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

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「バリオン多体系構造の新たな局面を考える」研究会　於　ますや旅館, 2014.3.8-9

Outline

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

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

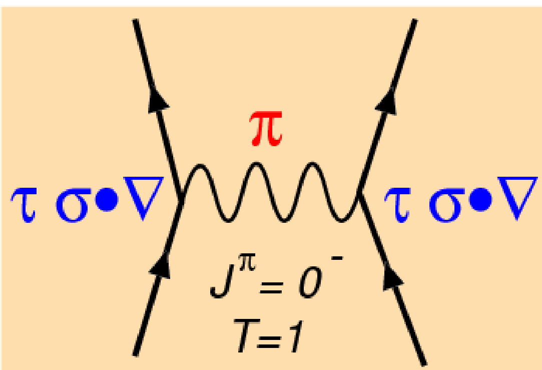
TM, A. Umeya, H. Toki, K. Ikeda PRC86 (2012) 024318

TM, A. Umeya, K. Horii, H. Toki, K. Ikeda PTEP (2014) 033B02

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

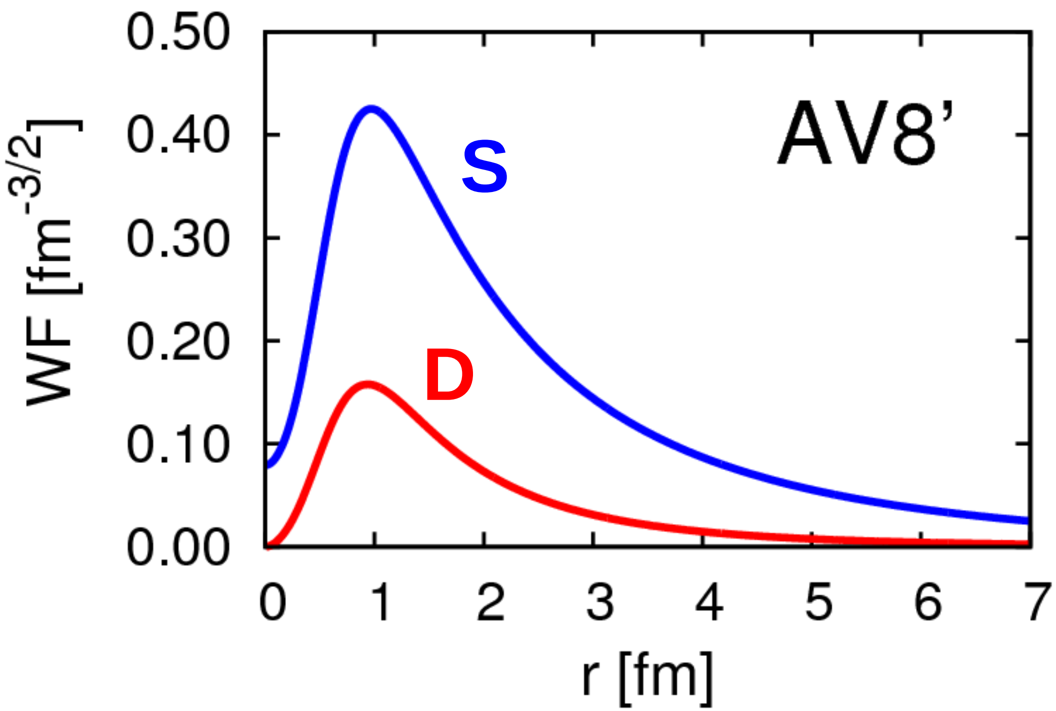
Involve large momentum

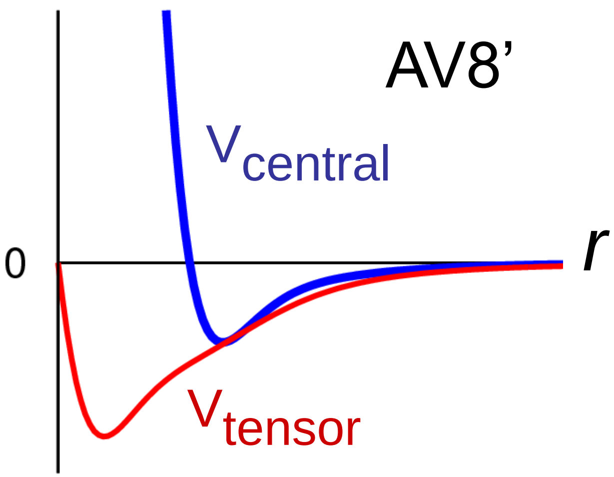
Tensor operator

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

- V_{tensor} produces the high momentum component.

Deuteron properties & tensor force





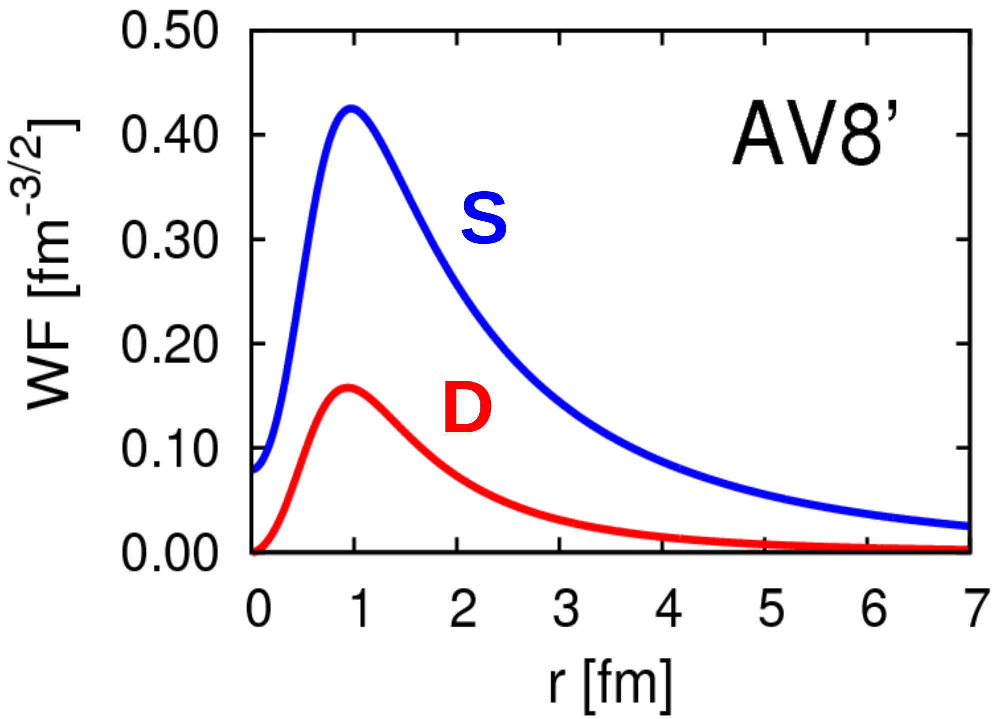
$R_m(s)$=2.00 fm

$R_m(d)$=1.22 fm

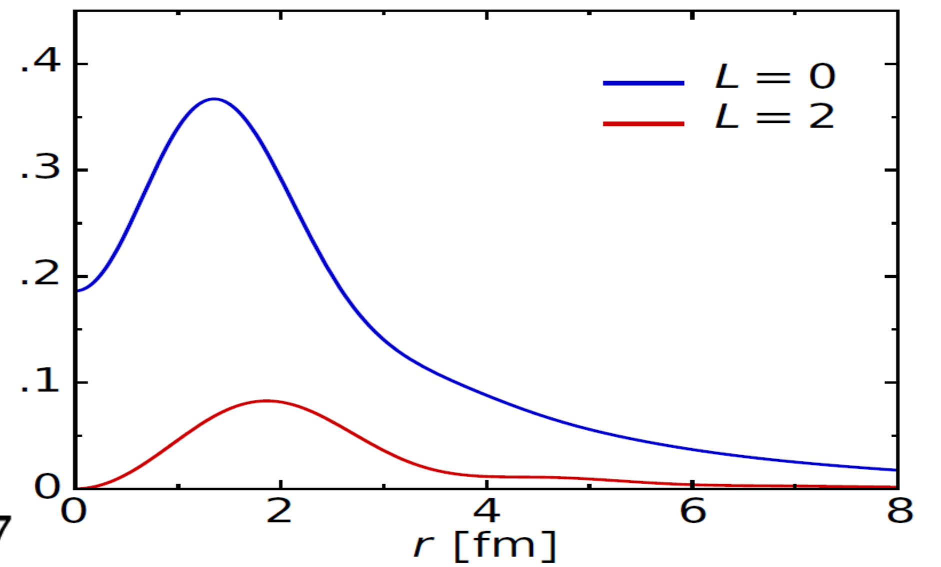
Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P(L=2)	5.77%
Radius	1.96 fm

