Importance of pion and The tensor optimized shell model

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Pion is important in Nuclear Physics！

- Yukawa(1934) predicted pion (size) as a mediator of nuclear interaction to form nucleus
- Mayer-Jensen(1949) introduced shell model (Phenomenological)
  beginning of Nuclear Physics
- Nambu(1960) introduced the chiral symmetry and its breaking produced mass and the pion as pseudo-scalar particle

Challenge

- Describe nuclei from the first principle (pion)
- Construct nucleus using NN interaction

Kobe：10Pflops=京

Pion is a pseudo-scalar particle (Nambu)

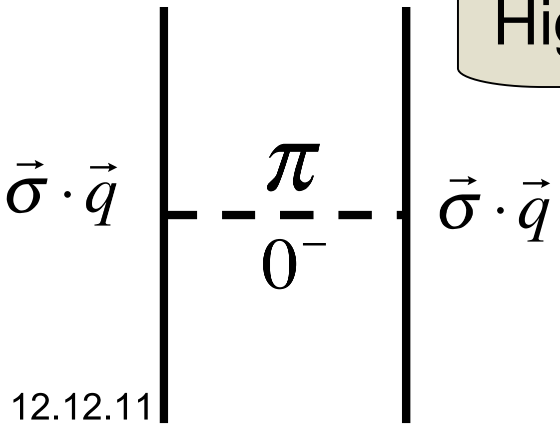
$$\vec{\sigma}_1 \cdot \vec{q} \frac{1}{m_\pi^2 + q^2} \vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3} \frac{q^2}{m_\pi^2 + q^2} S_{12}(\hat{q}) + \frac{1}{3} \frac{q^2}{m_\pi^2 + q^2} \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

$$= \frac{1}{3} \frac{q^2}{m_\pi^2 + q^2} S_{12}(\hat{q}) + \frac{1}{3}\left(1 - \frac{m_\pi^2}{m_\pi^2 + q^2}\right) \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

Low momentum

Pion	Tensor	spin-spin

High momentum

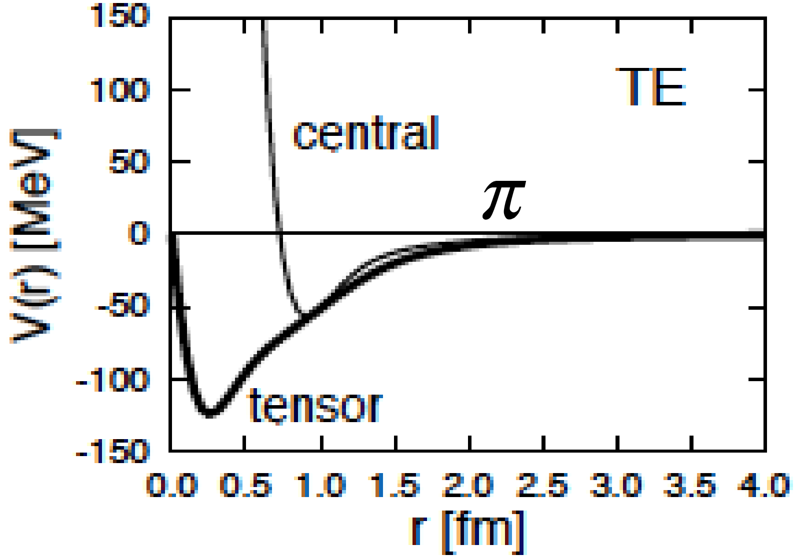


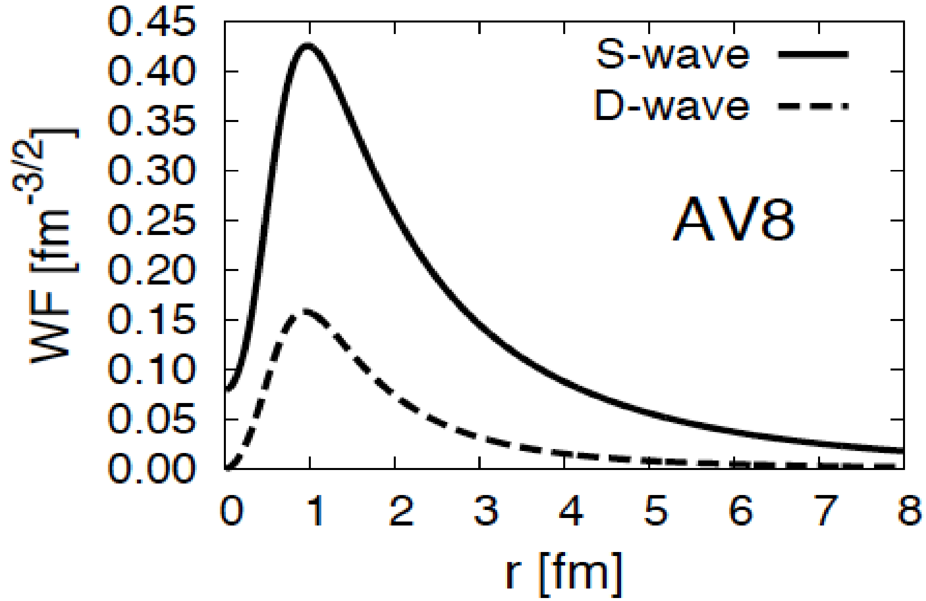
$$S_{12}(\hat{q}) = \sqrt{\frac{24\pi}{5}} \left[Y_2(\hat{q}) [\sigma_1 \sigma_2]_2 \right]_0$$

Difficult to handle

Deuteron (1^+)

NN interaction





$$\Psi_d = u(r)[Y_0(\hat{r}) \otimes \chi_1(\sigma_1\sigma_2)]_{1M} + w(r)[Y_2(\hat{r}) \otimes \chi_1(\sigma_1\sigma_2)]_{1M}$$

S=1 and L=0 or 2

Deuteron (1^+)

