テンソル最適化シェルモデルによるs-pシェル核構造

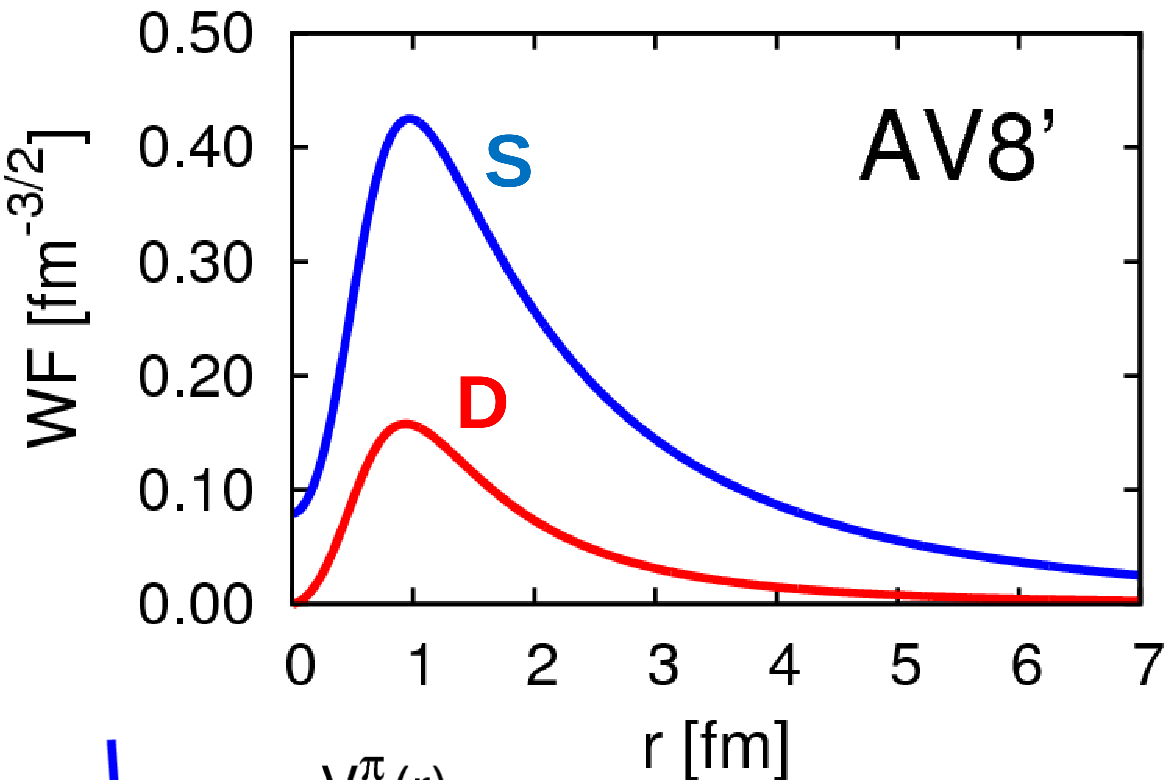
明 孝之
大阪工業大学

日本物理学会第67回年次大会
テンソル力による核子多体系の構造とそのダイナミックス 於 関西学院大学2012.3

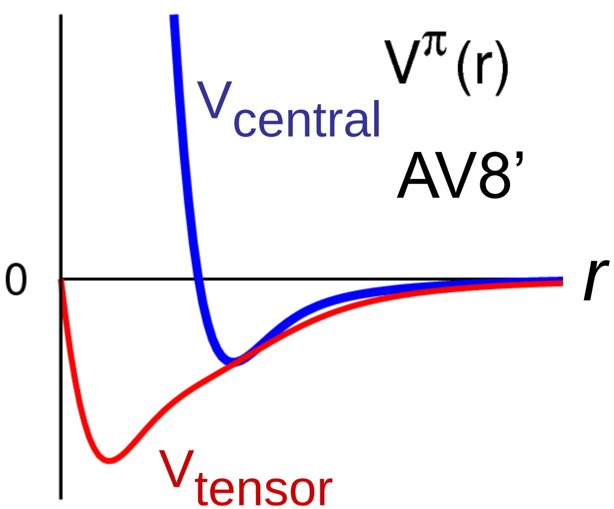
Purpose & Outline

- **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}
- Halo formation in ^{11}Li
  - 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