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

Deuteron Wave Function
- AV8' vs. Chiral EFT -

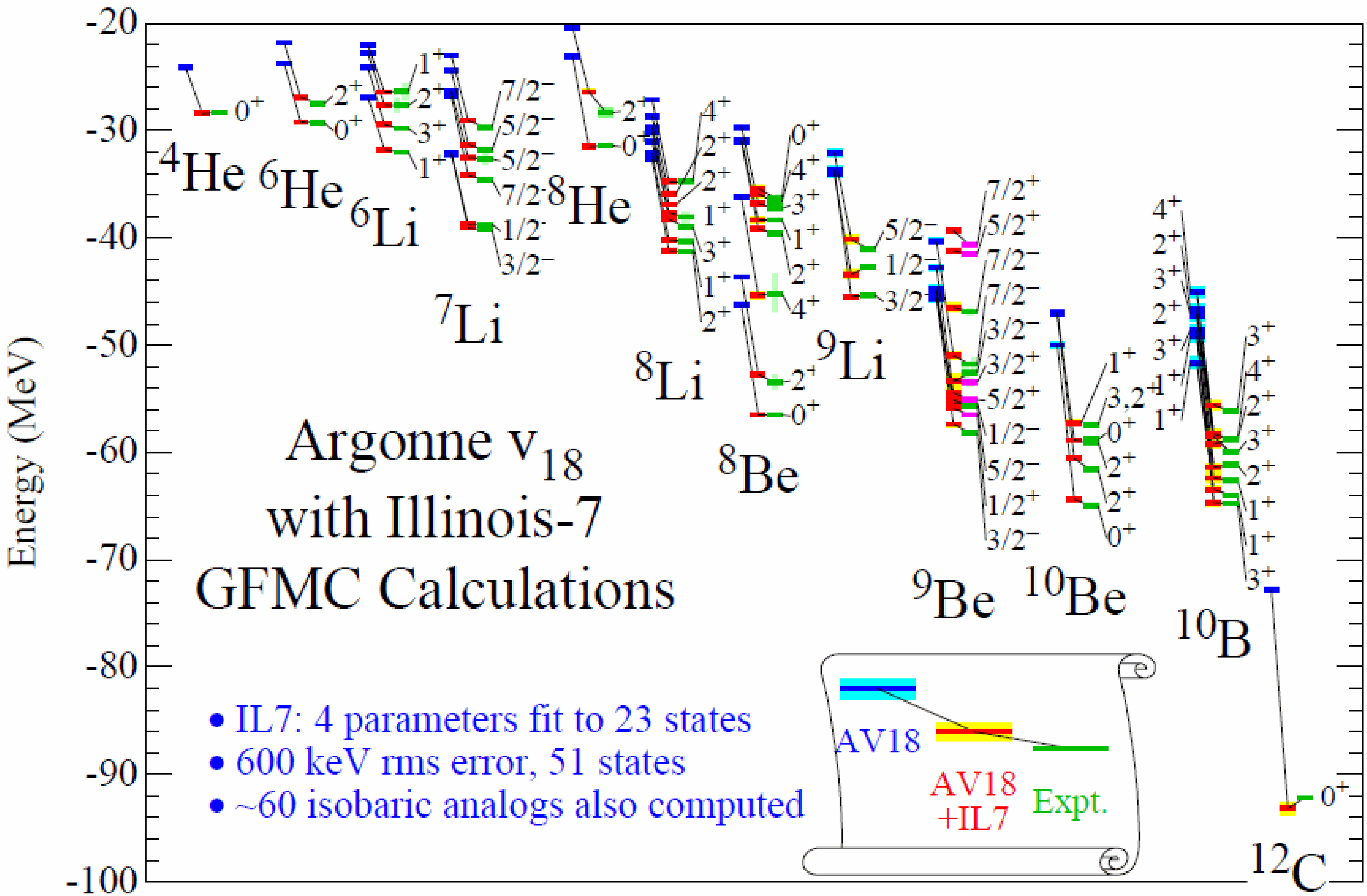


Chiral EFT



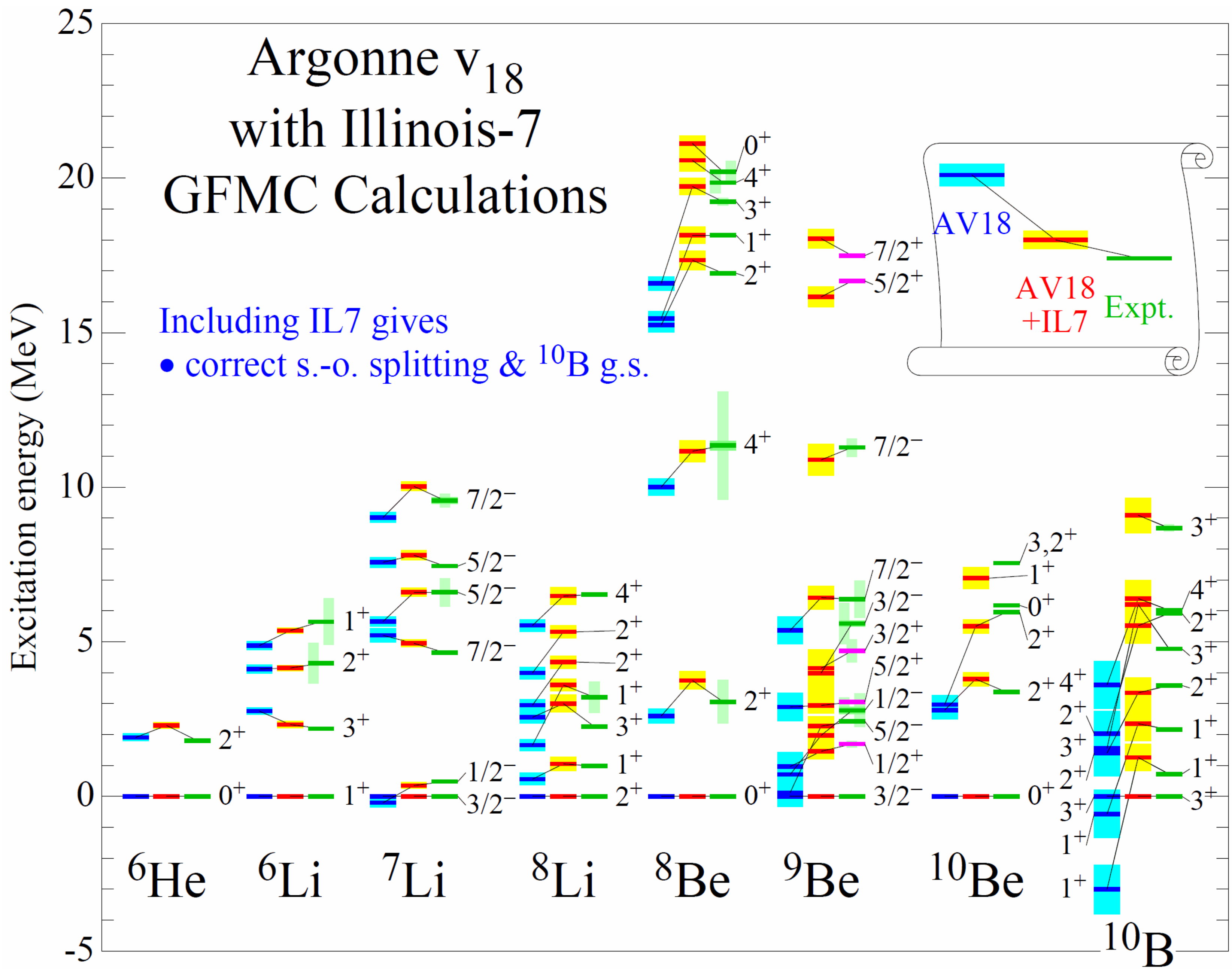
R. Roth @Bad Honnef 2012.3

Argonne Group calculation 2012



Talk by Wiringa
@Bad Honnef, 2012.3

$$\frac{V_\pi}{V_{NN}} \sim 80\%$$



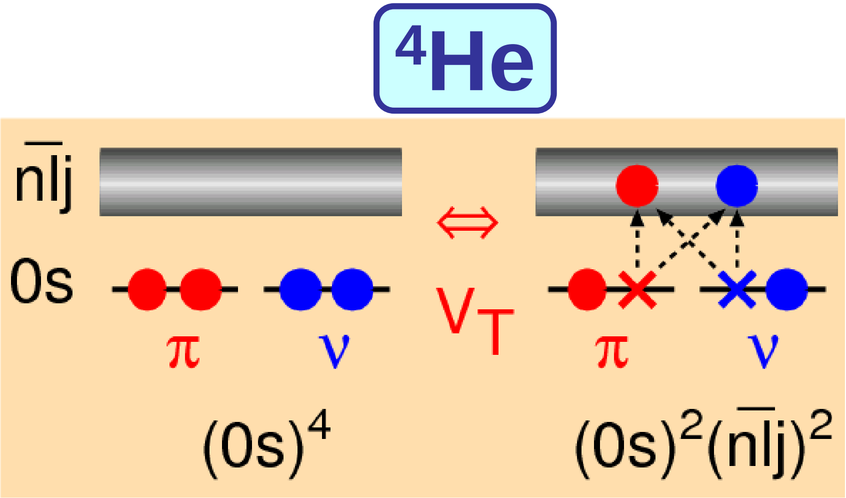
Argonne v18
with Illinois-7
GFMC Calculations
Including IL7 gives
• correct s.-o. splitting & 10B g.s.
AV18
AV18
+IL7
Expt.
Excitation energy (MeV)
25
20
15
10
5
0
-5
6He
6Li
7Li
8Li
8Be
9Be
10Be
10B

Tensor-optimized shell model (TOSM)

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

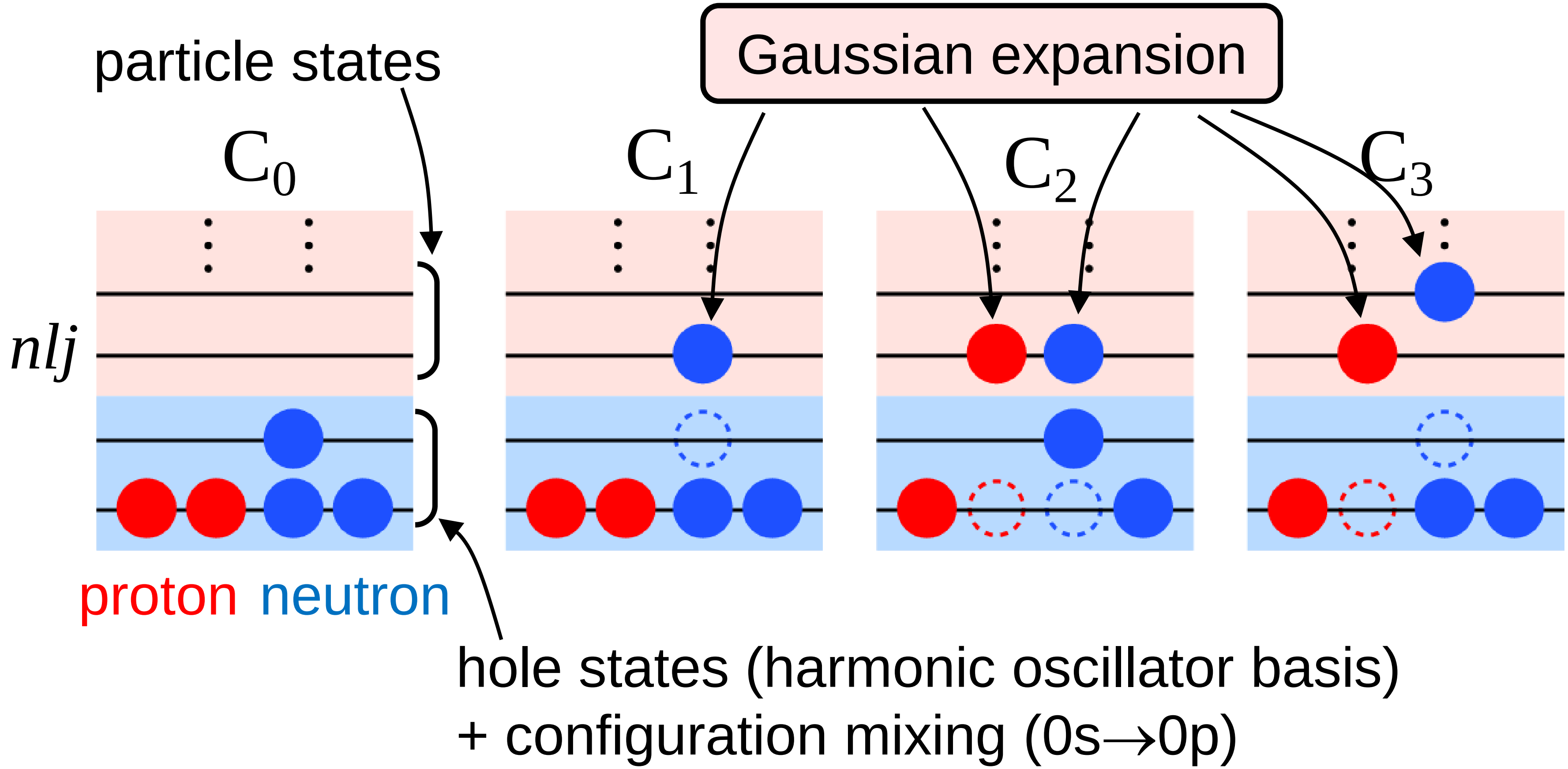
- 2p2h excitations with high-L orbits.
- V_{tensor} is **NOT** treated as residual interactions

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



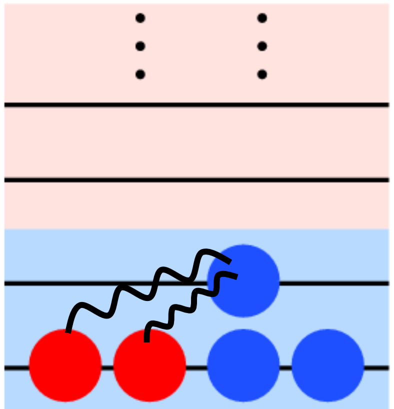
- Length parameters such as b_{0s}, b_{0p}, … are optimized independently, or superposed by many Gaussian bases.
  - Spatial shrinkage of ***D*-wave** as seen in deuteron.
    HF (Sugimoto, NPA740) , RMF (Ogawa, PRC73), AMD (Dote et al., PTP115)
- Satisfy few-body results with Minnesota central force (^{4,6}He)

