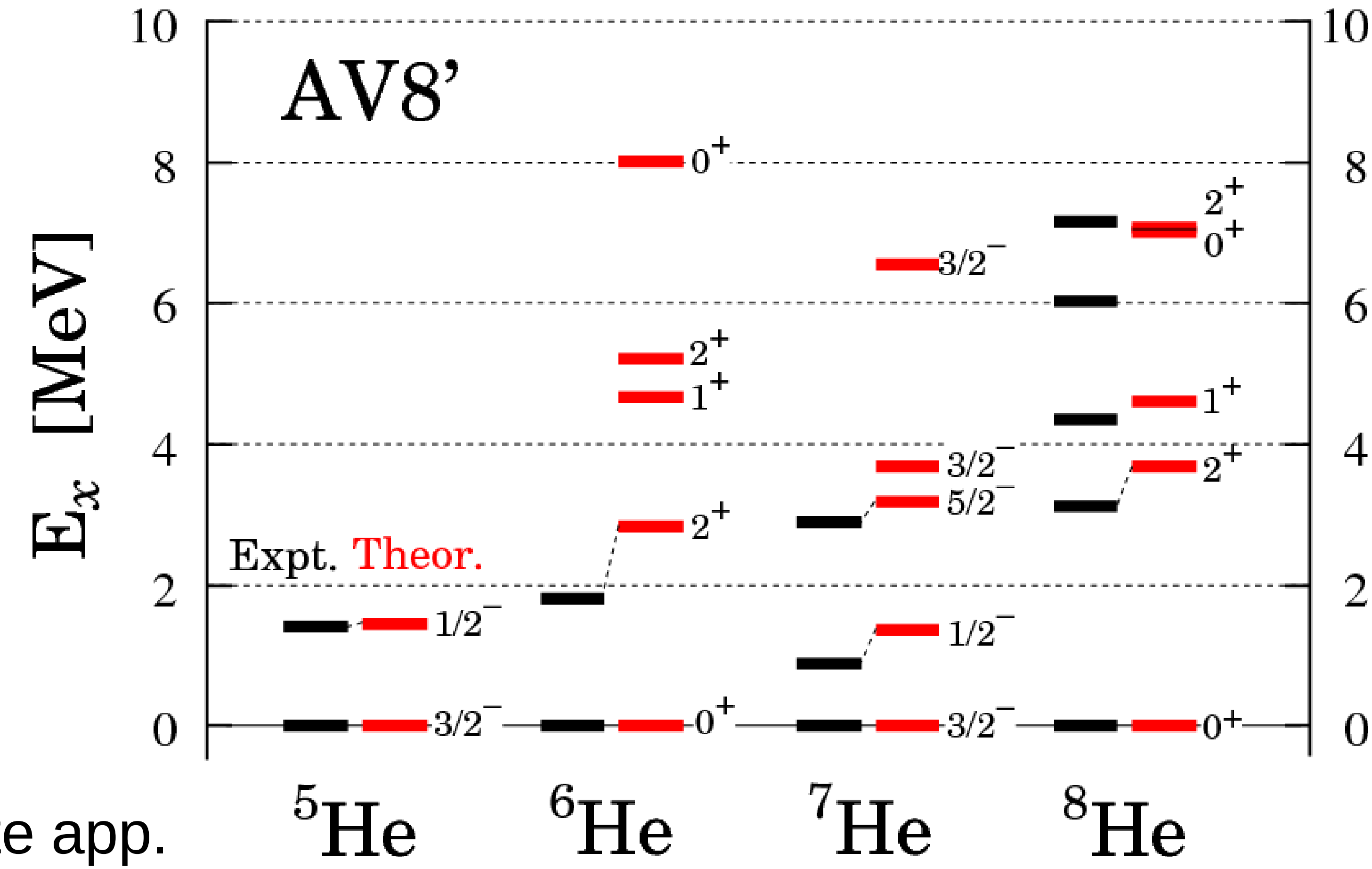
24st Fri. VIII-d

Horii, Toki, Myo, Ikeda PTP127(2012)1010

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

- Excitation energies in MeV

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