80% of attraction comes from tensor

D-wave component moves very fast

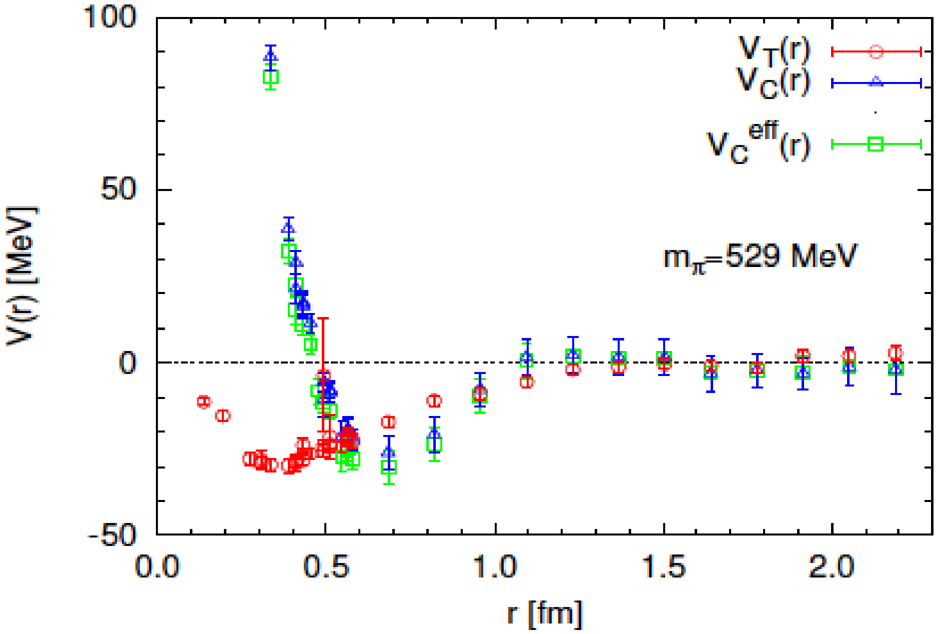
Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensorc	−16.64
(SD)	−18.93
(DD)	2.29
LS	−1.02
P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

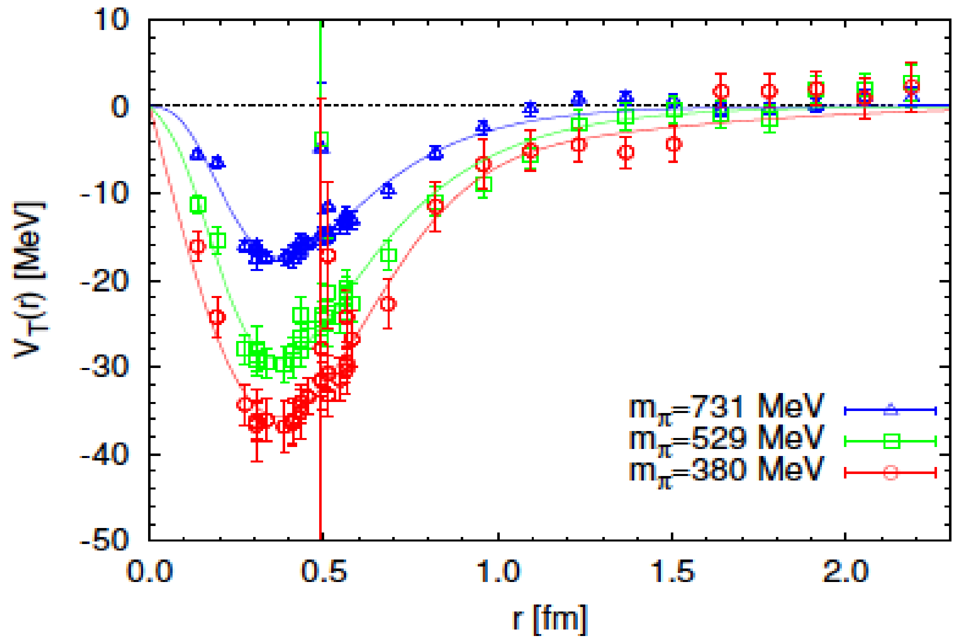
K.Ikeda, T.Myo, K.Kato,and H.Toki
Lecture Notes in Phys.818 (2010) 165

Progress of Theoretical Physics, Vol. 123, No. 1, January 2010

Theoretical Foundation of the Nuclear Force in QCD and Its Applications to Central and Tensor Forces in Quenched Lattice QCD Simulations

Sinya AOKI,[1] Tetsuo HATSUDA[2] and Noriyoshi ISHII[2]