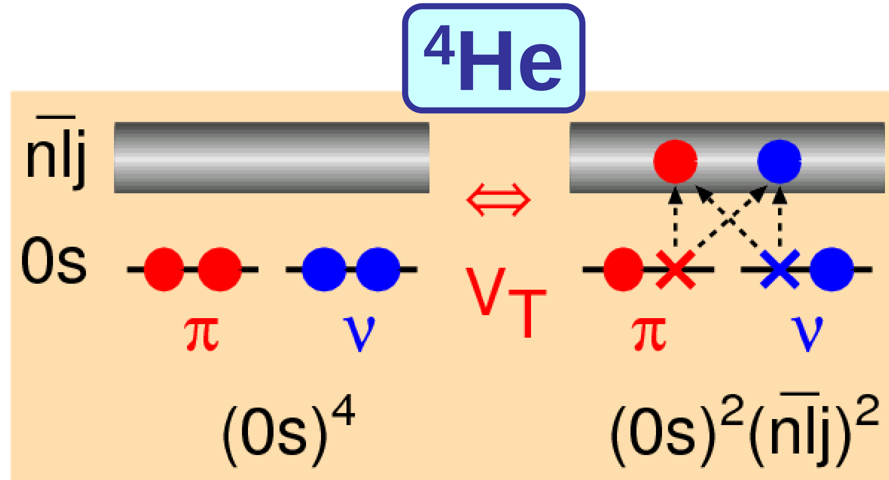
$R_m(d)$=1.22 fm

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

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

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

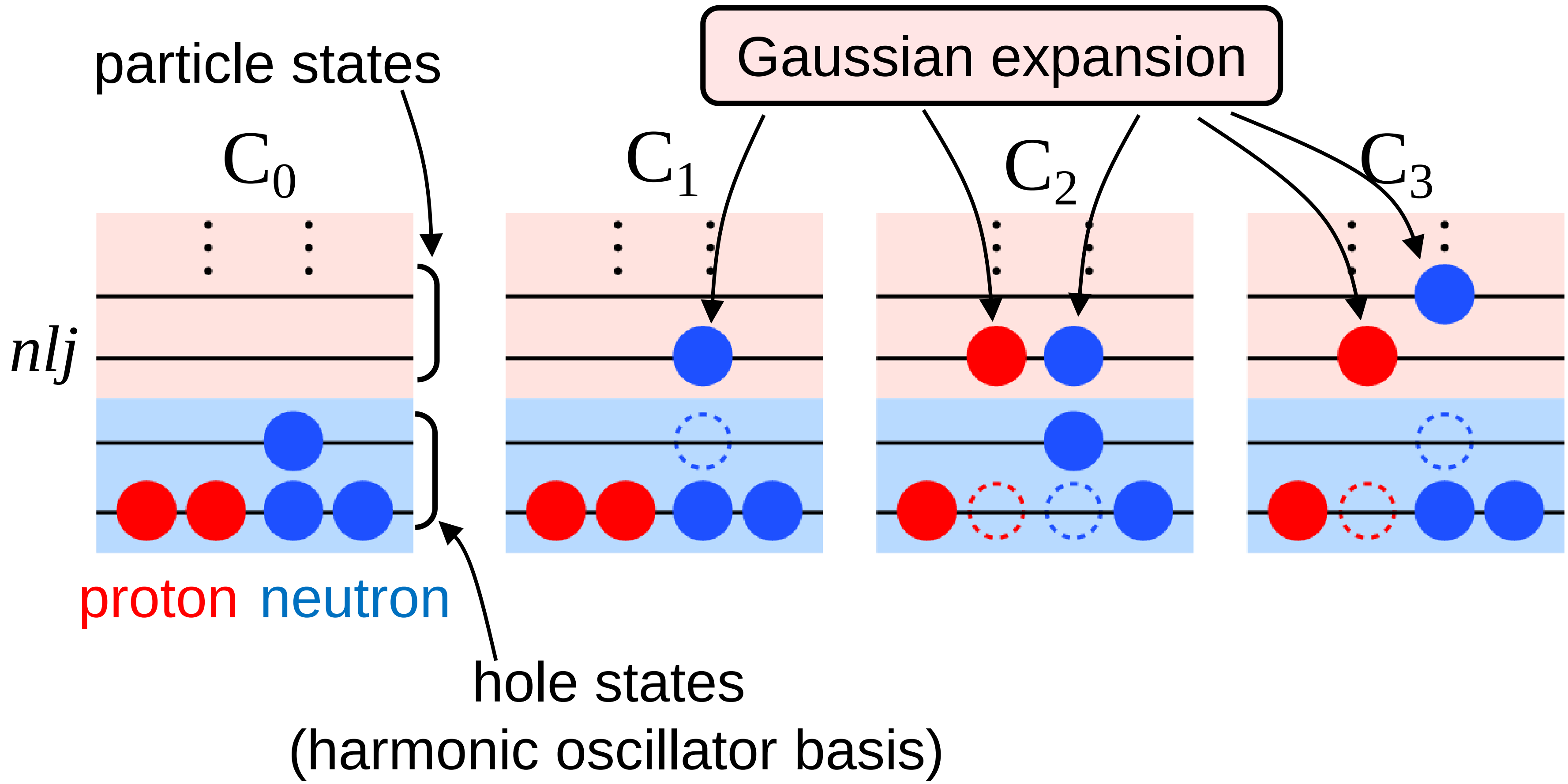
Gaussian basis function

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

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

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

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

Bare Hamiltonian

Shift operator depending on the relative distance

