テンソル最適化殻模型による軽い核での核力の役割

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Outline

- **Role of V_{tensor}** in light nuclei
  - He & Li isotopes, ^{8}Be with V_{bare}
- Tensor Optimized Shell Model (**TOSM**) to describe tensor correlation.
- Unitary Correlation Operator Method (**UCOM**) to describe short-range correlation.

He and Li isotopes

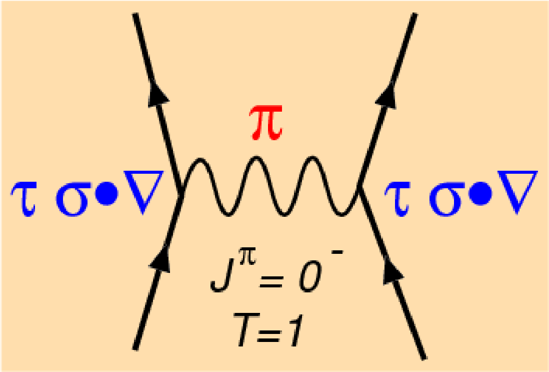
TM, A. Umeya, H. Toki, K. Ikeda PRC84 (2011) 034315

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

Pion exchange interaction vs. V_{tensor}

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

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



δ interaction

Yukawa interaction

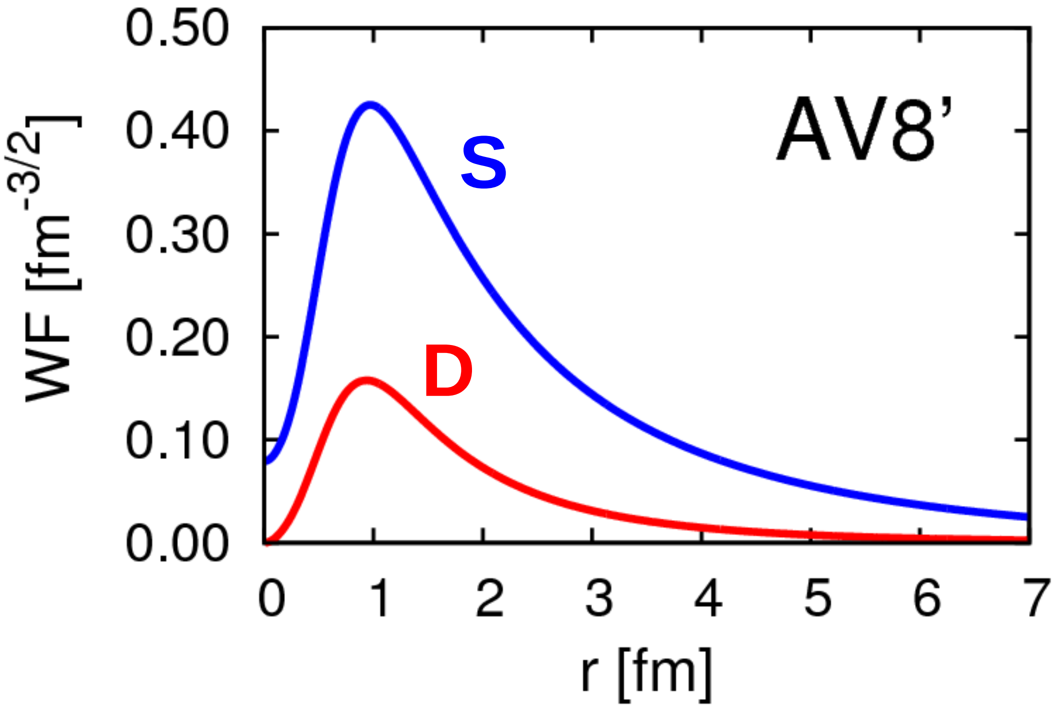
Involve large momentum

Tensor operator

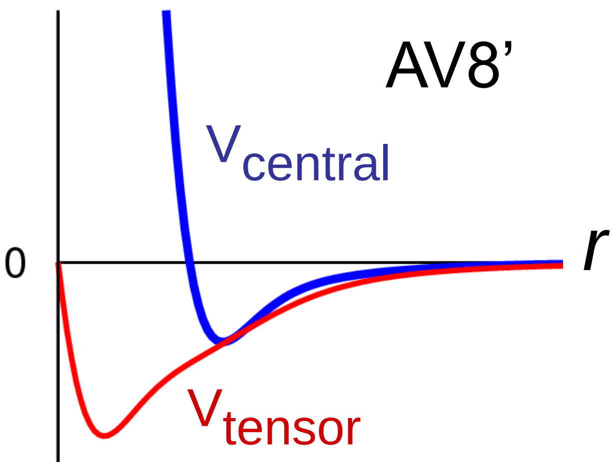
$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

- V_{tensor} produces the high momentum component.

Deuteron 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

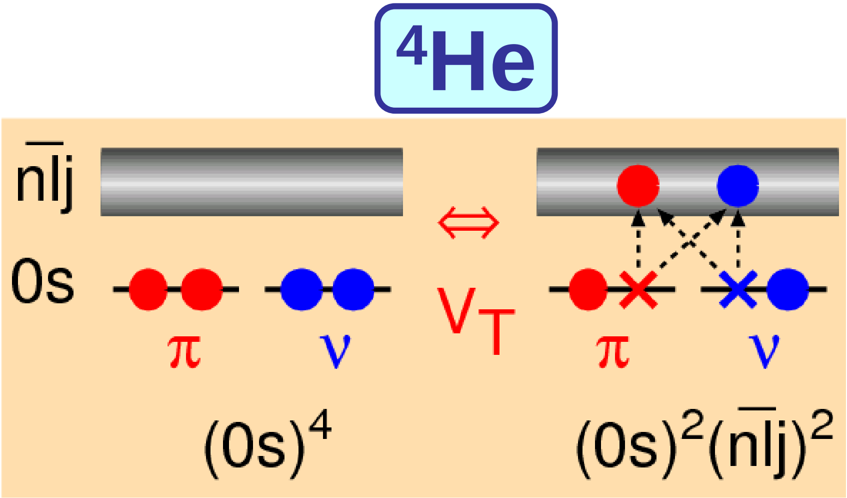
d-wave is "**spatially compact**" (high momentum)