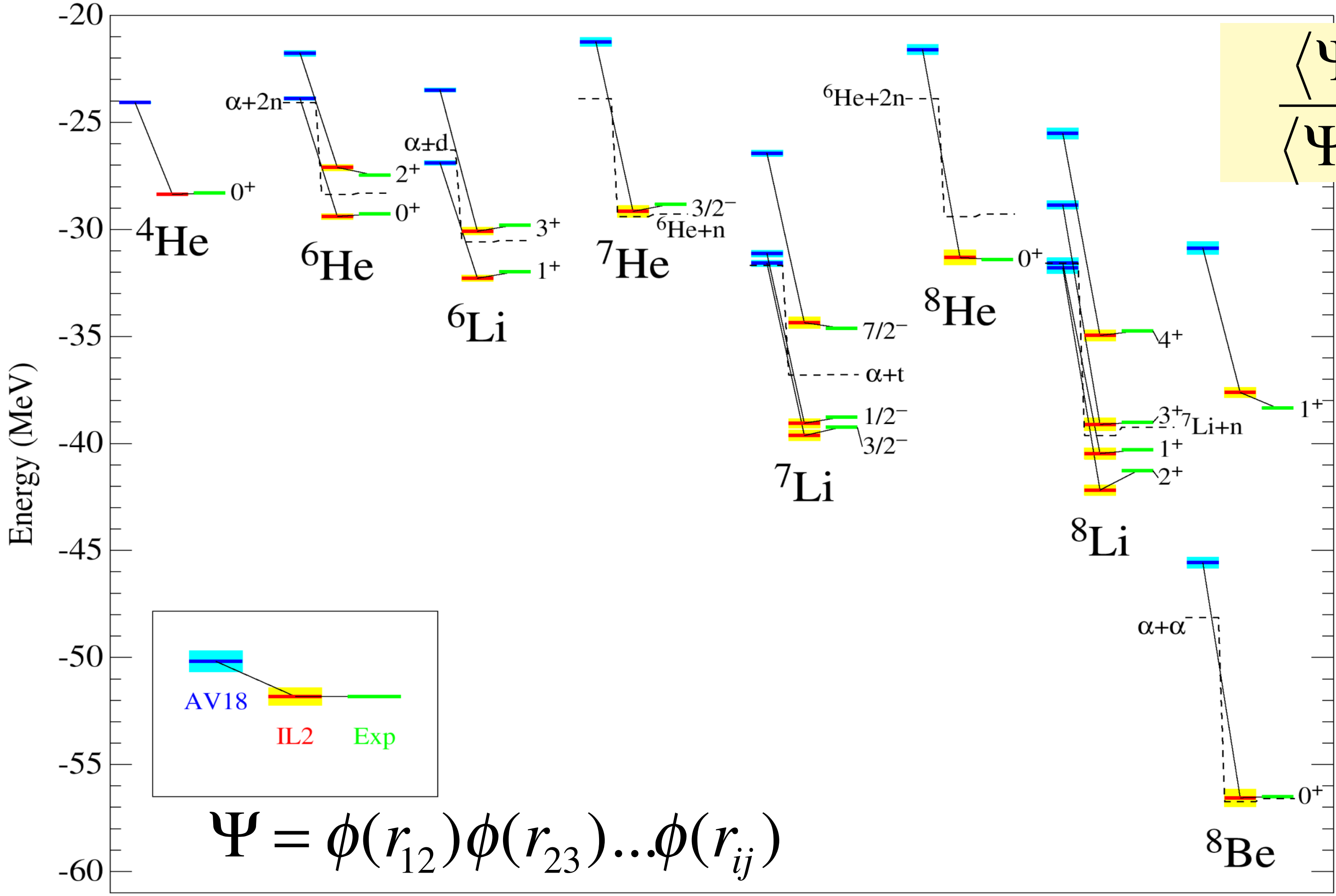


BE = 5MeV for ^{4}He

Variational calculation of few body system with NN interaction

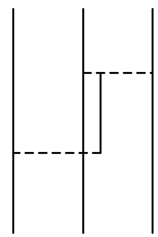
VMC+GFMC

$$\frac{\langle \Psi | V_\pi | \Psi \rangle}{\langle \Psi | V_{NN} | \Psi \rangle} \sim 80\%$$

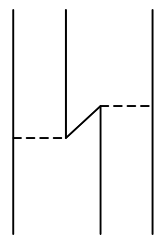


$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

V_{NNN}



Fujita-Miyazawa



Relativistic

C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

Heavy nuclei (Super model)	Pion is key

How to handle tensor interaction in heavy nuclei

- Transition from relative S-wave to D-wave provides large attraction
- In shell model, this is achieved by taking 2p-2h state (Myo et al.)
- Tensor optimized shell model (TOSM)

$$\Psi = C_0 |0\rangle + \sum_{\alpha} C_{\alpha} |2p - 2h : \alpha\rangle$$

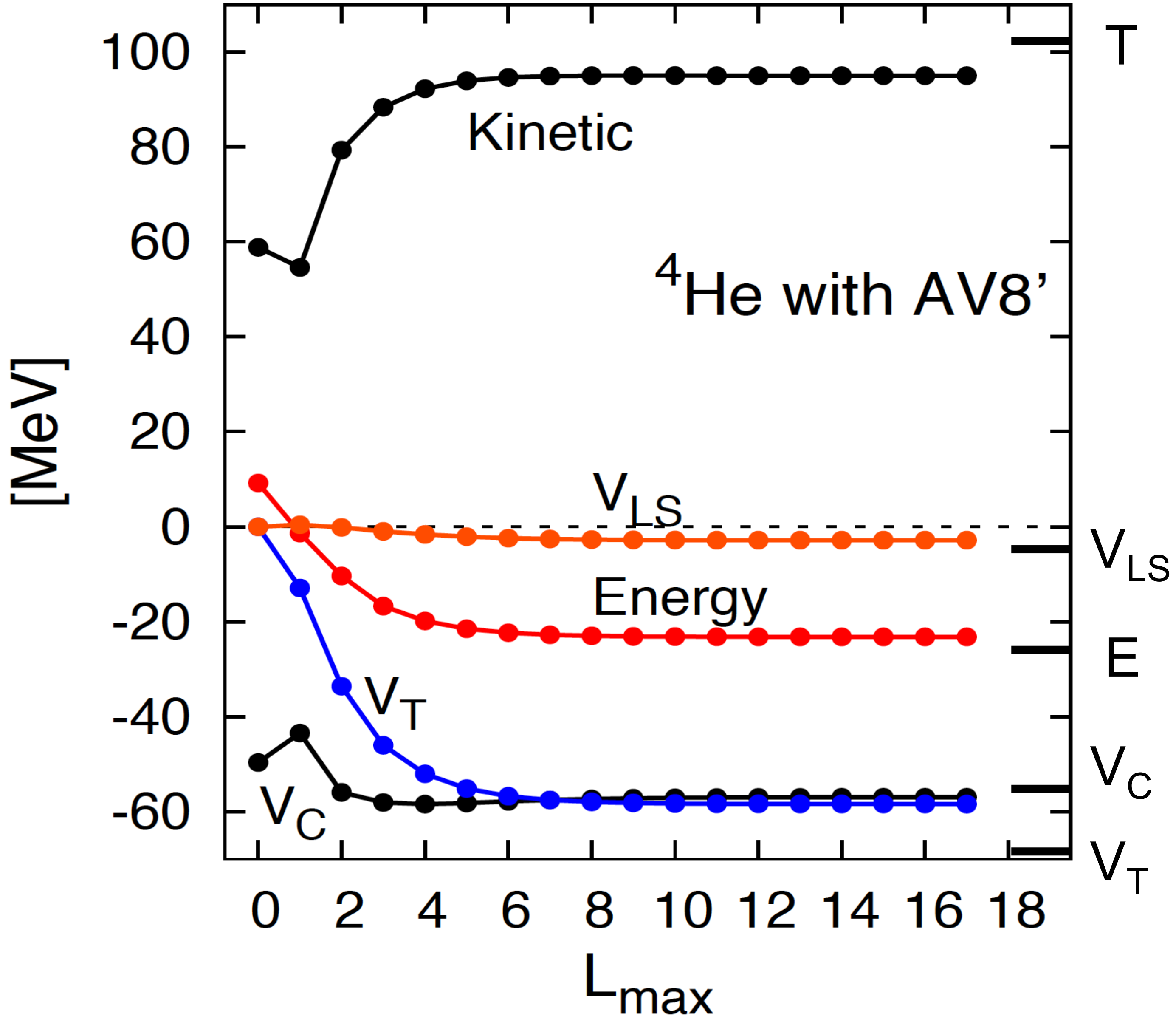
- Short range correlation is treated by UCOM (Feldmeier et al.)