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

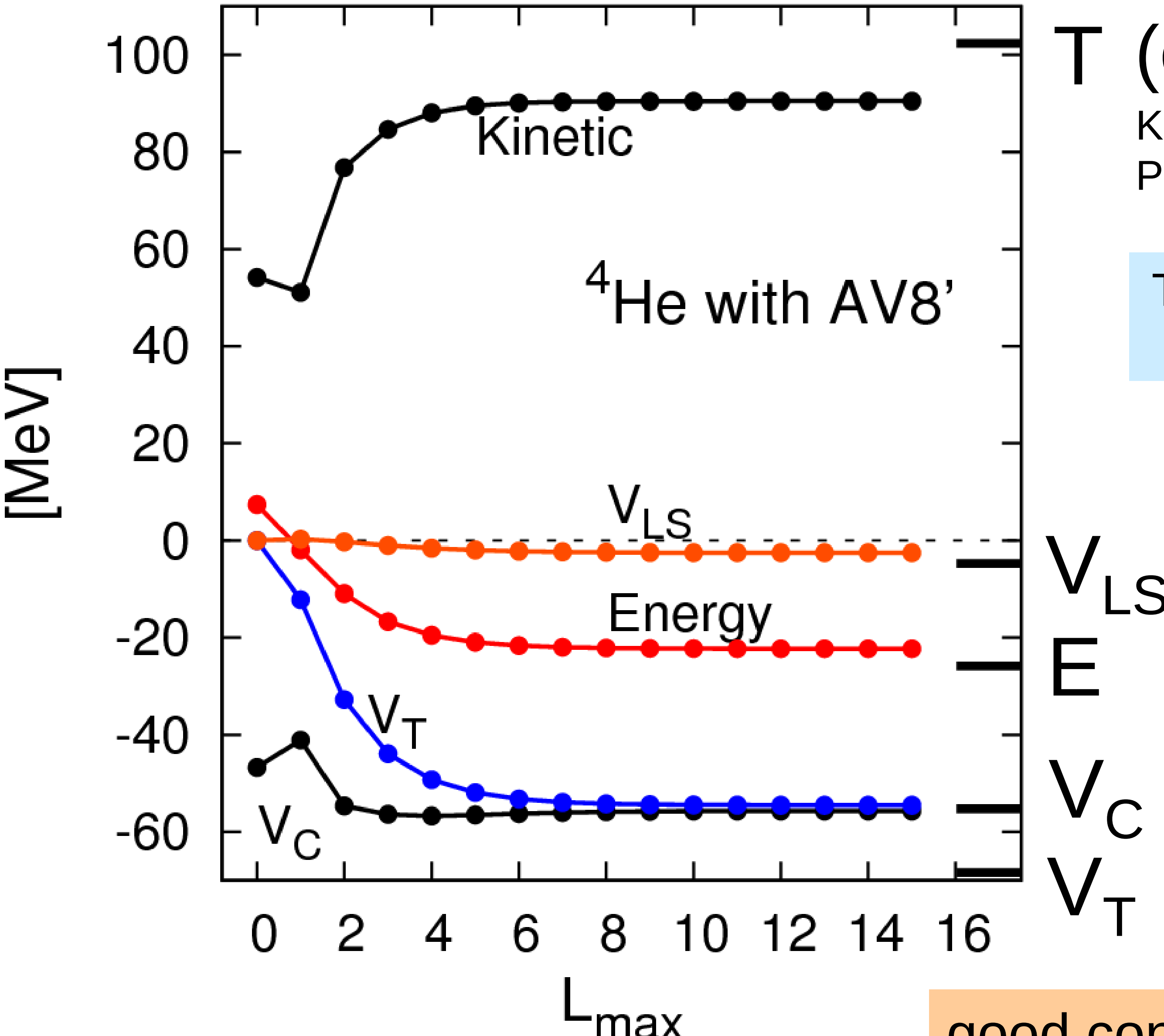
Amount of shift, variationally determined.

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

2-body cluster expansion

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

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



Kamada et al.
PRC64 (Jacobi)

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

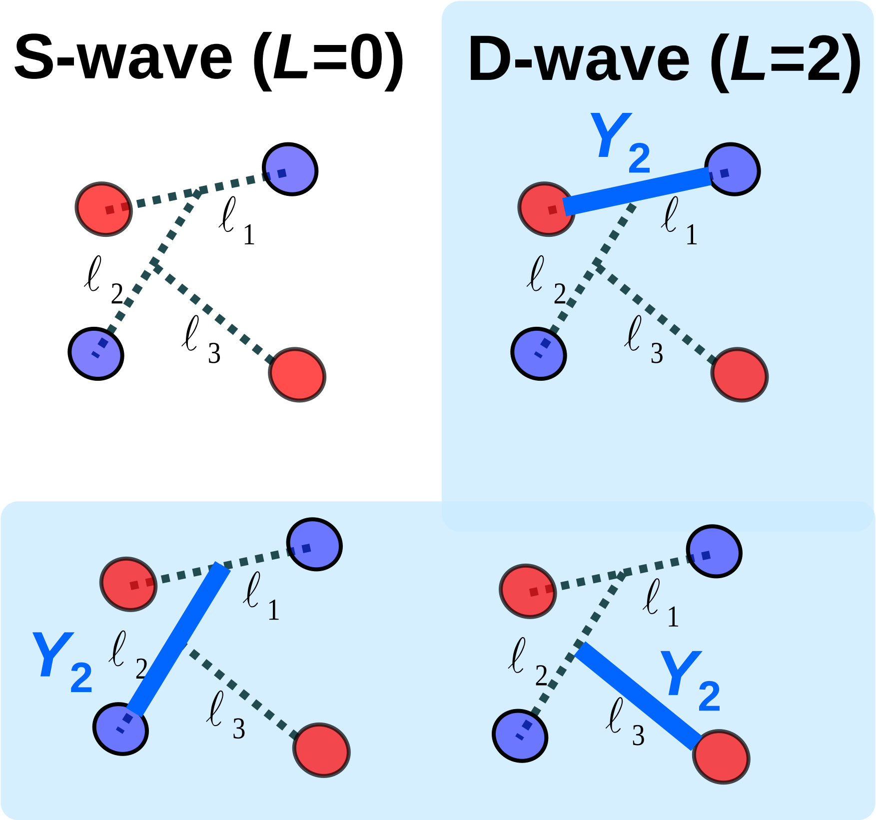
- variational calculation
- Gaussian expansion with 9 Gaussians

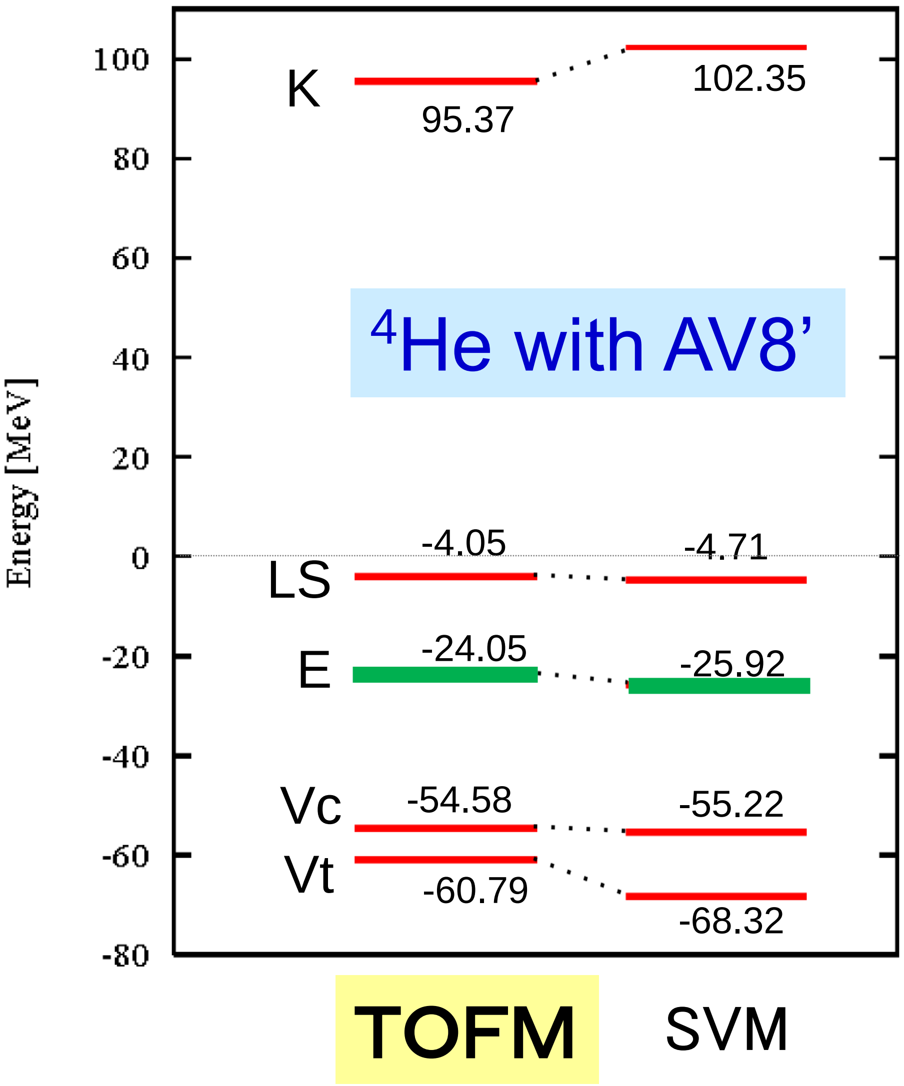
good convergence

Tensor Optimized Few-body Model

堀井ら
(RCNP)