Configurations in TOSM



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

Tensor force matrix elements



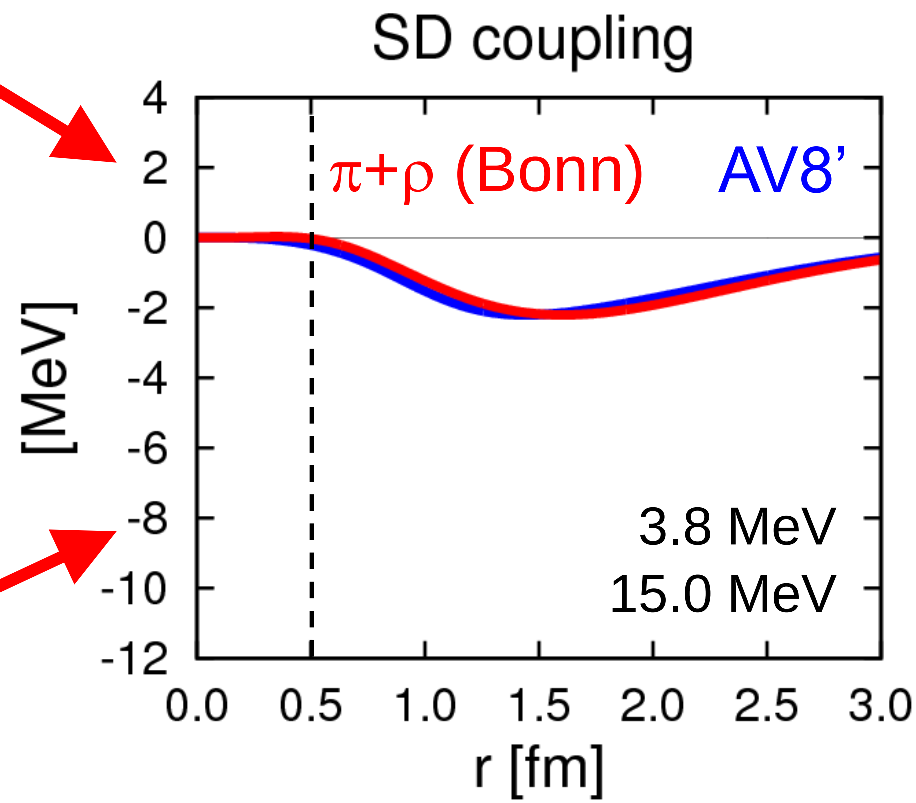
$b_D \sim b_S$

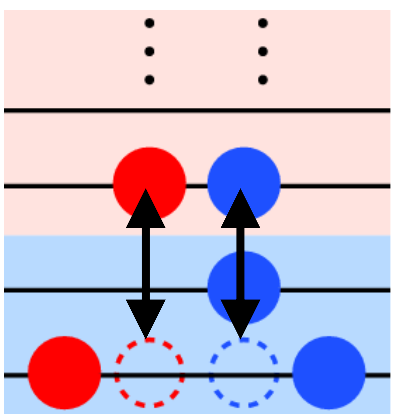
$V_T = V_{residual}$

1st order

$$M_{SD}(r) = r^2 \phi_S(r, b_S) \cdot V_T \cdot \phi_D(r, b_D)$$

Integrand of Tensor ME





$b_D \sim b_S \times 0.5$

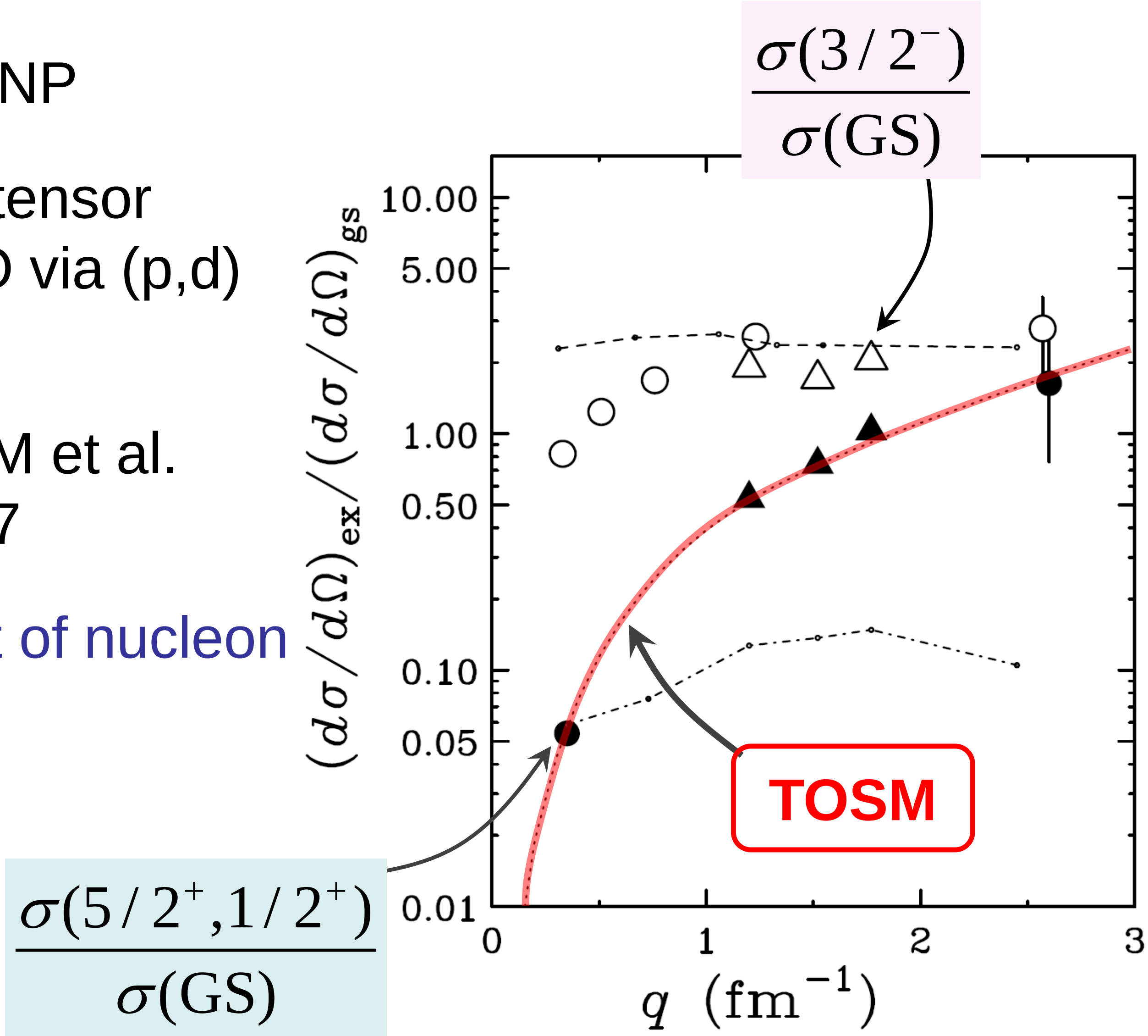
$V_T \neq V_{residual}$

0p0h-2p2h

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

High-k component of nucleon in nucleus

- ^{16}O(p,d)^{15}O @RCNP
- Probing effect of tensor interactions in ^{16}O via (p,d) reaction
- Ong, Tanihata, TM et al. PLB725(2013)277
- Compact *SD*-orbit of nucleon in ^{16}O with TOSM



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

Unitary Correlation Operator Method

(short-range part)

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

TOSM

short-range correlator

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

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

Bare Hamiltonian

Shift operator depending on the relative distance

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

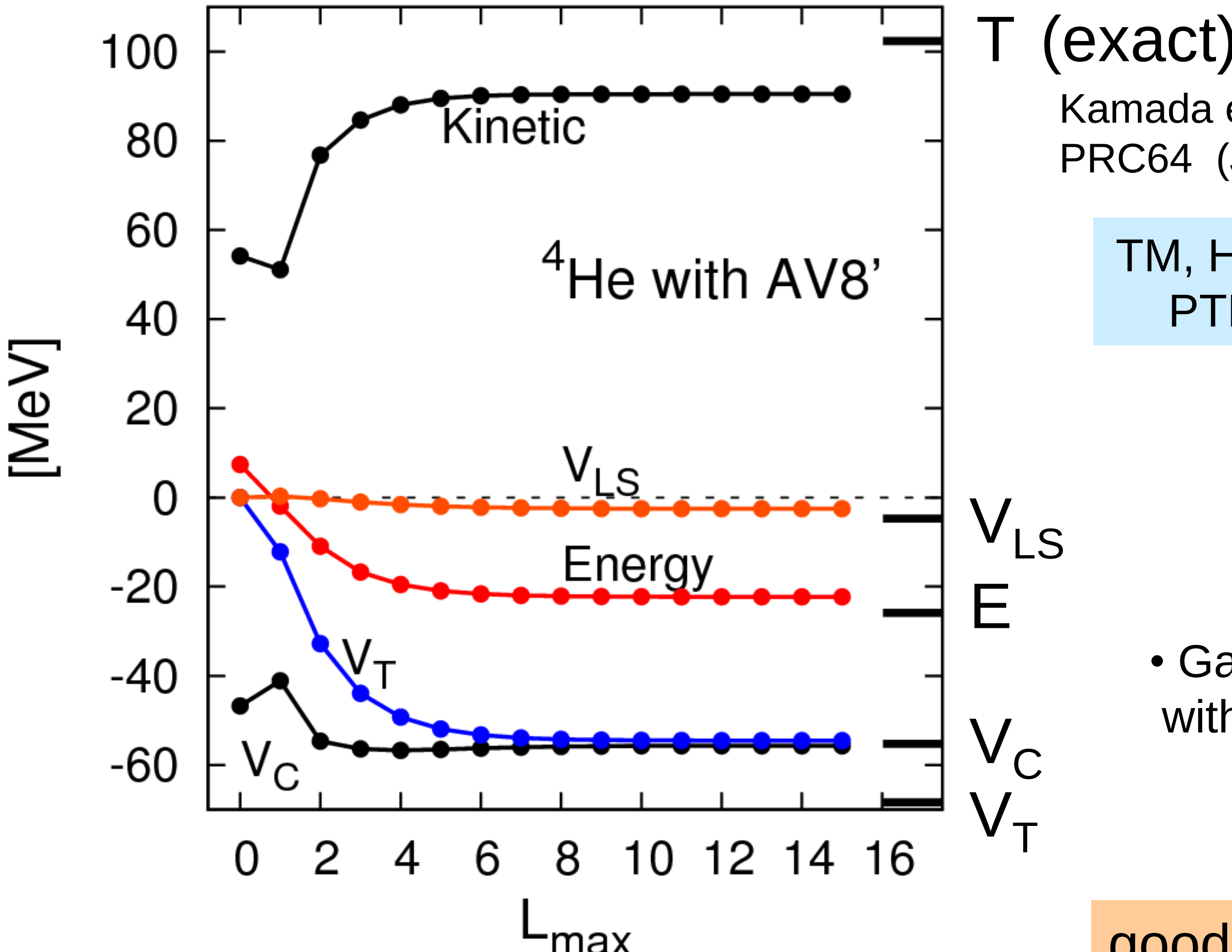
Amount of shift, variationally determined.

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

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

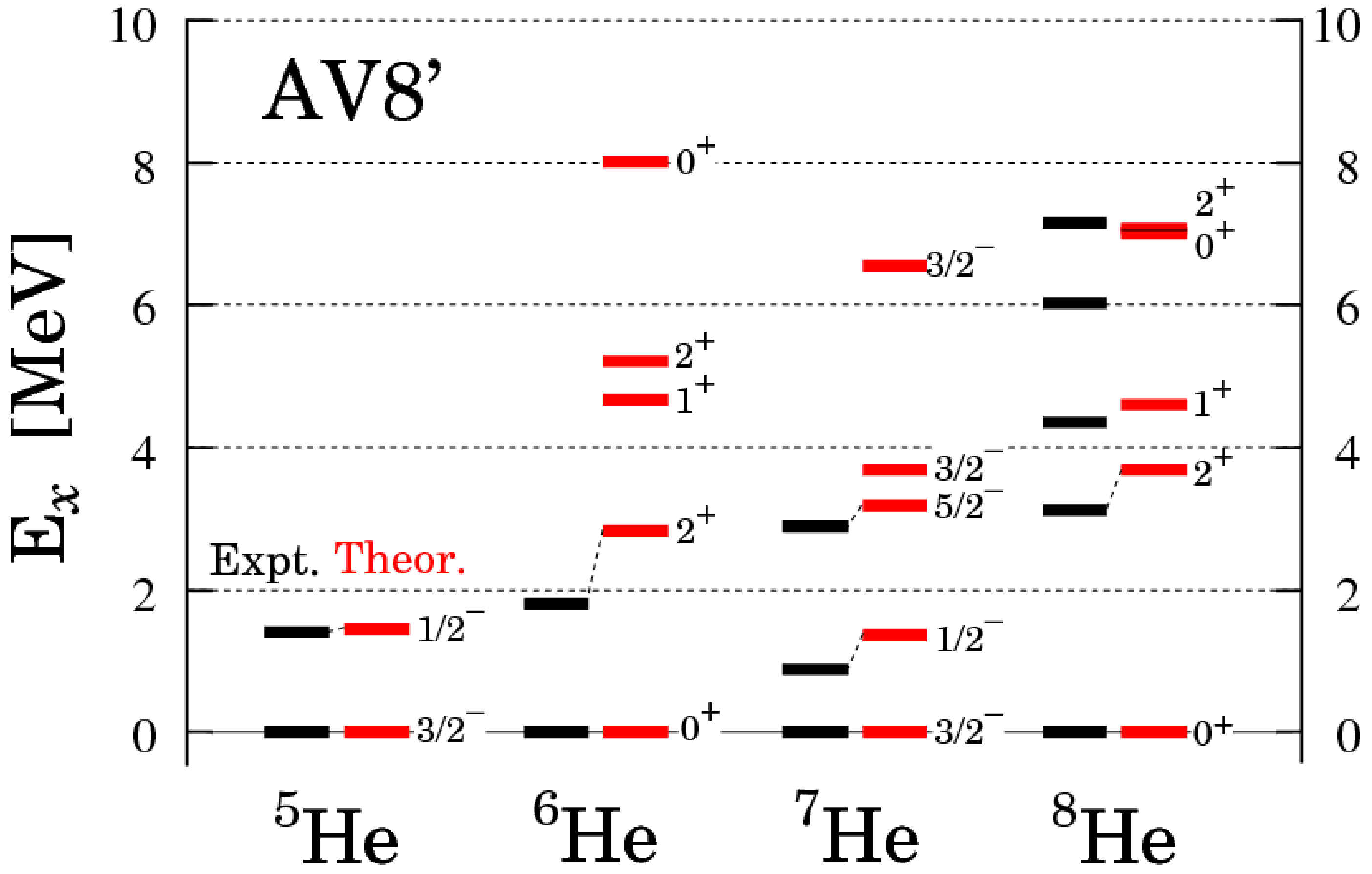
- variational calculation
- Gaussian expansion with 9 bases