Tensor-optimized shell model (TOSM)

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

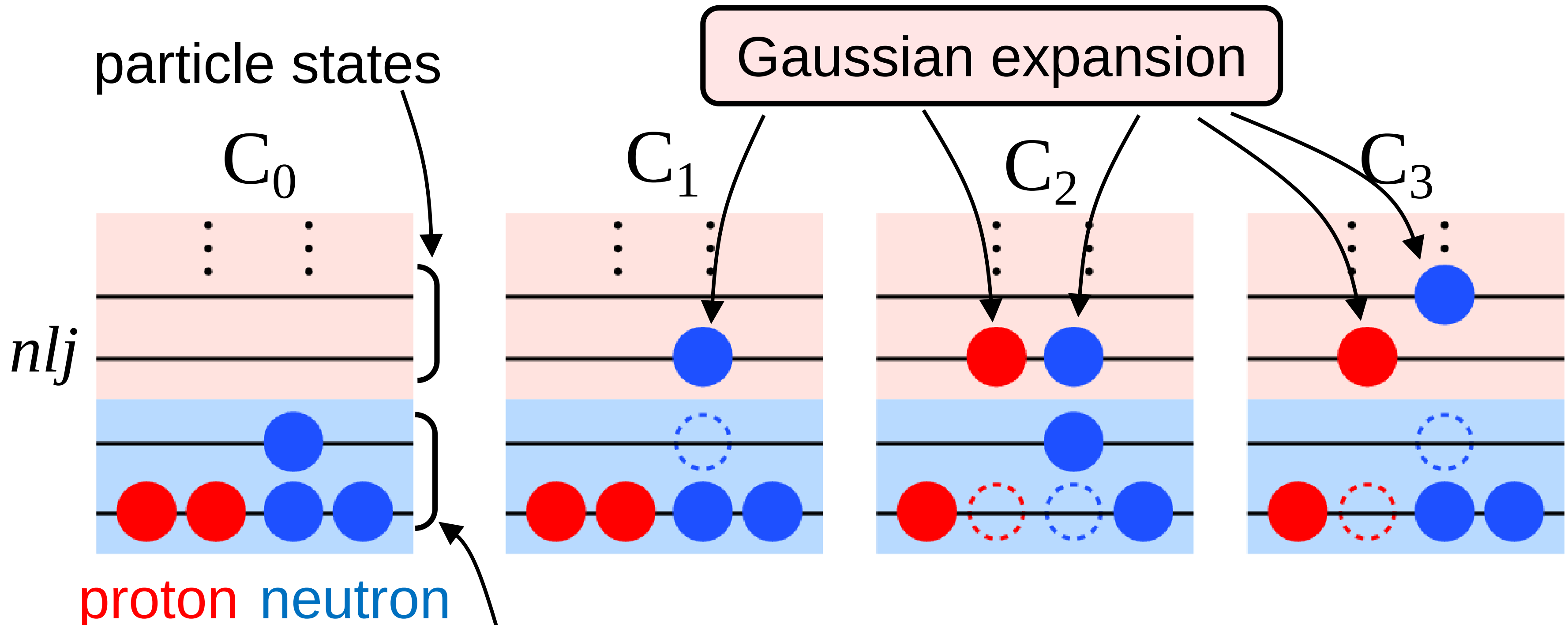
- 2p2h excitations with high-L orbits.
- V_{tensor} is **NOT** treated as residual interactions

  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)

Configurations in TOSM



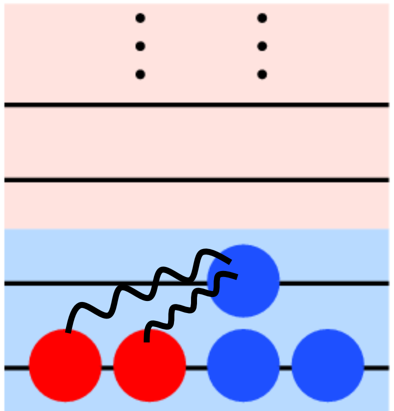
hole states (harmonic oscillator basis)
+ configuration mixing (0s→0p)