- Same as TOSM concept
- Correlated Gaussian basis
  + Global vector used in SVM



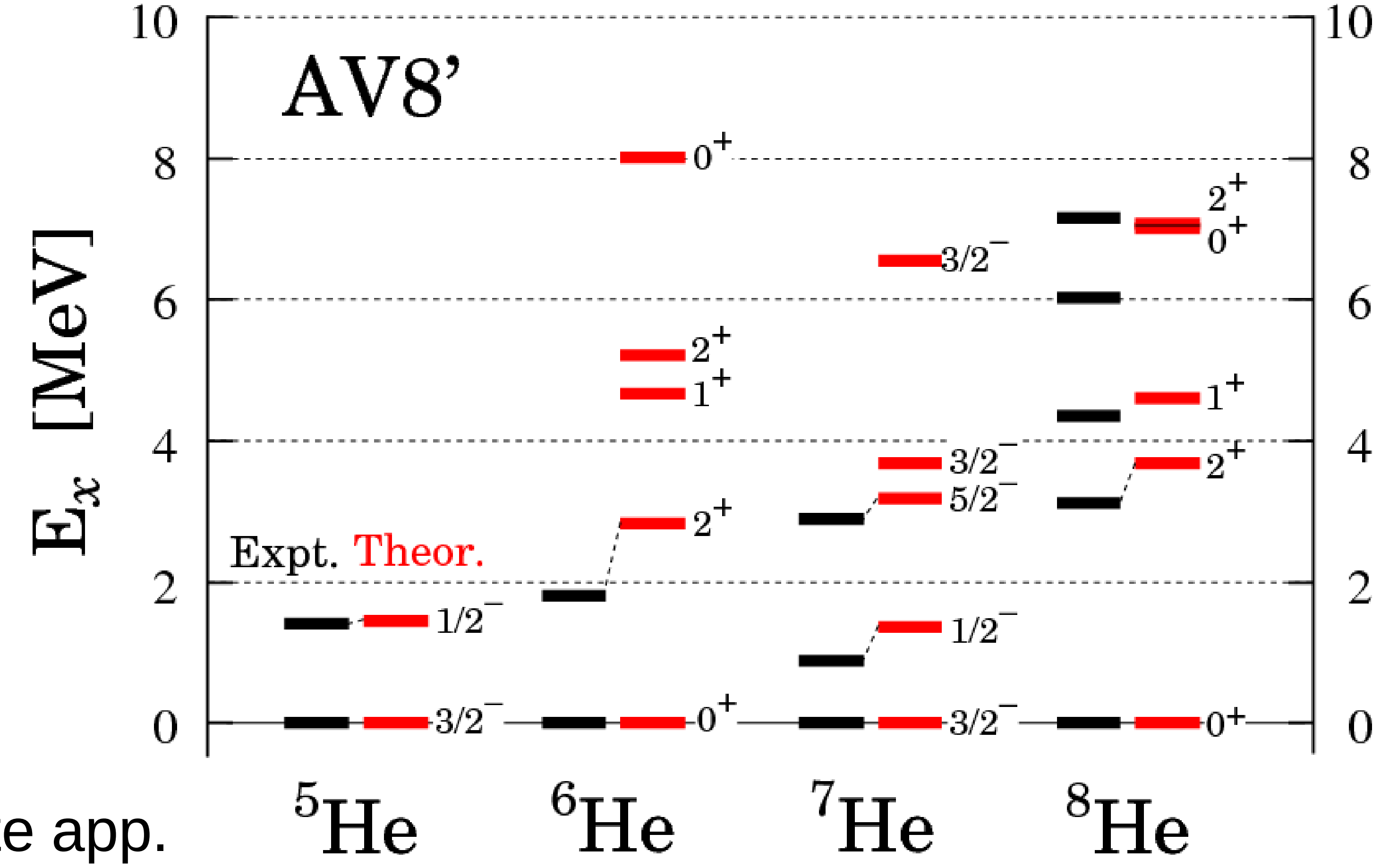


Few Body System 42(2008)33 Y.Suzuki, et al

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

- Excitation energies in MeV

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

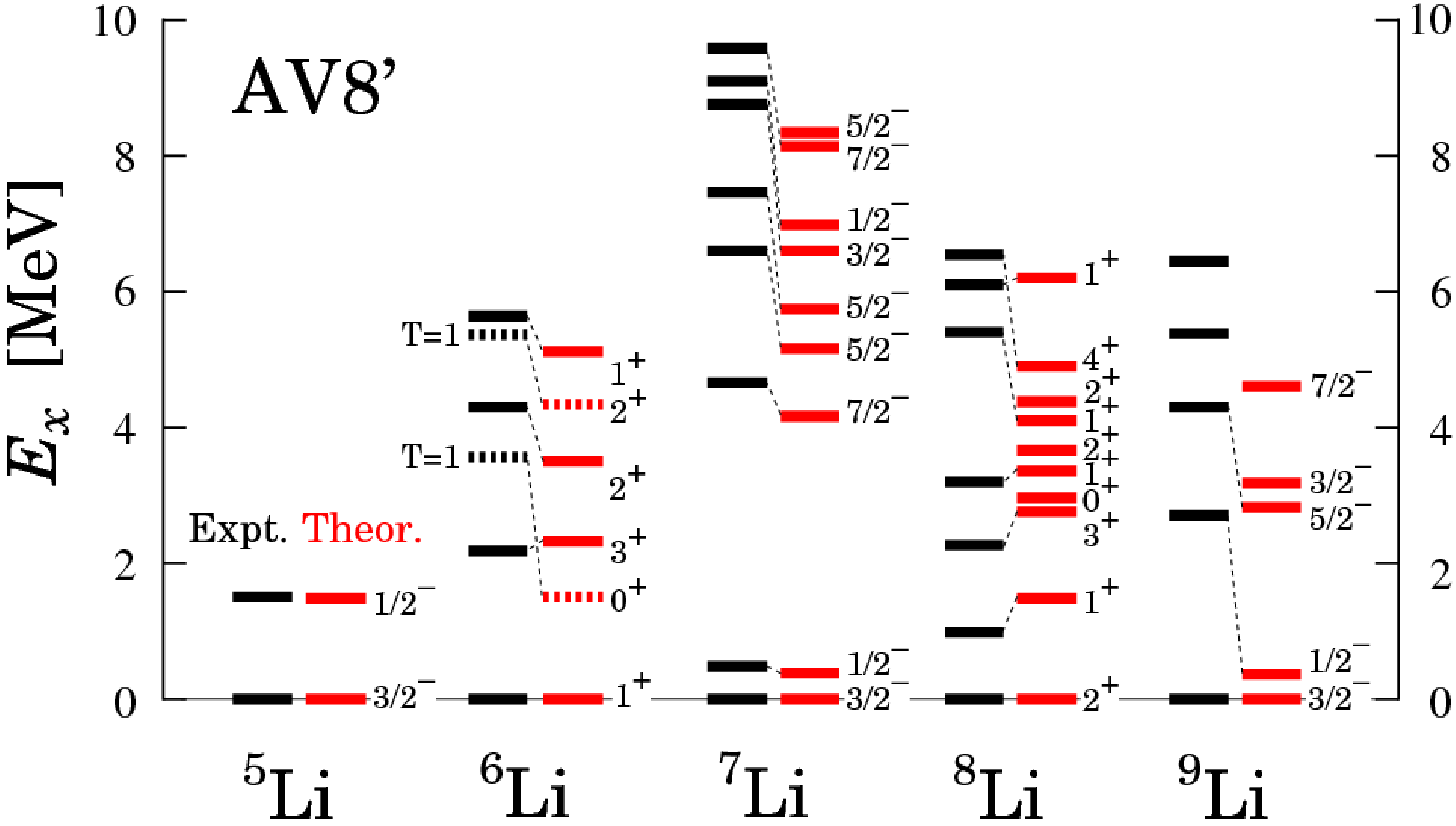


- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

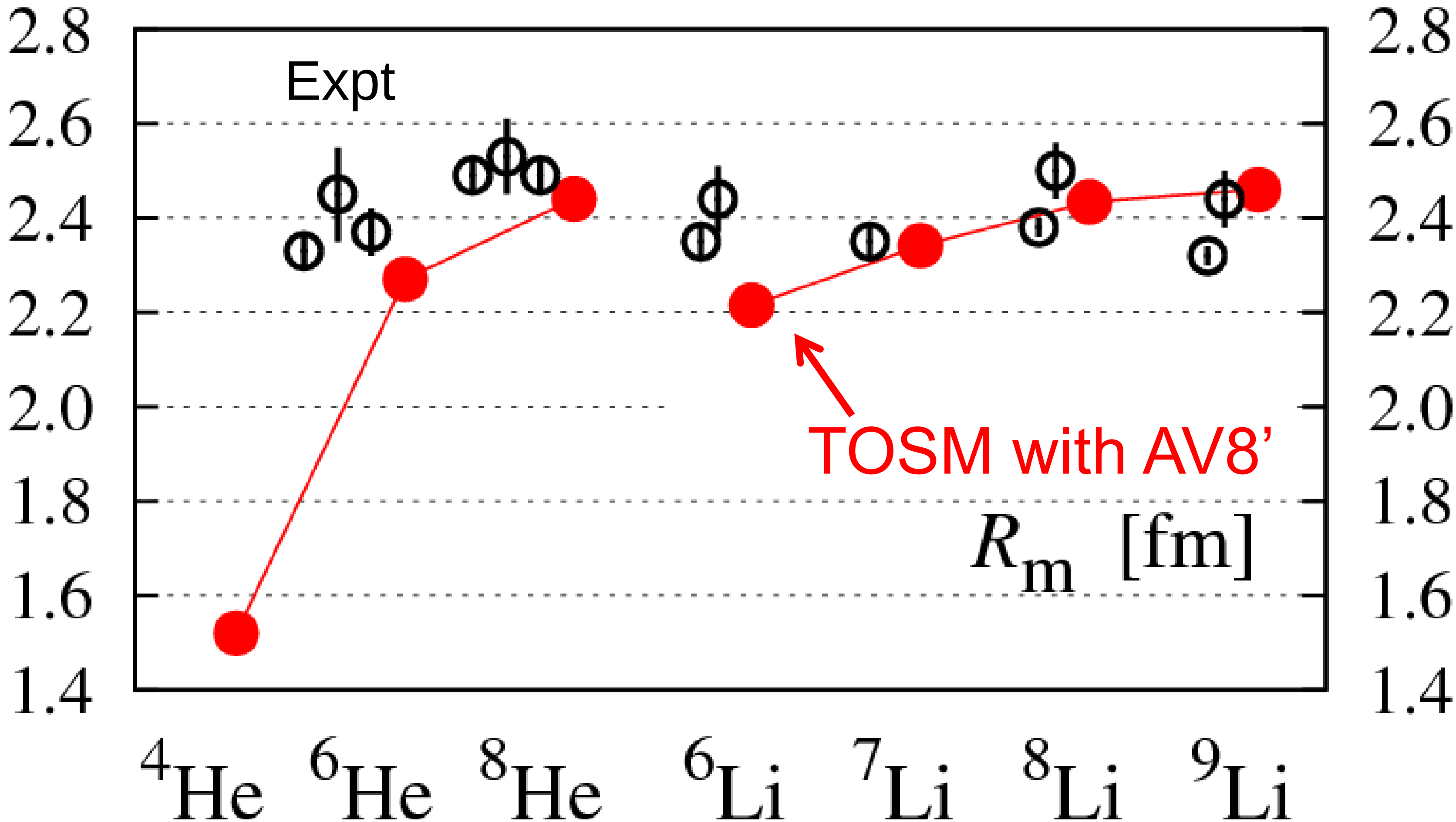
$^{5\text{-}9}$Li with TOSM+UCOM

- Excitation energies in MeV