good convergence

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

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

- Excitation energies in MeV

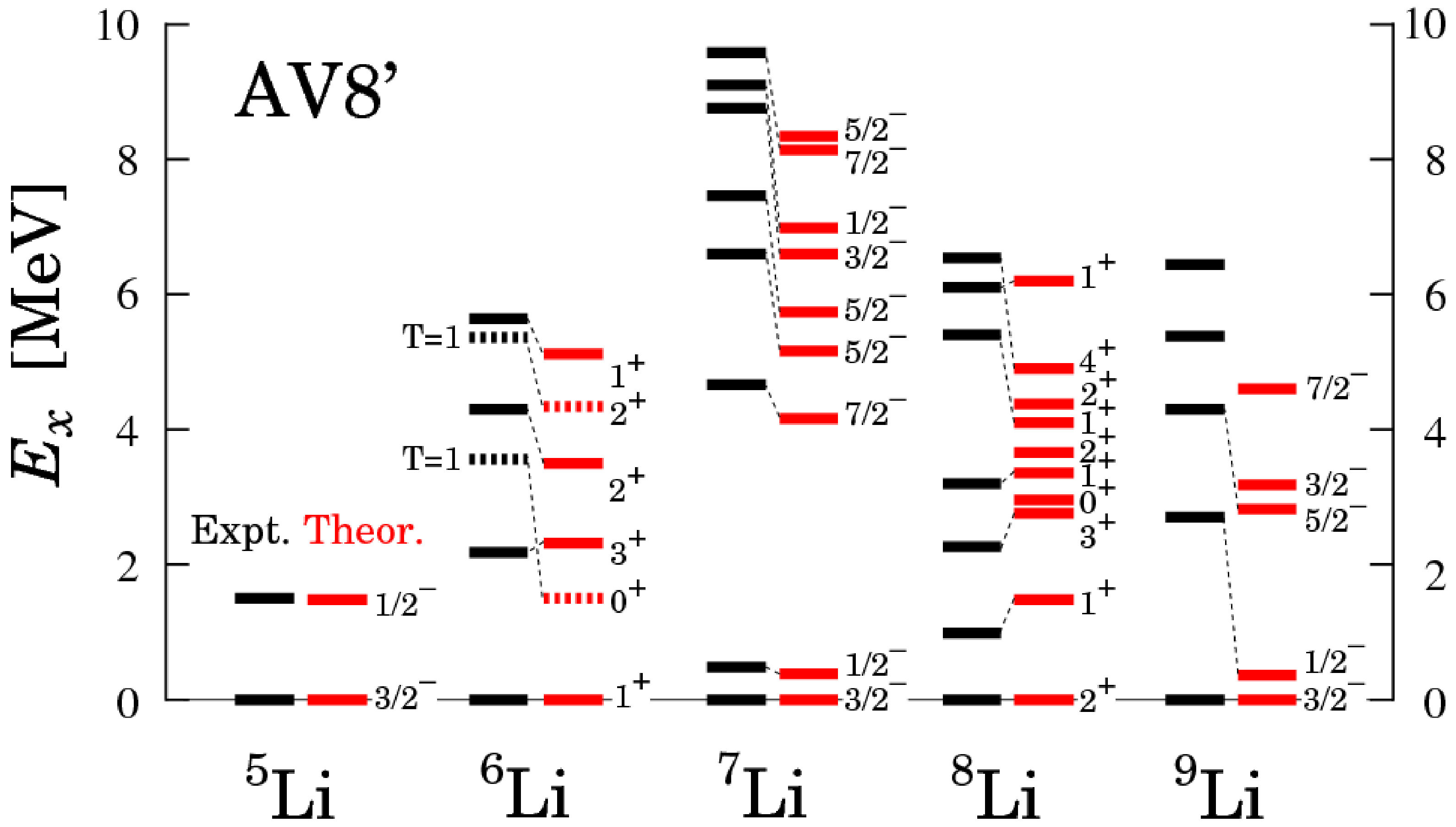


- Bound state app.
- No V_{NNN}
- Excitation energy spectra are reproduced well

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

- Excitation energies in MeV

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

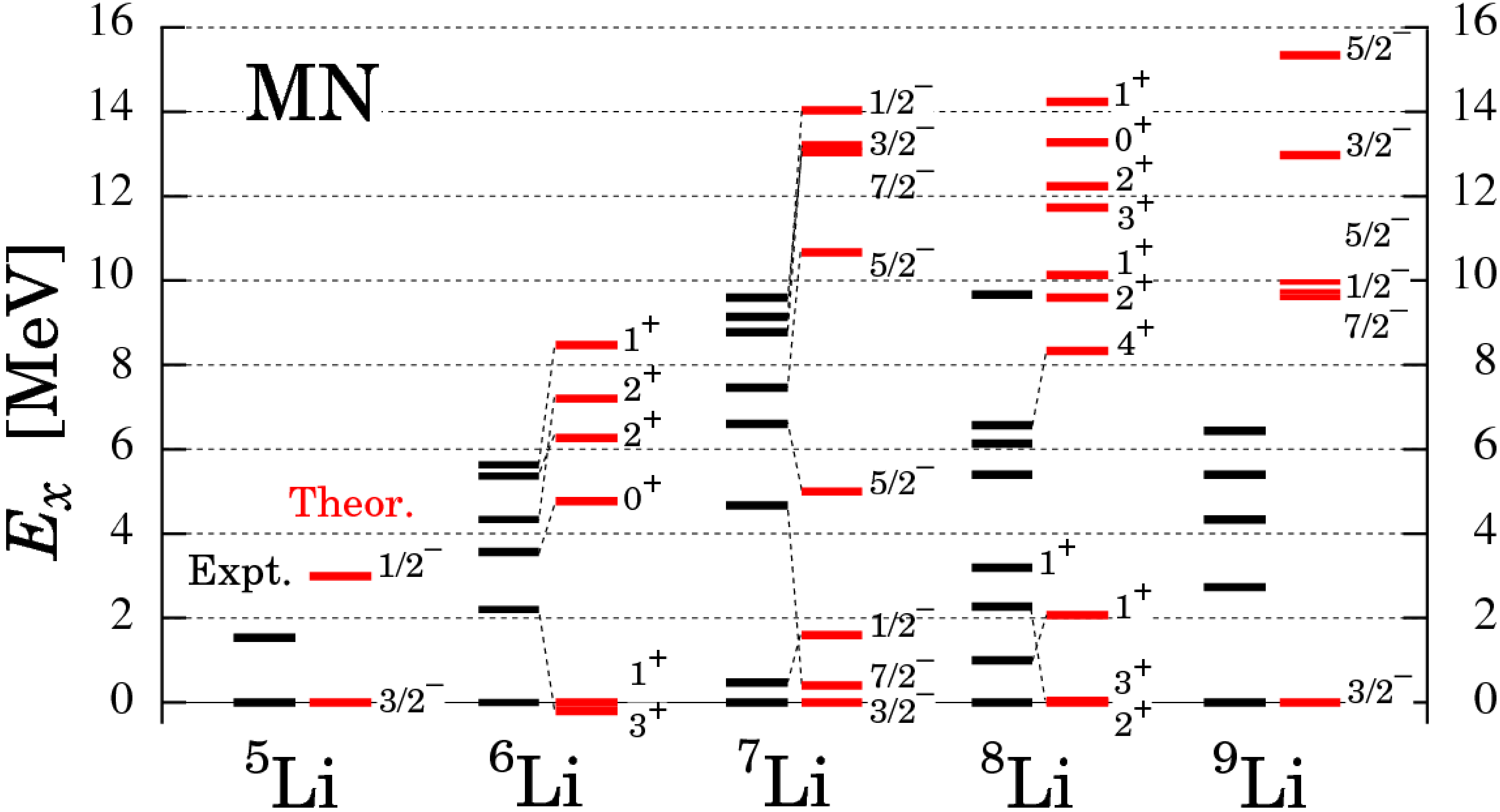


- Excitation energy spectra are reproduced well

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

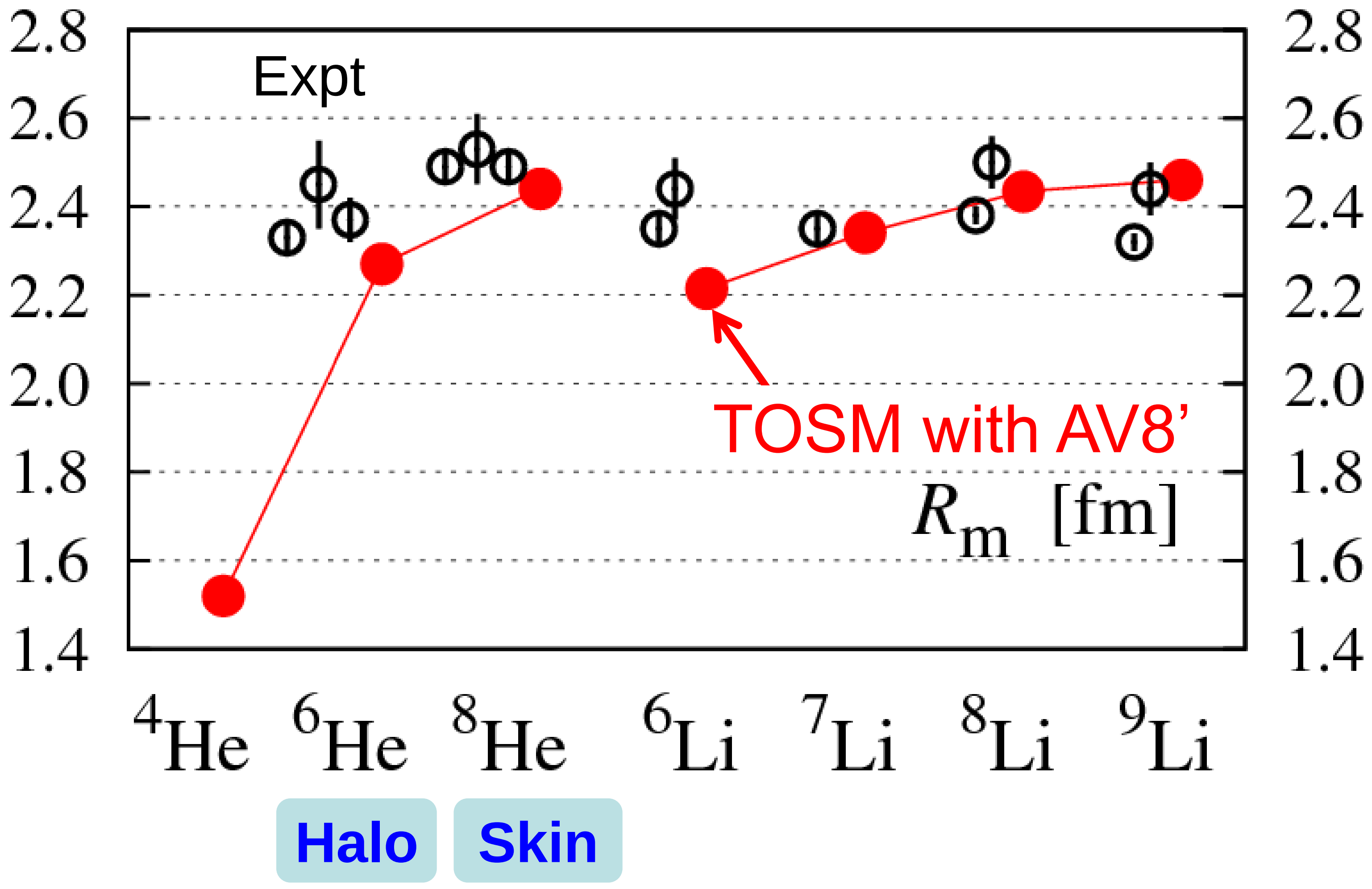
Minnesota force
NO tensor

- Excitation energies in MeV



- Too large excitation energy

Matter radius of He & Li isotopes

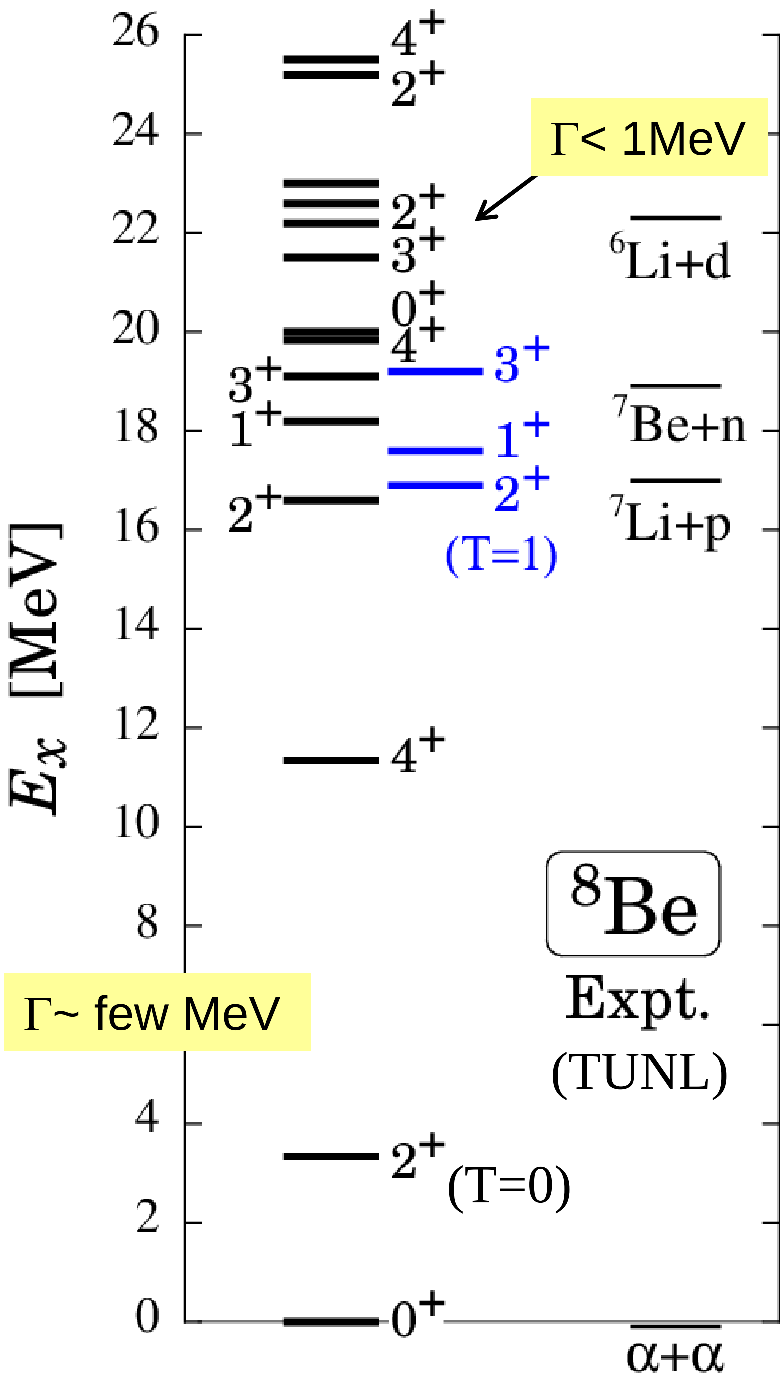


I. Tanihata et al., PLB289('92)261
O. A. Kiselev et al., EPJA 25, Suppl. 1('05)215.

A. Dobrovolsky, NPA 766(2006)1
G. D. Alkhazov et al., PRL78('97)2313