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

Tensor force matrix elements

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

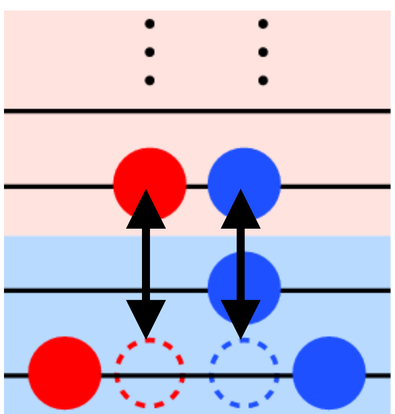
: Integrand of Tensor ME



$b_D \sim b_S$

$\mathrm{V_T} = \mathrm{V_{residual}}$

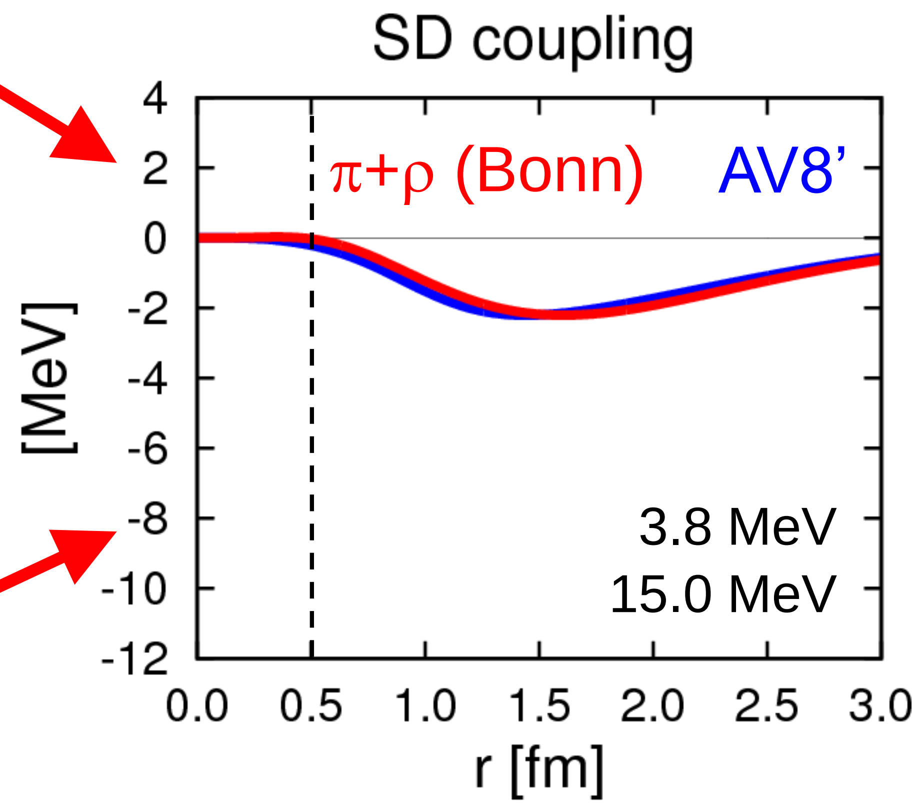
1st order



$b_D \sim b_S \times 0.5$

$\mathrm{V_T} \neq \mathrm{V_{residual}}$

0p0h-2p2h



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

Effect of Tensor force in TOSM

- 1^{st} 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.

- Coupling between 0p0h-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***. **PLB**

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

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

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

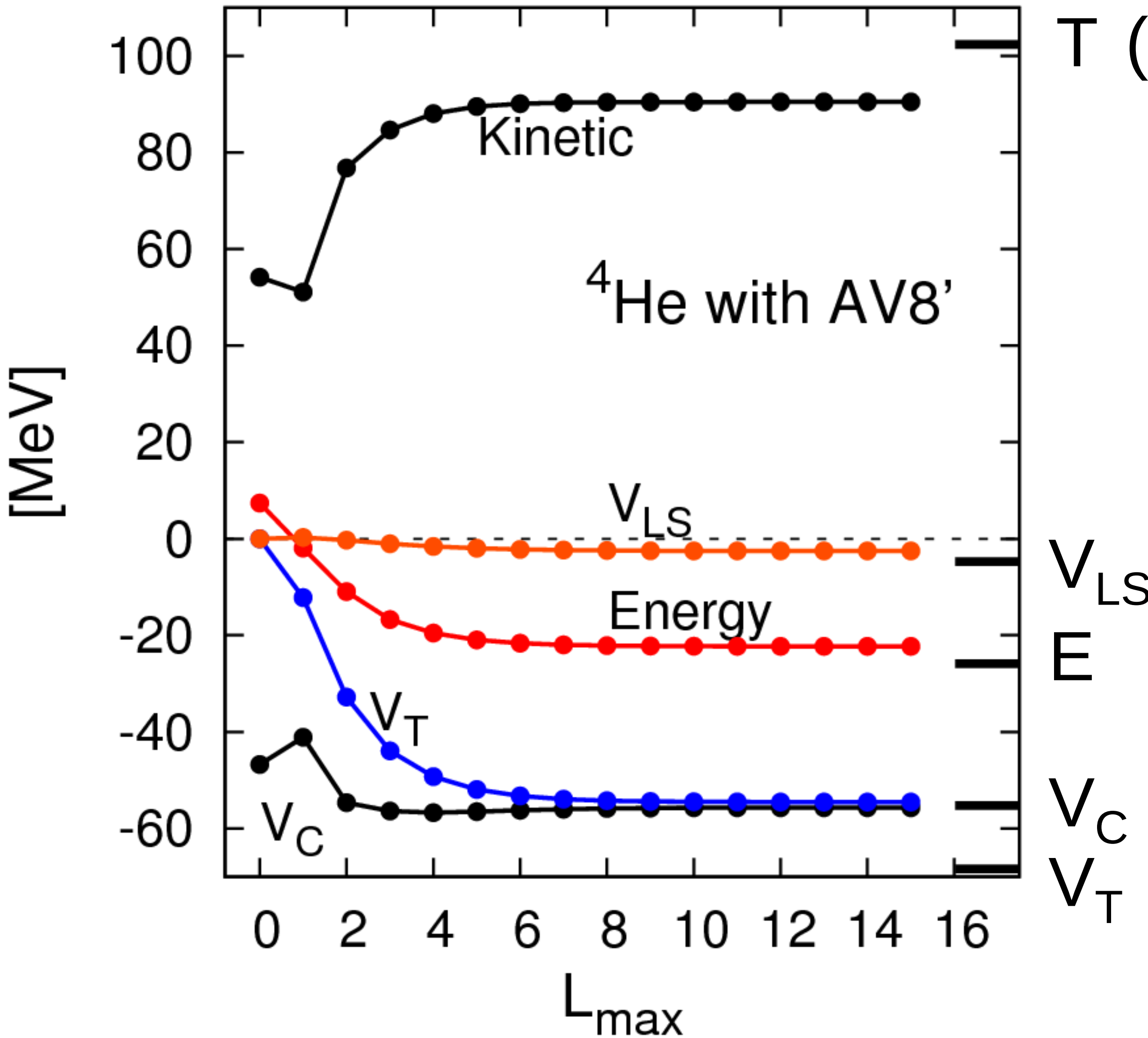
Gaussian basis function

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

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



Kamada et al.
PRC64 (Jacobi)

