Role of the tensor correlation in neutron halo nuclei

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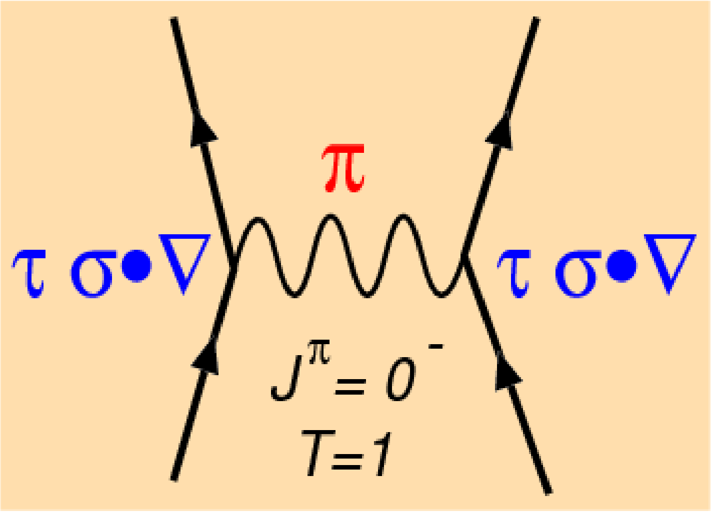
Contents

- He isotopes with tensor correlation
  - Tensor-optimized shell model (TOSM)
- Li isotopes with tensor and pairing correlations
  - Breaking of magic number, halo formation
- Unitary Correlation Operator Method (UCOM) for short-range correlation
  - TOSM+UCOM with bare interaction

Motivation

- Tensor force (V_{tensor}) plays a significant role in the nuclear structure.
  - In ^{4}He, $\langle V_{tensor} \rangle \sim \langle V_{central} \rangle$
  - $\frac{V_\pi}{V_{NN}}$ ~ 80% (GFMC)

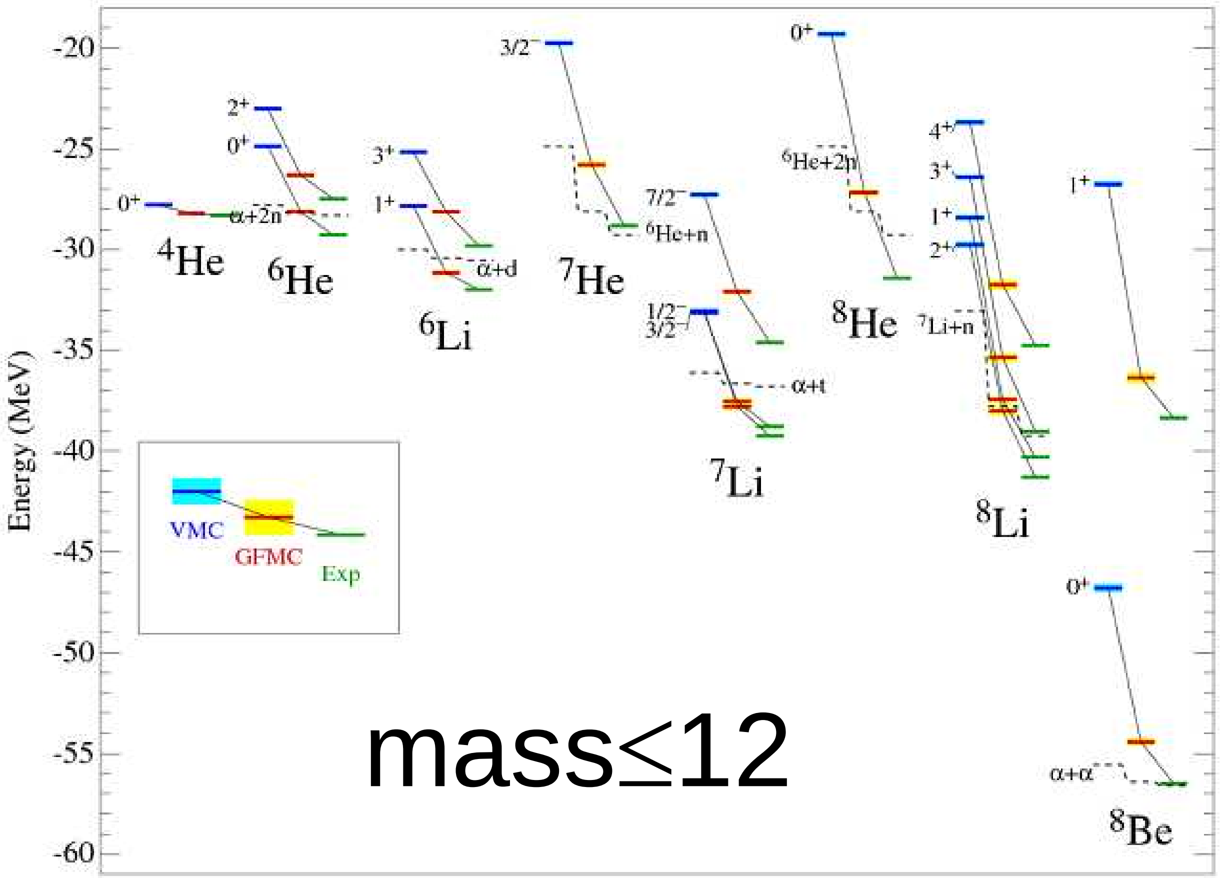


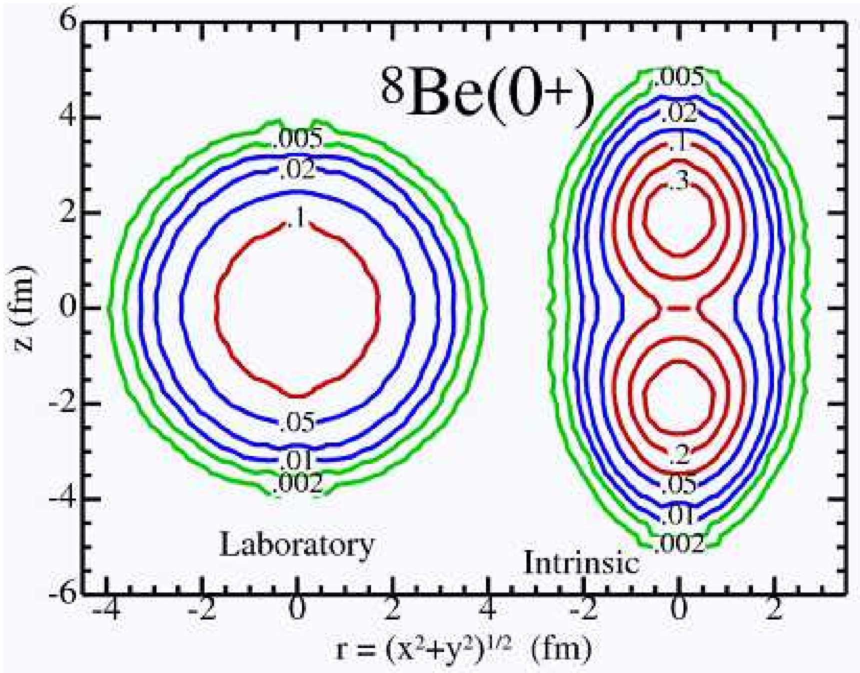
R.B. Wiringa, S.C. Pieper, J. Carlson, V.R. Pandharipande, PRC62(2001)

- We would like to understand the role of V_{tensor} in the nuclear structure by describing tensor correlation explicitly.
  - model wave function (shell model and cluster model).
  - spatial properties, p-h correlation, …
- Spectroscopy of neutron-rich nuclei : He and Li isotopes

Variational calculation in real space

Green's function
Monte Calro





α-α structure

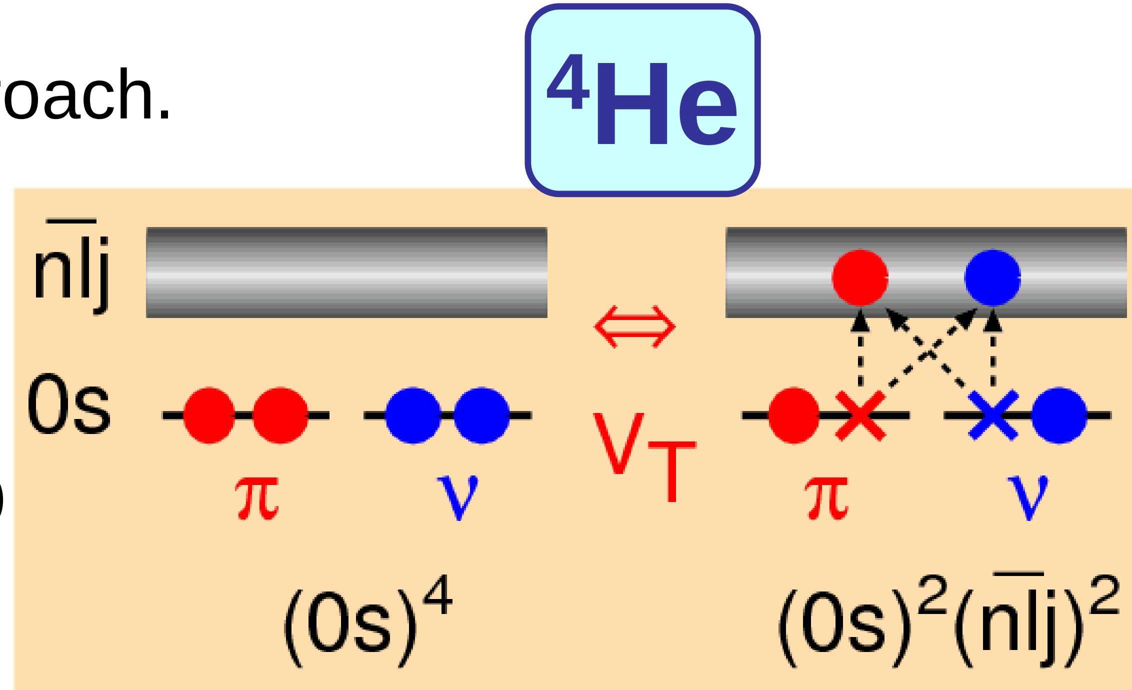
C.Pieper, R.B.Wiringa,
Annu.Rev.Nucl.Part.Sci.51(2001)
R.B.Wilinga,S.C.Pieper,J.Carlson, V.R.Pandaripande,
PRC62(2000)014001.

Tensor-optimized shell model (TOSM)

- Tensor correlation
  in the shell model type approach.

- Configuration mixing
  with high-L orbit
  within 2p2h excitations

  TM, Kato, Ikeda, PTP113(2005)
  TM et al., PTP117(2007)
  T.Terasawa, PTP22(1959)



- Length parameters $\{b_\alpha\}$ such as $b_{0s}, b_{0p1/2}, \ldots$ are determined independently and variationally.
  - Describe high momentum component from V_{tensor}

    CPPHF by Sugimoto et al,(NPA740) / Akaishi (NPA738)
    CPP-RMF by Ogawa et al.(PRC73), CPP-AMD by Dote et al.(PTP115)

Hamiltonian and variational equations

$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij}, \quad v_{ij} : \text{central+tensor+LS+Coulomb}$$

$$\Phi = \sum_k C_k \cdot \psi_k \qquad \psi_k : \text{ shell model type configuration}$$

$$\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0 \quad \Rightarrow \quad \frac{\partial \langle H - E \rangle}{\partial b_\alpha} = 0, \quad \frac{\partial \langle H - E \rangle}{\partial C_k} = 0$$