P. Mueller et al., PRL99(2007)252501

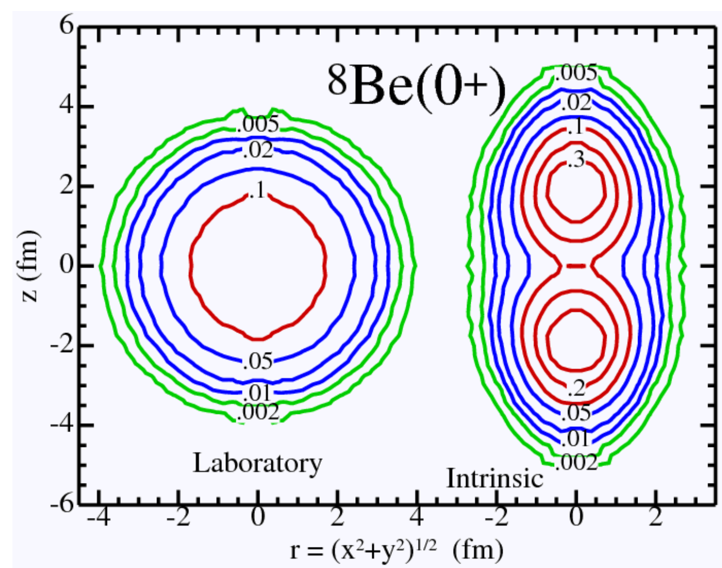
Be isotopes

^{8}Be	TM, A. Umeya, K. Horii, H. Toki, K. Ikeda PTEP (2014), in press
^{9}Be, ^{10}Be	JPS meeting

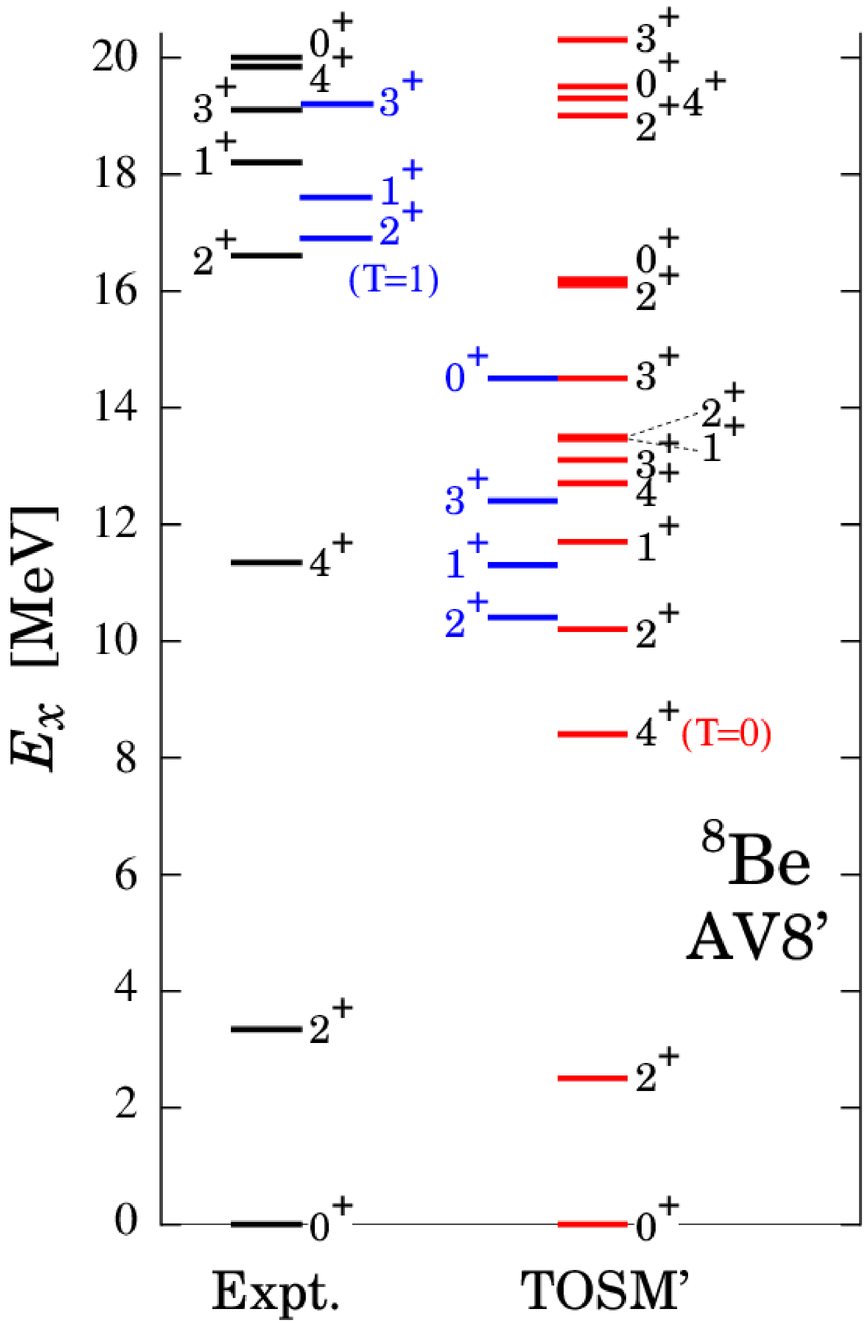


^{8}Be spectrum

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

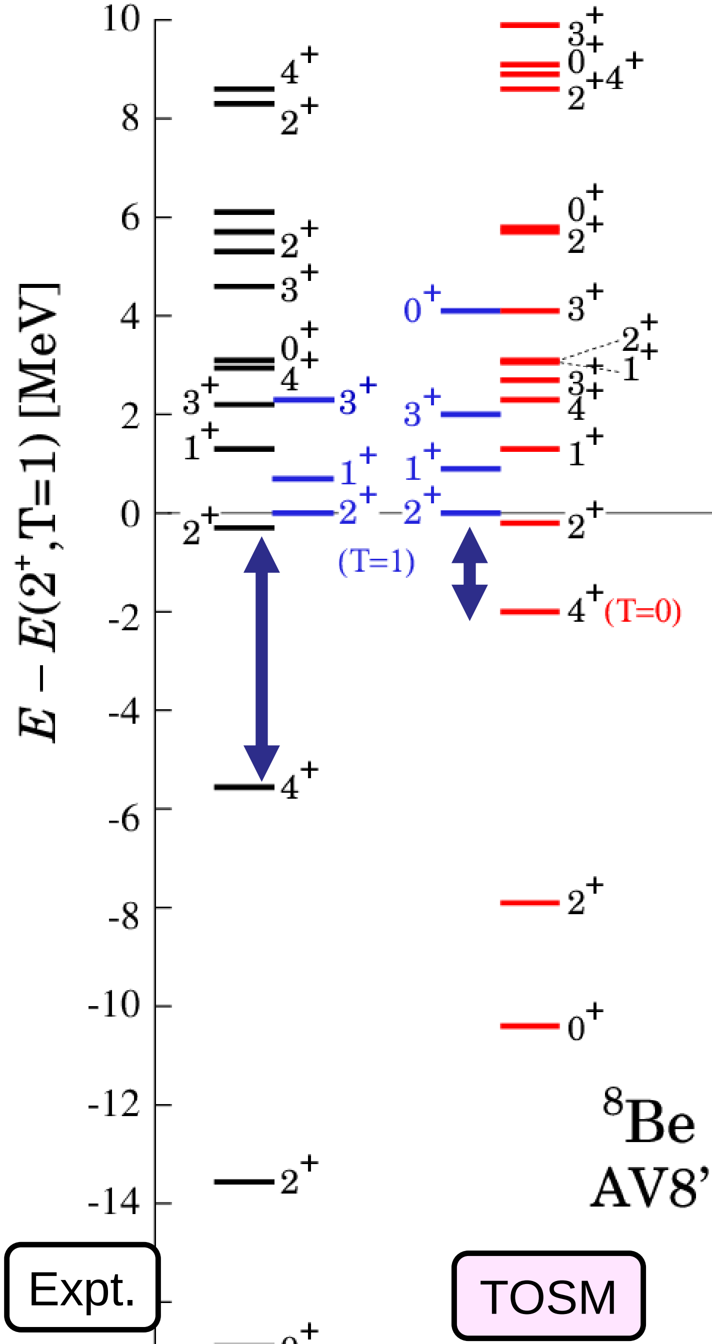


α-α structure



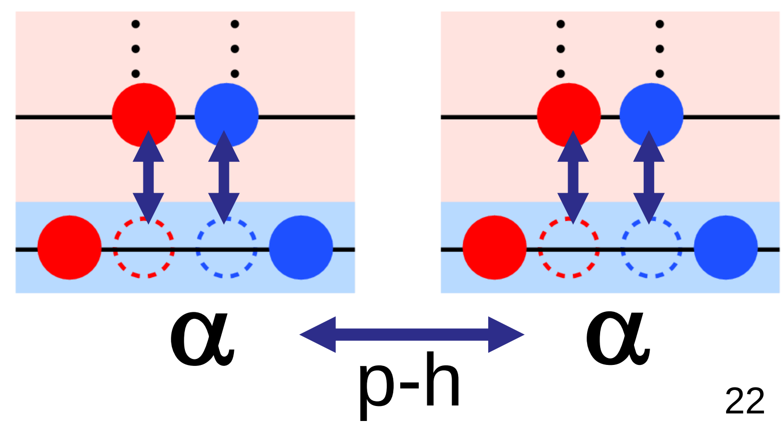
^{8}Be in TOSM – AV8' –

- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)
- ground band
- highly excited states
  - small E_x
  - correct level order (T=0,1)
- $R_m(^8\text{Be})$=2.21 fm
  - Brink 2α model: 2.48 fm
  - ^{4}He :1.52 fm
  - ^{12}C :2.35 fm ~ R_m(exp)

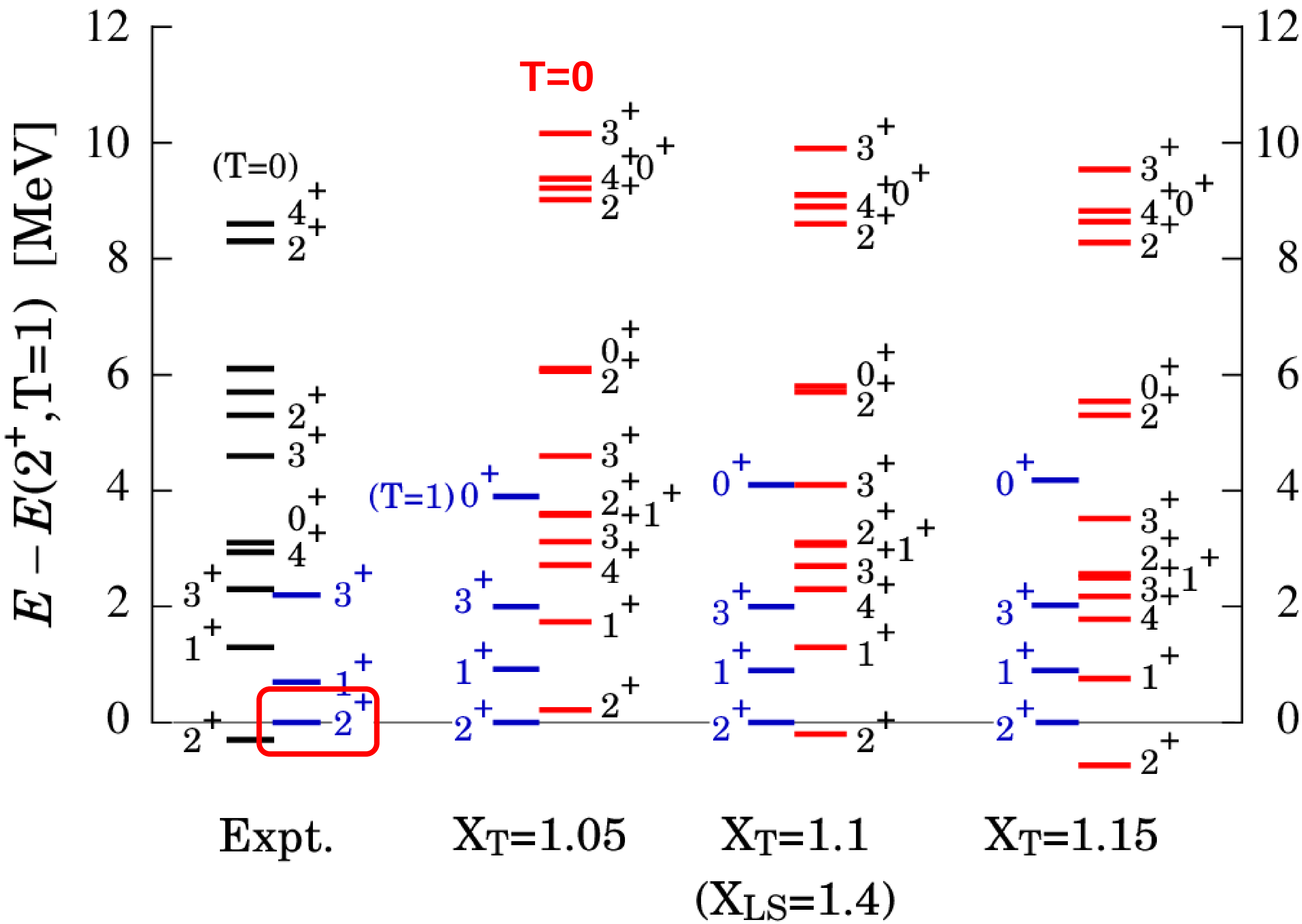


^{8}Be in TOSM – AV8' –

- $V_T \times 1.1$, $V_{LS} \times 1.4$
  - simulate ^{4}He benchmark (Kamada et al., PRC64)
- correct level order (T=0,1)
- α : 0p0h+2p2h with high-k
  → naively 2α needs 4p4h.