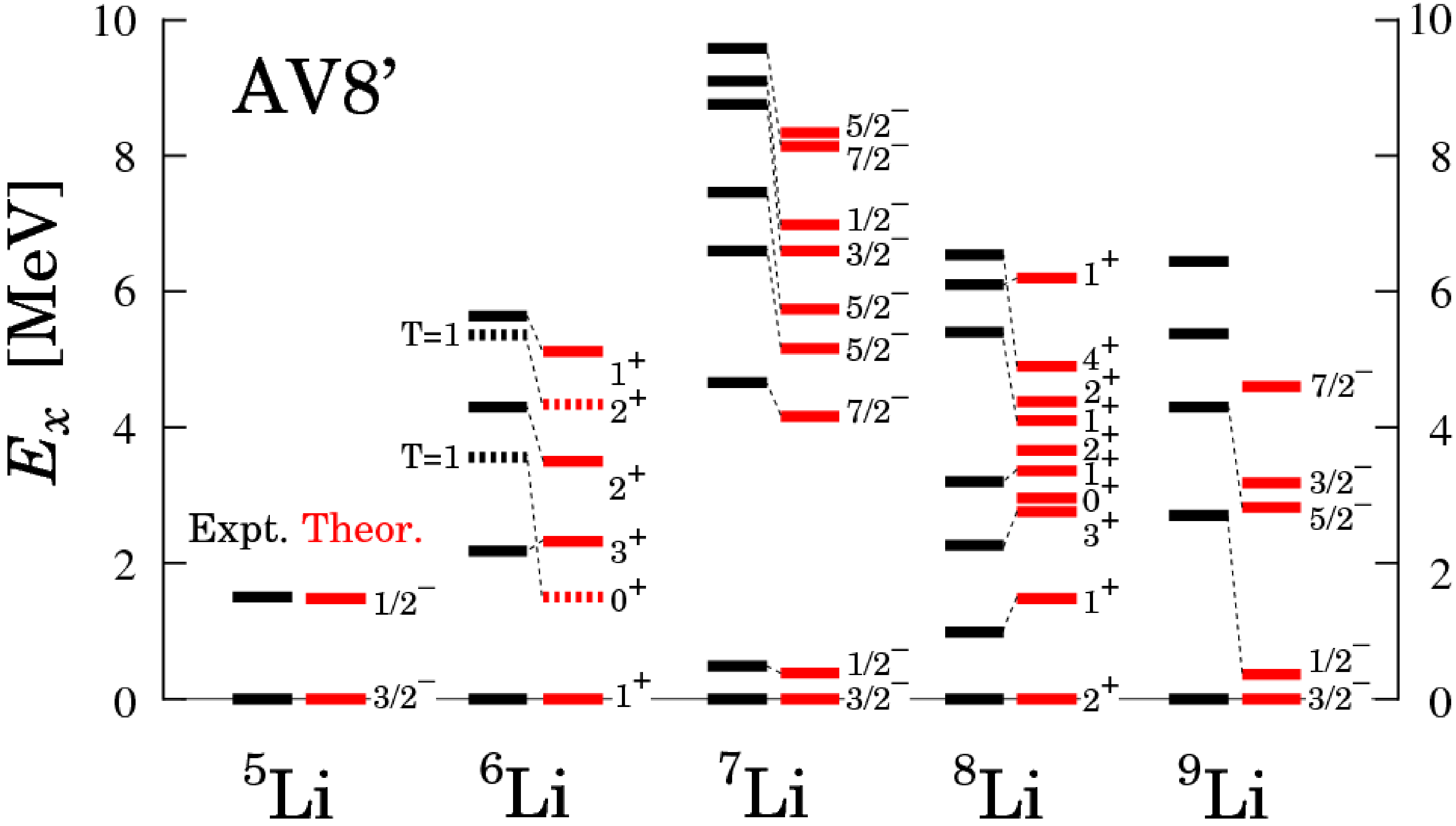
- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

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

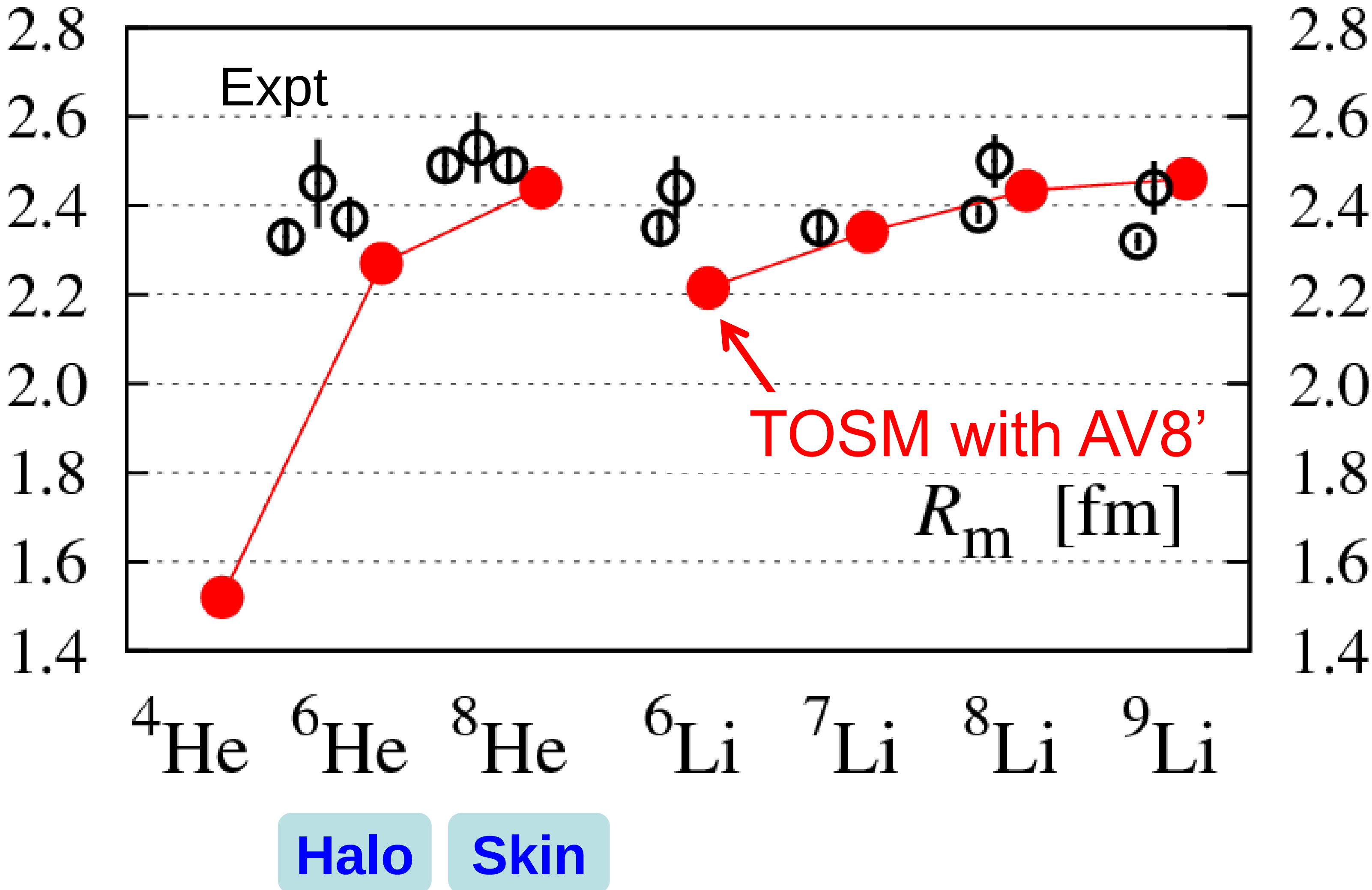
TM, A. Umeya, H. Toki, K. Ikeda
PRC, in press