TM, Kato, Ikeda, PTP113('05)763
TM, Sugimoto, Kato, Toki, Ikeda PTP117('07)257

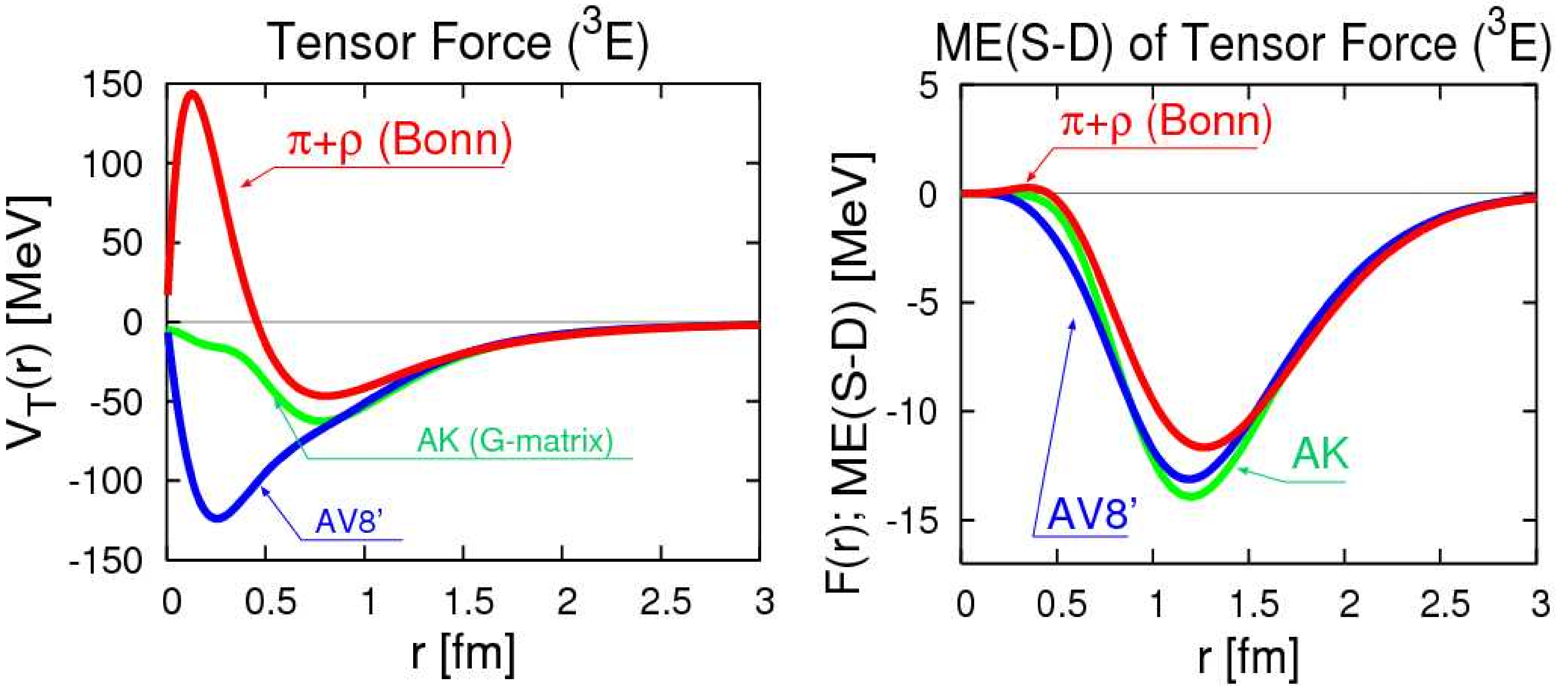
- Effective interaction : Akaishi force (NPA738)
  - G-matrix from AV8' with k_Q=2.8 fm^{-1}
  - Long and intermediate ranges of V_{tensor} survive.
  - Adjust $V_{central}$ to reproduce B.E. and radius of ^{4}He

Property of the tensor force

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

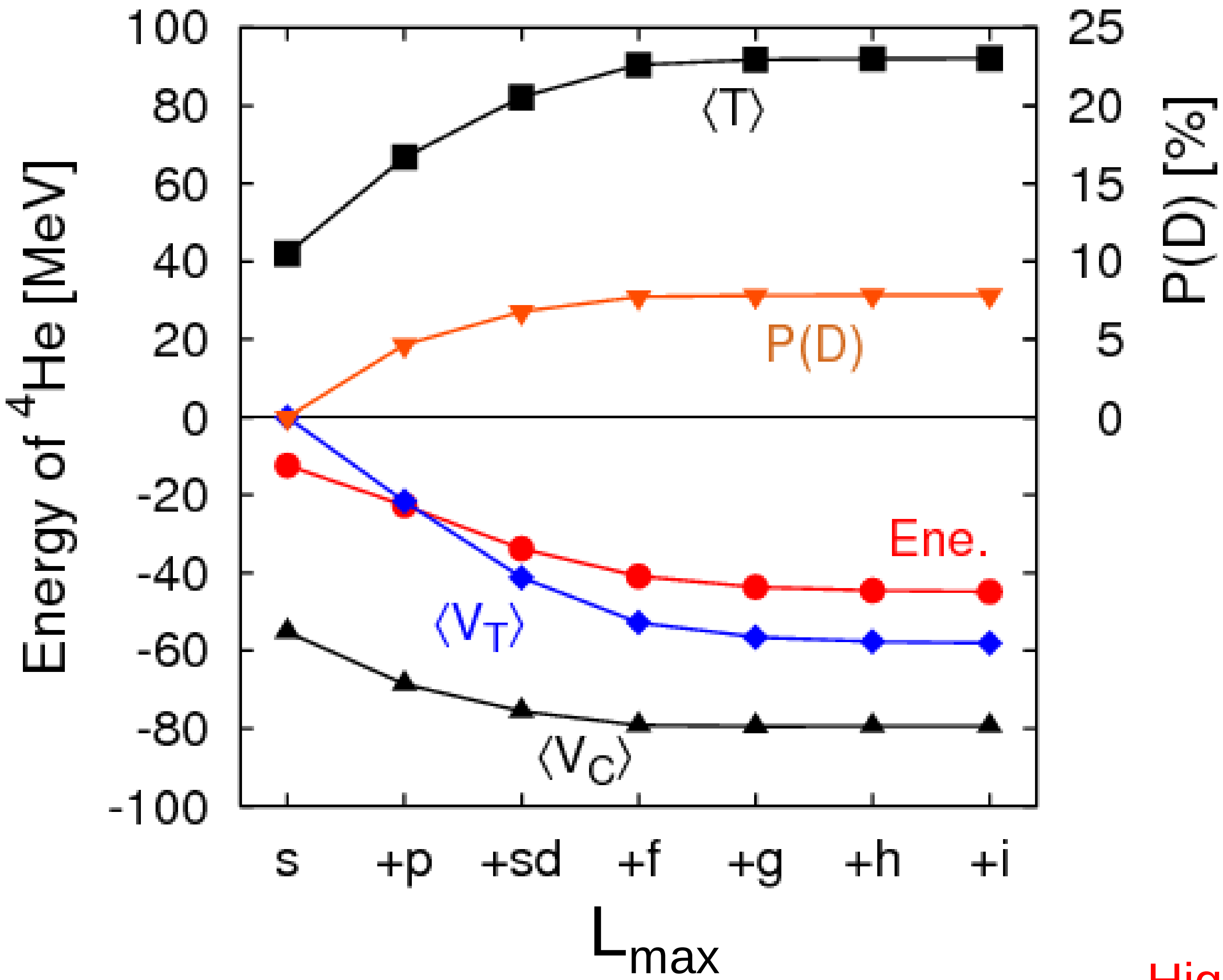
$$V_{tensor} = V_T(r) \cdot S_{12}$$

$$b_{0s} = 1.4 \cdot \sqrt{2}\ \text{[fm]} \qquad b_{0d} = b_{0s} / 2$$



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

^{4}He with TOSM



good convergence

Length parameters

Orbit	b_{nlj}/b_{0s}
$0p_{1/2}$	0.65
$0p_{3/2}$	0.58
$1s_{1/2}$	0.63
$0d_{3/2}$	0.58
$0d_{5/2}$	0.53
$0f_{5/2}$	0.66
$0f_{7/2}$	0.55

Higher shell effect $\sim 16\hbar\omega$

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.

^{4}He in TOSM

Energy (MeV)	– 28.0
$\langle V_{tensor} \rangle$	– 51.0

$(0s_{1/2})^4$		85.0 %
$(0s_{1/2})^2_{JT}(0p_{1/2})^2_{JT}$	JT=10	5.0
	JT=01	0.3
$(0s_{1/2})^2_{10}(1s_{1/2})(0d_{3/2})_{10}$		2.4
$(0s_{1/2})^2_{10}(0p_{3/2})(0f_{5/2})_{10}$		2.0
P[D]		9.6

4 Gaussians instead of HO

$$\langle T \rangle = 71.2 \text{ MeV}$$

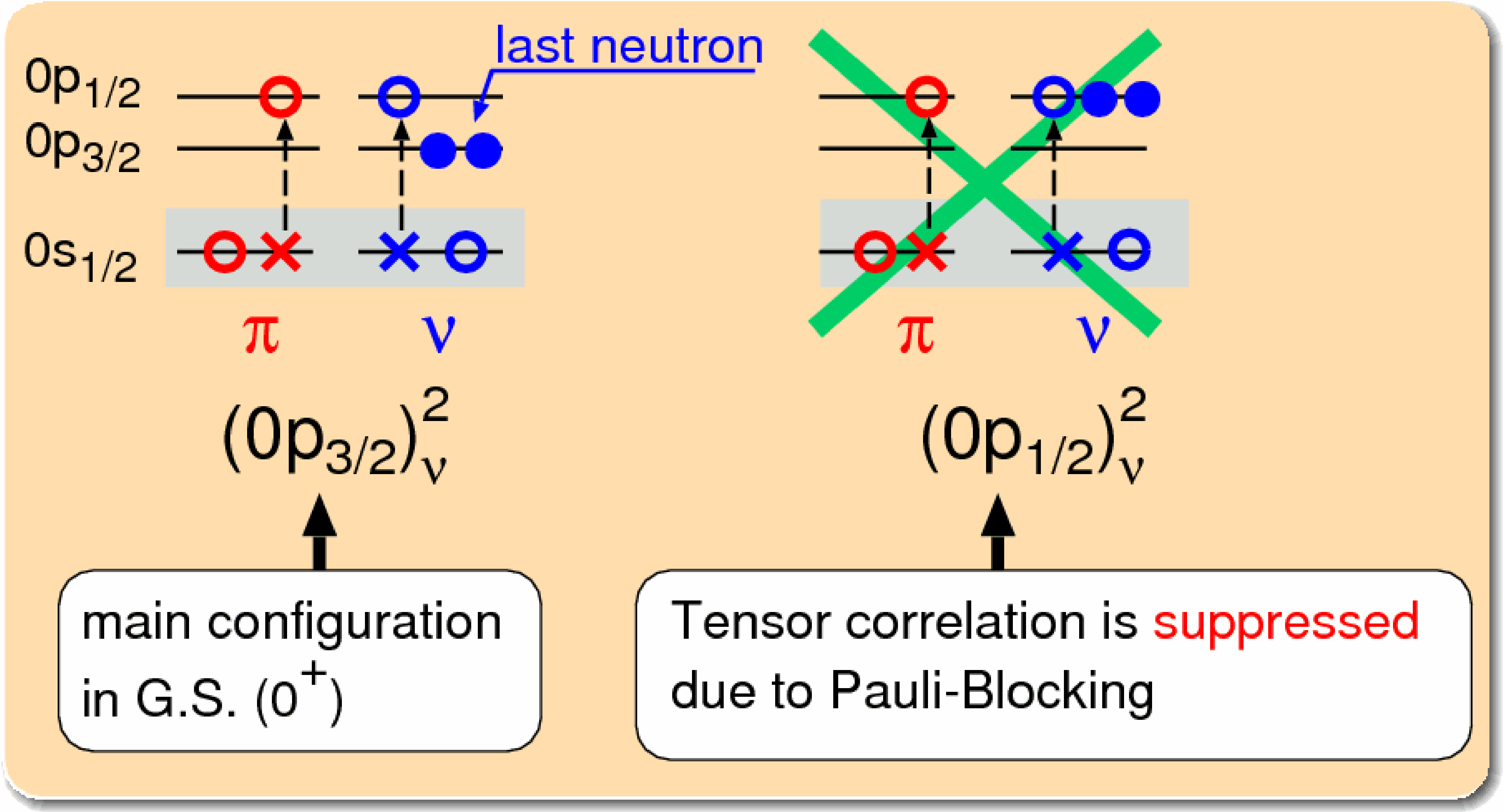
$$\langle V_{central} \rangle = -48.6 \text{ MeV}$$

c.m. excitation = 0.6 MeV

- 0^- of pion nature.
- deuteron correlation with (J,T)=(1,0)

Cf. R.Schiavilla et al. (GFMC) PRL98('07)132501

Tensor correlation in ^6He



Ground state

Excited state

^{6}He in coupled ^{4}He+n+n model

- System is solved based on RGM

$$H(^6\mathrm{He}) = H(^4\mathrm{He}) + H_{nn} \qquad \Phi(^6\mathrm{He}) = \mathcal{A}\left\{\sum_{i=1}^{N} \psi_i(^4\mathrm{He}) \cdot \chi_i(nn)\right\}$$

$$\sum_{i=1}^{N} \left\langle \psi_j(^4\mathrm{He}) \middle| H(^6\mathrm{He}) - E \middle| \mathcal{A}\left\{\psi_i(^4\mathrm{He}) \cdot \chi_i(nn)\right\} \right\rangle = 0$$

$\psi_i(^4\mathrm{He})$: shell model type configuration → TOSM

- Orthogonality Condition Model (OCM) is applied.