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

- variational calculation

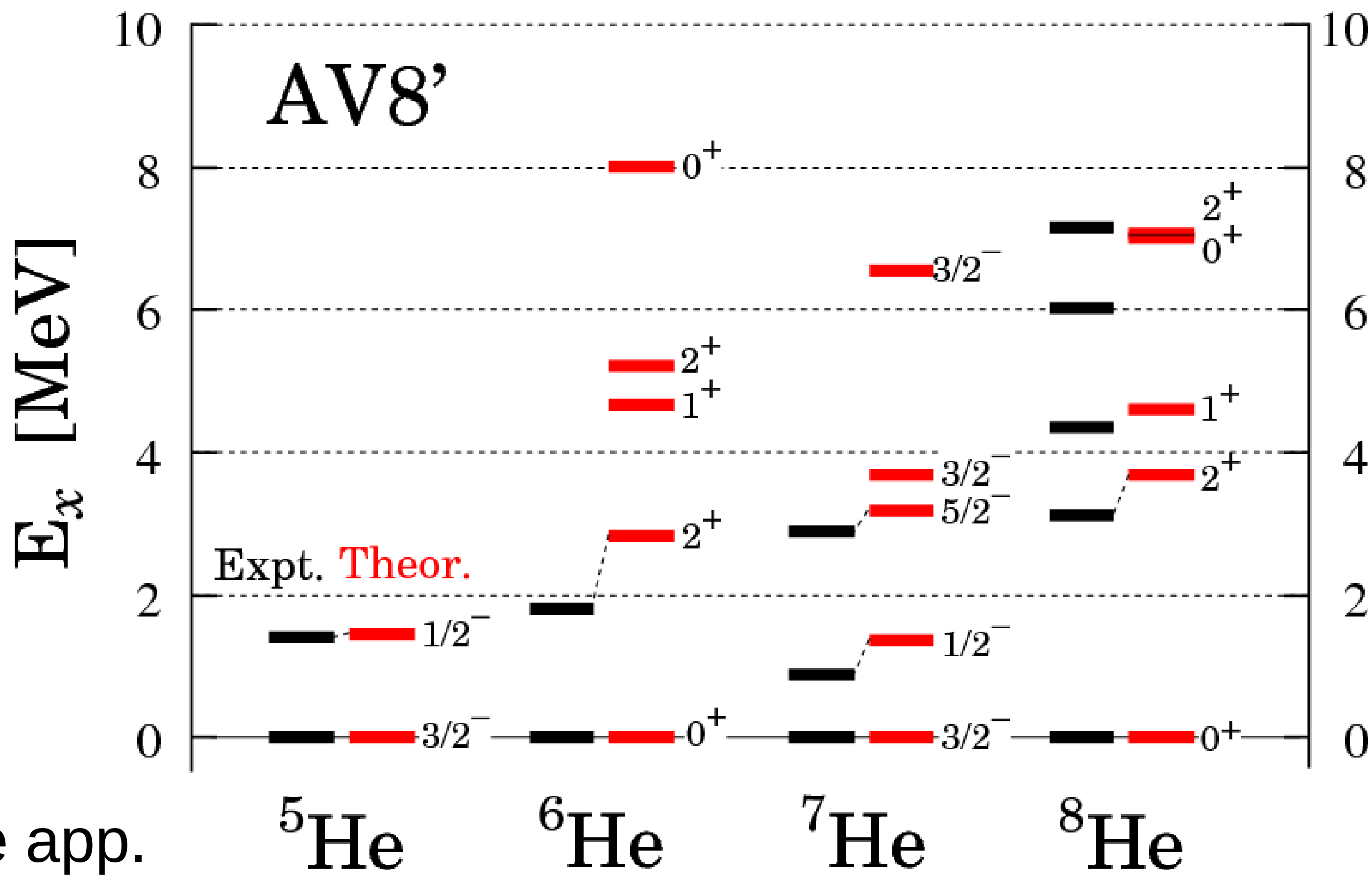
- Gaussian expansion with 9 bases

good convergence

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

- Excitation energies in MeV

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



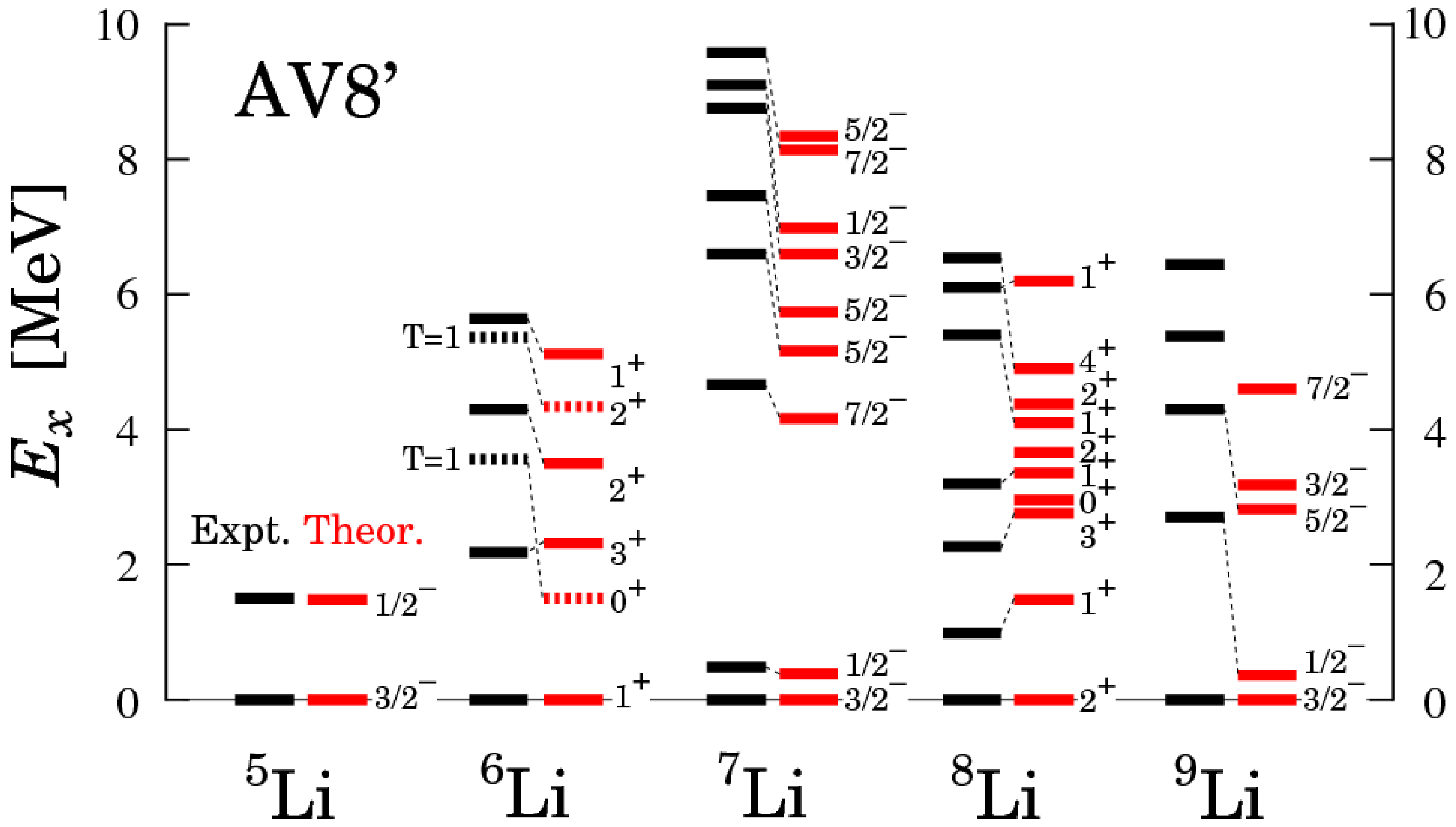
- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