- Excitation energy spectra are reproduced well

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

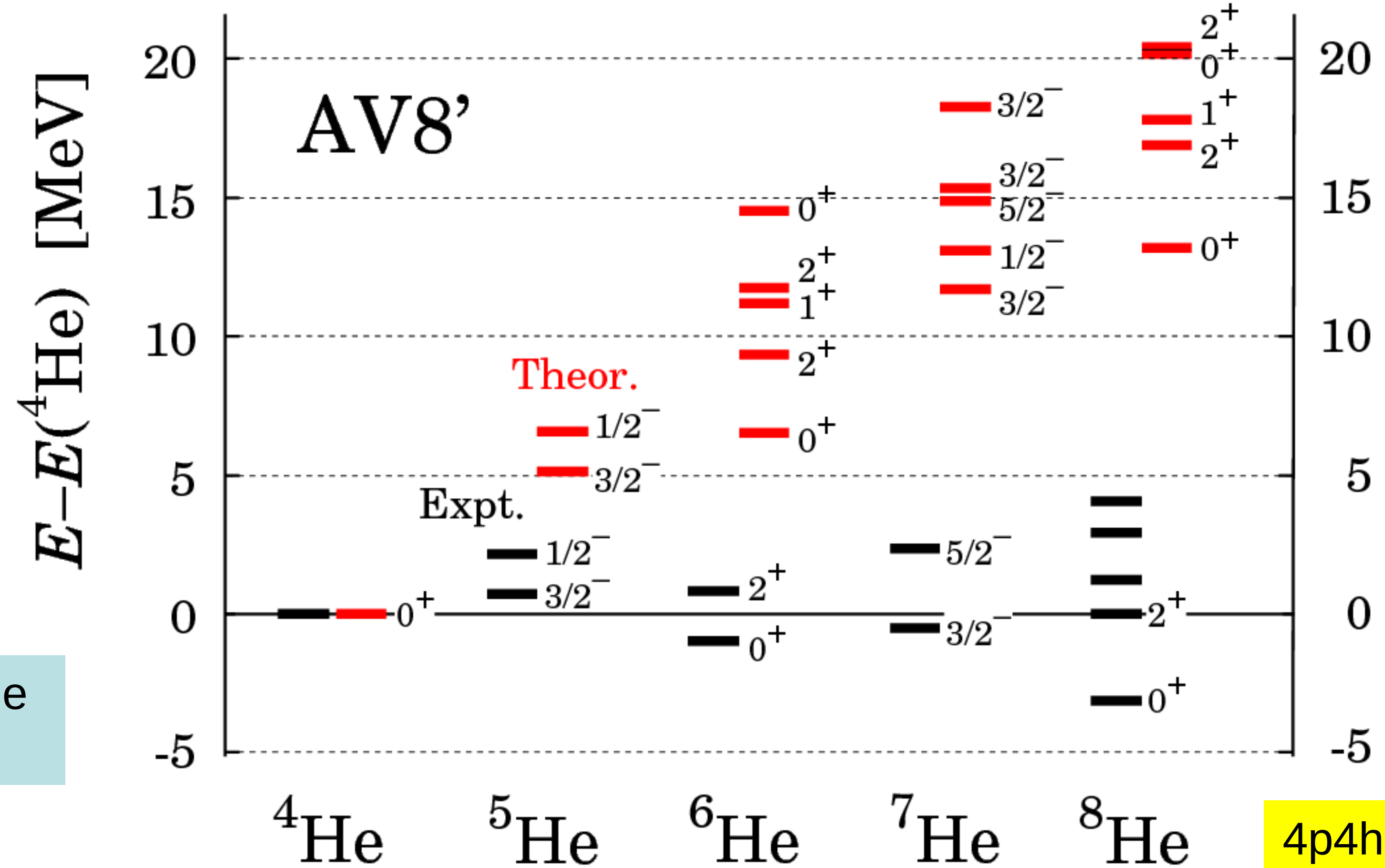
O. A. Kiselev et al., EPJA 25, Suppl. 1('05)215.

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

$^{4-8}$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

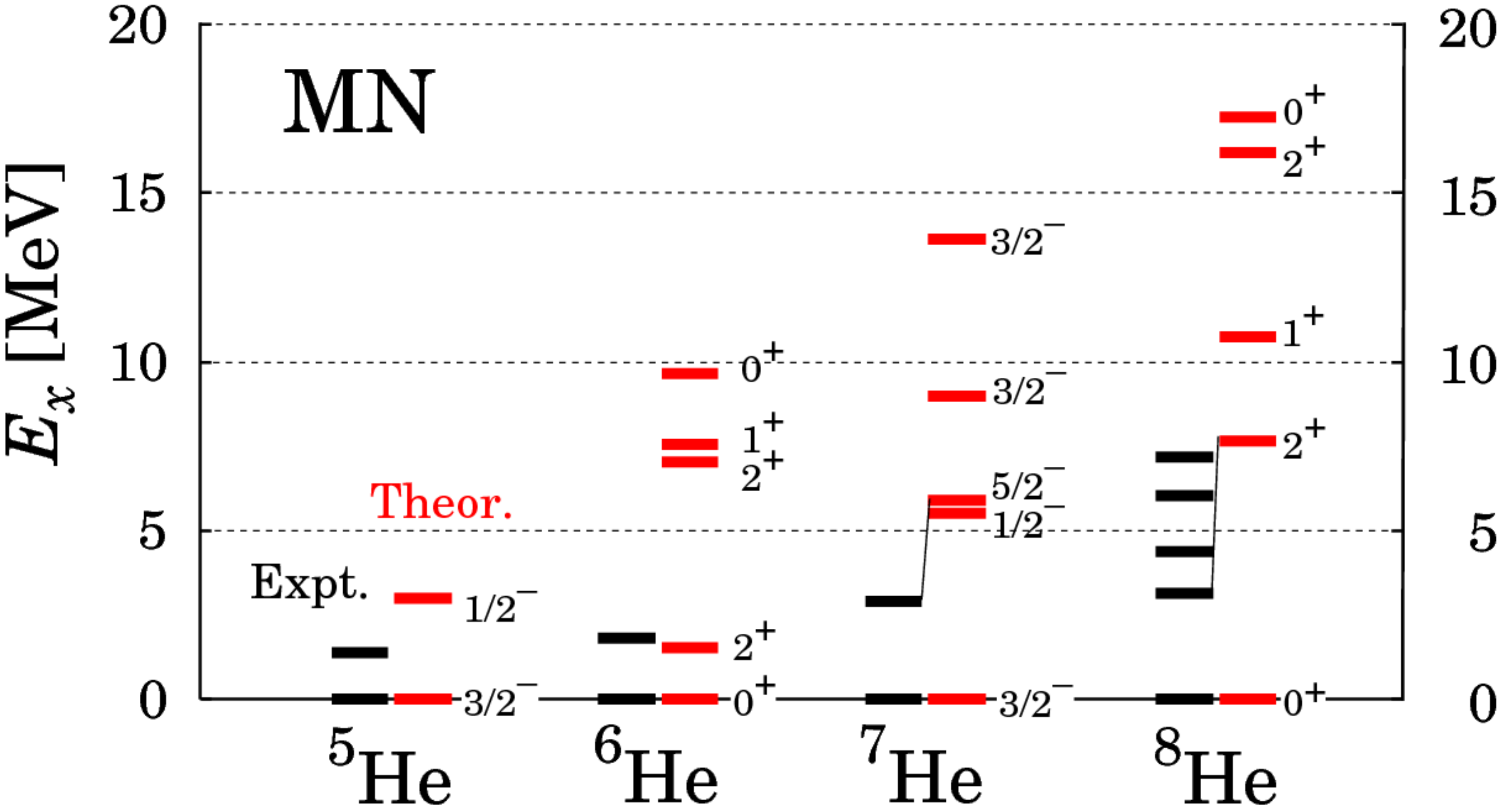
4p4h in TOSM

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

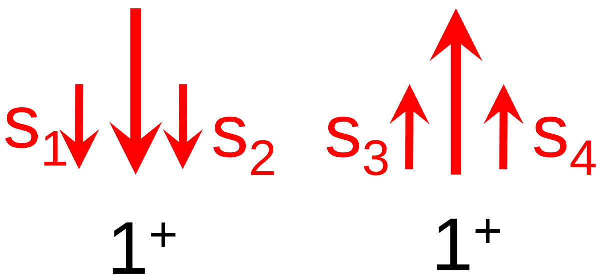
- ^{4}He contains $p_{1/2}$ of "***pn*-pair**"
  - Same feature in ^{5}He-^{8}He ground state