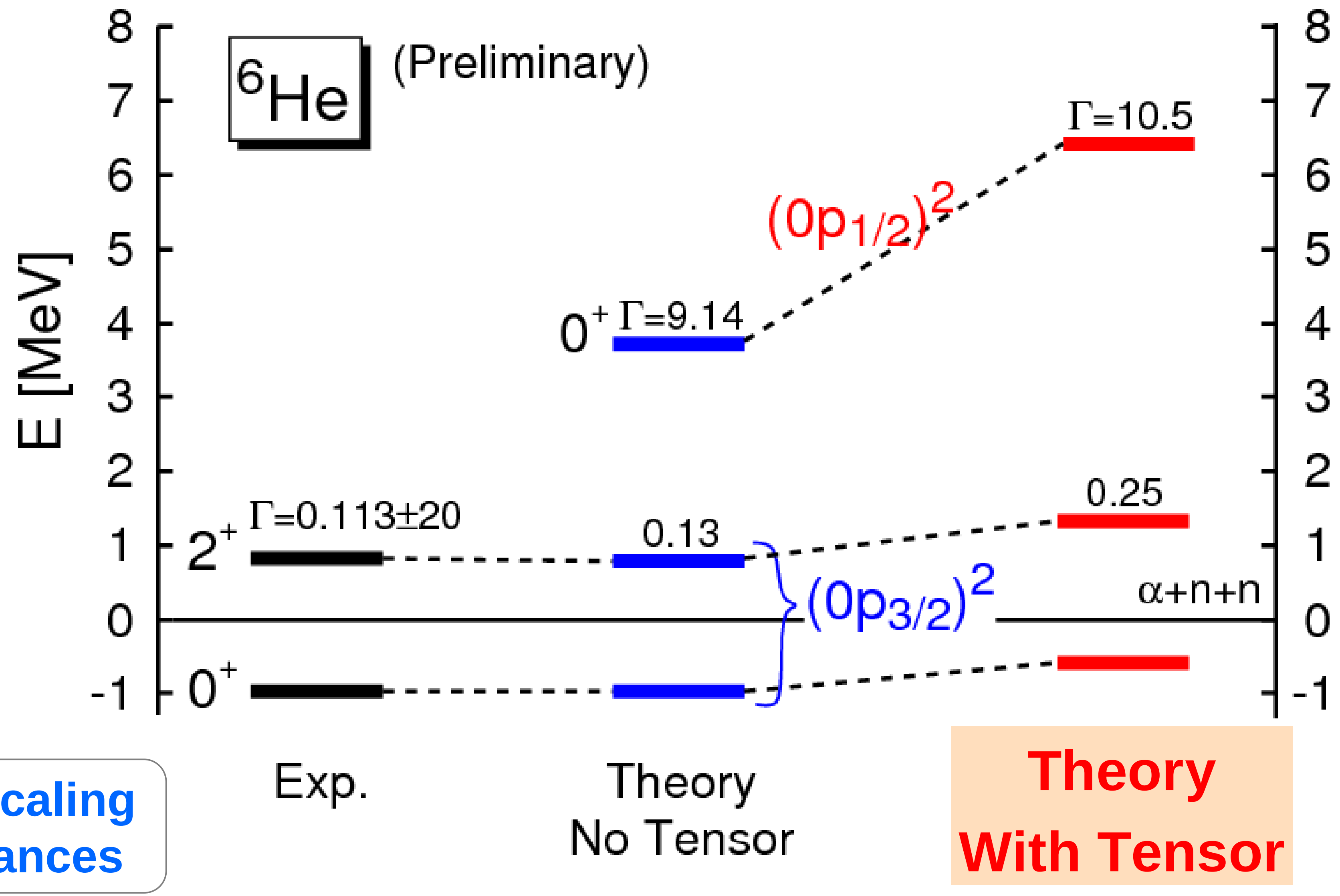
$$\sum_{i=1}^{N} \left[H_{ij}(^4\mathrm{He}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12}) \cdot \delta_{ij} \right] \chi_j(nn) = E\chi_i(nn)$$

$H_{ij}(^4\mathrm{He}) = \left\langle \psi_i \middle| H(^4\mathrm{He}) \middle| \psi_j \right\rangle$: Hamiltonian for ^{4}He

$\chi(nn) = \mathcal{A}\{\varphi_1 \varphi_2\}$: 2 neutrons with Gaussian expansion method

$\left\langle \varphi_i \middle| \phi_\alpha \right\rangle = 0,\ \{\phi_\alpha \in {}^4\mathrm{He}\}$: Orthogonality to the Pauli-forbidden states

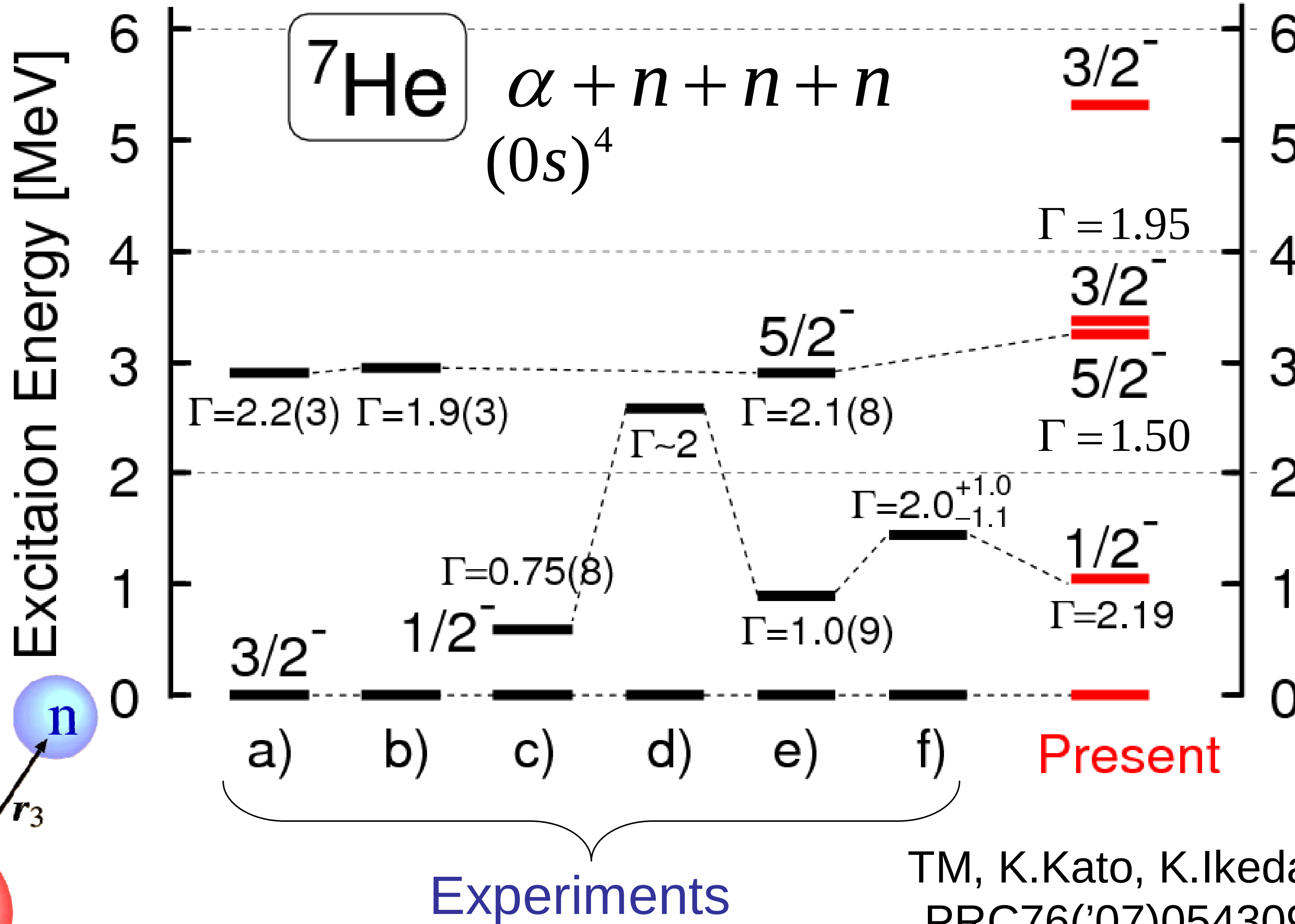
^{6}He in coupled ^{4}He+n+n model

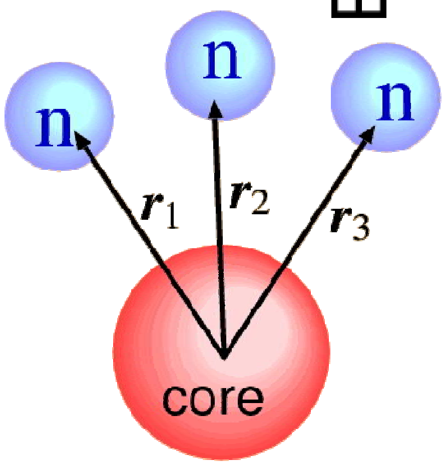


Complex scaling for resonances

- $(0p_{3/2})^2$ can be described in Naive ^{4}He+n+n model
- $(0p_{1/2})^2$ loses the energy → Tensor suppression in 0^+_2

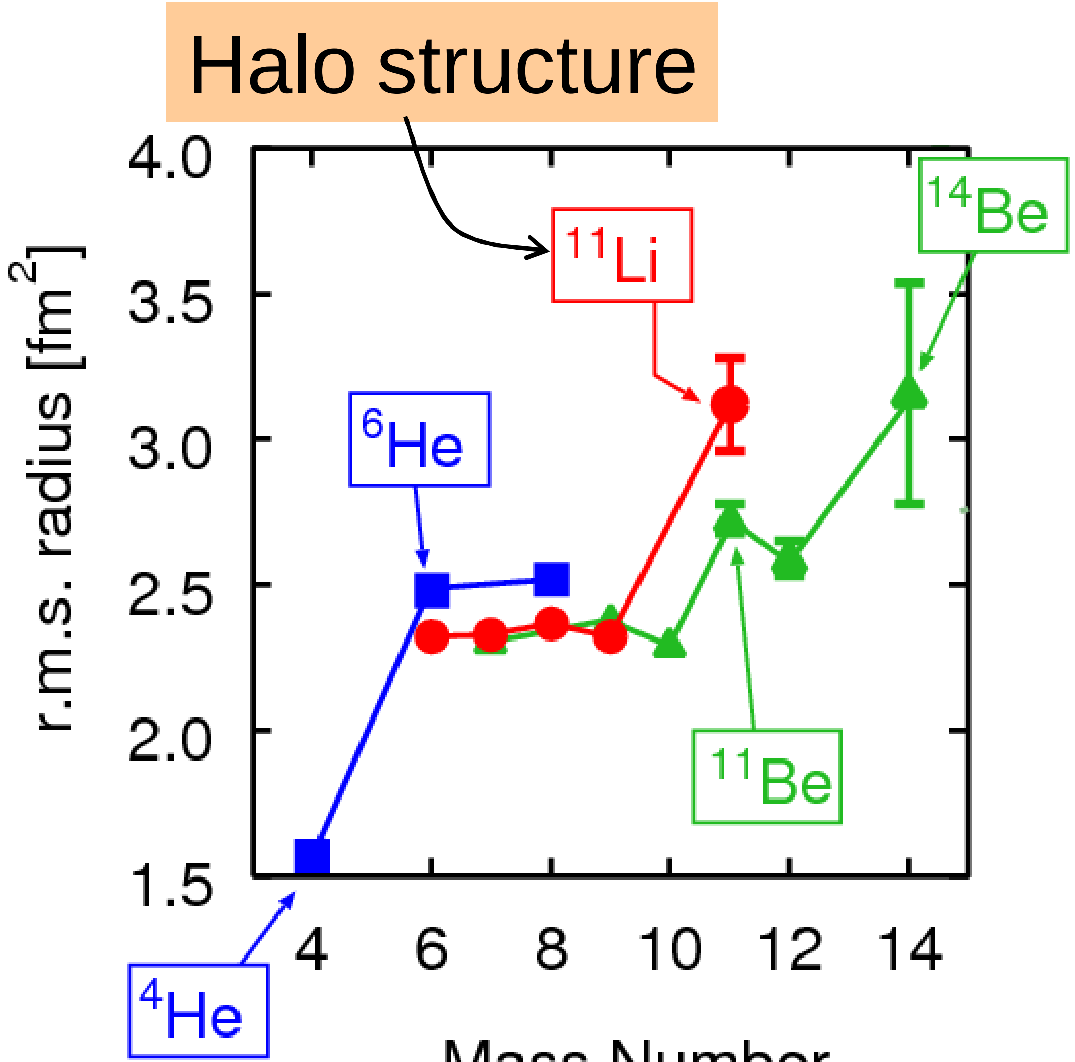
^{7}He (unbound) : Expt vs. Theory





TM, K.Kato, K.Ikeda
PRC76('07)054309
complex scaling

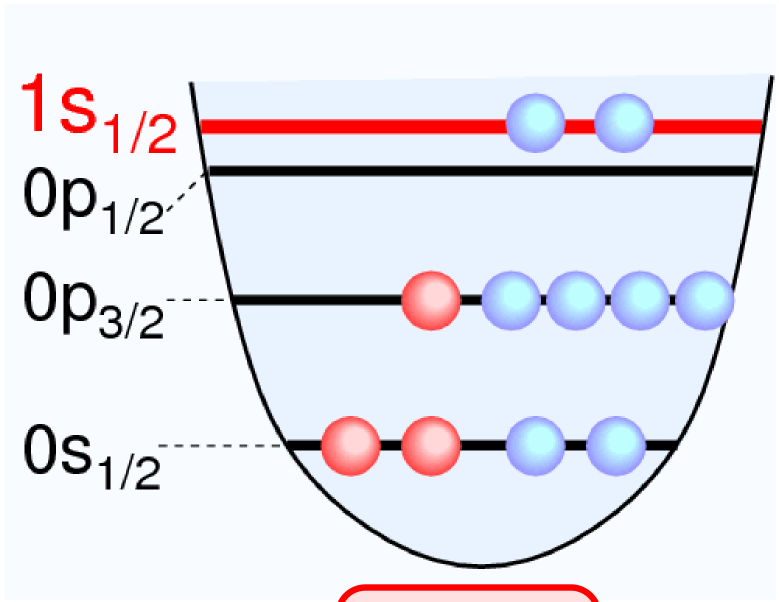
Characteristics of Li-isotopes



I. Tanihata et. al
PLB206(1988)592

- Breaking of magicity N=8
  - $^{10-11}$Li, $^{11-12}$Be
  - ^{11}Li … $(1s)^2 \sim 50\%$.