TOSM (+UCOM) with AV8'

$$\Psi = C_0|0\rangle + \sum_{\alpha} C_\alpha |2p2h:\alpha\rangle$$

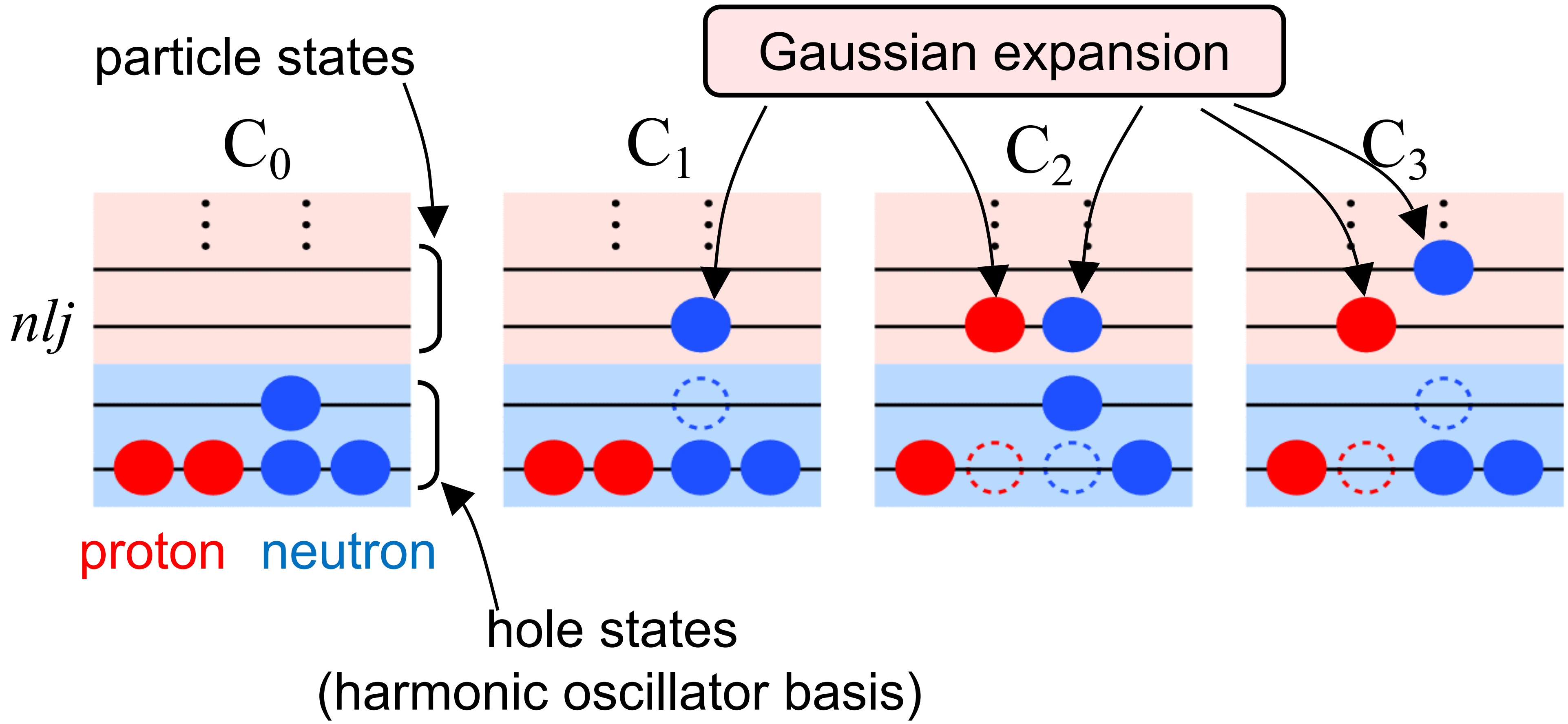
(Myo Toki Ikeda)
PTP 121 (2009)

$$|2p\rangle = |[l_1 l_2]_L\rangle$$



Few body Calculation (Kamda et al (2001))