- Excitation energies in MeV



- 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

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

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

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

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

$s_1 \downarrow \Downarrow \downarrow s_2$ $\quad$ $s_3 \uparrow \Uparrow \uparrow s_4$

$1^+(pn)$ $\quad$ $1^+(pn)$

V_T

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

$\ell_1 = \ell_2 = 0$

$\ell_3 = 1$

$\ell_4 = 1$

$L=2$

$s_1 \downarrow \Downarrow \downarrow s_2$ $\quad$ $s_3 \downarrow \Downarrow \downarrow s_4$

V_T

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

$\ell_1 = \ell_2 = 0$

$\ell_3 = 0$

$\ell_4 = 2$

$L=2$

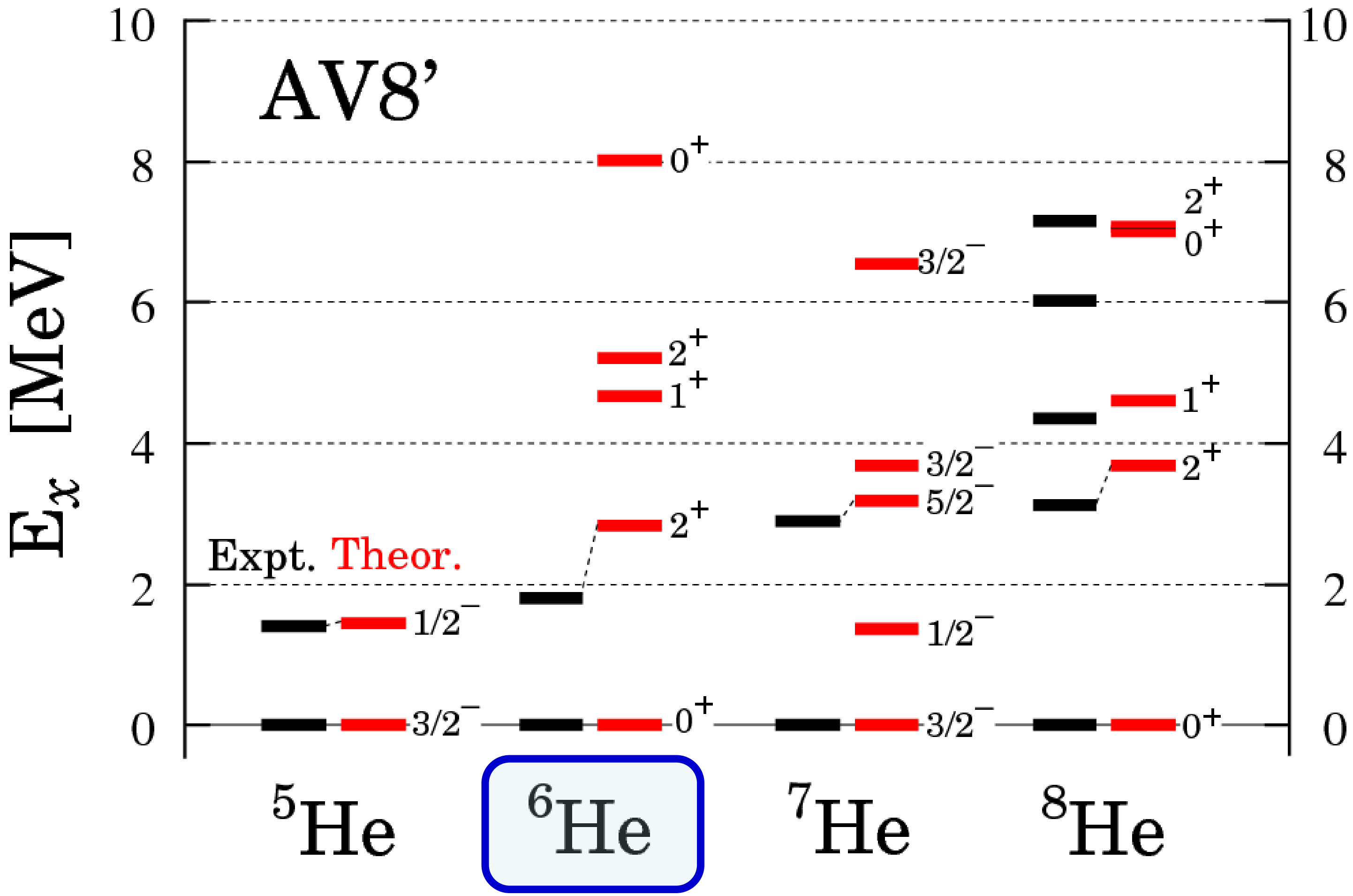
$s_1 \downarrow \Downarrow \downarrow s_2$ $\quad$ $s_3 \downarrow \Downarrow \downarrow s_4$