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



11Li

^{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.

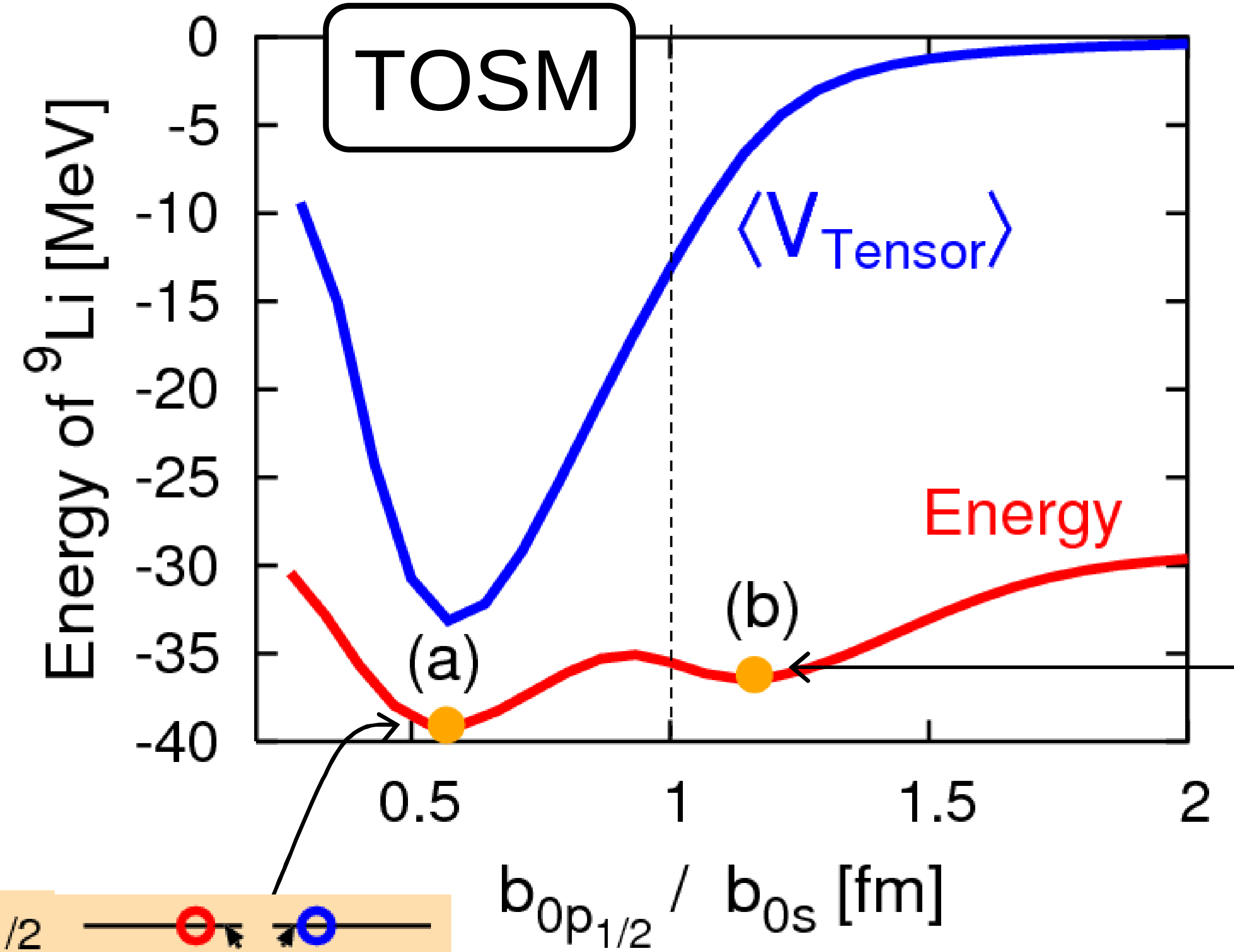
$$\sum_{i=1}^{N} \left[H_{ij}(^{9}\mathrm{Li}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12}) \cdot \delta_{ij} \right] \chi_j(nn) = E \chi_i(nn)$$

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

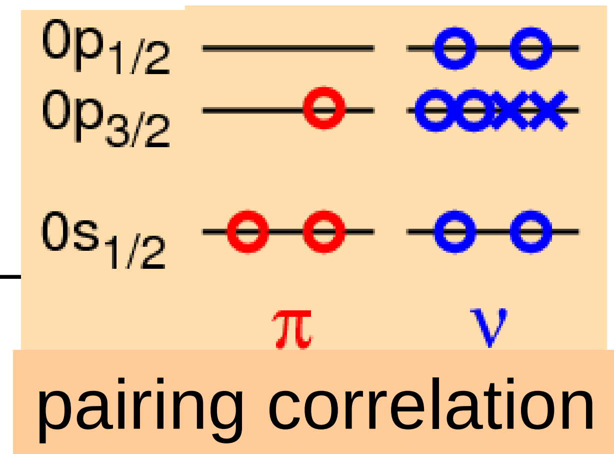
$\chi(nn) = \mathcal{A}\{\varphi_1 \varphi_2\}$: 2 neutrons with Gaussian expansion method

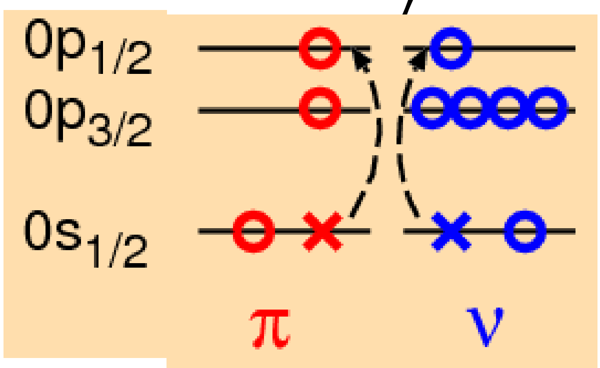
$\langle \varphi_i | \phi_\alpha \rangle = 0, \ \{\phi_\alpha \in {}^{9}\mathrm{Li}\}$: Orthogonality to the Pauli-forbidden states

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



0s+0p+1s0d within 2p2h excitations.

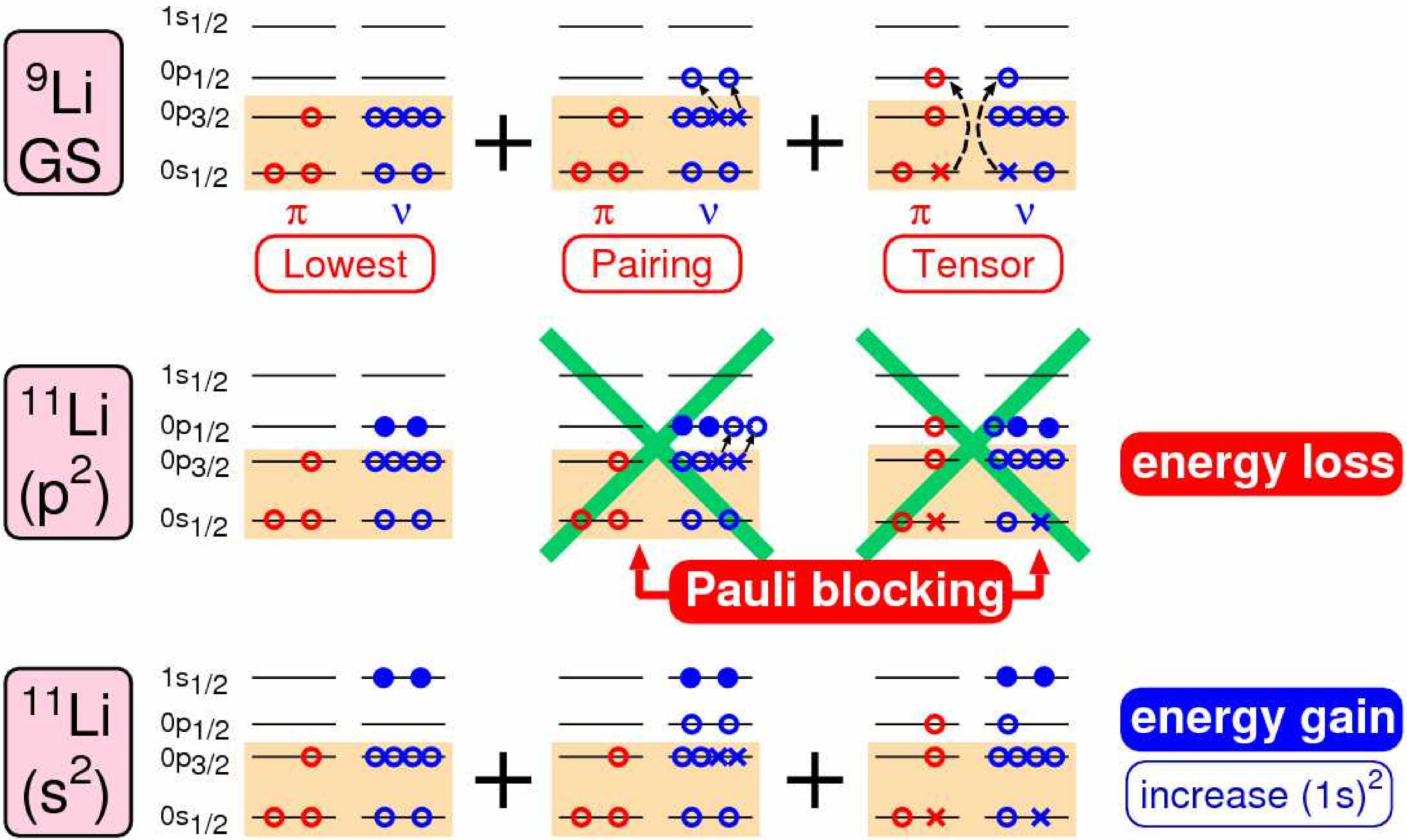




Dominant part of the tensor correlation

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

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



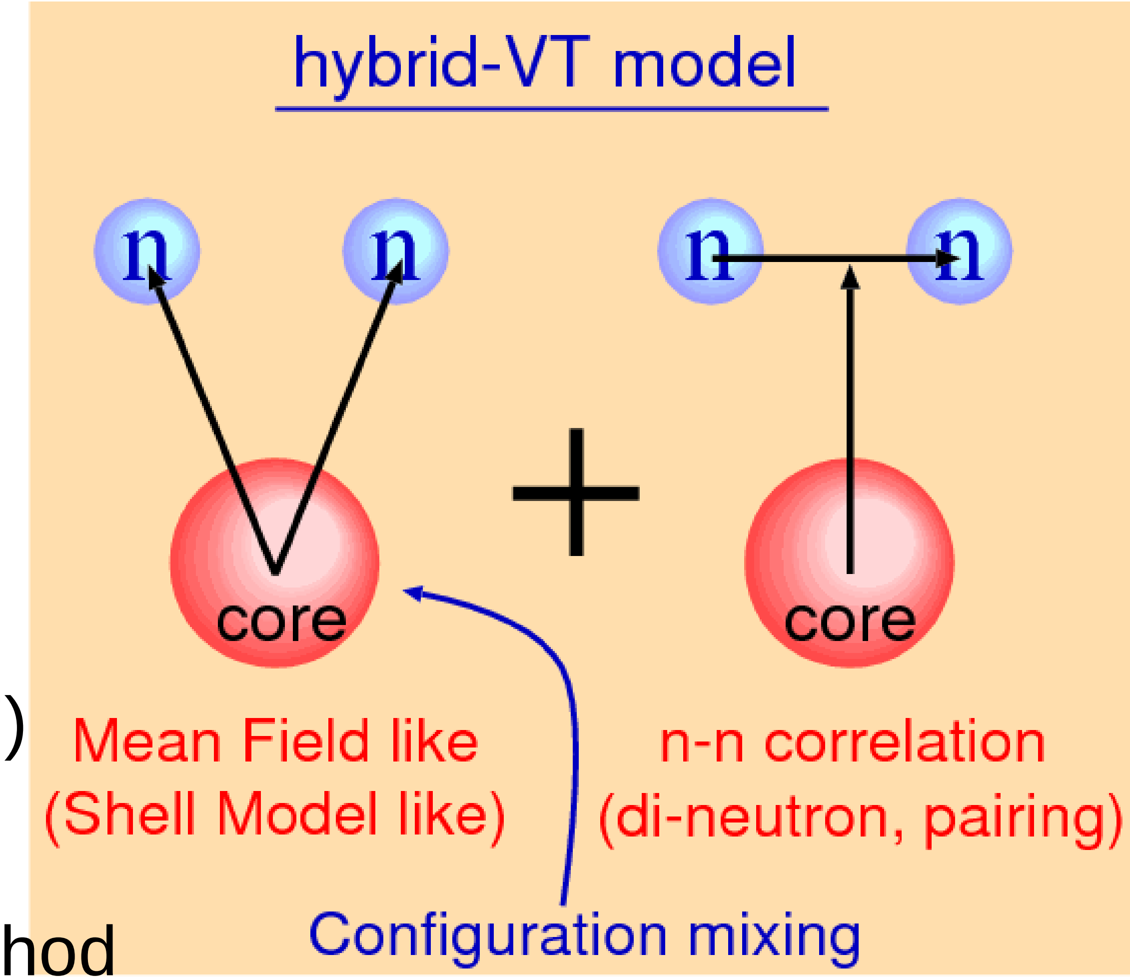
Pairing-blocking :

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.