Selectivity of the tensor coupling in ^{4}He

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

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

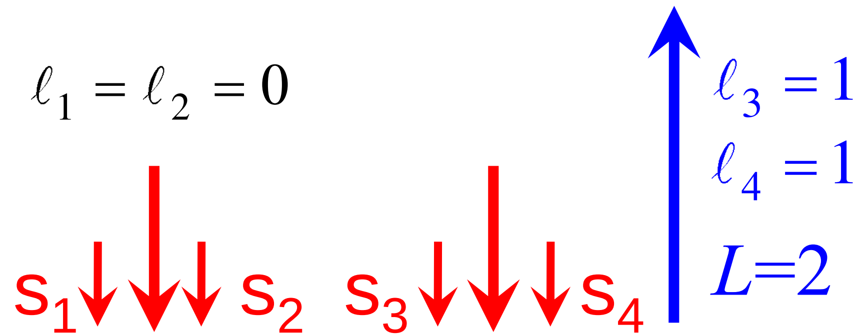
$\ell_1 = \ell_2 = \ell_3 = \ell_4 = 0$



V_T

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

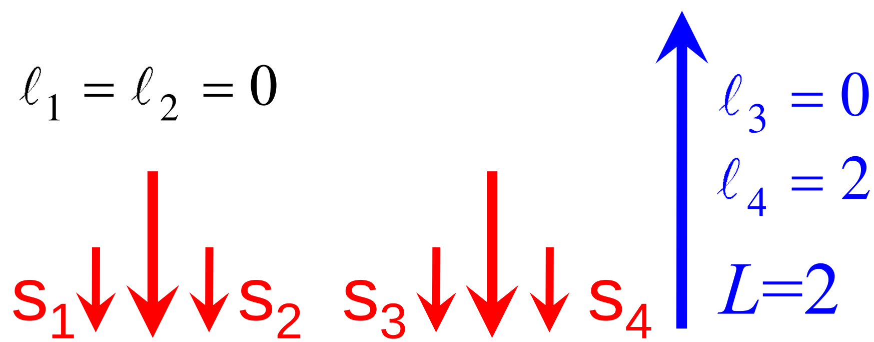
$\ell_1 = \ell_2 = 0$



V_T

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

$\ell_1 = \ell_2 = 0$



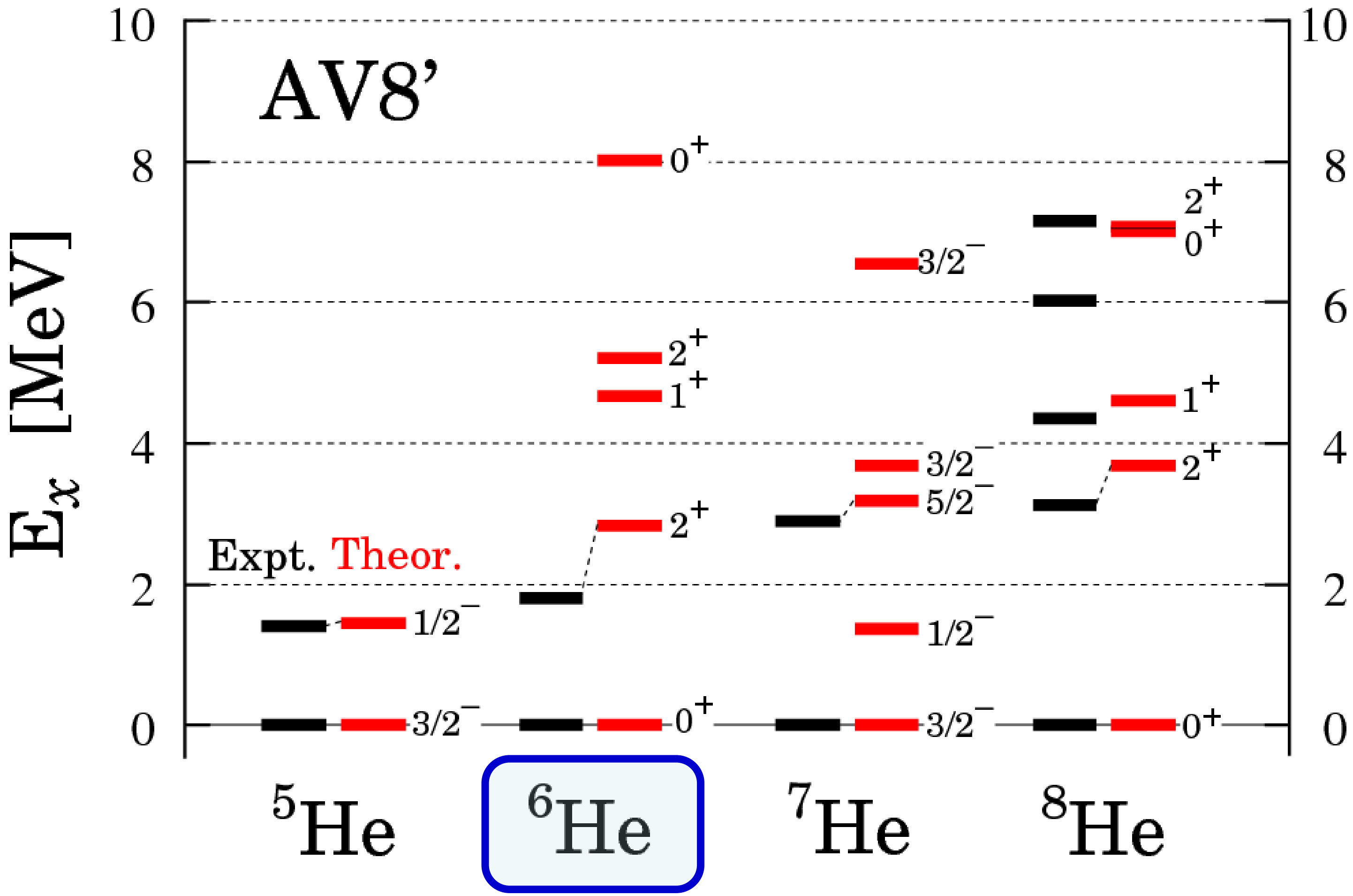
Selectivity of tensor operator

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

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

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

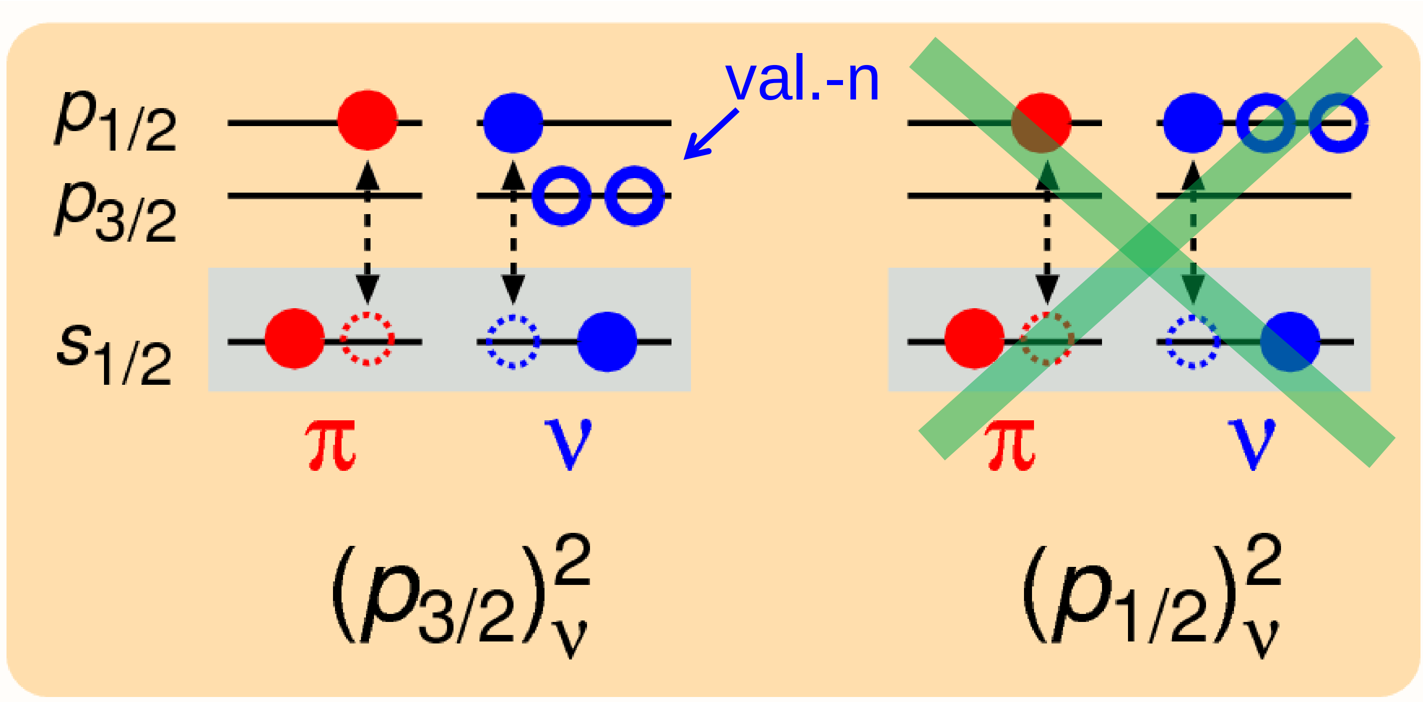
- Excitation energies in MeV



- 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

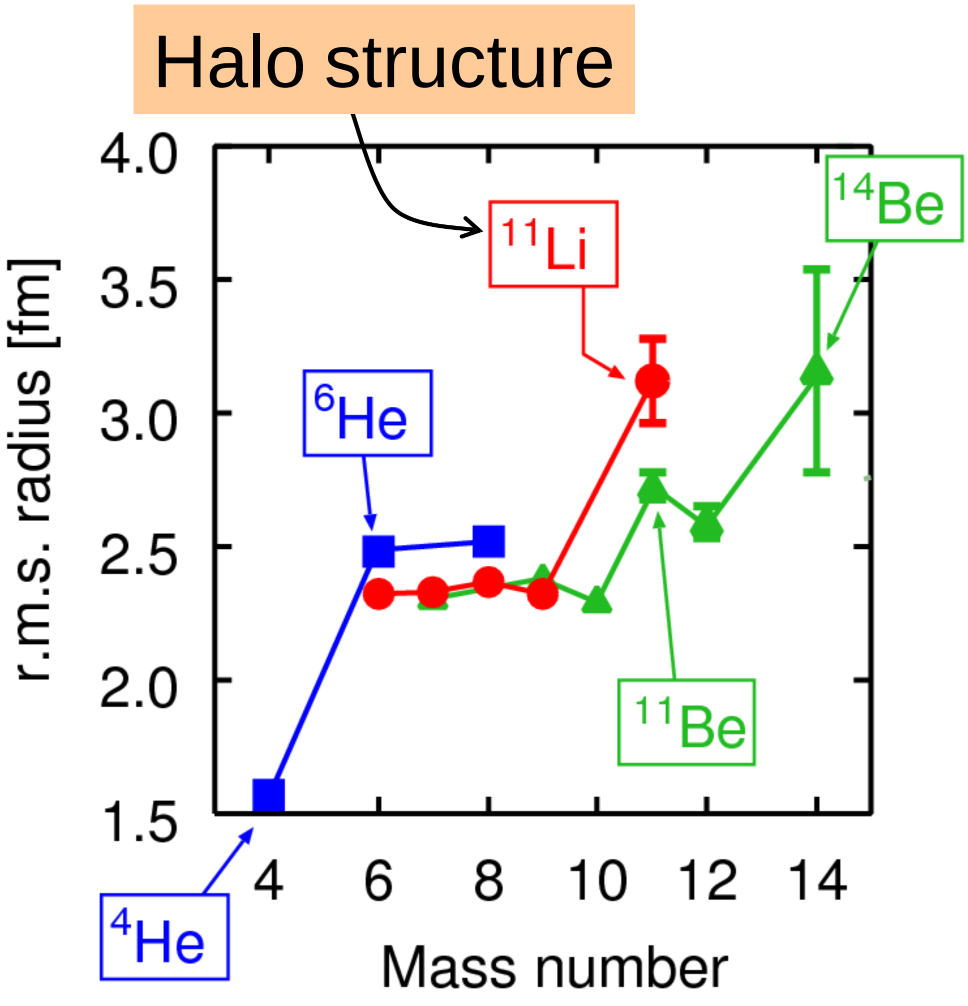
$\hbar\omega$=18.4 MeV (hole)

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)

Characteristics of Li-isotopes

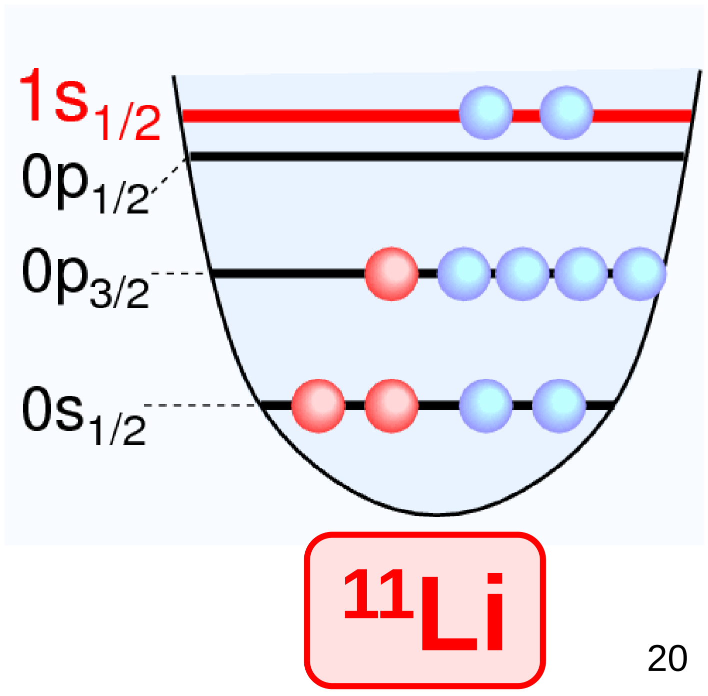


Tanihata et al., PRL55(1985)2676.
PLB206(1998)592.