V_{tensor} dependence of ^{8}Be



- *S*-wave UCOM can be simulated with X_T~1.1 (PTP121)
- Stronger tensor correlation in <u>**T=0 states**</u> than T=1 states.

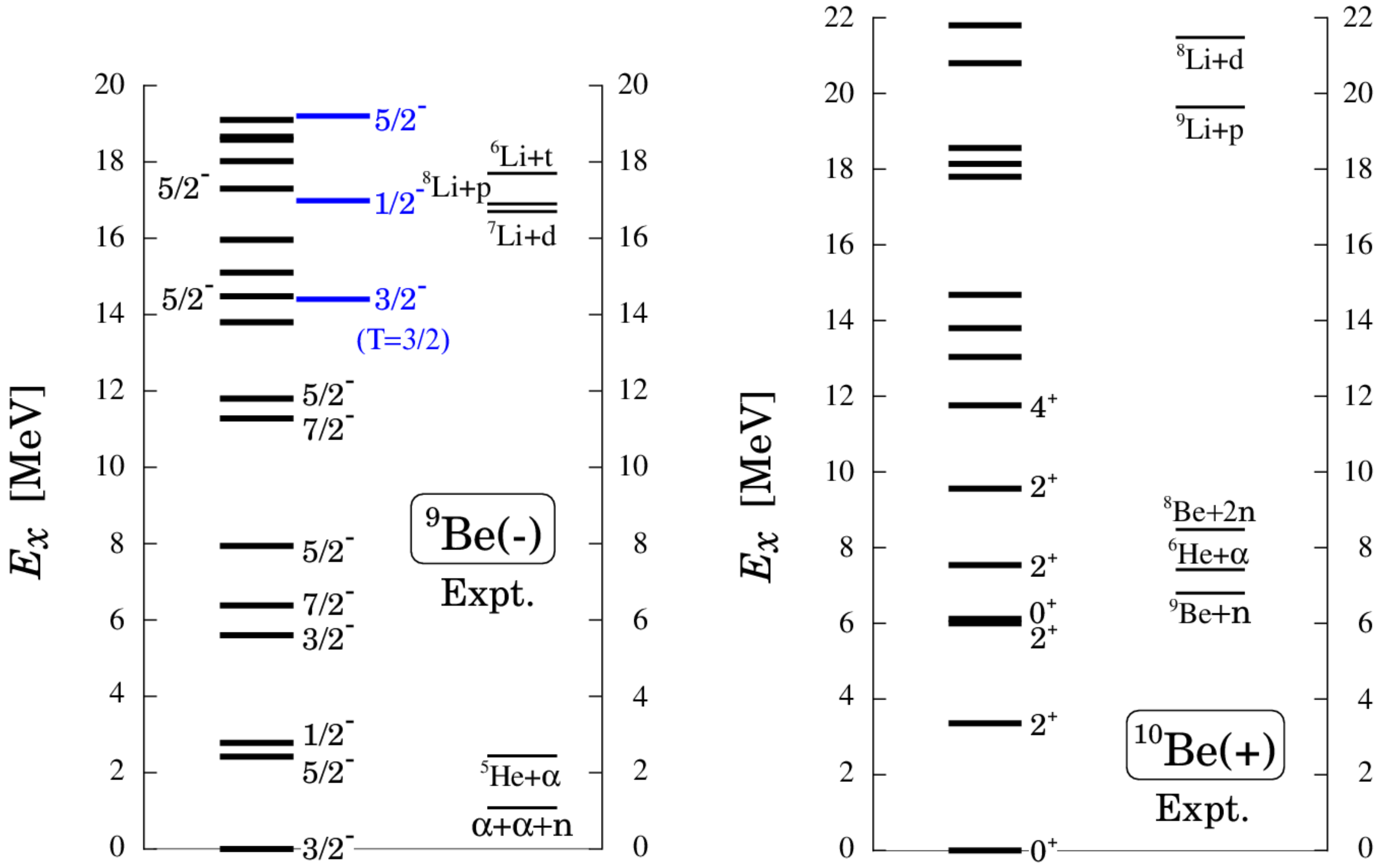
Hamiltonian components in ^{8}Be

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

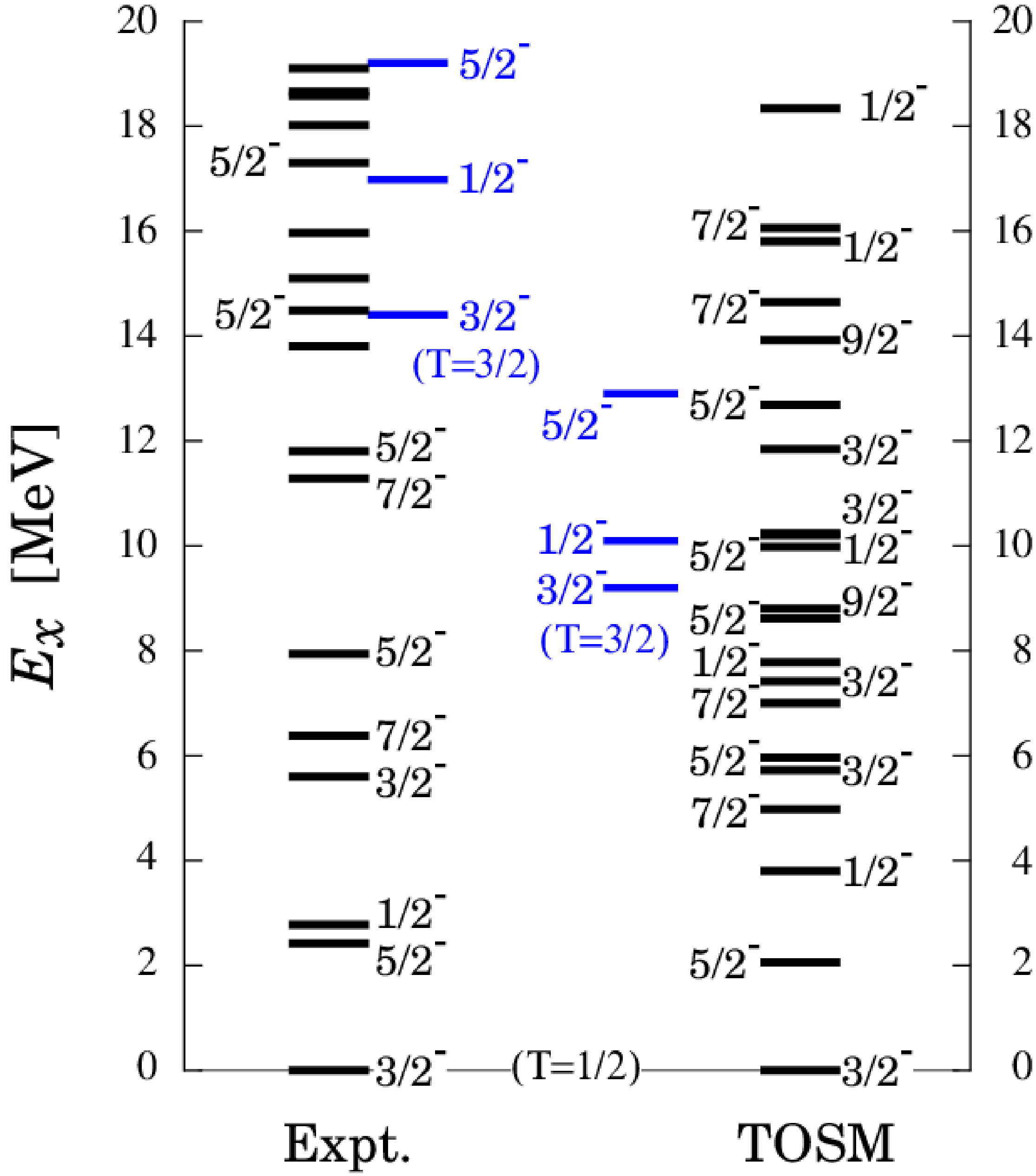
^{9,10}Be energy spectra

TUNL

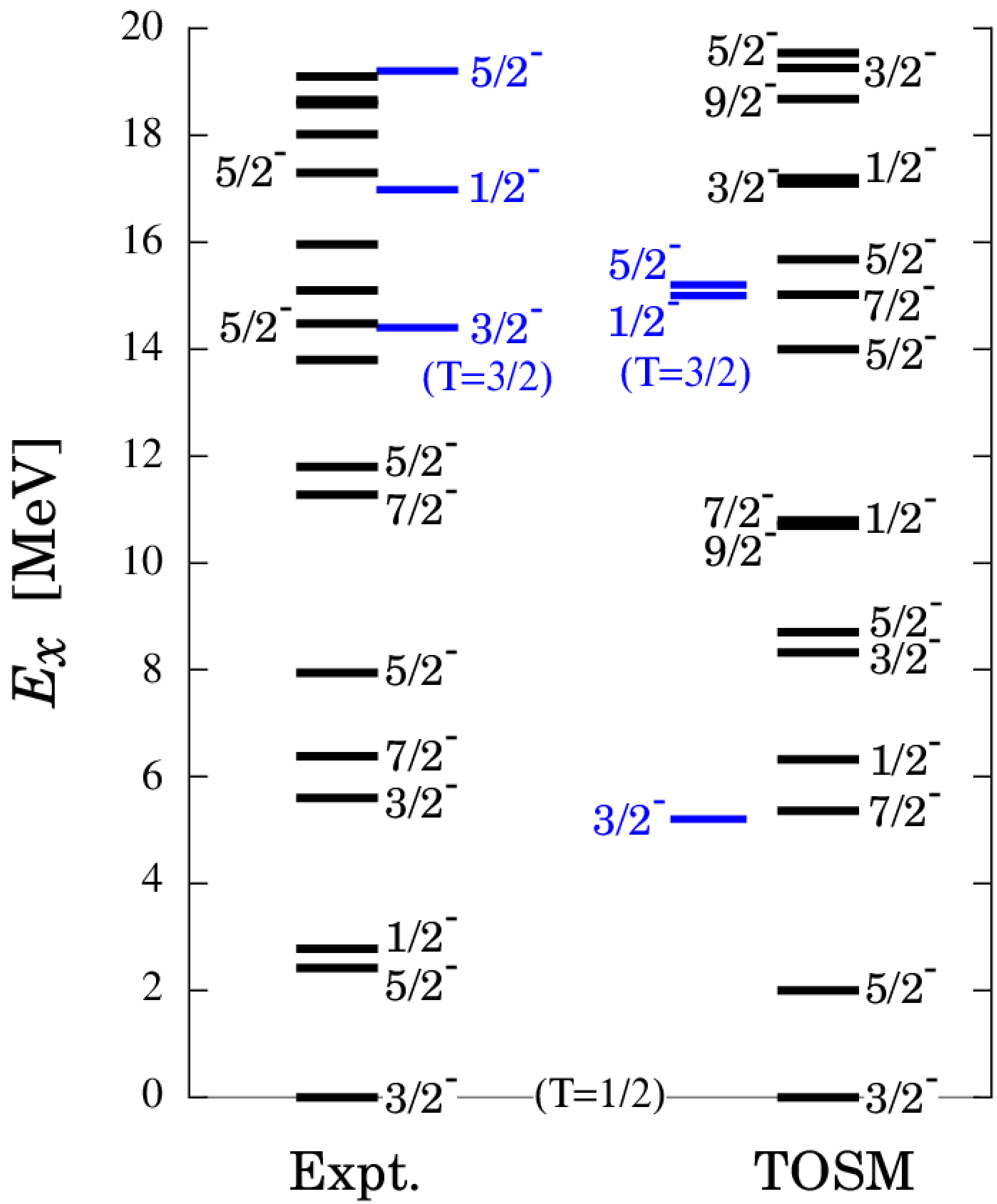


^{9}Be in TOSM – AV8' –

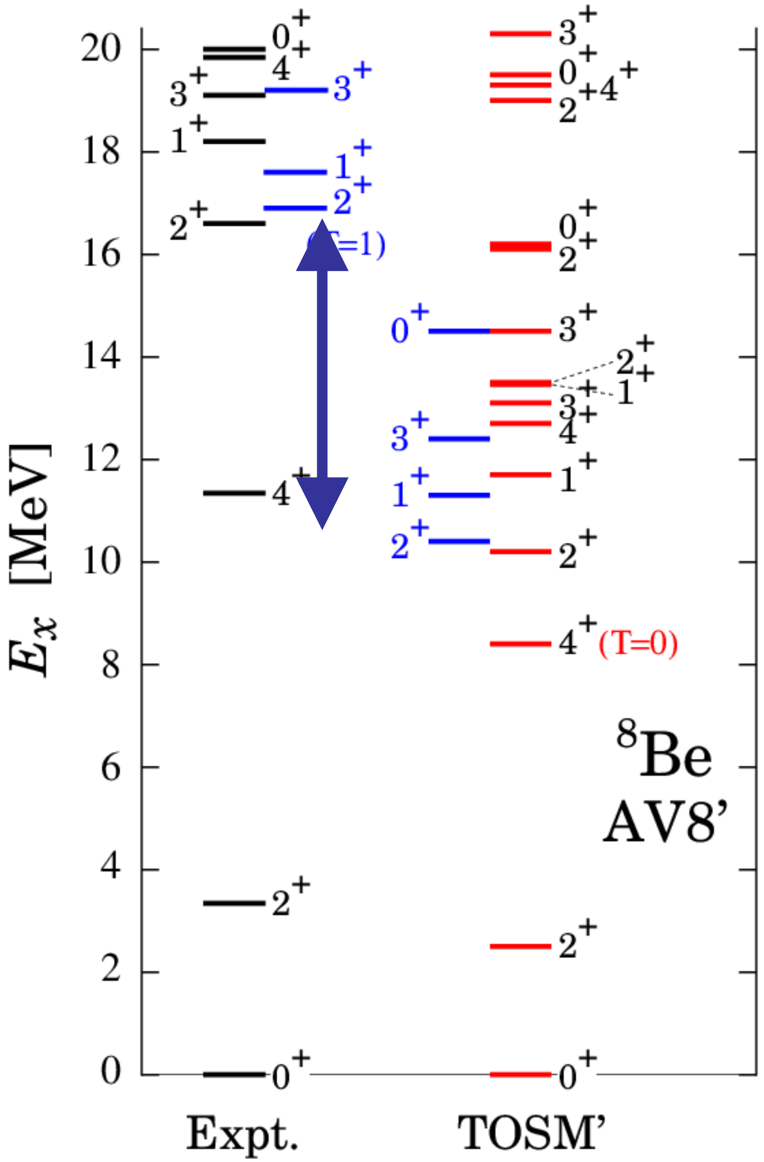
Preliminary



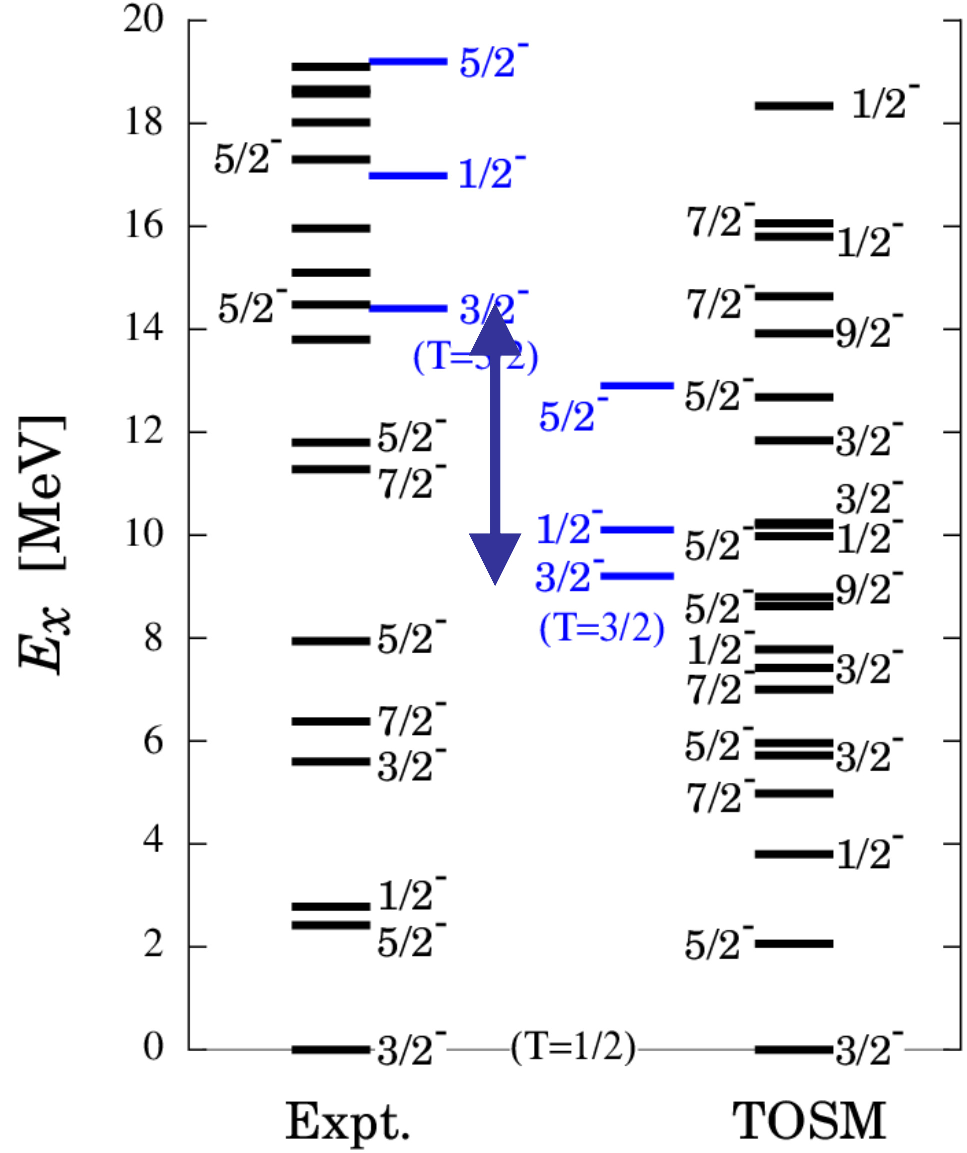
^{9}Be in TOSM – Minnesota –



^{8}Be & ^{9}Be

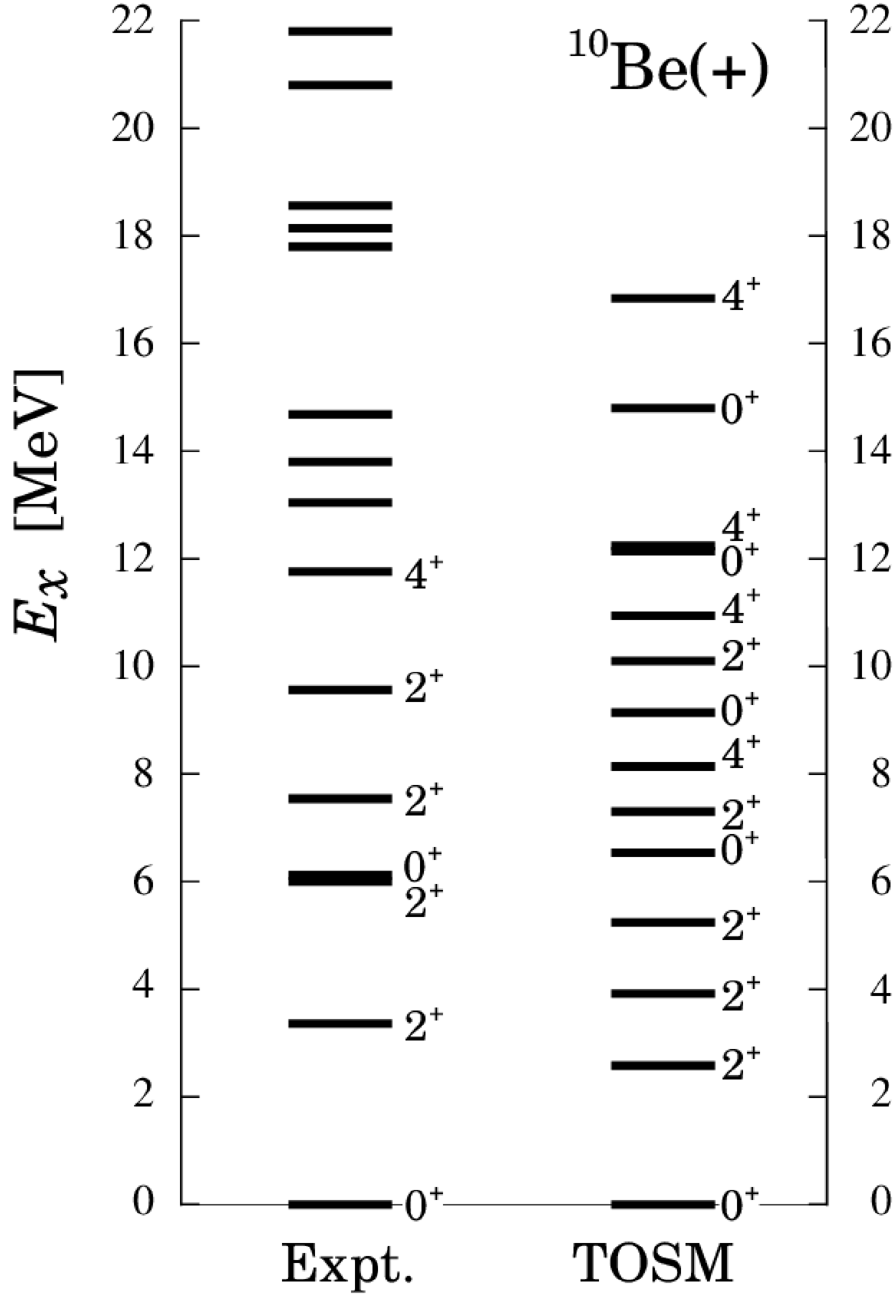


E_x [MeV]
0
2
4
6
8
10
12
14
16
18
20
Expt.
TOSM'
(T=1)
(T=0)
^{8}Be
AV8'



E_x [MeV]
0
2
4
6
8
10
12
14
16
18
20
Expt.
TOSM
(T=1/2)
(T=3/2)

^{10}Be in TOSM – AV8' –



Preliminary

Toward the description of cluster states

- **Tensor Optimized Shell Model (TOSM)**
  - TM, A.Umeya, H. Horii, H. Toki, K. Ikeda
  - He, Li, Be isotopes
- **Tensor Optimized Few-body Model (TOFM)**
  - K. Horii, H.Toki, TM, K. Ikeda, PTP127(2012)1019
- **Tensor Optimized AMD (Tensor-AMD)**
  - Clustering & tensor force

