

**Symposium: Quarks to Universe in Computational Science  
(QUCS2012)**

**Dec. 12–16, 2012**

***Lambda hypernuclei of He isotope  
with TOSM + UCOM***

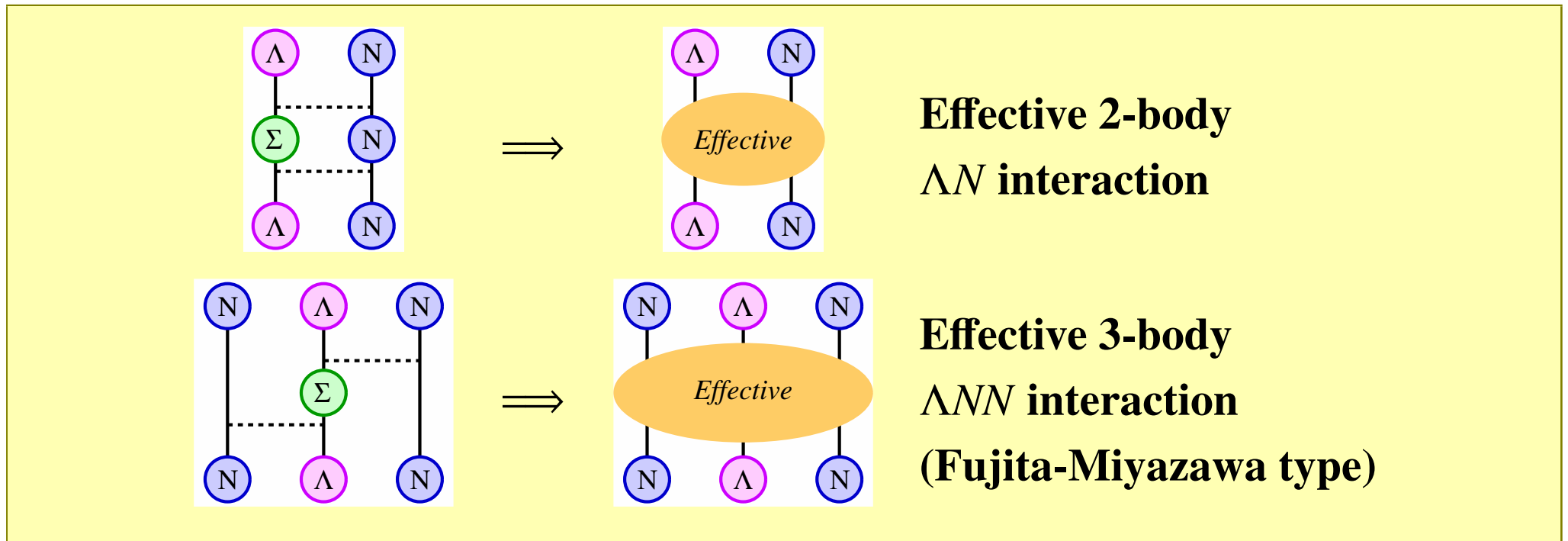
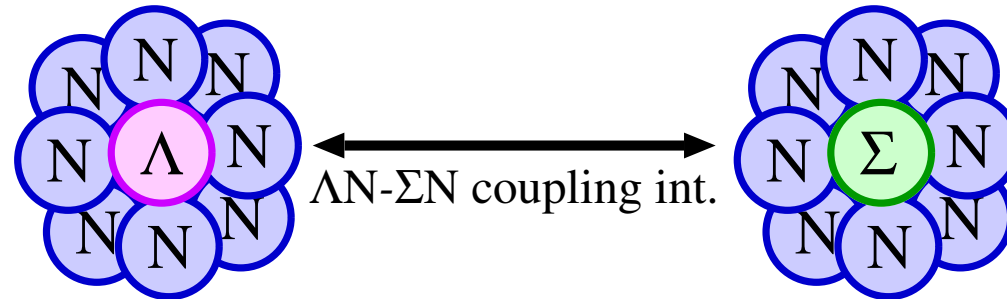
**Atsushi UMEYA (Nippon Institute of Technology)**

**Takayuki MYO (OIT), Emiko HIYAMA (RIKEN)**

**Hiroshi TOKI (RCNP), Kiyomi IKEDA (RIKEN)**

# One of the open questions in $S=-1$ sector of $YN$ interaction

## $\Lambda N$ - $\Sigma N$ coupling interaction



**Strength of the  $\Lambda N$ - $\Sigma N$  coupling interaction  $\rightarrow$  still unknown**

## $\Lambda N$ - $\Sigma N$ coupling in neutron-rich hypernuclei

**Neutron-rich hypernuclei are suited for investigating the  $\Lambda N$ - $\Sigma N$  coupling**

**$\Sigma$  hyperon: Isospin  $I = 1$**

**Neutron-rich nuclei: Large isospin**

**$\Rightarrow$  Large  $\Sigma$ -mixing**

## $\Lambda N$ - $\Sigma N$ coupling in neutron-rich hypernuclei

Neutron-rich hypernuclei are suited for investigating the  $\Lambda N$ - $\Sigma N$  coupling