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

- Excitation energies in MeV

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

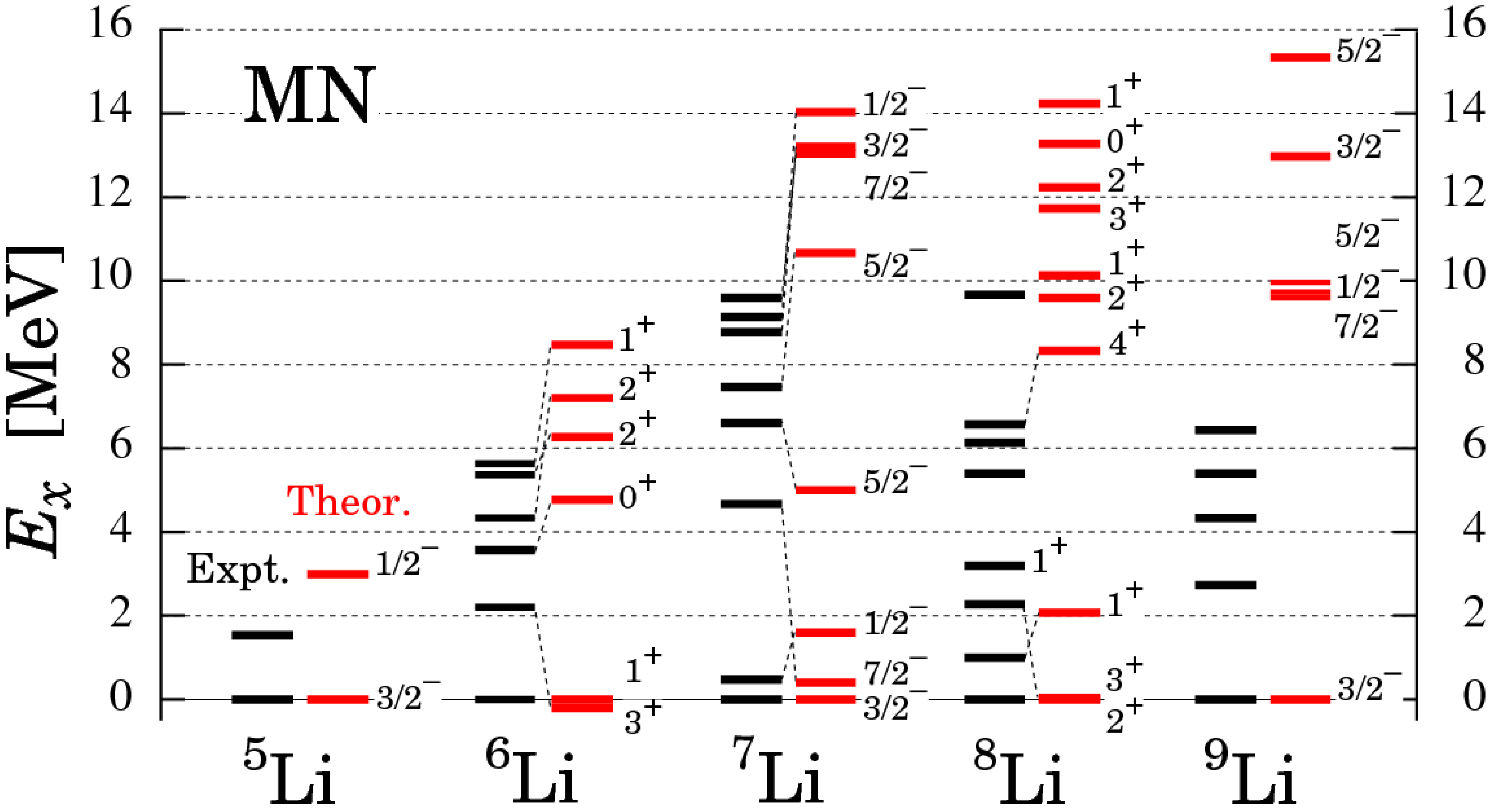


- Excitation energy spectra are reproduced well

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

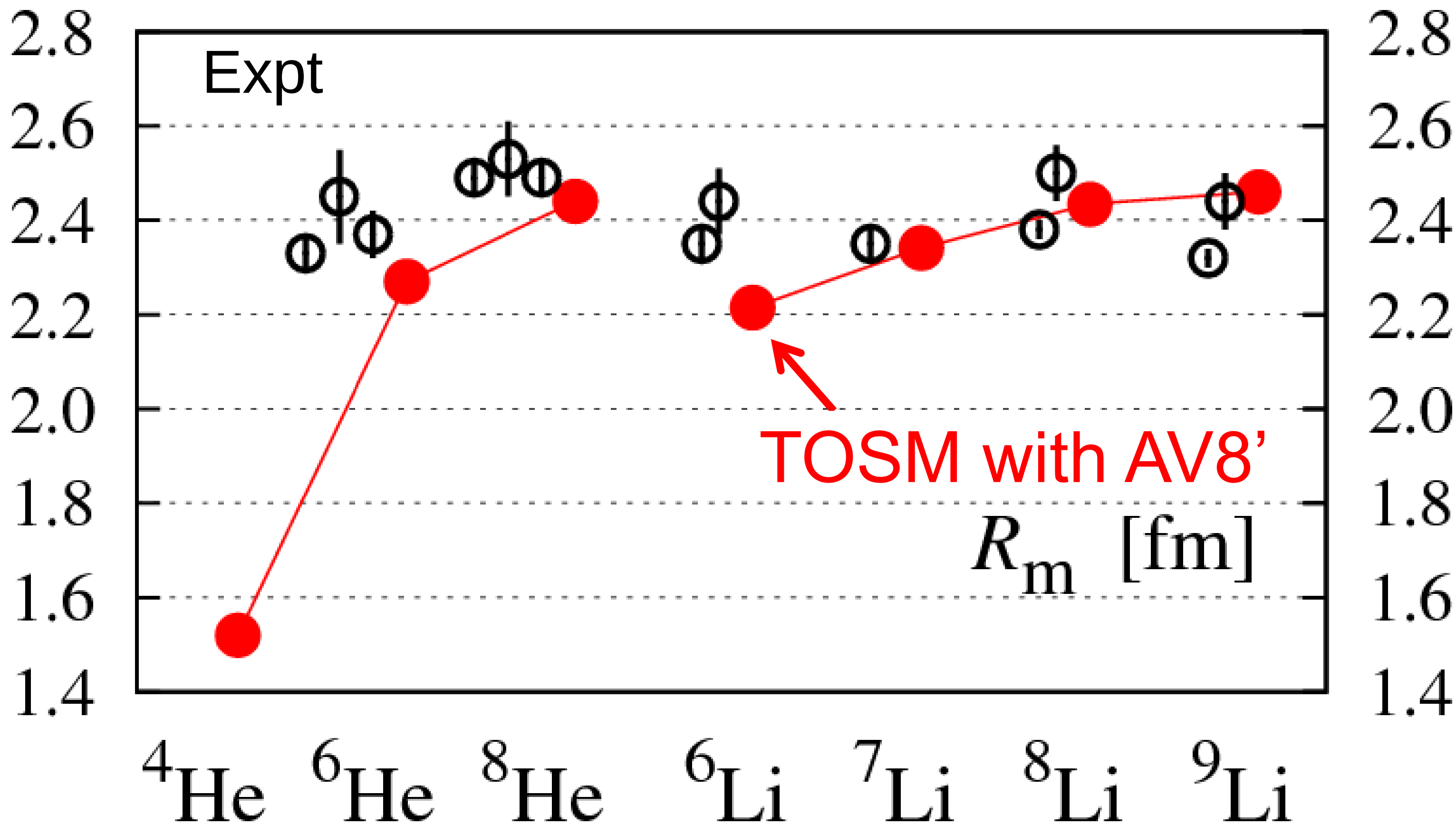
Minnesota force
NO tensor

- 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}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