Selectivity of tensor operator

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

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

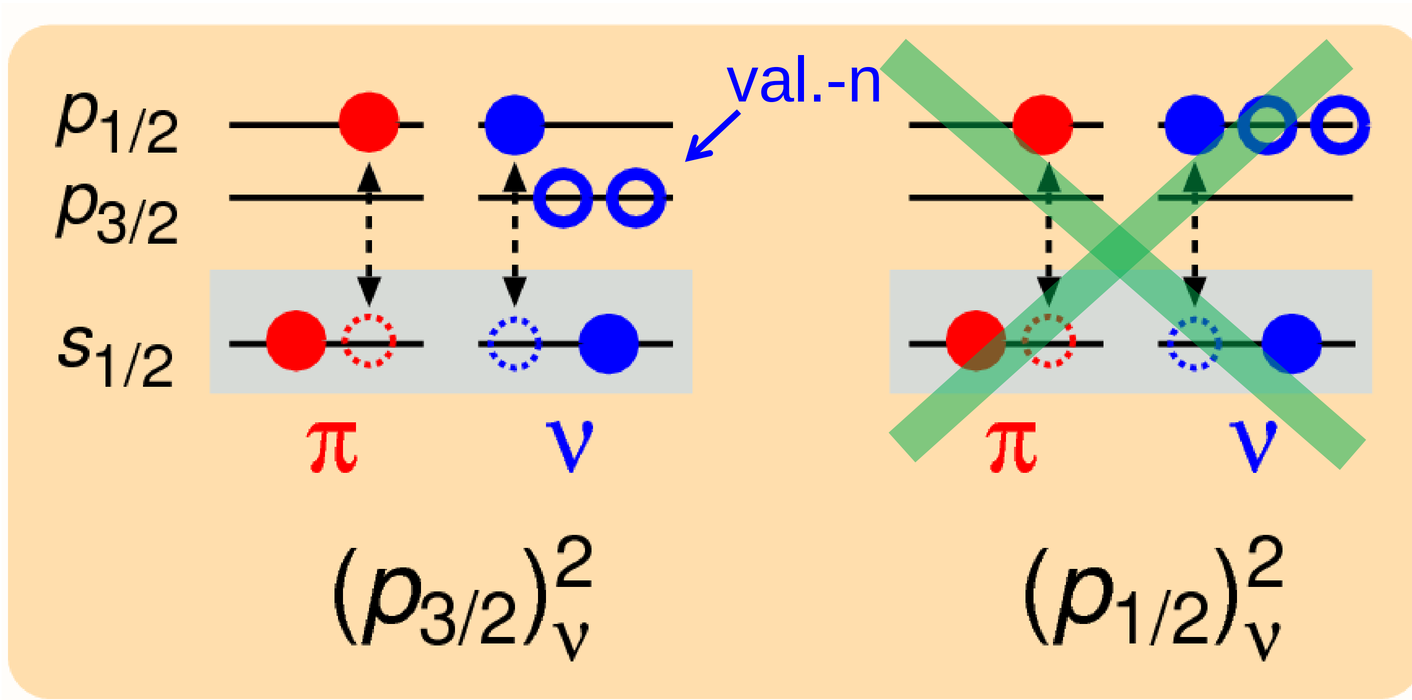
- Excitation energies in MeV



- 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)

LS splitting energy in ^{6}He

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

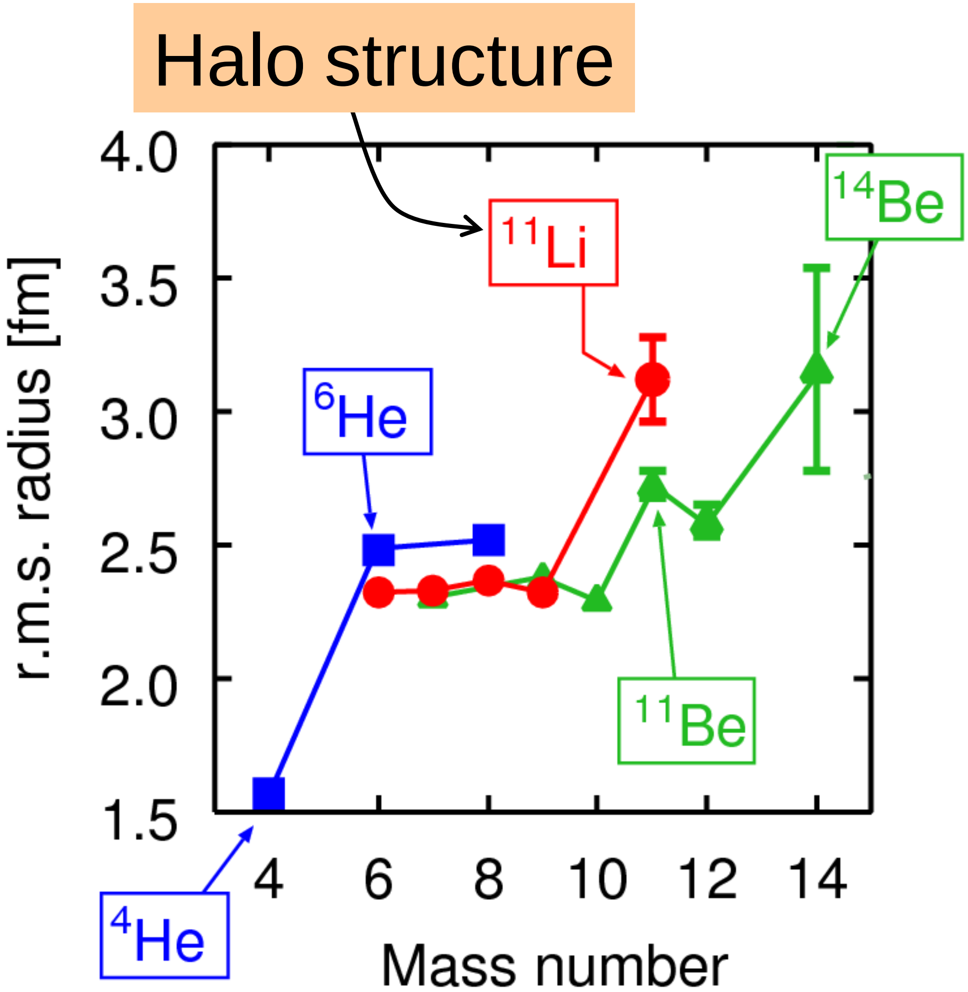
- Terasawa, Arima PTP23 ('60)
- Nagata, Sasakawa, Sawada, Tamagaki, PTP22('59)
- Myo, Kato, Ikeda, PTP113 ('05)