Formulation of Tensor-AMD

$$\left|\Phi_{\text{T-AMD}}\right\rangle = C_0\left|\Phi_{\text{AMD}}\right\rangle + \sum_{i<j}^{A}\sum_{S,T} F_{ij}^{ST}(\vec{r}_{ij})\left|\Phi'_{\text{AMD}}\right\rangle$$

$$F^{ST}(\vec{r}) = r^2 S_{12} \sum_n C_n^{ST} \exp(-\rho_n^{ST} r^2)$$

- Variational parameters
  - ν, $\mathbf{Z}_i$ (i=1, ..., A) , spin-direction (up/down)
  - C_0 , $C^{ST}{}_n$, $\rho^{ST}{}_n$ (Gaussian expansion)
  - Tensor-type correlation for **relative motion**
  - Decided by using cooling equation +parity projection.

S. Nagata, T. Sasakawa, T. Sawada, R. Tamagaki, PTP22,274 (1959).

Tensor matrix elements

$$\left|\Phi_{\mathrm{AMD}}\right\rangle = \frac{1}{\sqrt{A!}}\det\left\{\varphi_1,\ldots,\varphi_A\right\}$$

$$\left|\varphi\right\rangle = \left|\mathbf{Z}\right\rangle\left|\chi^{\sigma\tau}\right\rangle$$

$$\left\langle \mathbf{r}\middle|\mathbf{Z}\right\rangle \propto \exp\left[-\nu\left(\mathbf{r}-\frac{\mathbf{Z}}{\sqrt{\nu}}\right)^2\right]$$

Matrix elements

$$\left\langle \varphi_i\varphi_j\cdots\middle|\hat{O}\middle|\varphi_{i'}\varphi_{j'}\cdots\right\rangle_{\mathrm{A}}$$