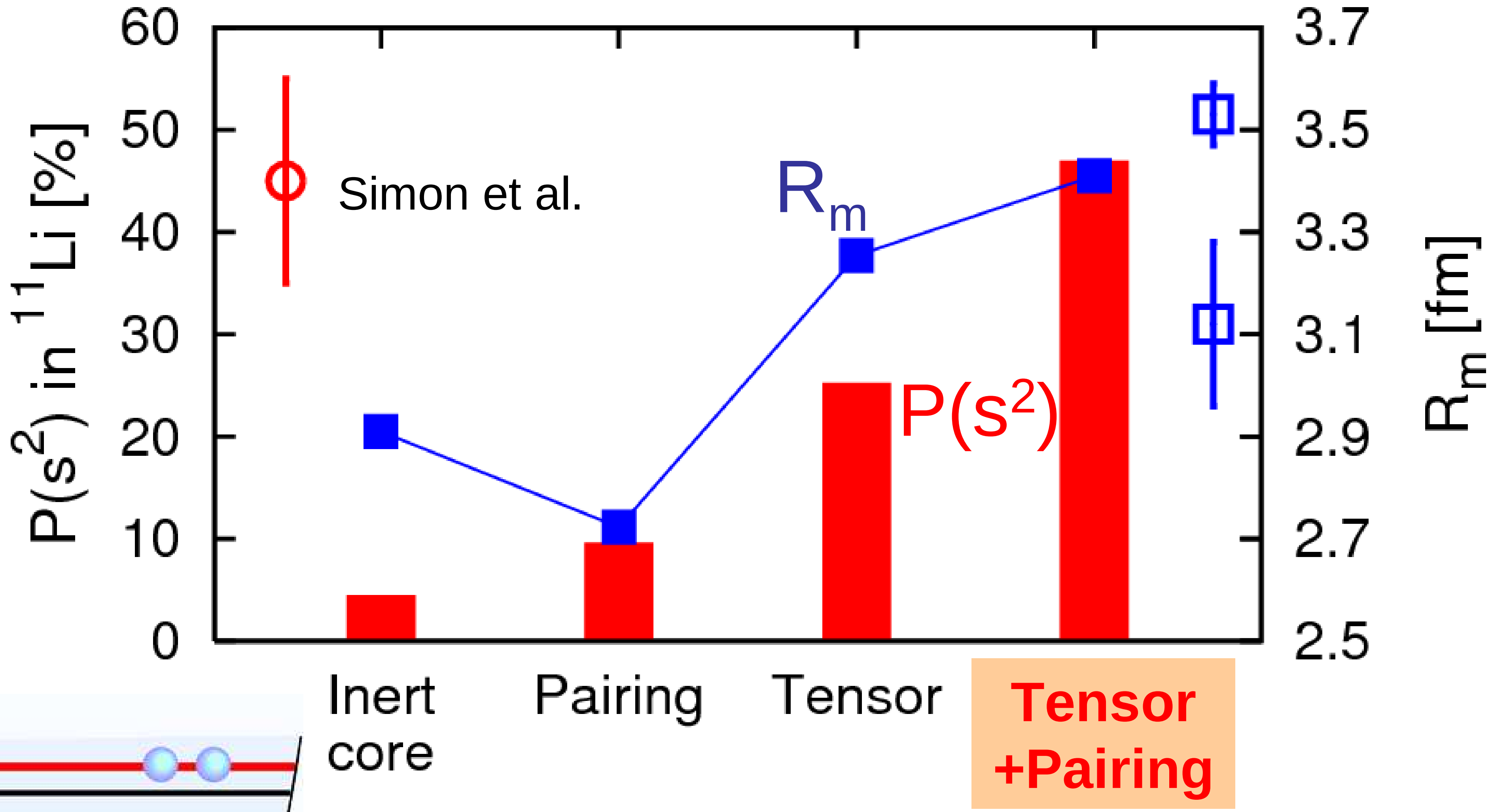
Hamiltonian for ^{11}Li

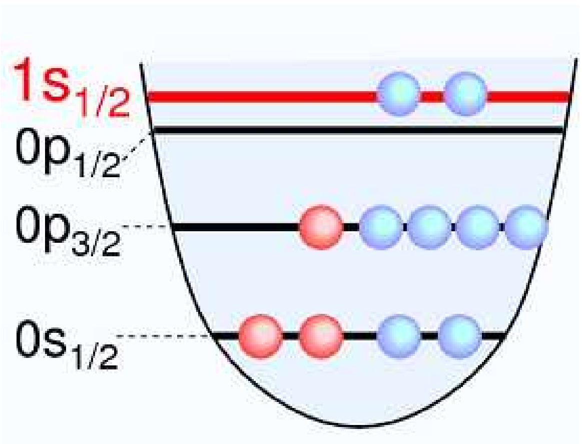
- $V_{9Li\text{-}n}$: folding potential
  - Same strength for s- and p-waves
  - Adjust to reproduce S_{2n}=0.31 MeV
- $V_{n\text{-}n}$: Argonne potential (AV8')
- 2n : Gaussian expansion method



[Ref] TM, S. Aoyama, K. Kato, K. Ikeda, PTP108(2002)

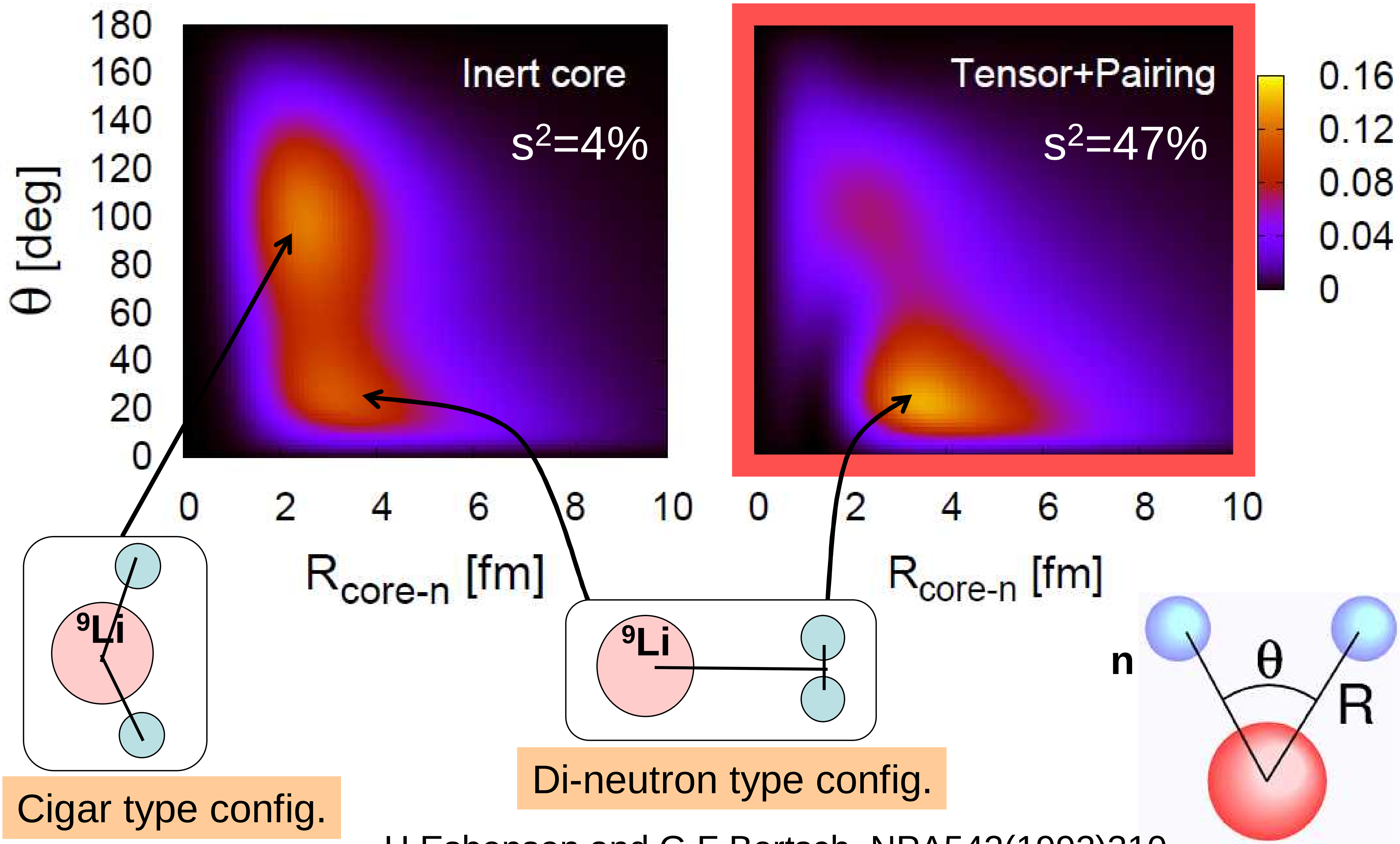
^{11}Li G.S. properties (S$_{2n}$=0.31 MeV)





TM, K.Kato, H.Toki, K.Ikeda, PRC76('07)024305

2n correlation density in ^{11}Li

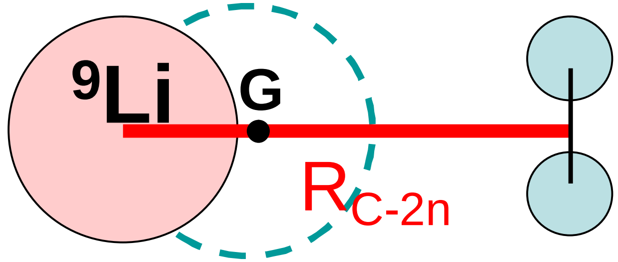


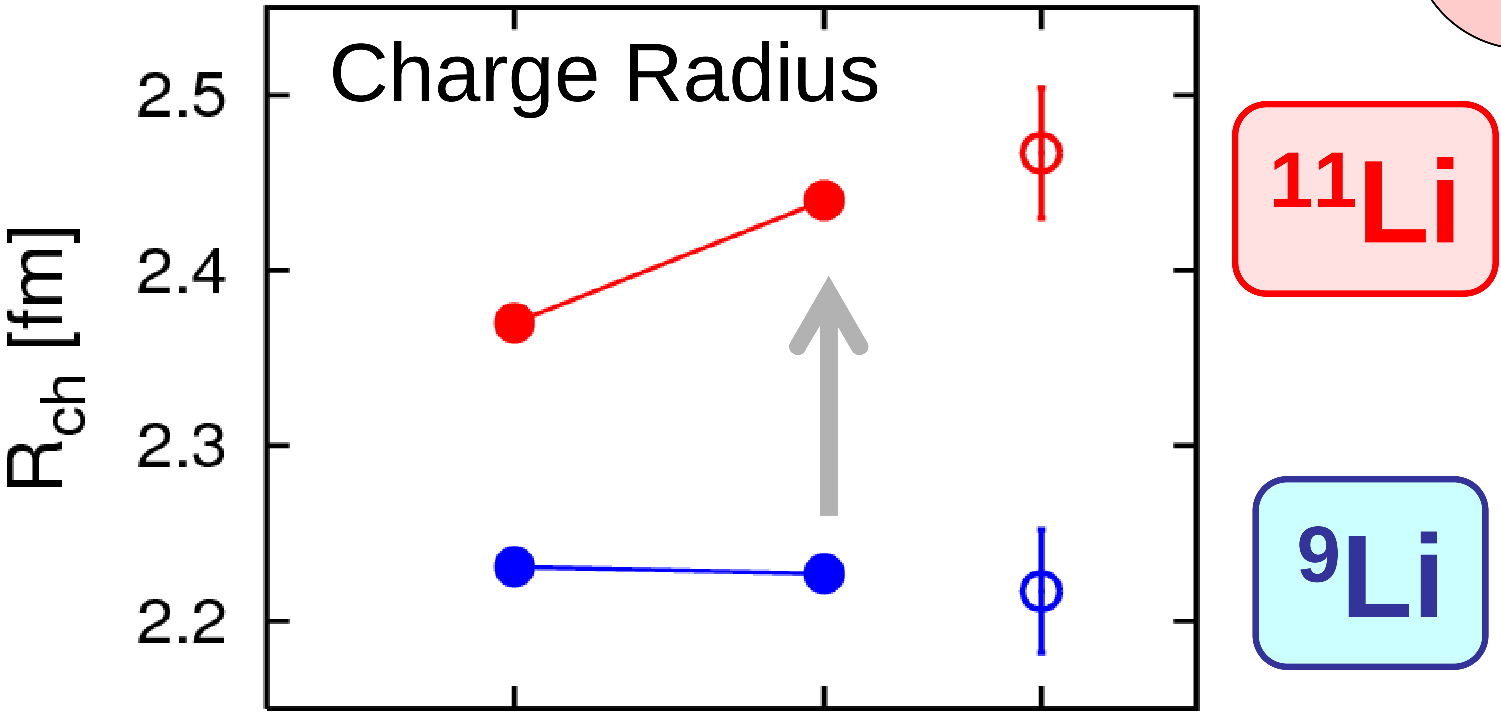
H.Esbensen and G.F.Bertsch, NPA542(1992)310