Halo formation in ^{11}Li

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.

Characteristics of Li-isotopes

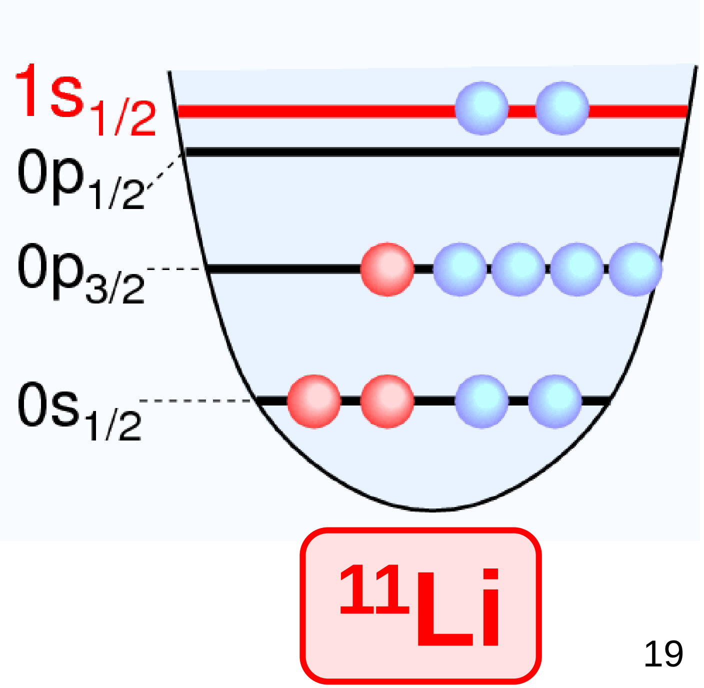


Tanihata et al., PRL55(1985)2676.
PLB206(1998)592.