$0\text{p}0\text{h}: \ (0s)^4_{00}$

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

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

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

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

V_T

$2\text{p}2\text{h}: (0s)^2_{10}(0p_{1/2})^2_{10}$

$\ell_1 = \ell_2 = 0$

$\ell_3 = 1$

$\ell_4 = 1$

$L=2$

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

V_T

$2\text{p}2\text{h}: (0s)^2_{10}[(1s)(0d_{3/2})]_{10}$

$\ell_1 = \ell_2 = 0$

$\ell_3 = 0$

$\ell_4 = 2$

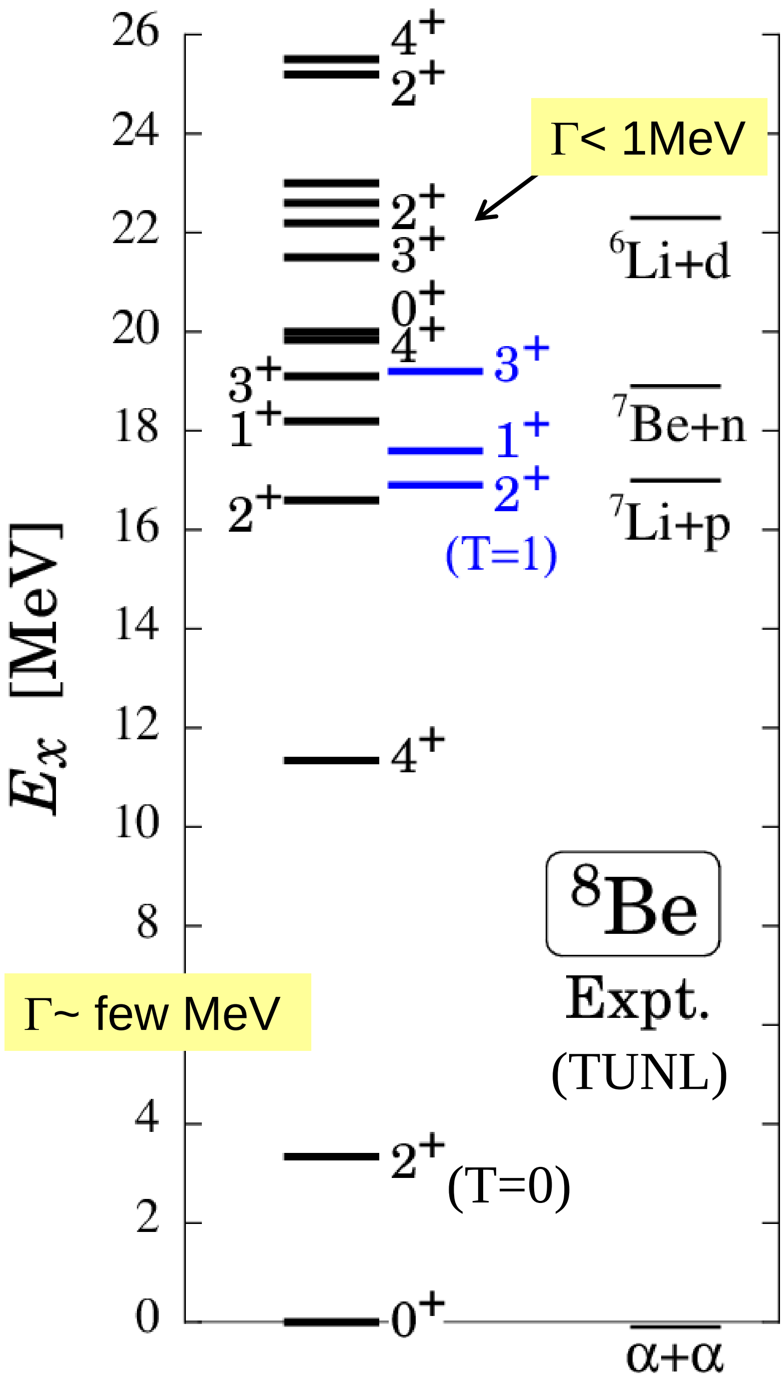
$L=2$

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

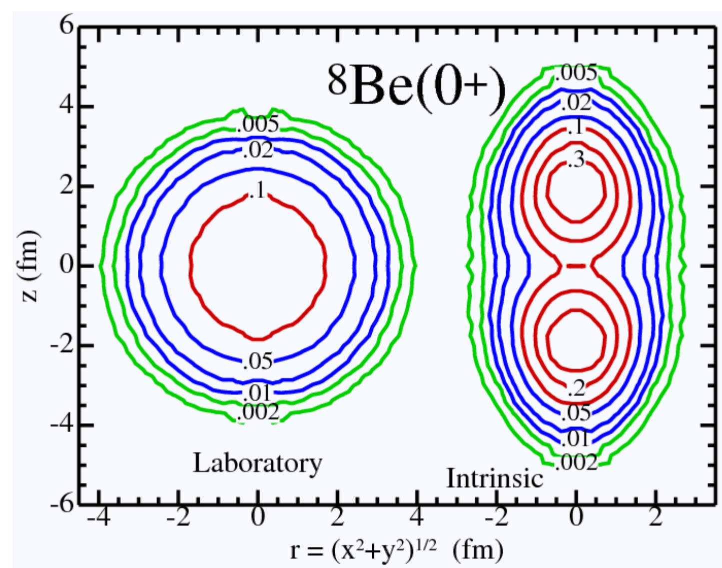
Selectivity of S_{12}

ΔL=2, ΔS=-2

^{8}Be spectrum

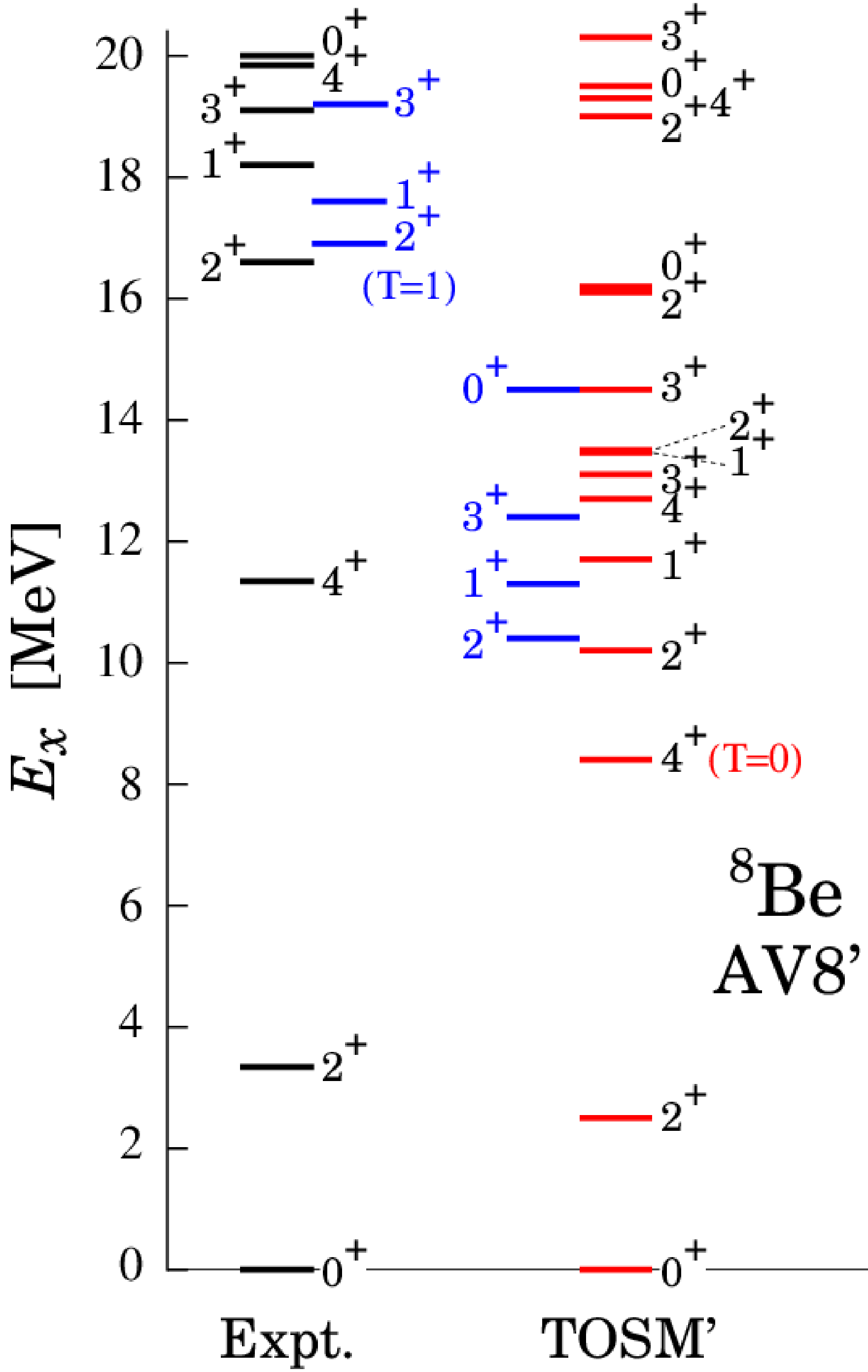


- Argonne Group
  - Green's function Monte Carlo
    C.Pieper, R.B.Wiringa,
    Annu.Rev.Nucl.Part.Sci.51 (2001)