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

Charge Radii of Li isotopes

$$R^2_{\mathrm{proton}}(^{11}\mathrm{Li}) = R^2_{\mathrm{proton}}(^{9}\mathrm{Li}) + \left(\frac{2}{11}\right)^2 R^2_{\mathrm{C\text{-}2n}}$$





Inert core | Tensor +Pairing | Expt. (Sanchez et al., PRL96(2006))

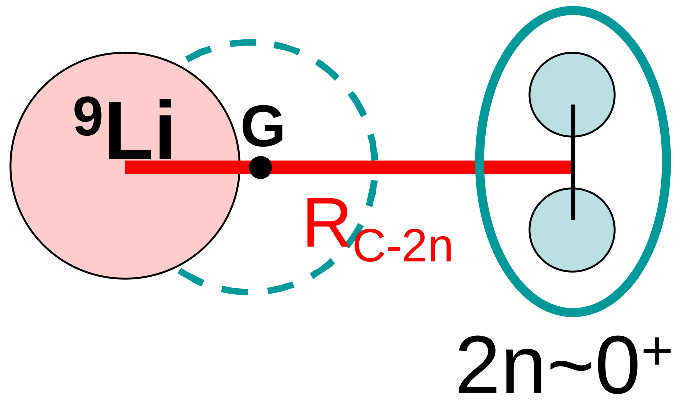
	Inert core	Tensor +Pairing	
$R_{C\text{-}2n}$	4.67	5.69	[fm]
$P(s^2)$	4	47	%

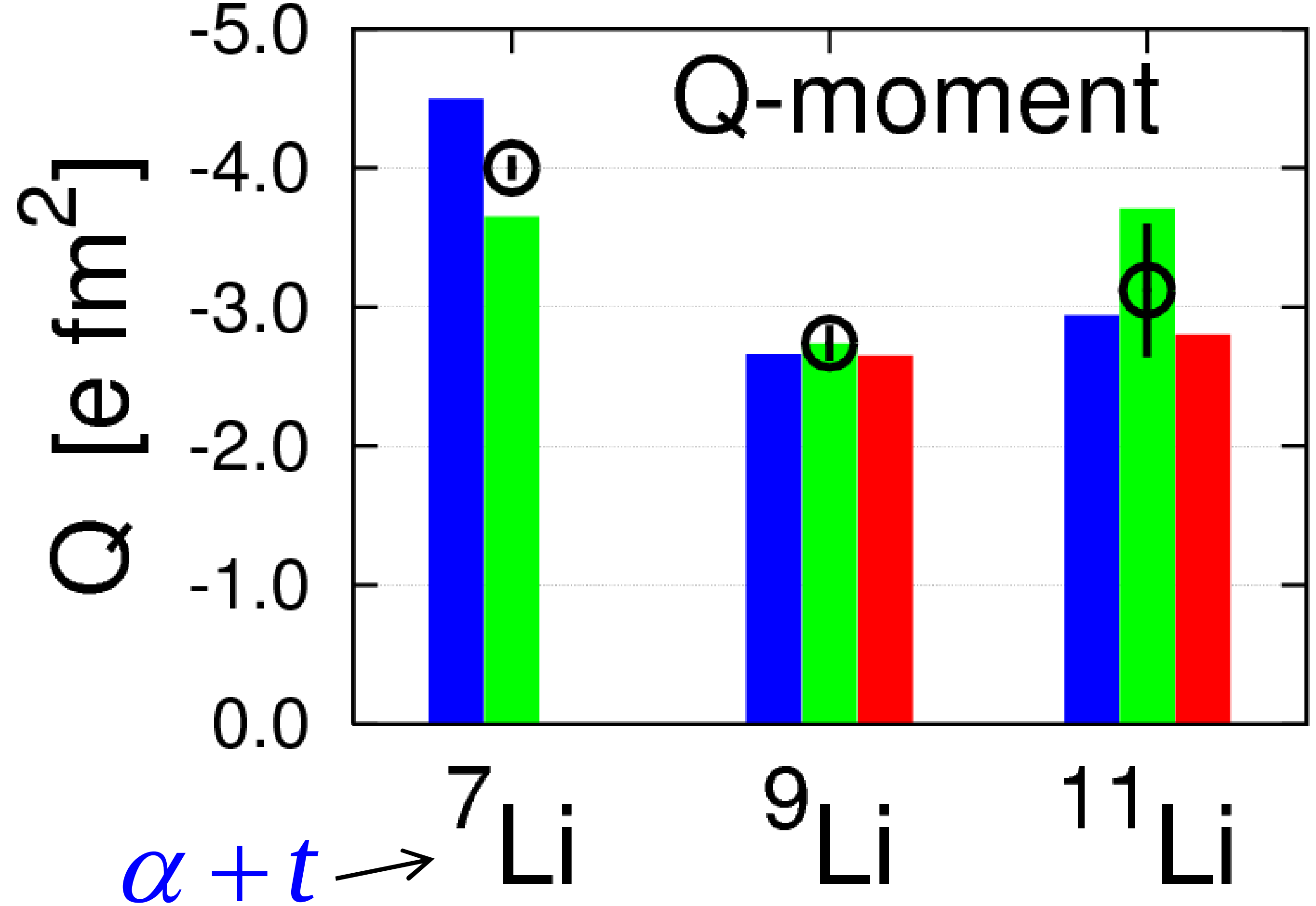
Q-moment of Li-isotopes

$$Q_2(^{11}\mathrm{Li}) = Q_2(^{9}\mathrm{Li}) + Q_2(R_{\text{C-2n}}) + \alpha \cdot [\mathcal{Y}_1(^{9}\mathrm{Li}), \mathcal{Y}_1(R_{\text{C-2n}})]_2$$

$\sim r^2 Y_2(\hat{r})$

Vanish due to 0^+ state of 2n

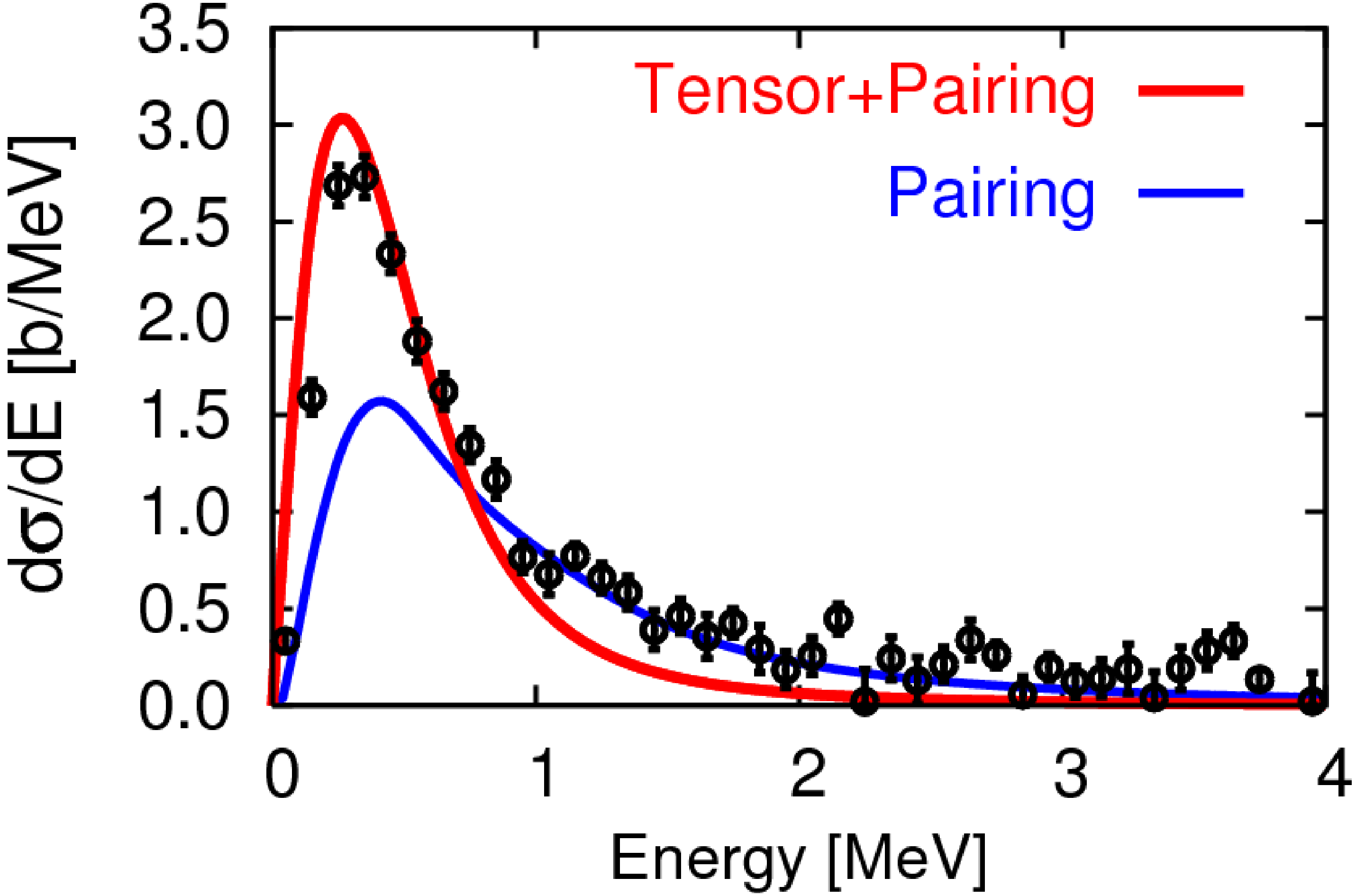




$\alpha + t \rightarrow$ ^{7}Li

Coulomb breakup strength of ^{11}Li

$$^{11}\text{Li (G.S.)} \rightarrow {}^{9}\text{Li} + n + n$$



No three-body resonance

E1 strength by using the Green's function method

+Complex scaling method

+Equivalent photon method (TM, Aoyama, Kato, Ikeda, PRC63('01)054313)

- 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:

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

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

T.M. et al., submitted to JPG

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

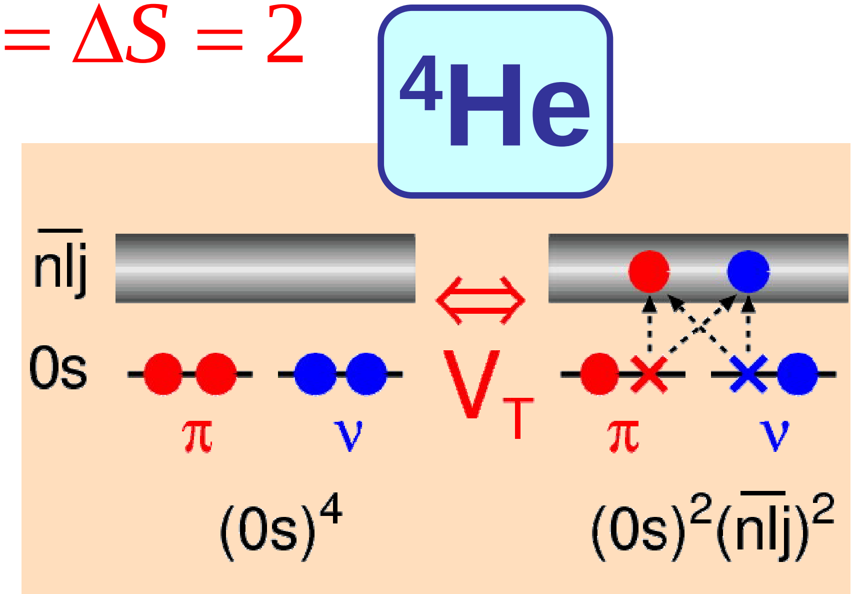
a_s = -10 ~ -25 fm

cf. $a_s(nn)$: -18.5 ± 0.5 fm

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

Tensor & Short-range correlations

- Tensor correlation in TOSM
  - $S_{12} \propto \left[Y_2(\hat{r}),[\vec{\sigma}_1,\vec{\sigma}_2]_2\right]_0 \rightarrow \Delta L = \Delta S = 2$
  - 2p2h mixing optimizing the particle states (radial & high-L)



- Short-range correlation
  - Short-range repulsion of the bare NN force in the relative wave function of nuclei
  - Unitary Correlation Operator Method (UCOM)