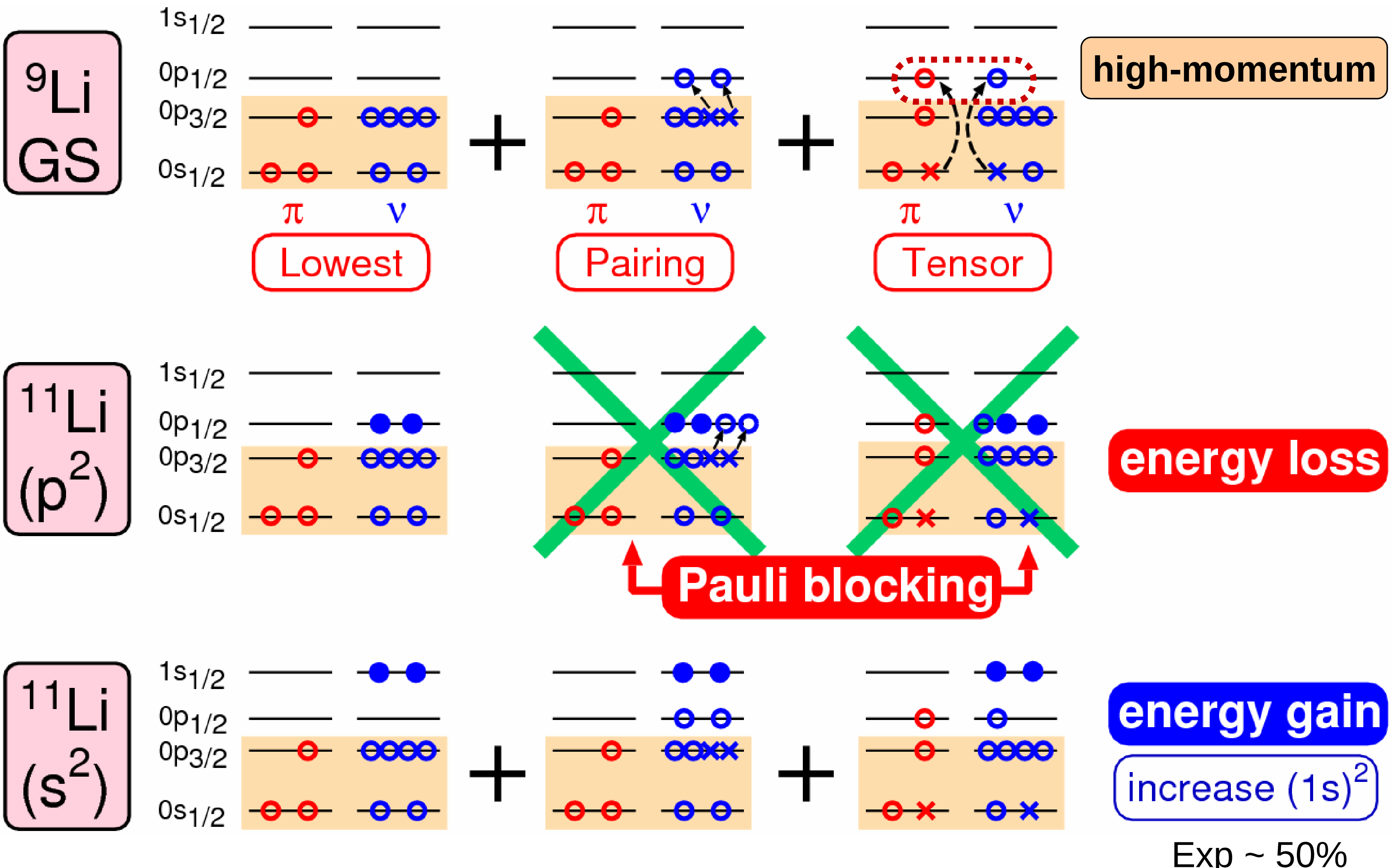
✓ Breaking of magicity N=8

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

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



Effects of tensor & pairing 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.

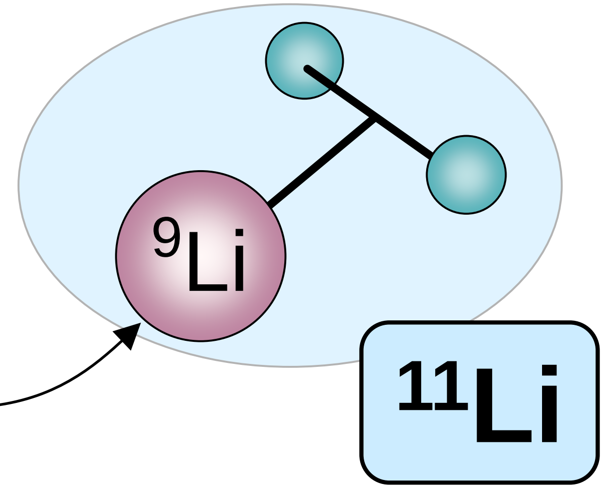
^{11}Li with ^{9}Li$_{\mathrm{TOSM}}$+n+n cluster model

- System is solved based on RGM

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

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

TOSM basis



- Orthogonality Condition Model (OCM) is applied.

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

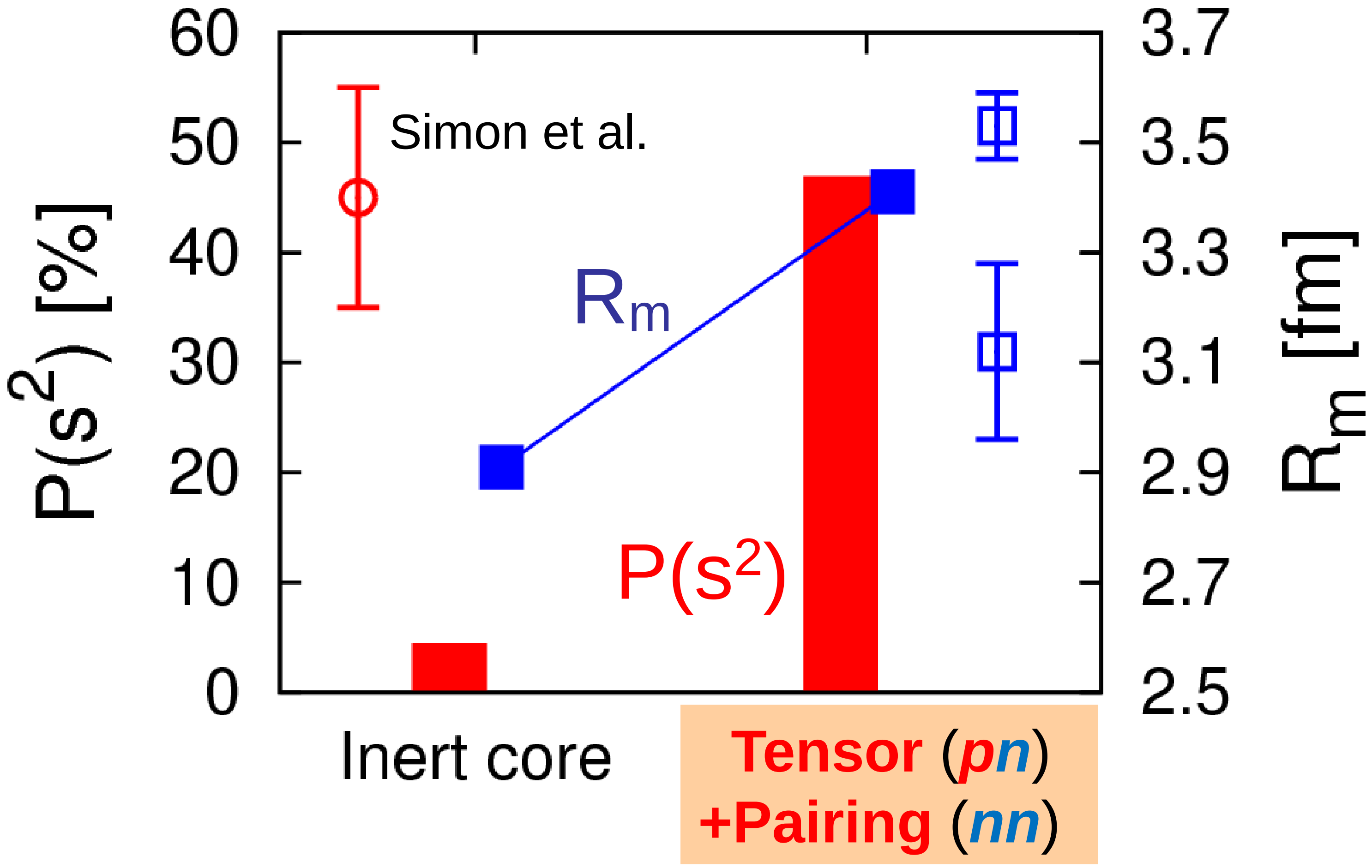
$$H_{ij}(^{9}\mathrm{Li}) = \left\langle \psi_i \middle| H(^{9}\mathrm{Li}) \middle| \psi_j \right\rangle$$: Hamiltonian for ^{9}Li with TOSM