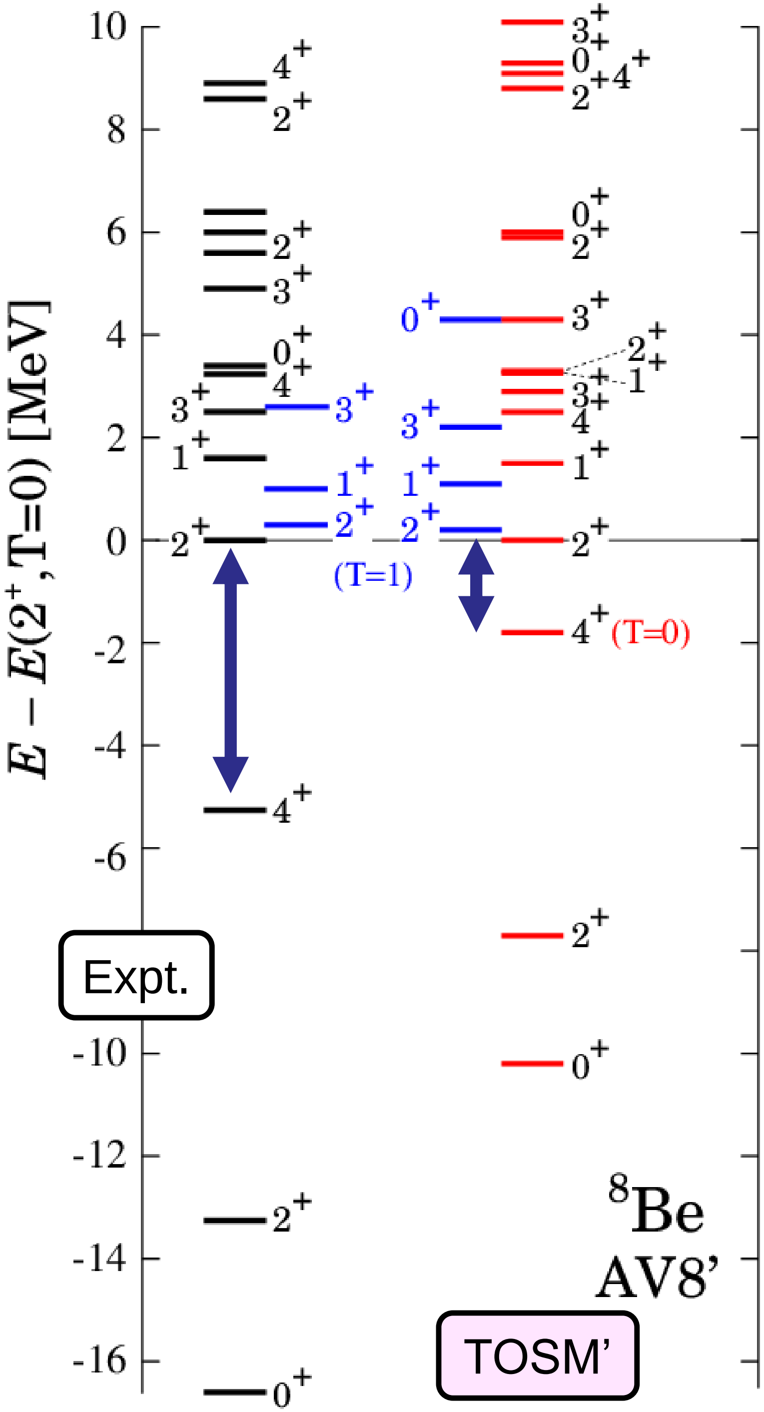
α-α structure

^{8}Be in TOSM' – AV8' –



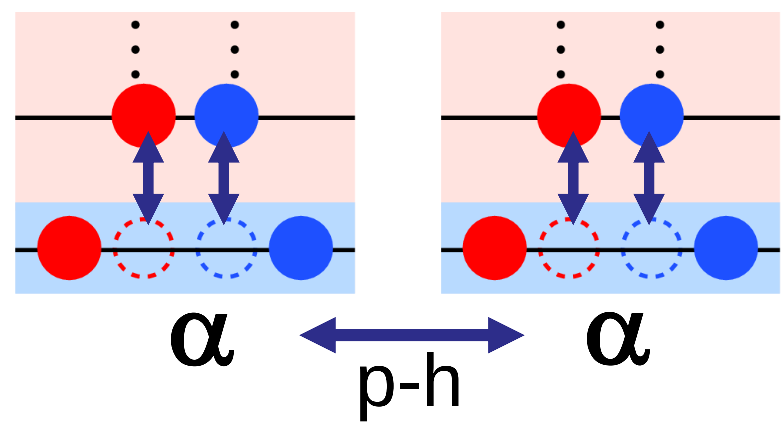
- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)
- ground band
- highly excited states
  - small E_X
  - correct level order (T=0,1)
- $R_m(^8\text{Be})$=2.26 fm
  - Brink 2α model: 2.48 fm

^{8}Be in TOSM’ – AV8’ –



- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)

- **α** : 0p0h+2p2h with high-*k*
  → naively 2**α** needs 4p4h.



Hamiltonian components in ^{8}Be

State		Kinetic	Central	Tensor
^{4}He		95	–56	–62
^{8}Be	0^+_1	192	–115	–97
	2^+_1	191	–112	–95
	2^+_2	185	–98	–92
	$2^+_{T=1}$	168	–94	–82

- Grand state
  - Kinetic & Central ~ twice of ^{4}He
  - Tensor ~ 1.6 of ^{4}He
  - larger ⟨H⟩ components than highly excited states.
- Kinetic & Tensor
  - *T*=0 states > *T*=1 states

Summary

- **TOSM+UCOM** using V_{bare}.
  - Strong tensor correlation from 0p0h-2p2h.
- He & Li isotopes
  - Energy spectra, Radius
  - ^{4}He contains **"*pn*-pair of $p_{1/2}$"** due to V_T.
- ^{8}Be, T=0 & T=1.
  - Two aspects : Grand band states & highly excited states.
  - Indication of more configurations such as 4p4h to describe 2α structure in the grand band states.