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

    T. Neff, H. Feldmeier NPA713(2003)311

Unitary Correlation Operator Method

$$\Psi_{\text{corr.}} = C \cdot \Phi_{\text{uncorr.}} \leftarrow \text{SM, HF, FMD}$$

short-range correlator

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

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

$g_{ij} = g_{ij}^{\dagger}$: Hermitian generator

$$R_+'(r) = \frac{s(R_+(r))}{s(r)}$$

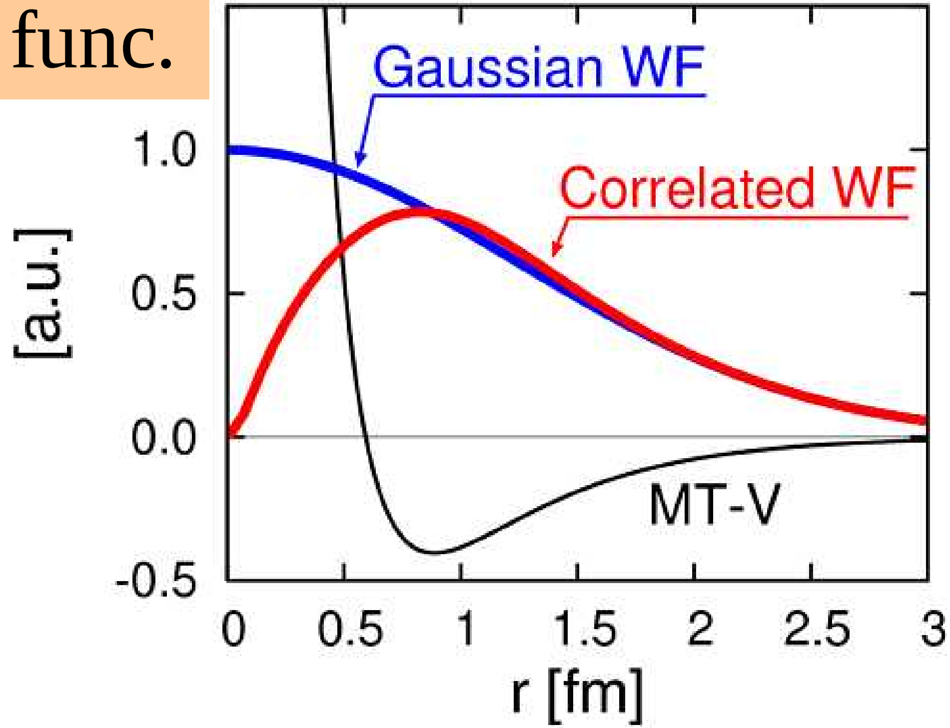
H. Feldmeier, T. Neff, R. Roth, J. Schnack, NPA632(1998)61

Short-range correlator : C

$$C: \; r \to R_+(r) \text{ for Hamiltonian,}$$
$$r \to R_-(r) \text{ for relative wave func.}$$

$$C^\dagger r \; C = R_+(r)$$

$$R_-(R_+(r)) = r$$



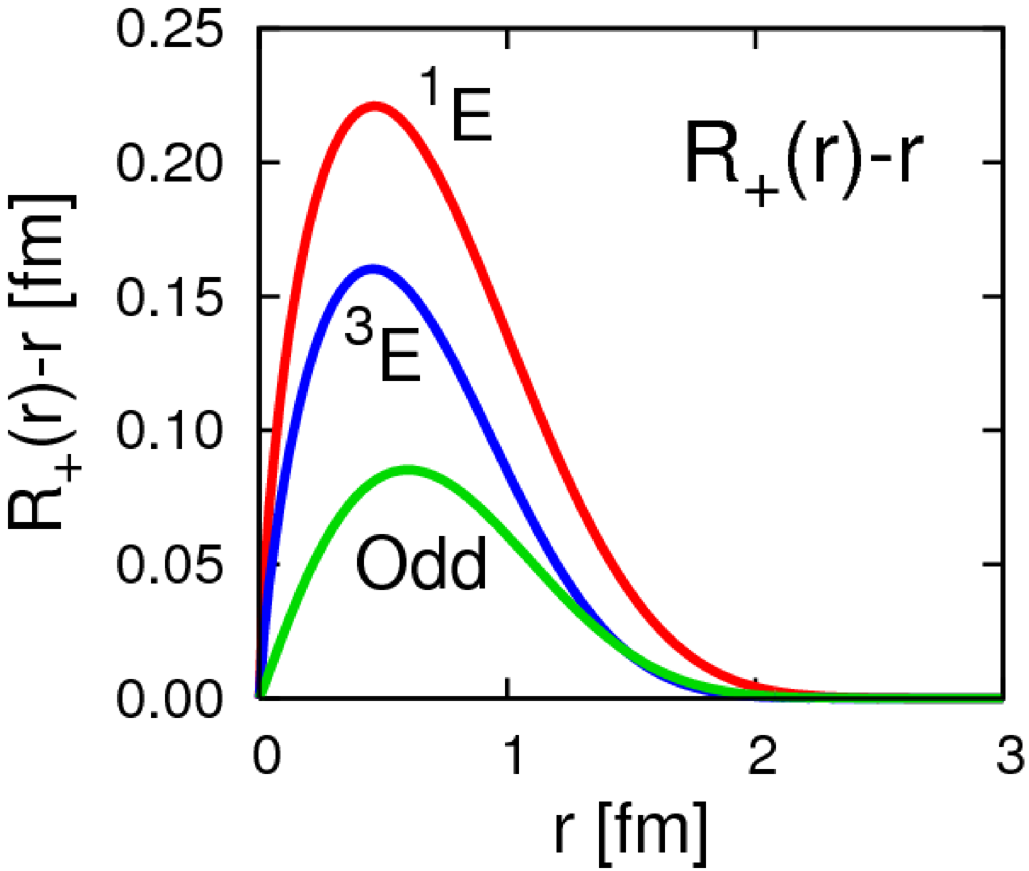
Hamiltonian in UCOM

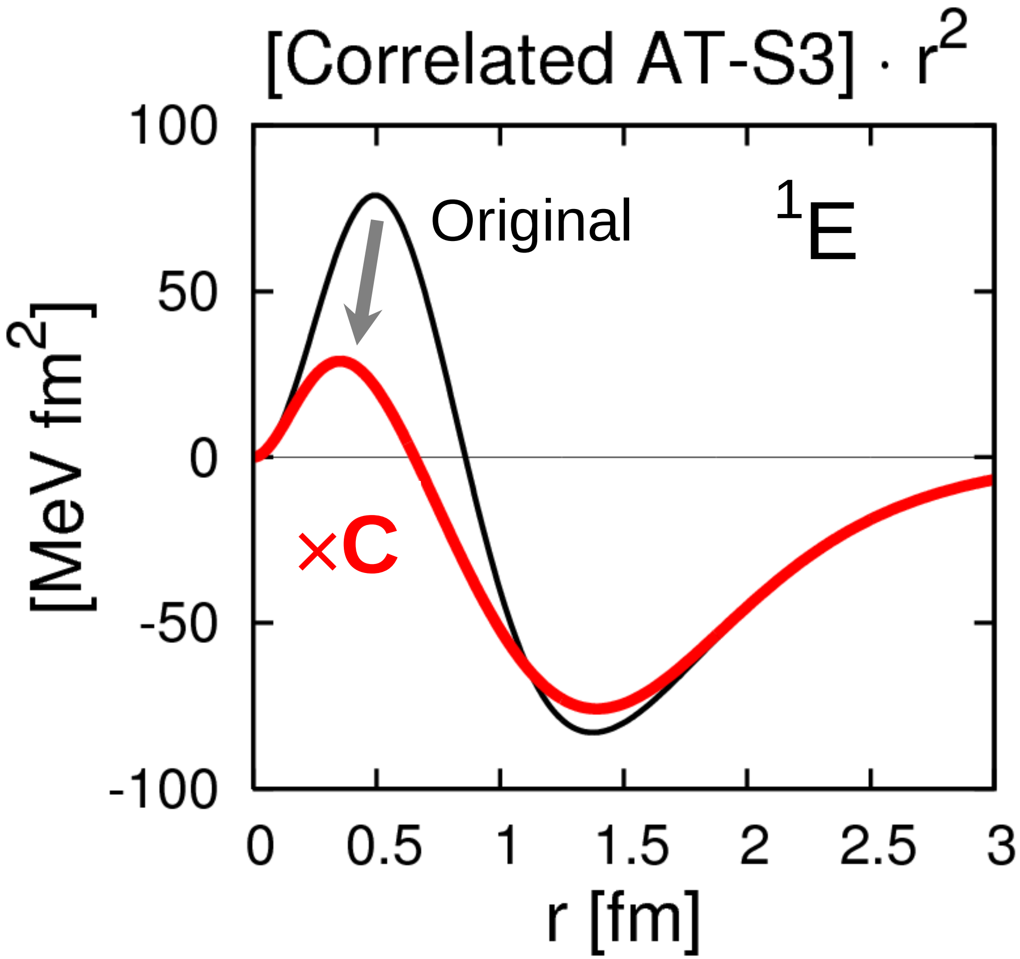
$$C^\dagger H C = \widehat{H} = \widehat{T} + \widehat{V}$$

$$\widehat{T} \simeq T + \Delta T, \quad \Delta T = \sum_{i<j} u_{ij}^2 \qquad \widehat{V} \simeq \sum_{i<j} v(R_+(r_{ij}))$$