Configurations in TOSM

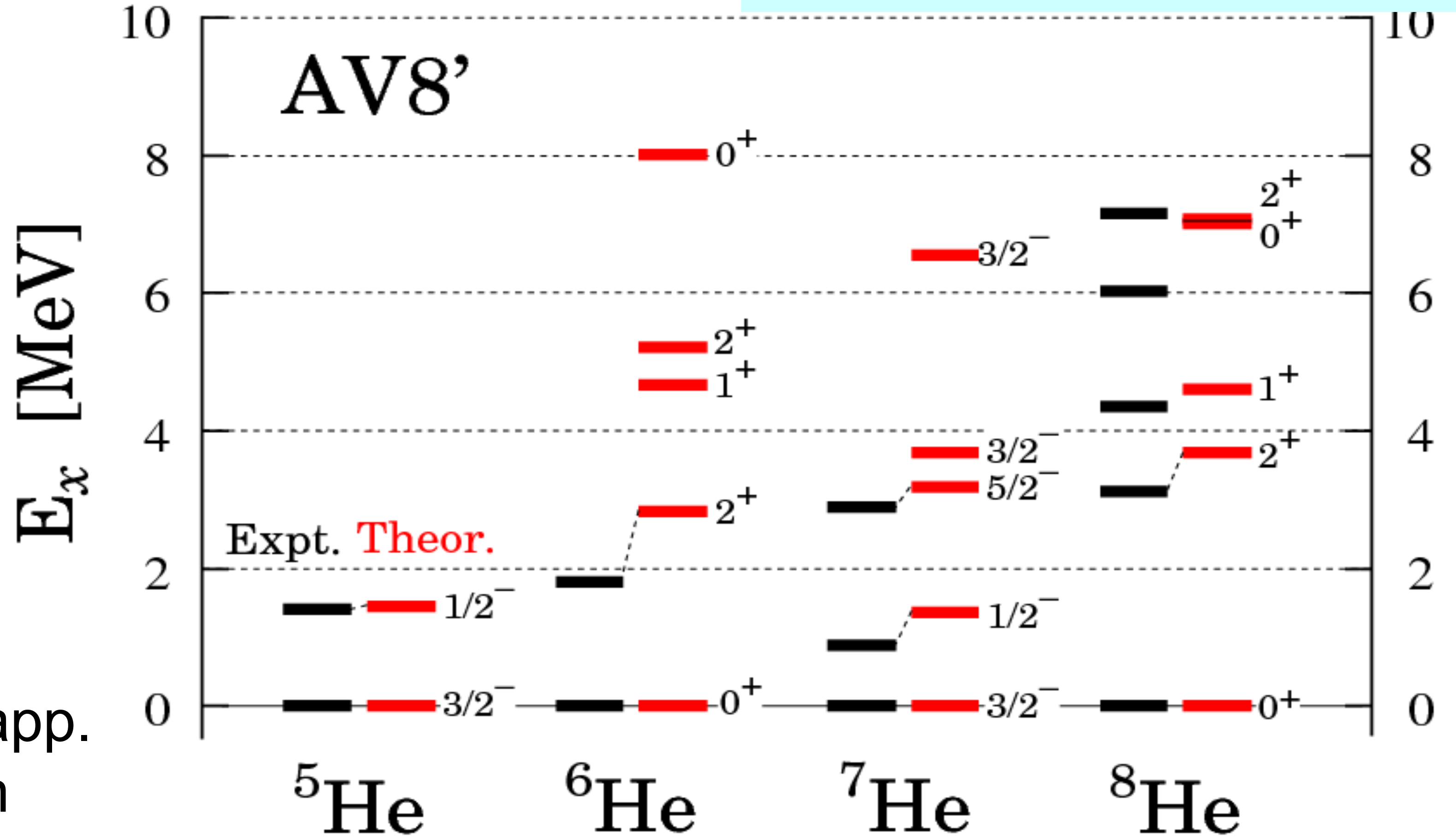


Application to Hypernuclei by Umeya
to investigate ΛN-ΣN coupling

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

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

- Excitation energies in MeV



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

- Excitation energy spectra are reproduced well

Extension of Hartree-Fock theory with TOSM

Y.Ogawa H.Toki
Annals of Physics 326 (2011) 2039

$$\langle 0 | S_{12} | 0 \rangle = 0 \qquad S_{12} = \sqrt{\frac{24\pi}{5}} [Y_2(\hat{r}) \times [\sigma_1 \times \sigma_2]_2]^{(0)}.$$

We cannot treat the tensor interaction in HF space.

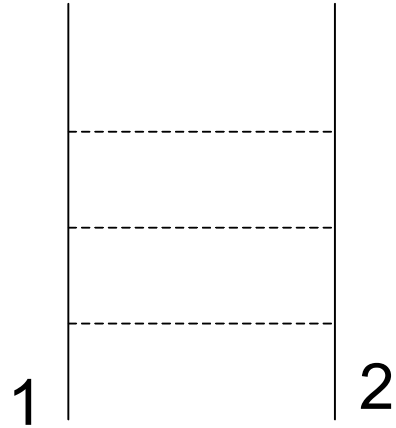
TOSM ansatz

$$|\Psi\rangle = C_0 |0\rangle + \sum_\alpha C_\alpha |2p - 2h : \alpha\rangle$$

$$\delta \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = 0 \qquad \langle \Psi | \Psi \rangle = |C_0|^2 + \sum_\alpha |C_\alpha|^2 = 1$$

We improve Brueckner-Hartree-Fock theory

Comparison of BHF and EBHF



Hartree-Fock equations look very similar

BHF

$$\langle 0|T+G|0\rangle = \langle 0|T+V|0\rangle - \sum_{\alpha\beta} \langle 0|V|\alpha\rangle\langle\alpha| \frac{1}{H_{HF} - E_{HF}^{h} + V} |\beta\rangle\langle\alpha|V|0\rangle$$

EBHF

$$\langle 0|H_{eff}|0\rangle = |C_0|^2 \langle 0|T+V|0\rangle - |C_0|^2 \sum_{\alpha\beta} \langle 0|V|\alpha\rangle\langle\alpha| \frac{1}{H-E} |\beta\rangle\langle\beta|V|0\rangle$$

TOSM wave function

$$|\Psi\rangle = C_0|0\rangle + \sum_{\alpha} C_\alpha |2p-2h:\alpha\rangle$$

$$\langle\Psi|\Psi\rangle = |C_0|^2 + \sum_{\alpha} |C_\alpha|^2 = 1$$

80~90%
Shell model

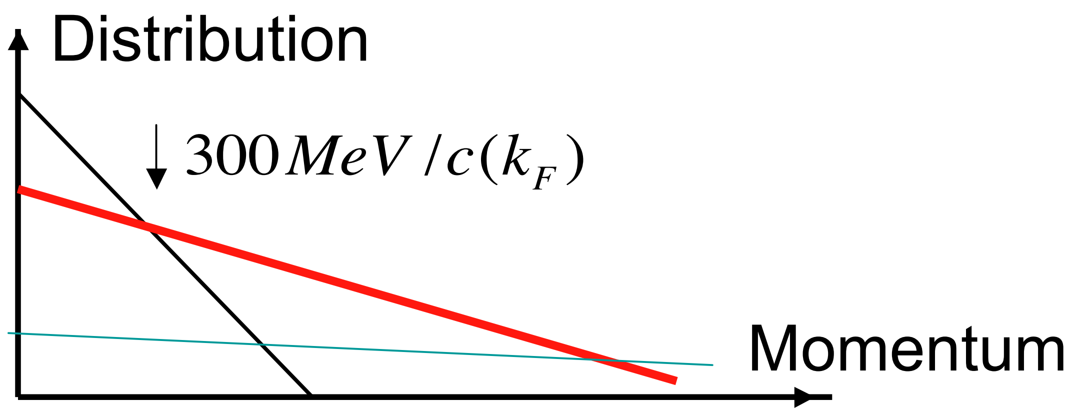
High momentum
Component

Matrix element

Shell model

$$\langle\Psi|\hat{O}|\Psi\rangle = |C_0|^2\langle 0|\hat{O}|0\rangle + \sum_{\alpha\beta} C_\alpha^* C_\beta \langle\alpha|\hat{O}|\beta\rangle$$