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

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

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

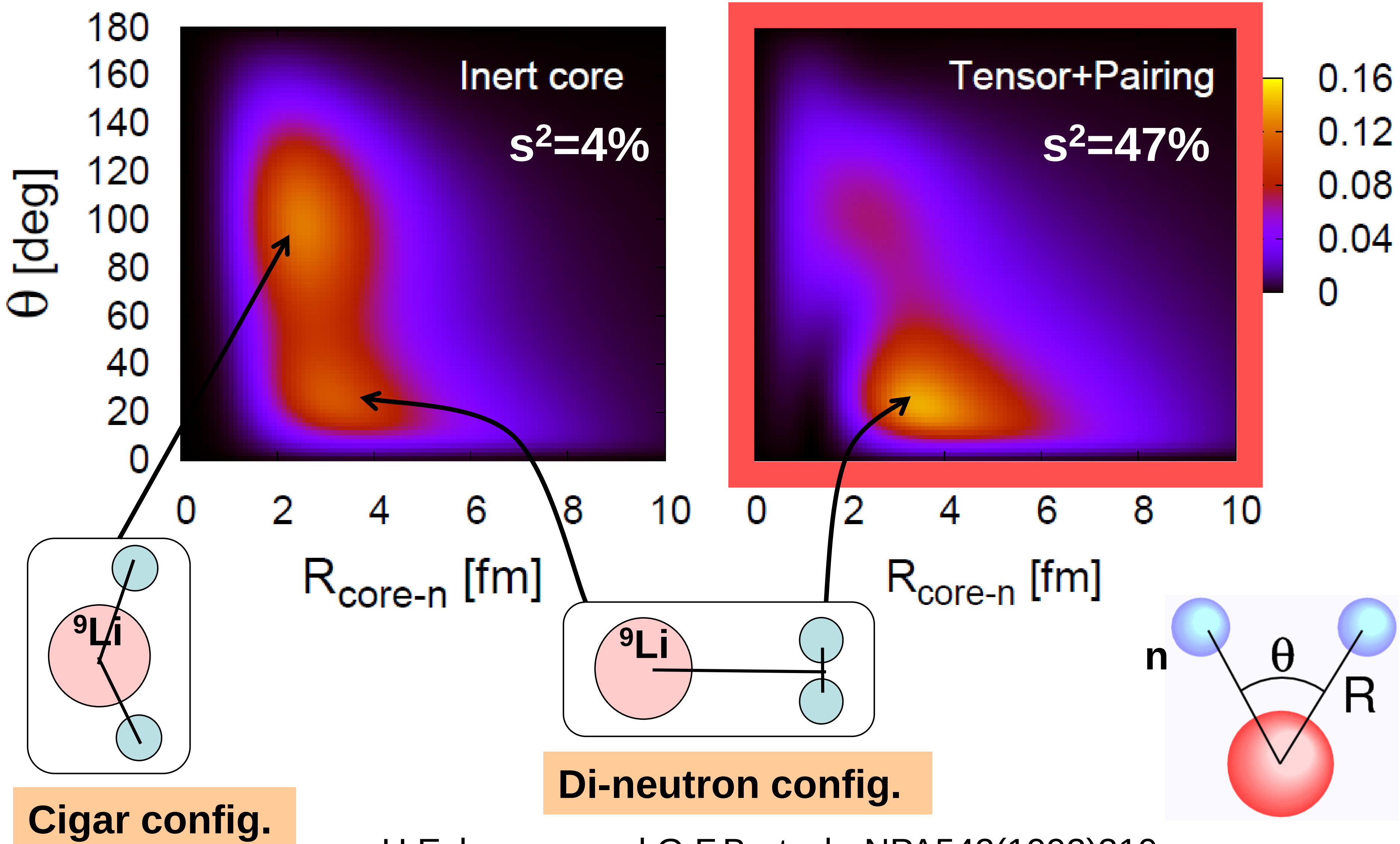
^{11}Li properties (S_{2n}=0.31 MeV)