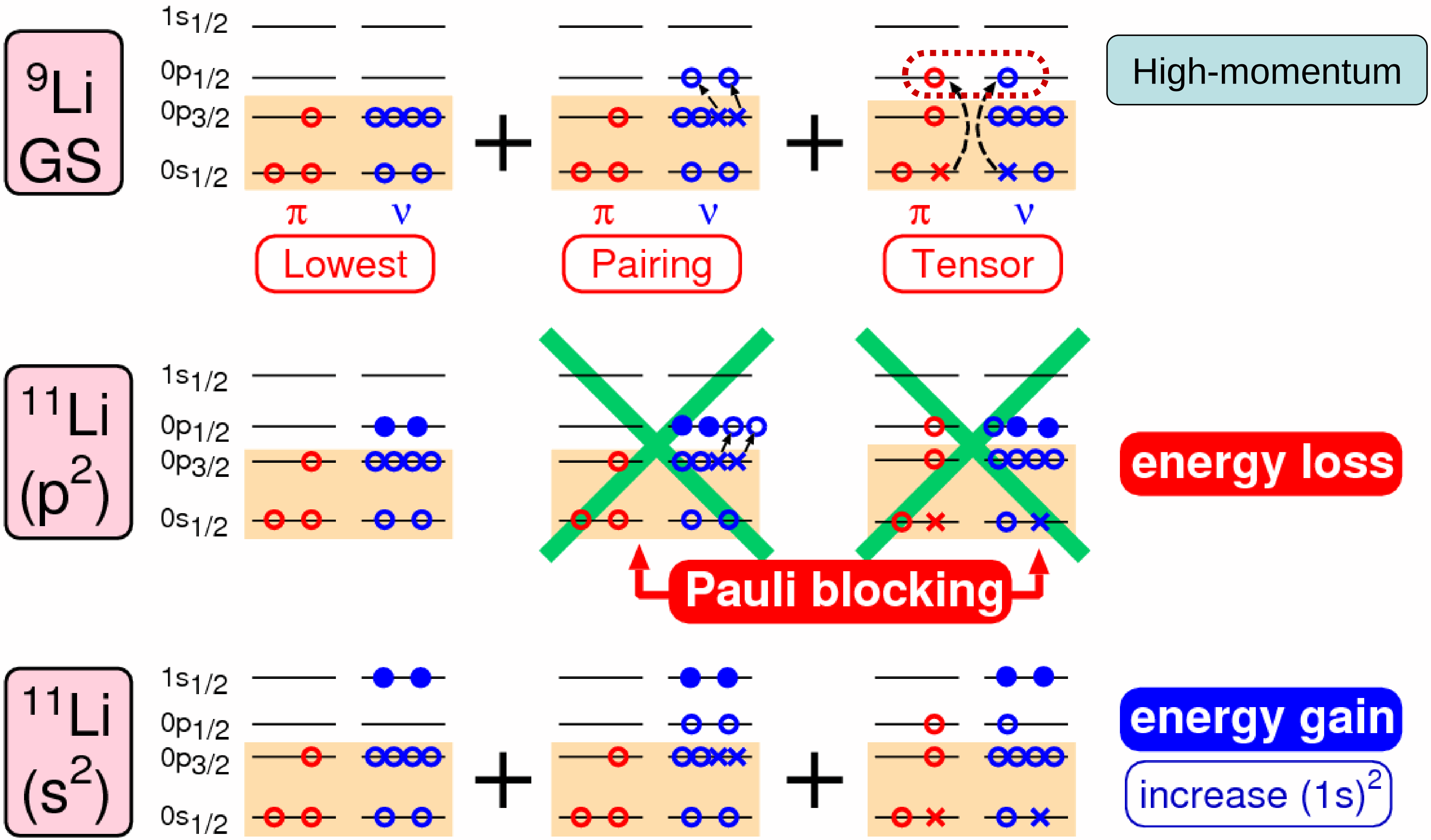
✓ Breaking of magicity N=8

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

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



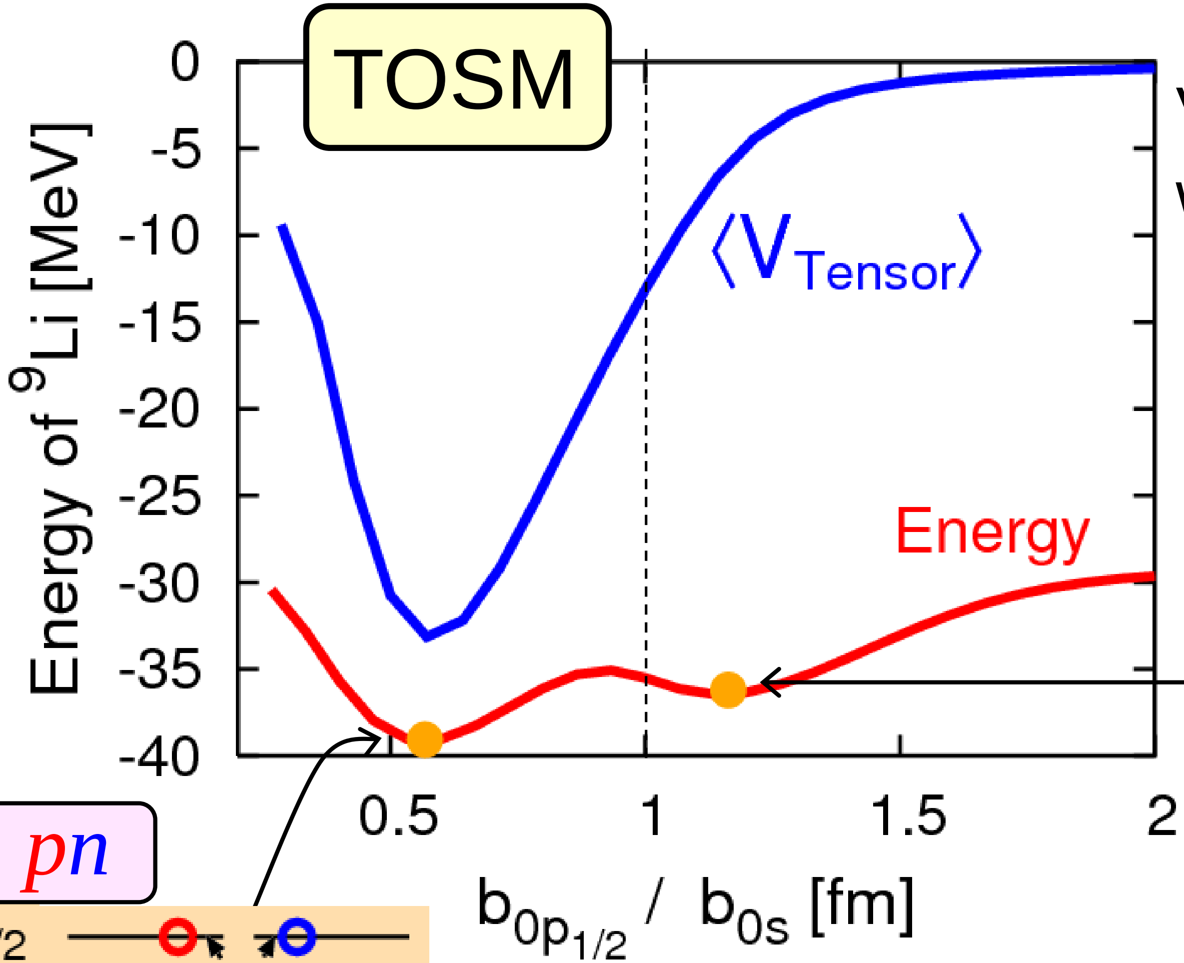
Expected effects of pairing and tensor correlations in ^{11}Li



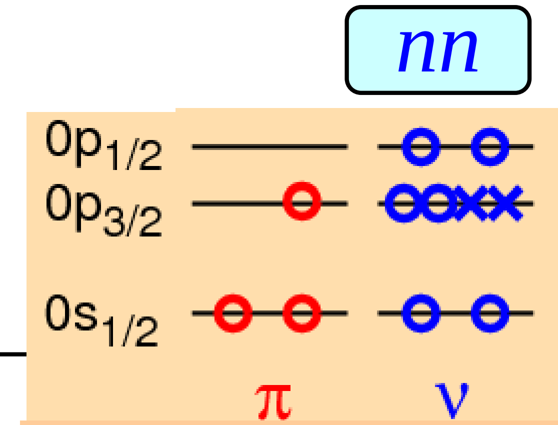
Pairing-blocking :

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.

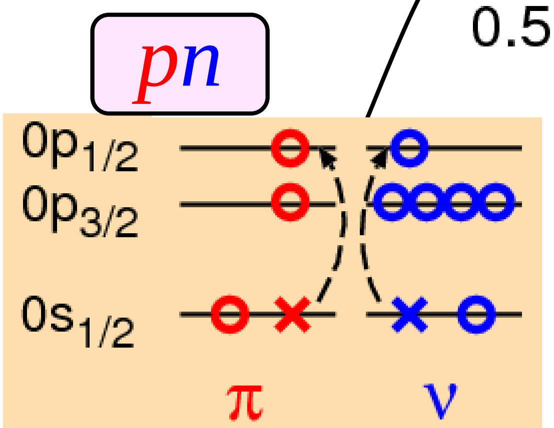
Energy surface for *b*-parameter in ^{9}Li



V_{tensor} is optimized with shrunk HO basis



pairing correlation



Dominant part of the tensor correlation

cf. 1st order (residual interaction): T. Otsuka et al. PRL95(2005)232502.

^{11}Li in coupled ^{9}Li+n+n model

- System is solved based on RGM

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

$$\sum_{i=1}^{N} \left\langle \psi_j(^{9}\mathrm{Li}) \middle| H(^{11}\mathrm{Li}) - E \middle| \mathcal{A}\left\{\psi_i(^{9}\mathrm{Li}) \cdot \chi_i(nn)\right\}\right\rangle = 0$$

$\psi_i(^{9}\mathrm{Li})$: shell model type configuration → TOSM

- Orthogonality Condition Model (OCM) is applied.

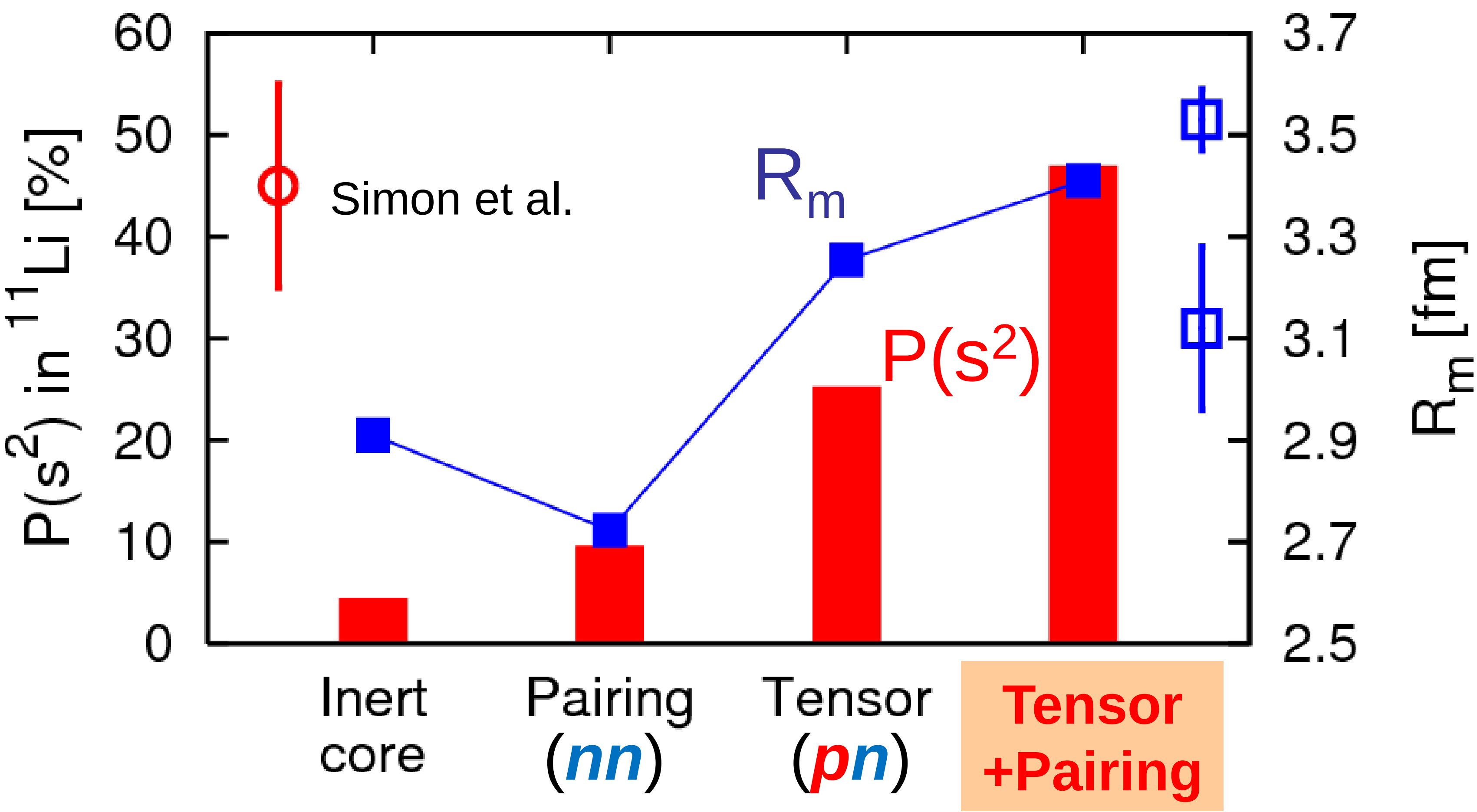
$$\sum_{i=1}^{N} \left[H_{ij}(^{9}\mathrm{Li}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12}) \cdot \delta_{ij} \right] \chi_j(nn) = E \chi_i(nn)$$

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

$\chi(nn) = \mathcal{A}\{\varphi_1 \varphi_2\}$: 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