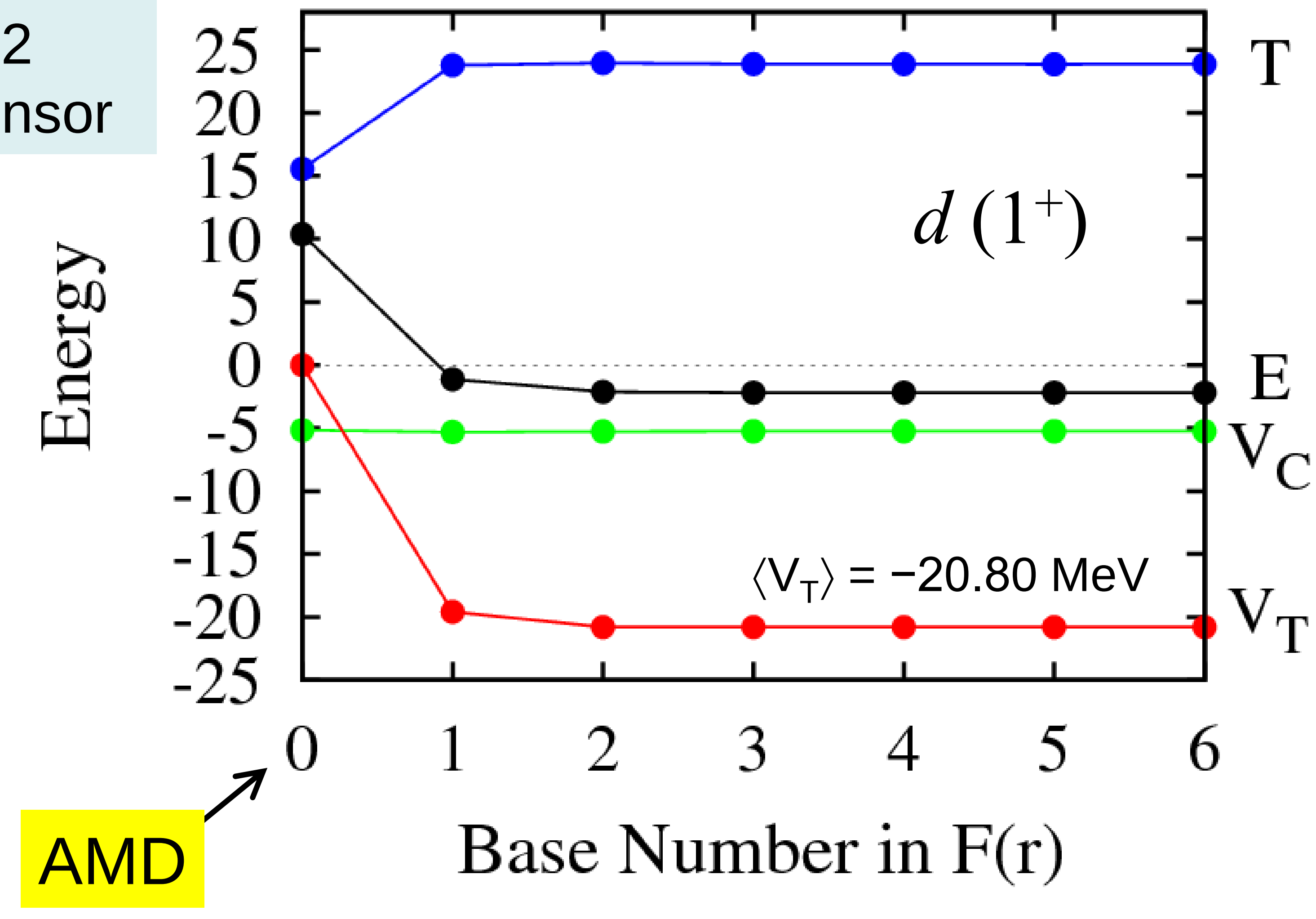
Corr. func.(bra) → Hamiltonian → Corr. func.(ket)

$$\hat{O} = S_{12}\cdot S_{12}\cdot S_{12}$$

- 6-body matrix elements within 2-body Hamiltonian.
- At most, <u>4-body matrix elements</u> to be evaluated.
  – 6-body ME : {2-body ME} $\times$ {2-body ME} $\times$ {2-body ME}
  – 5-body ME : {3-body ME} $\times$ {2-body ME}

Deuteron in Tensor-AMD

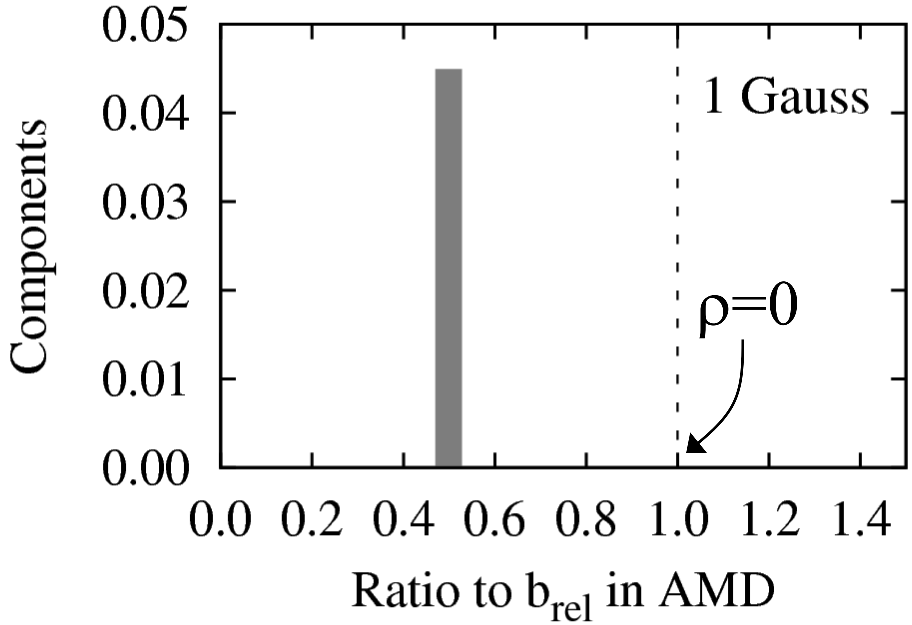
- Volkov No.2
- Furutani tensor



- Good convergence

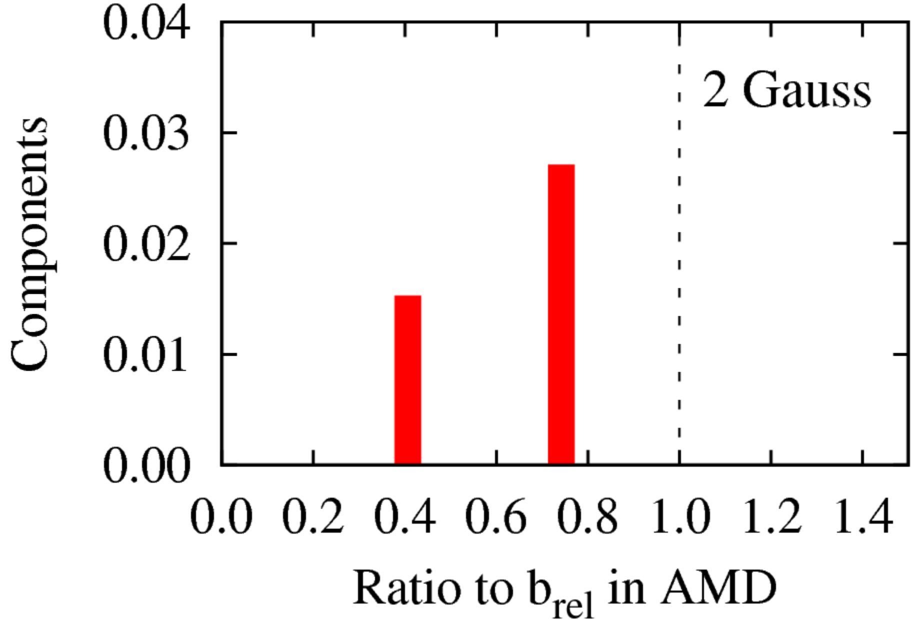
$$F(\boldsymbol{r}) = r^2 S_{12} \Sigma_n C_n \exp(-\rho_n r^2)$$

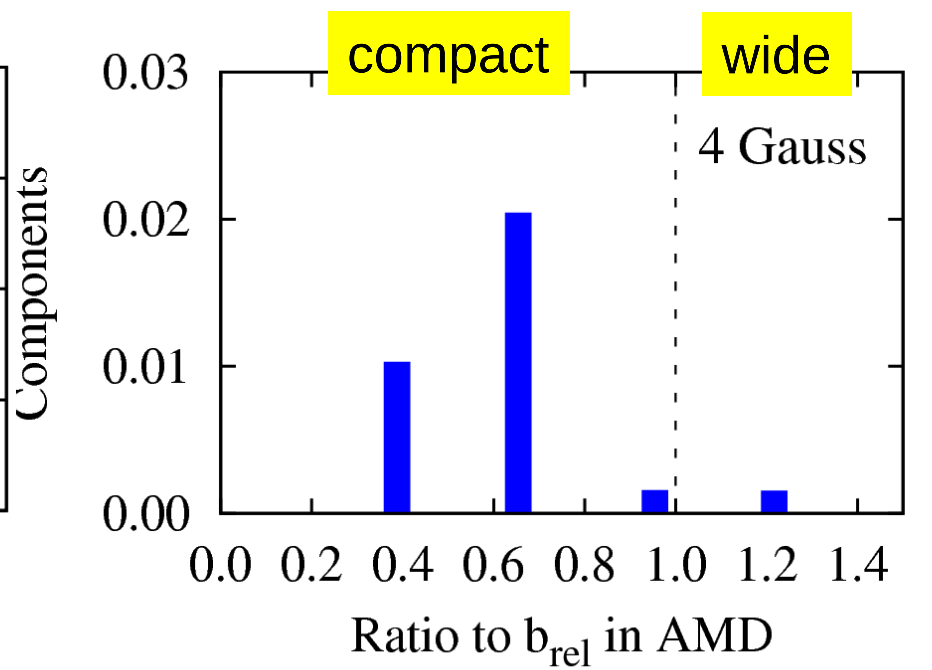
Gaussian expansion in $F(\boldsymbol{r})$



$$F(\boldsymbol{r}) = r^2 S_{12} \sum_n C_n \exp(-\rho_n r^2)$$

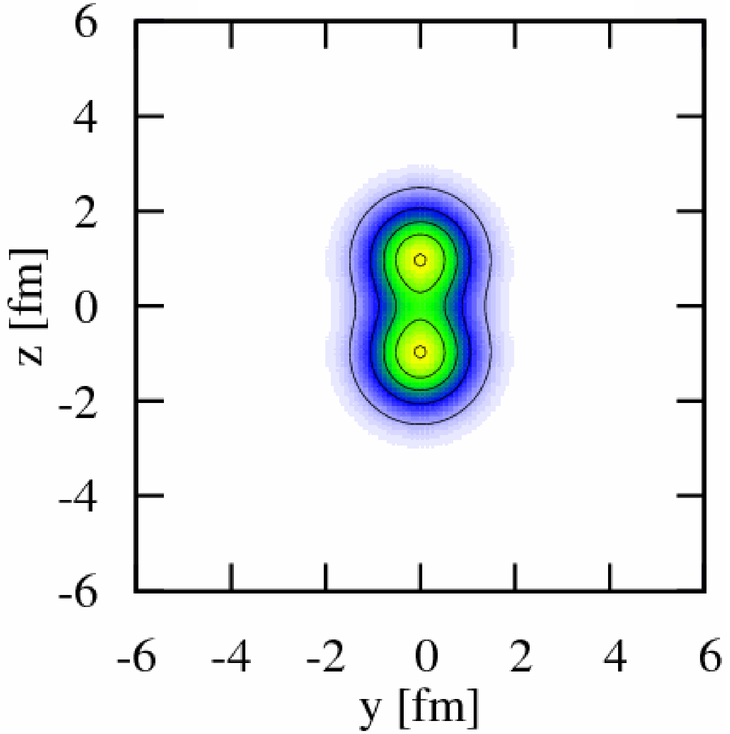
- Ratio to the Gaussian length (fm) of AMD basis
- Compact component is dominant in relative *D*-state





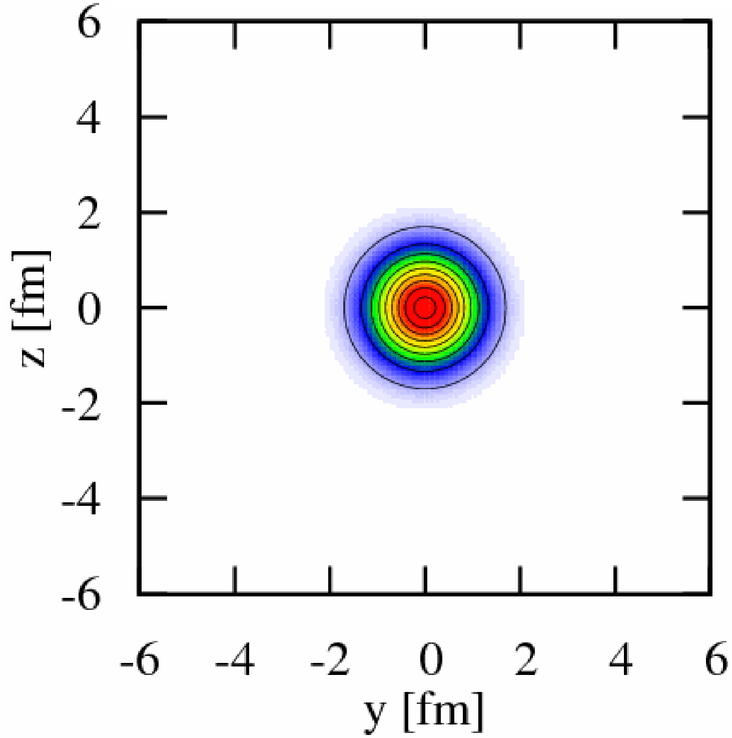
Intrinsic density of deuteron

AMD



$\langle V_T \rangle_{AMD} = -0.63$ MeV

AMD part
in Tensor-AMD



Describe *S*-wave in *d*

$\langle V_T \rangle_{T\text{-}AMD} = -20.80$ MeV

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.
- Be isotopes
  - ^{8}Be: grand band & highly excited states (T=0 & T=1). similar tendency in ^{9}Be.
  - more configurations of such as 4p4h to describe 2α structure in the grand band.