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

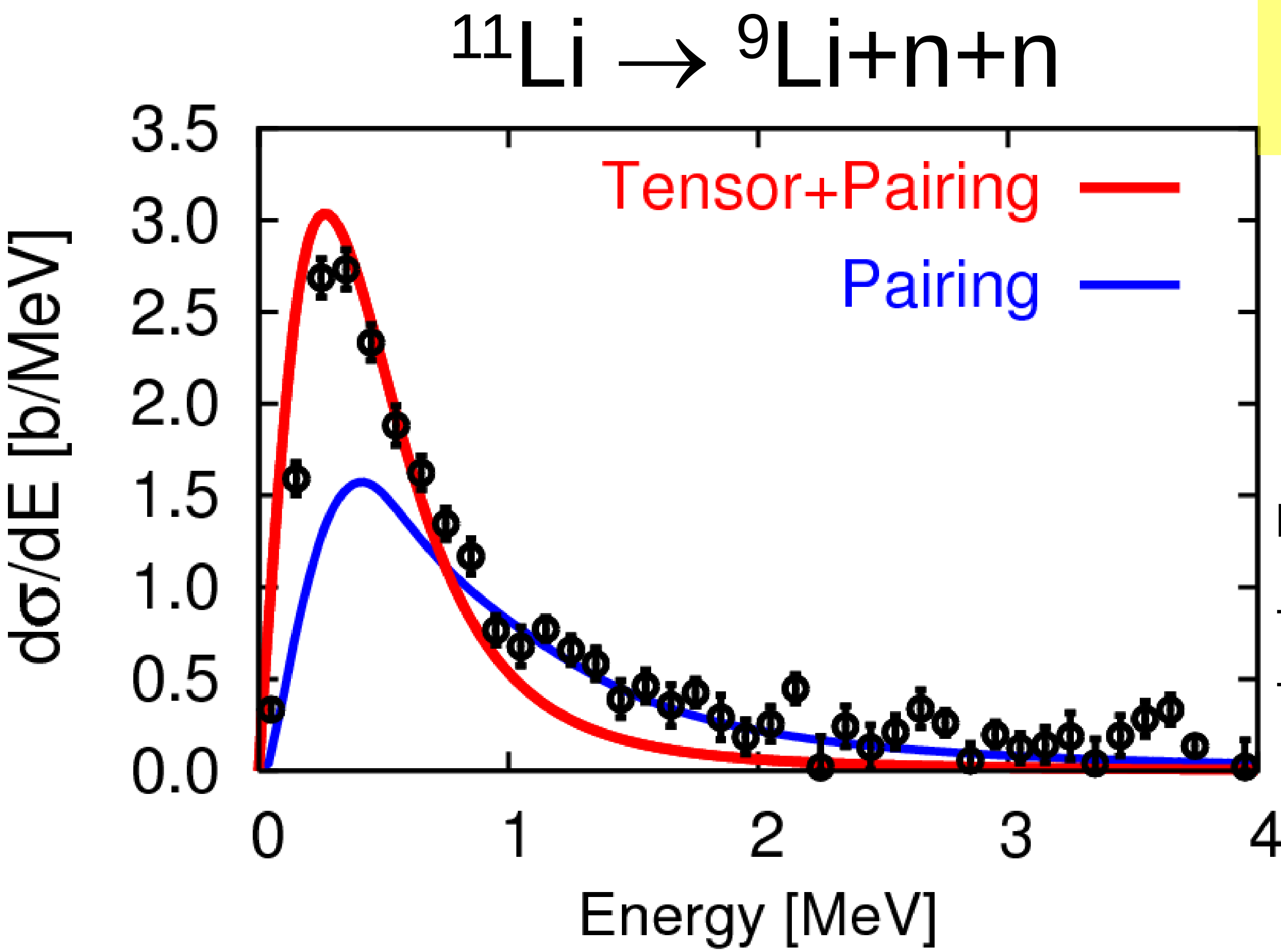
2n correlation density in ^{11}Li



H.Esbensen and G.F.Bertsch, NPA542(1992)310

K. Hagino and H. Sagawa, PRC72(2005)044321

Coulomb breakup strength of ^{11}Li



Kikuchi (Thu.) VI-a
binary correlation

No three-body resonance

E1 strength
+ **Complex scaling**
+Equivalent photon method

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

Virtual *s*-wave states in ^{10}Li

- **$1s_{1/2}$ virtual state:**

  $(0p_{3/2})_\pi (1s_{1/2})_\nu \rightarrow 1^-, 2^-$

a_s : scattering length of ^{9}Li+n

J^π	Inert core	**Tensor +Pairing**
1^-	+1.4 fm	–5.6 fm
2^-	+0.8 fm	–17.4 fm

Expt. M. Thoennessen et al., PRC59 (1999)111.
M. Chartier et al. PLB510(2001)24.
H.B. Jeppesen et al. PLB642(2006)449.

a_s = –10 ~ –25 fm

cf. $a_s(nn) = -18.5 \pm 0.5$ fm

Pauli-blocking naturally describes virtual s-state in ^{10}Li

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.
- **Halo formation in ^{11}Li** with tensor and pairing correlations.
  - Coexistence of tensor and pairing correlations
  - Pauli-blocking caused by halo neutrons

Collaborators

- Kaori Horii (RCNP, Osaka Univ.)
- Yuma Kikuchi (RCNP, Osaka Univ.)
- Atsushi Umeya (Nippon Institute of Technology)

- Kiyoshi Kato (Hokkaido Univ.)
- Hiroshi Toki (RCNP, Osaka Univ.)
- Kiyomi Ikeda (RIKEN Nishina center)