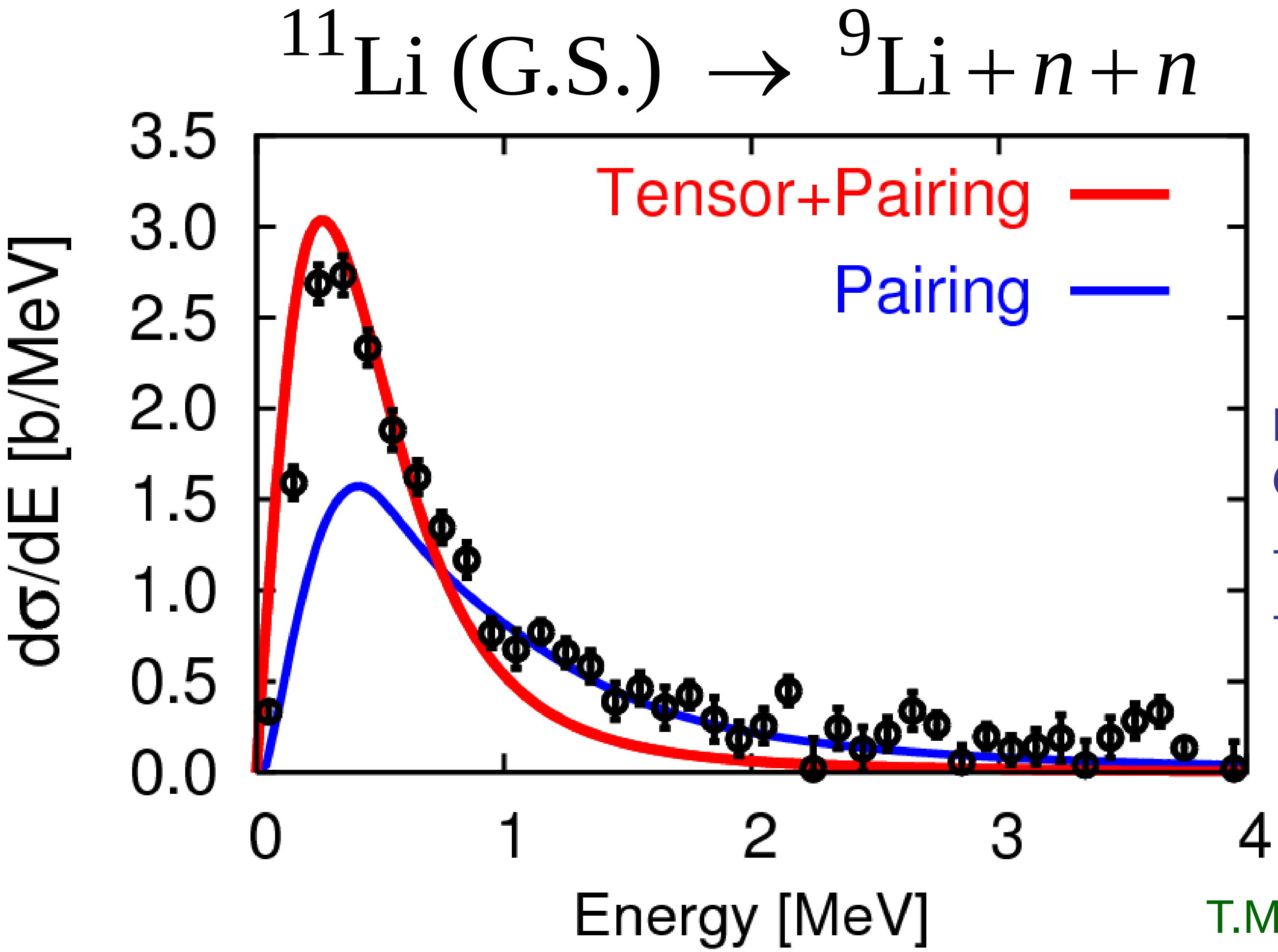
^{11}Li G.S. properties (S_{2n}=0.31 MeV)



$E(s^2)-E(p^2)$	2.1	1.4	0.5	-0.1	[MeV]

Pairing correlation couples $(0p)^2$ and $(1s)^2$ for last 2n

Coulomb breakup strength of ^{11}Li



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.

Summary

- **TOSM+UCOM** with bare nuclear force.
- ^{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 than **those with $p_{1/2}$**.
- **Halo formation in ^{11}Li** with tensor and pairing correlations.

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

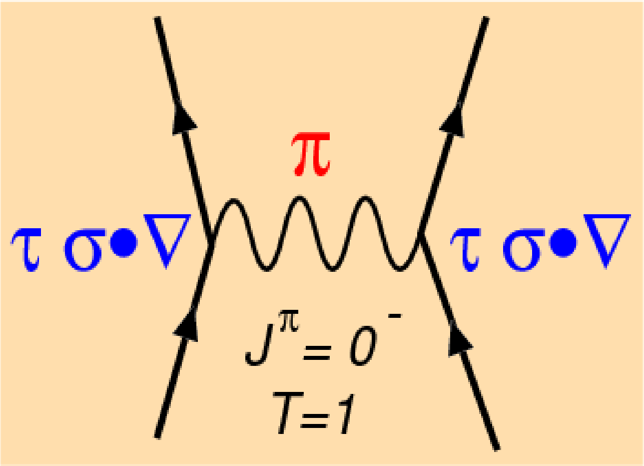
Springer, Lecture Notes in Physics 818 (2010)

"Clusters in Nuclei" Vol.1, 165-221.

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

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

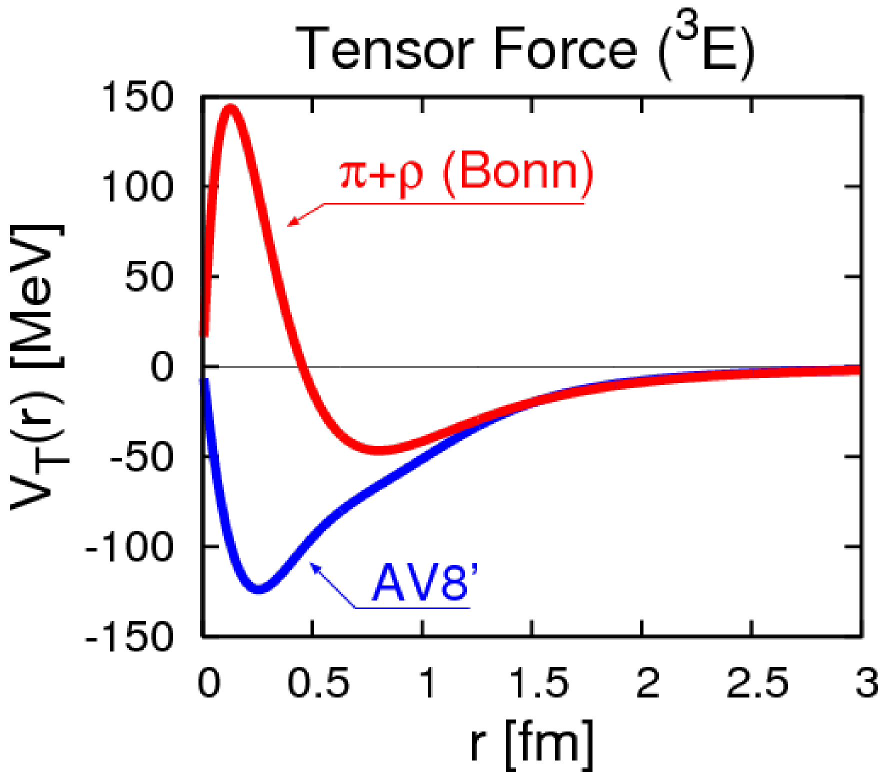
- V_{tensor} produces the high momentum component.

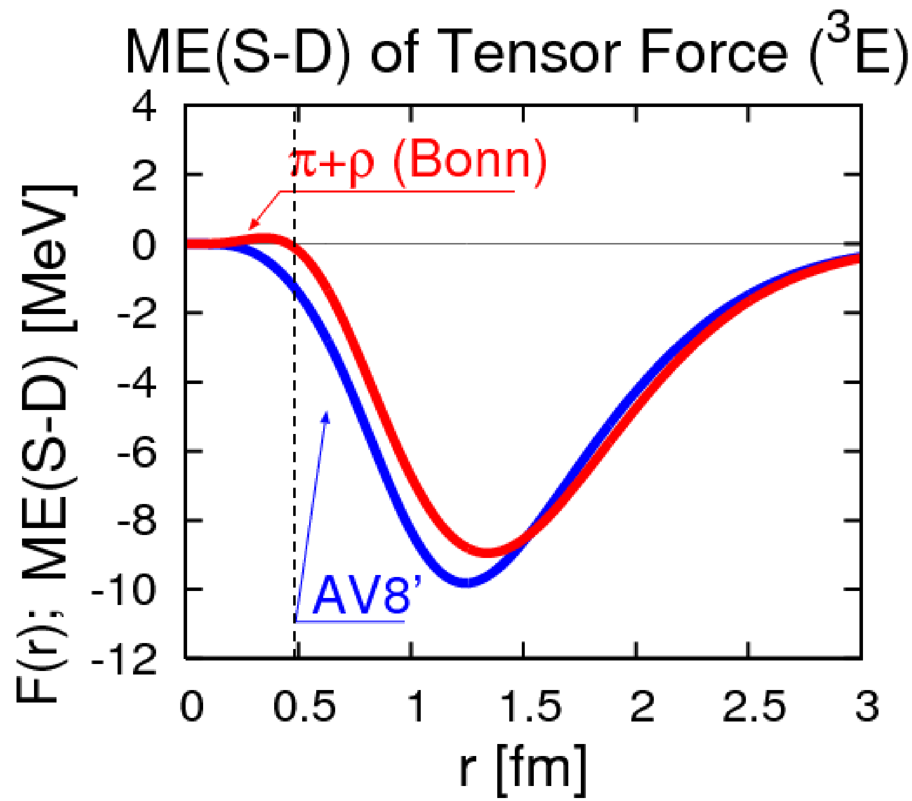
Property of the tensor force

$V_{tensor} = V_T(r) \cdot S_{12}$

$F(r) = r^2 \cdot \phi_{0s}(r,b_{0s}) \cdot V_T(r) \cdot \phi_{0d}(r,b_d)$

$b_s = 1.4 \cdot \sqrt{2}$ [fm] $b_d = b_s / 2$





- Centrifugal potential (1GeV@0.5fm) pushes away the L=2 wave function.