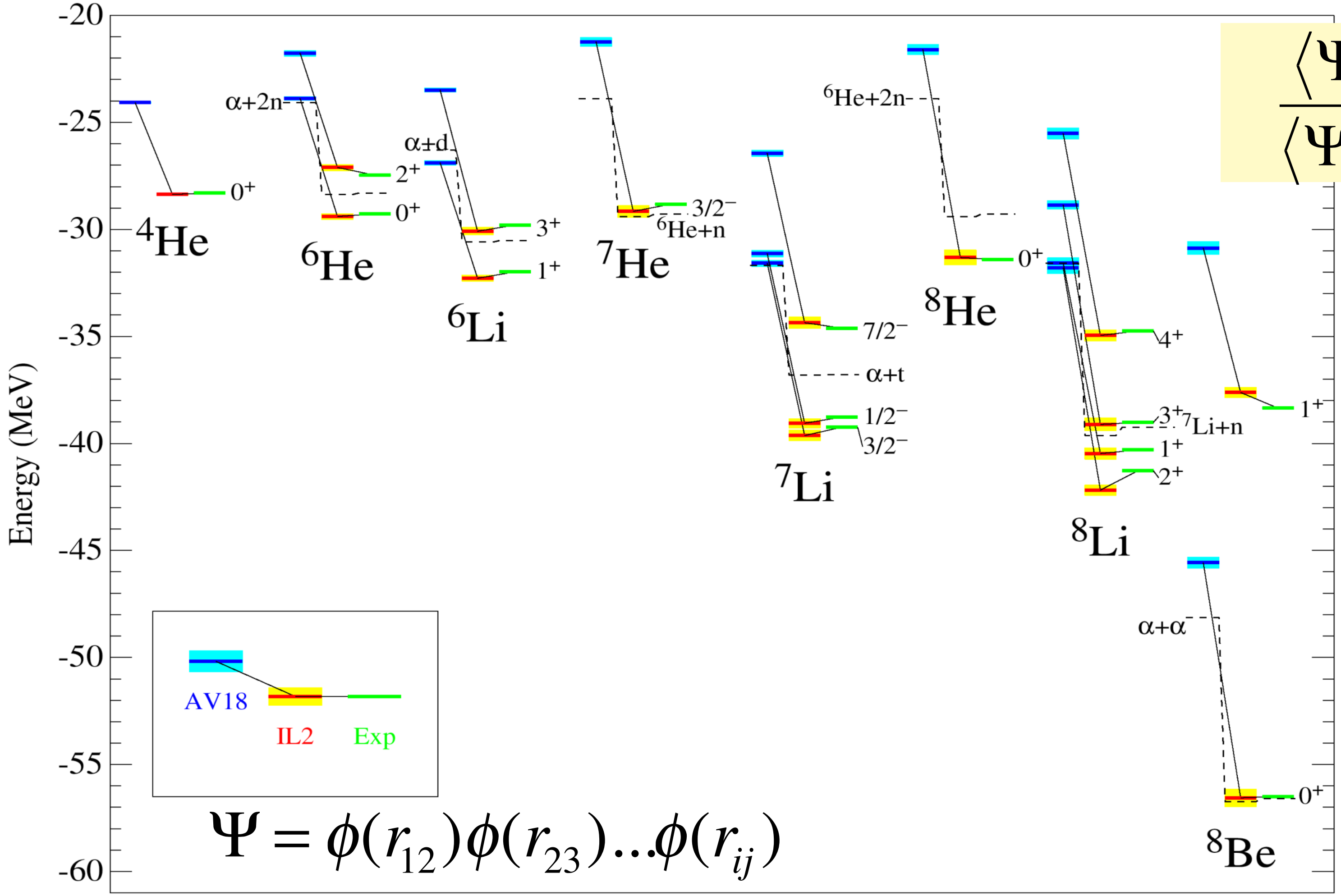
Tensor state



Variational calculation of few body system with NN interaction

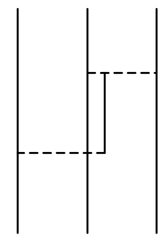
VMC+GFMC

$$\frac{\langle \Psi | V_\pi | \Psi \rangle}{\langle \Psi | V_{NN} | \Psi \rangle} \sim 80\%$$

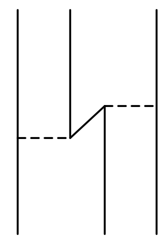


$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

V_{NNN}



Fujita-Miyazawa



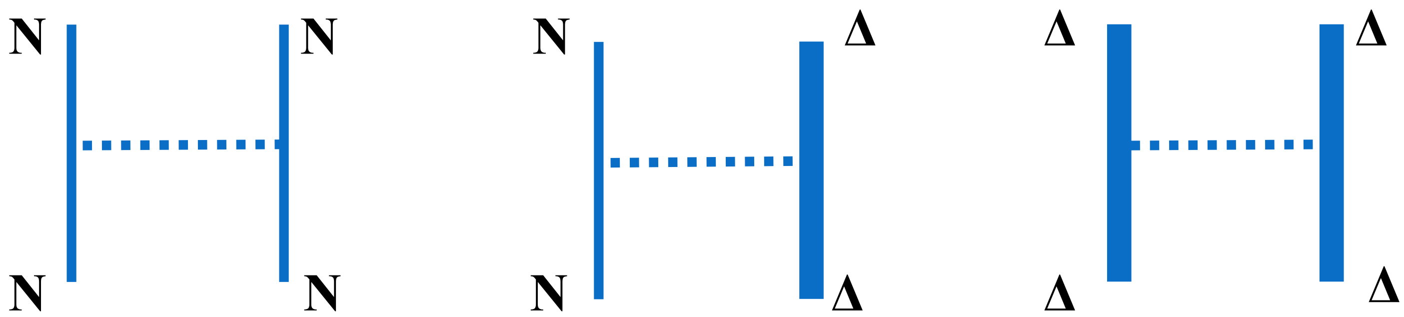
Relativistic

C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

Heavy nuclei (Super model) | Pion is key

Importance of delta

We treat delta explicitly for three body interaction.