2-body approximation in the cluster expansion of operator

Form of R_+ in UCOM

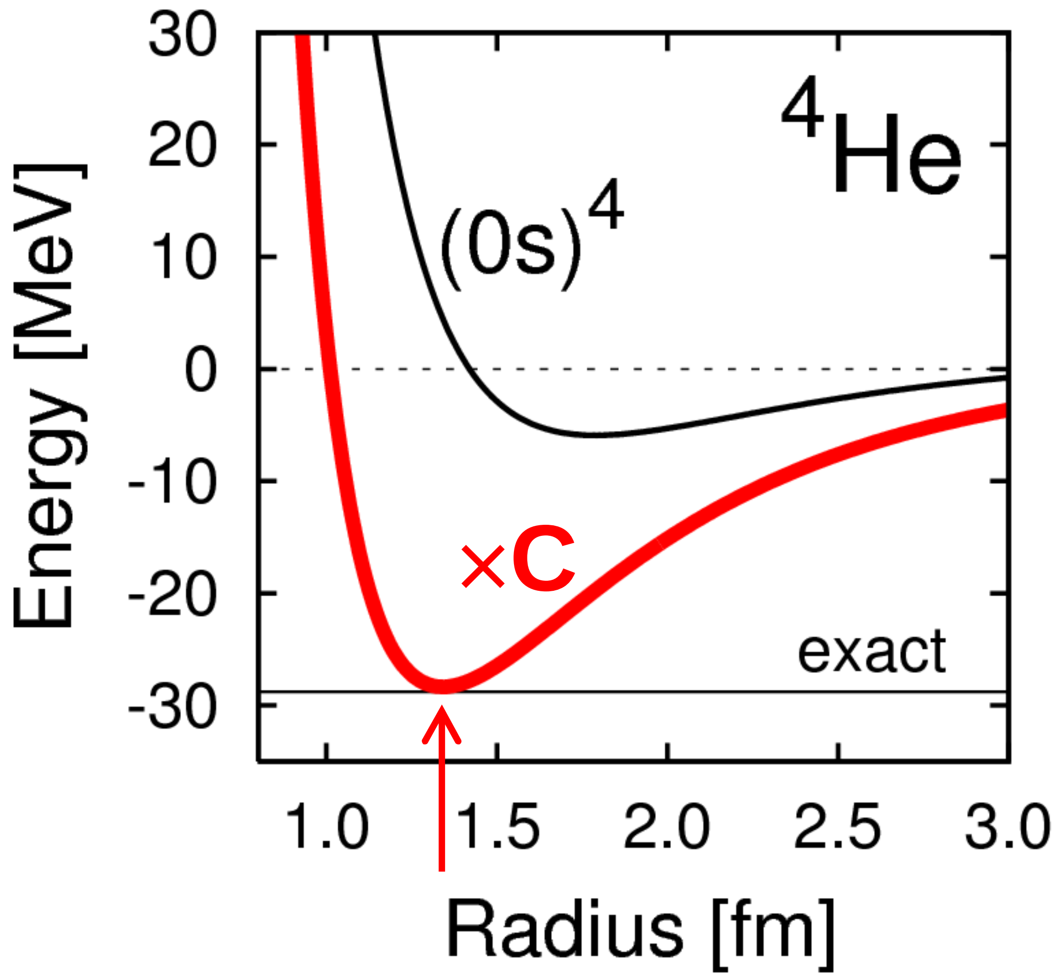


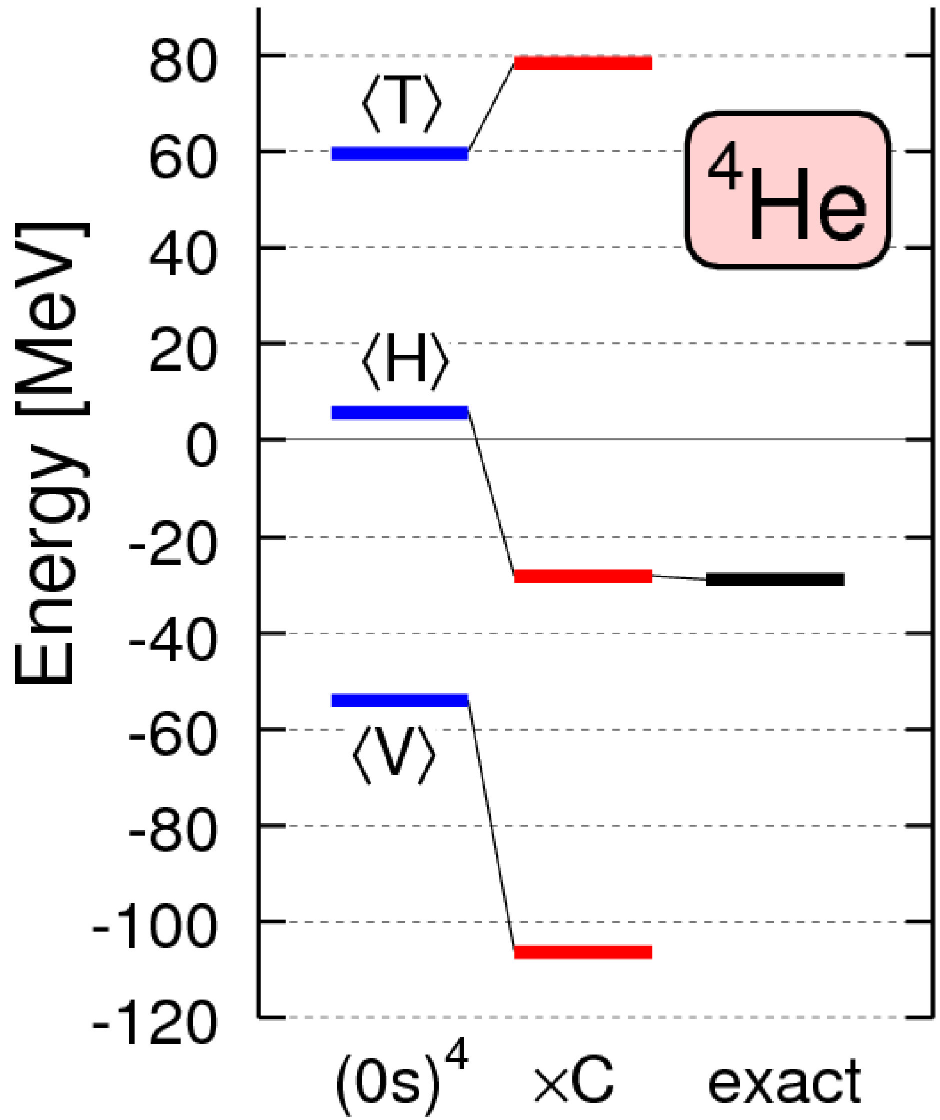


Functional form given by referring to the Deuteron's exact case

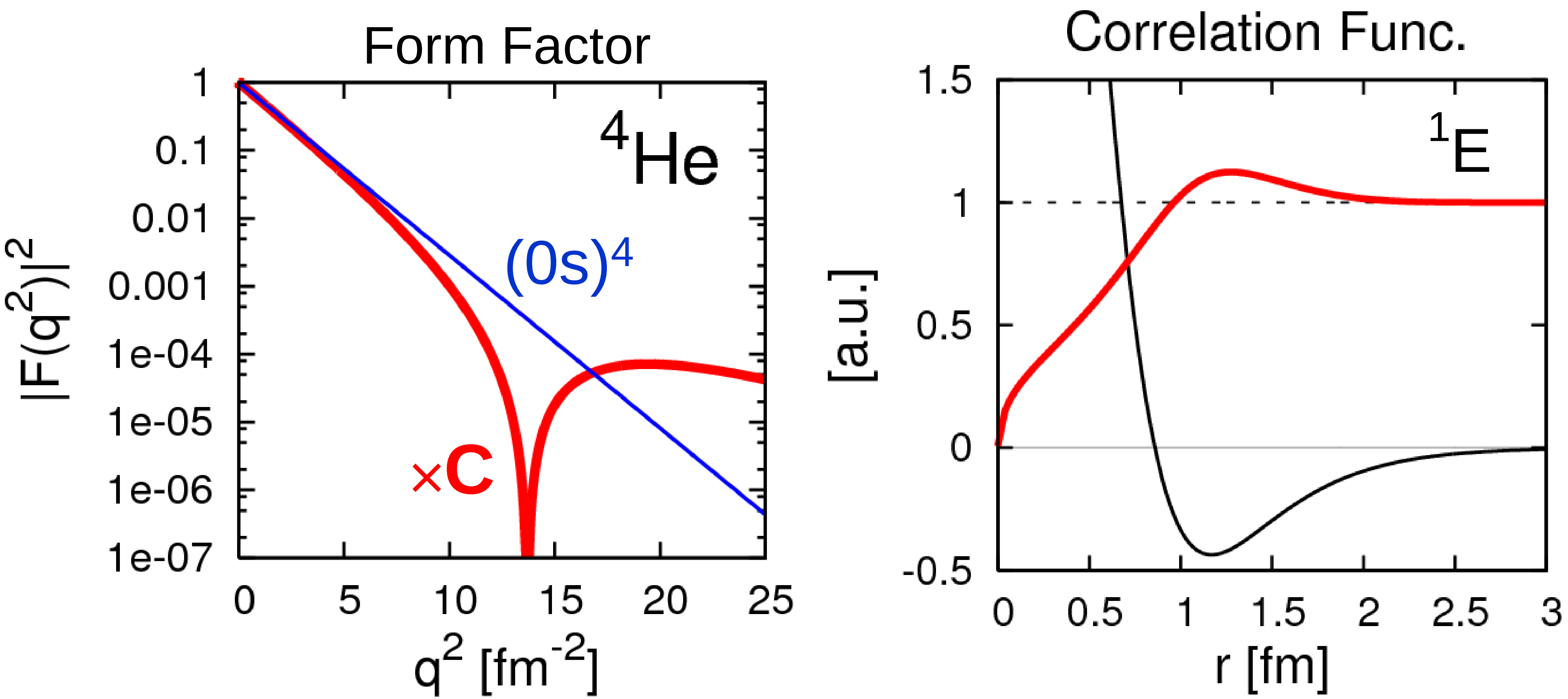
Afnan-Tang : central only
about **1GeV** repulsion

^{4}He with UCOM (Afnan-Tang)



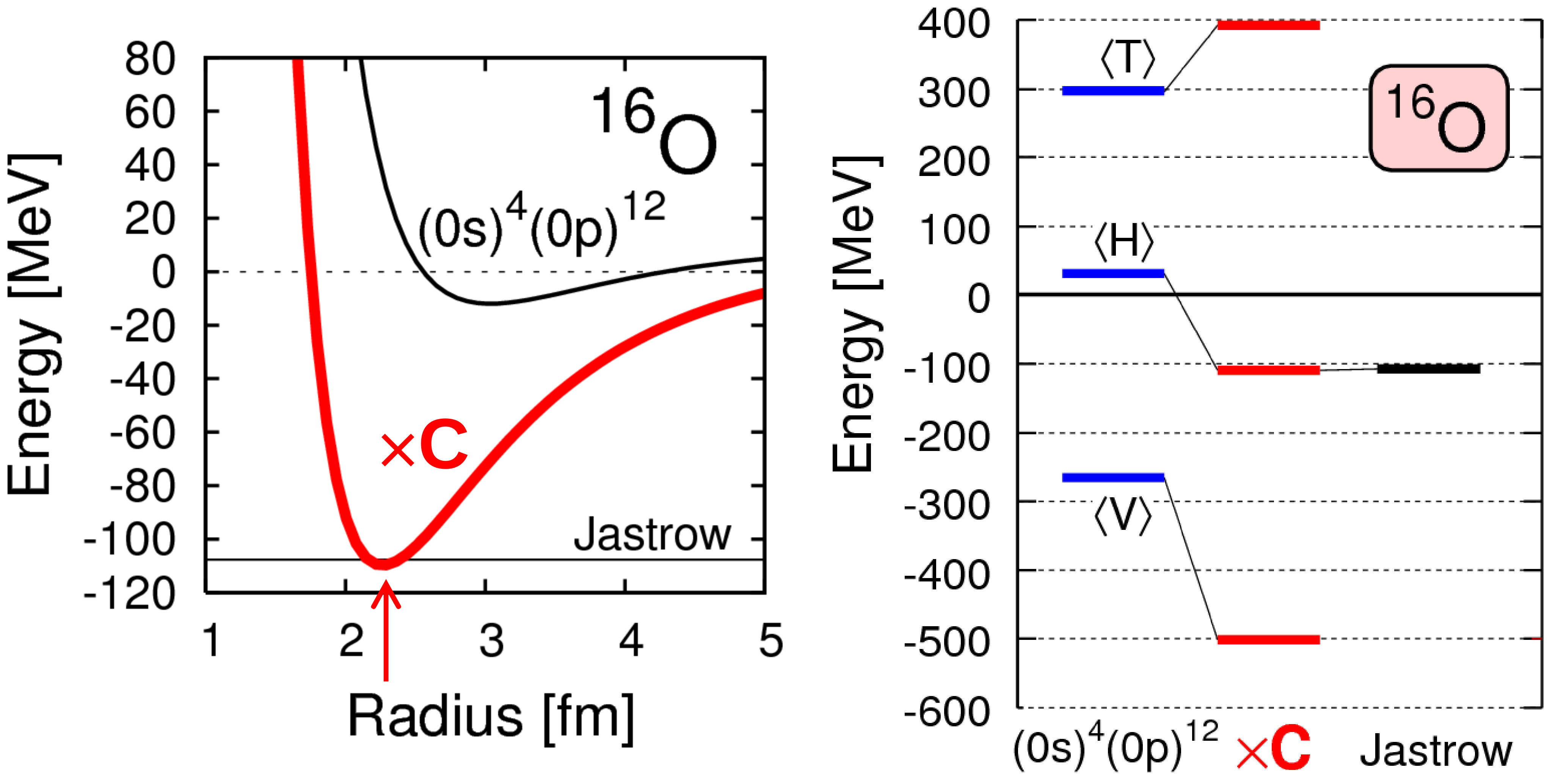


Charge form factor and Corr. Func.

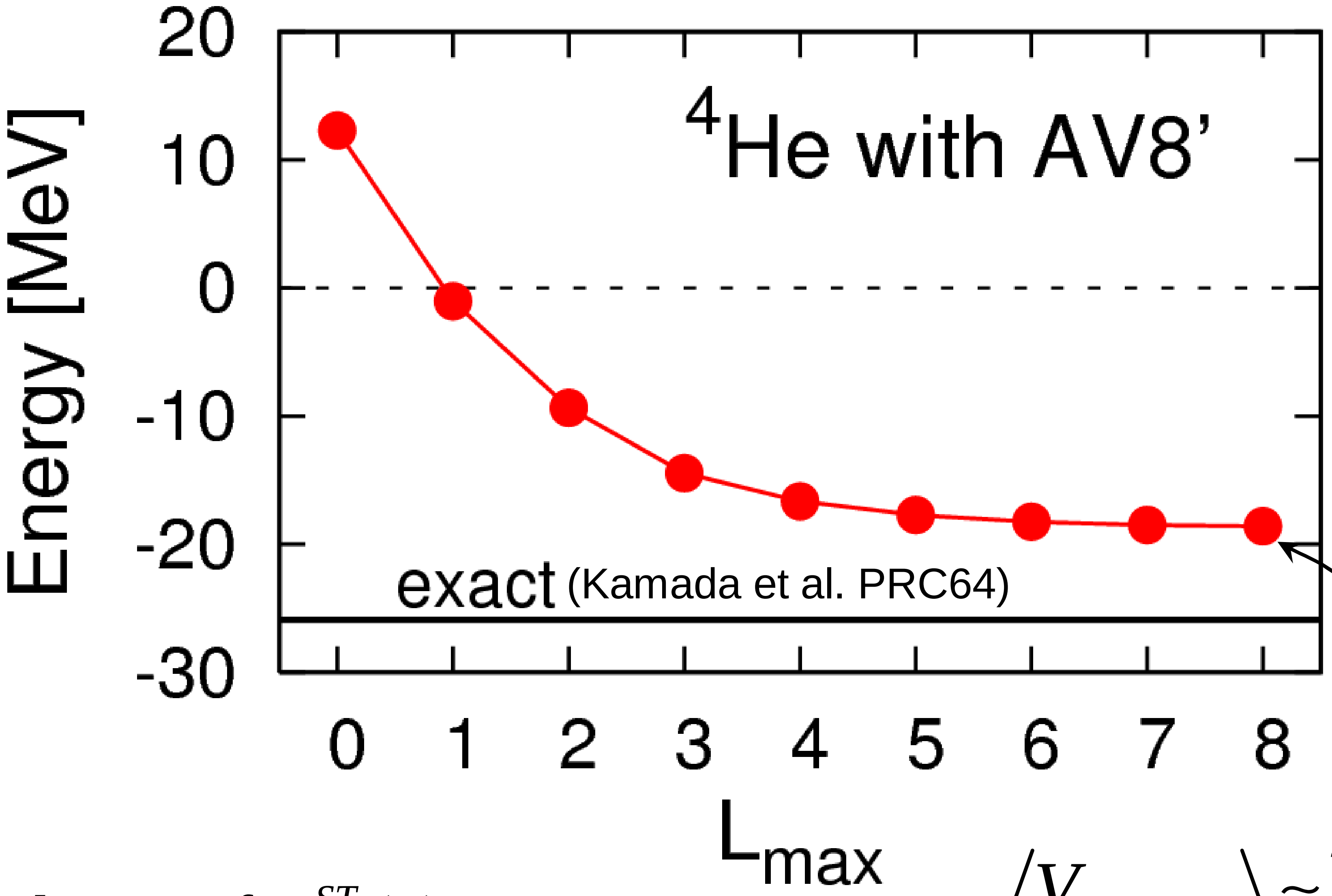


$$P[(0s)^4] = 0.95$$

^{16}O with UCOM (Afnan-Tang)



^{4}He in TOSM+UCOM



Central+
LS+Tensor

$\langle V_{\text{tensor}} \rangle \simeq -50$ MeV

Choice of $R_+^{ST}(r)$

R. Roth et. al , PRC72(2005)034002

Summary

- Tensor correlation in nuclei.
  - Tensor-optimized shell model (TOSM).
  - He isotopes : LS splitting
  - Li isotopes: Magic number breaking and halo
- Short-range correlation
  - Unitary Correlation Operator Method (UCOM).
- In TOSM+UCOM, we can study the nuclear structure starting from the bare interaction.