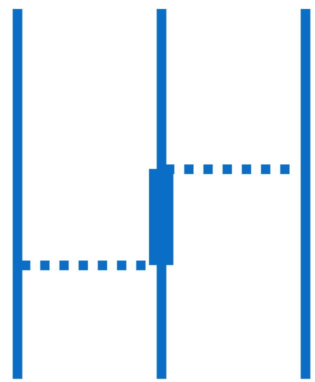


NN channel NΔ channel ΔΔ channel

Two body potential including delta

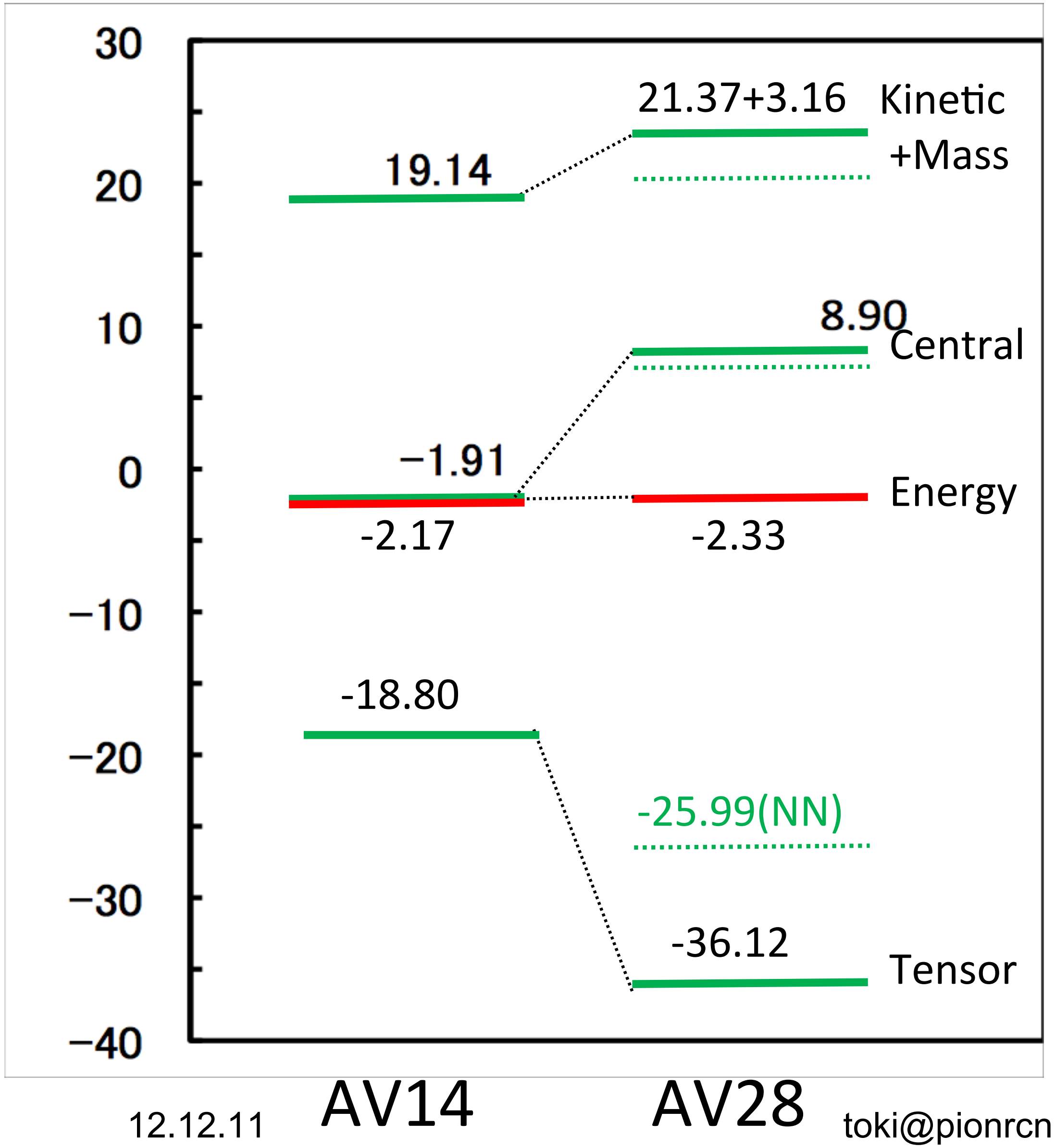
→ Argonne delta model potential (AV28)

R.B. Wiringa et al, PRC 29, 1207(1984) AV14 & AV28



Three body interaction

Effect of delta in deuteron



Deuteron 1^+	AV14	AV28
L・S	0.36	0.86
L^2	3.07	3.63
$(L\cdot S)^2$	-4.03	-4.14
P_{NN} [$^3S_1$] %	93.96	93.22
P_{NN} [$^3D_1$]	6.04	6.23
$P_{\Delta\Delta}$ [$^3S_1$]		0.04
$P_{\Delta\Delta}$ [$^3D_1$]		0.02
$P_{\Delta\Delta}$ [$^7D_1$]		0.43
$P_{\Delta\Delta}$ [$^7G_1$]		0.04

Prior studies for nuclei with delta

No calculations for $A \geq 4$

Too many states are necessary.

TOSM

$$\Psi = |S\rangle + |D\rangle + |D_{N\Delta}\rangle + |D_{\Delta\Delta}\rangle$$

A=3

1. Hannover group (Germany)

Bonn potential + single delta

Sauer, PHYS. REV. C68, 024005 (2003)

2. Los Alamos group (Fadeev calculations)

AV28 potential → Not enough binding for ^3H

Approximation : double Δ up to L=2

A. Picklesimer etal. Phys. Rev. C46 (1992)

Wave function in deuteron

$$\Psi_{NN} = |^3S_1\rangle + |^3D_1\rangle$$

$$\Psi_{\Delta\Delta} = |^3S_1\rangle + |^3D_1\rangle + |^7D_1\rangle + |^7G_1\rangle$$ ←about 0.04 %

Results in ^{1}Even channel

^{1}E channel L=even, S=even, T=1

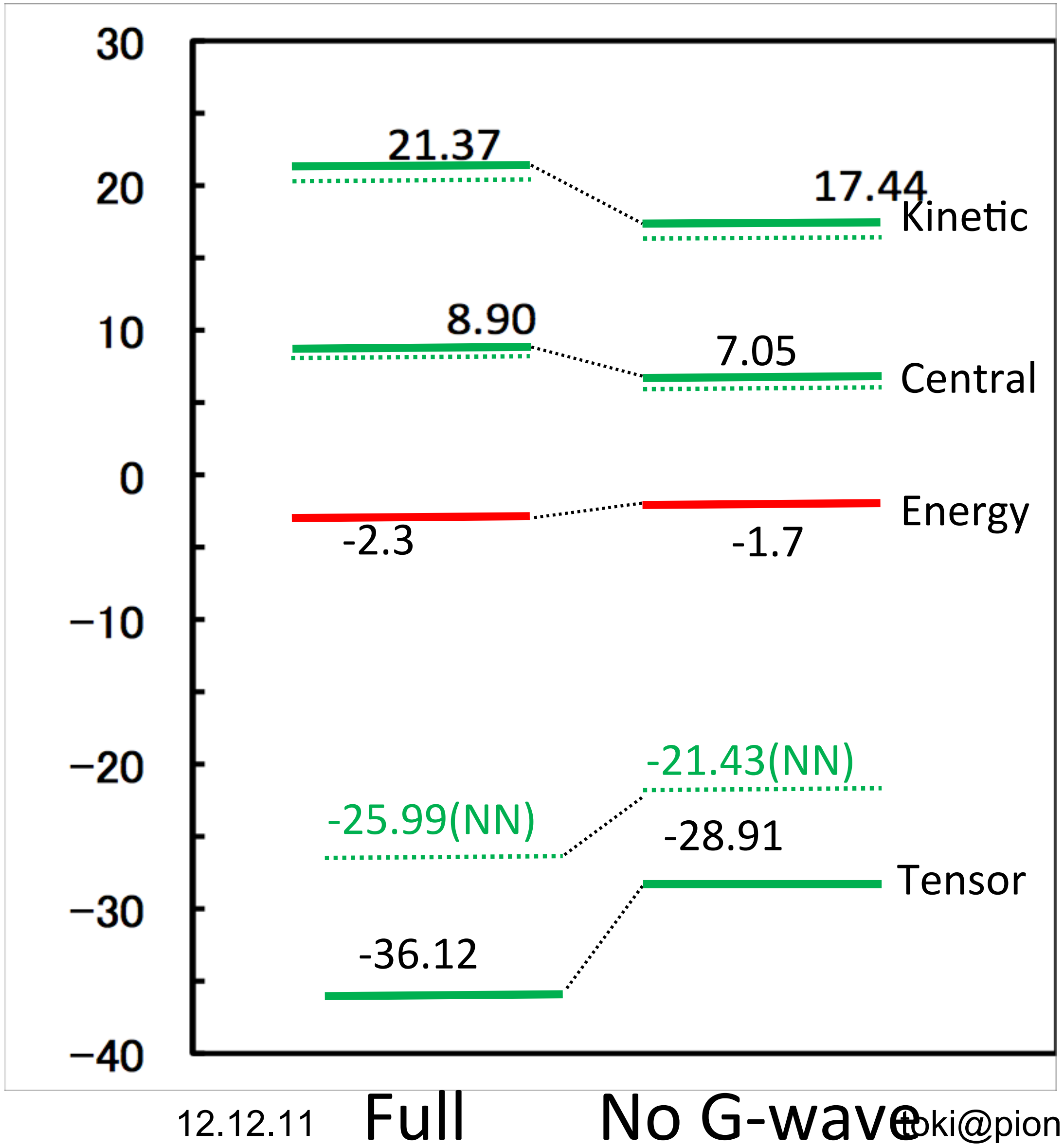
J=0	d=1.70 fm	no NΔ
Energy [MeV]	5.7	8.2
Kinetic	10.51(NN=9.23)	9.51 (NN=9.30)
Central	0.90(NN=0.70)	-0.12 (NN=-0.12)
Tensor	**-7.92**	**-1.75**
L･S	------	------
L^2	------	------
$(L･S)^2$	------	------
P_{NN} $[^1S_0]$ %	99.37	99.89
$P_{\Delta\Delta}$ $[^1D_0]$	0.01	0.007
$P_{\Delta\Delta}$ $[^5D_0]$	0.12	0.10
$P_{N\Delta}$ $[^5D_0]$	0.49	------

$$\Psi_{NN} = |^1S_0\rangle$$
$$\Psi_{\Delta\Delta} = |^1S_0\rangle + |^5D_0\rangle$$
$$\Psi_{N\Delta} = |^5D_0\rangle$$

Odd channels

Delta contribution is about 1/5~1/10 in odd channels

Delta with and without $^7G_1$



Deuteron 1^+	Full	No G-wave
L・S	0.86	0.66
L^2	3.63	2.82
$(L\cdot S)^2$	-4.14	-3.21
P_{NN} [$^3S_1$] %	93.22	94.29
P_{NN} [$^3D_1$]	6.23	5.28
$P_{\Delta\Delta}$ [$^3S_1$]	0.04	0.03
$P_{\Delta\Delta}$ [$^3D_1$]	0.02	0.01
$P_{\Delta\Delta}$ [$^7D_1$]	0.43	0.37
$P_{\Delta\Delta}$ [$^7G_1$]	0.04	-------

Pion (Tensor force) in finite nuclei

- Pion (Tensor force) is important in finite nuclei
- Tensor optimized shell model (TOSM) is used to treat the tensor force -- K computer
- Tensor force has a strong influence on the excitation spectra (TOSM)
- The wave function contains high momentum components
- Extended HF theory: BHF is reformulated
- Three body interaction by explicit treatment of delta
- Delta effect is very large