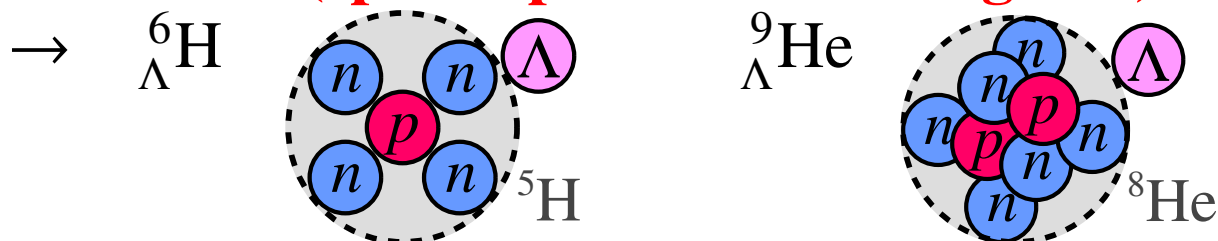
$\Sigma$  hyperon: Isospin  $I = 1$

$\Rightarrow$  Large  $\Sigma$ -mixing

Neutron-rich nuclei: Large isospin

## Productions of neutron-rich $\Lambda$ hypernuclei

- J-PARC E10 (spokes person: A. Sakaguchi)



- JLab Hall C E01-011 (spokes person: S.N. Nakamura)



## $\Lambda N$ - $\Sigma N$ coupling in neutron-rich hypernuclei

Neutron-rich hypernuclei are suited for investigating the  $\Lambda N$ - $\Sigma N$  coupling

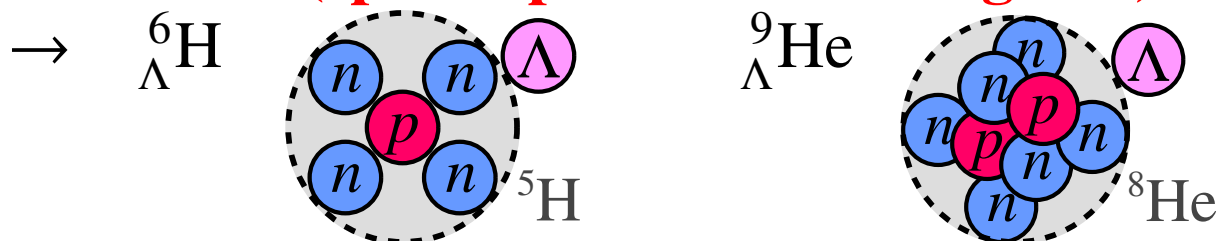
$\Sigma$  hyperon: Isospin  $I = 1$

$\Rightarrow$  Large  $\Sigma$ -mixing

Neutron-rich nuclei: Large isospin

## Productions of neutron-rich $\Lambda$ hypernuclei

- J-PARC E10 (spokes person: A. Sakaguchi)



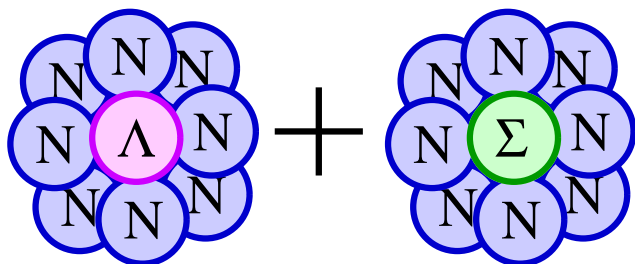
- JLab Hall C E01-011 (spokes person: S.N. Nakamura)



To clarify the structure of neutron-rich  $\Lambda$  hypernuclei

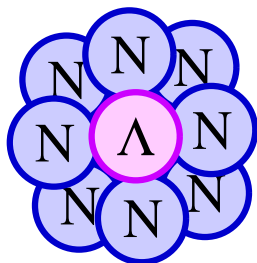
**Research plan**

***ab initio* calculation for neutron-rich hypernuclei  
with realistic interactions  
taking into account  $\Lambda N$ - $\Sigma N$  coupling explicitly**



$\Lambda$  channel +  $\Sigma$  channel

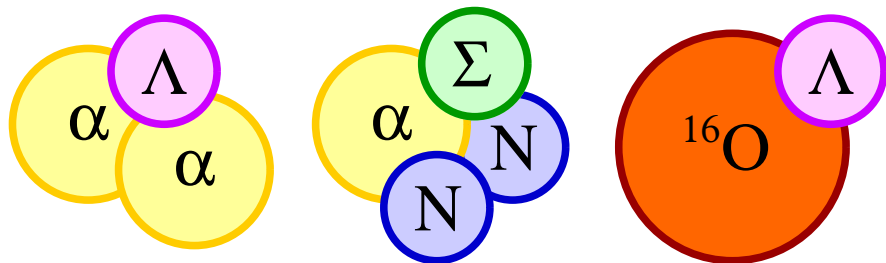
- great many configurations
- difficult and challenging calculation



only  $\Lambda$  channel (single channel)

- Few-body calculation
- No core shell model

⋮



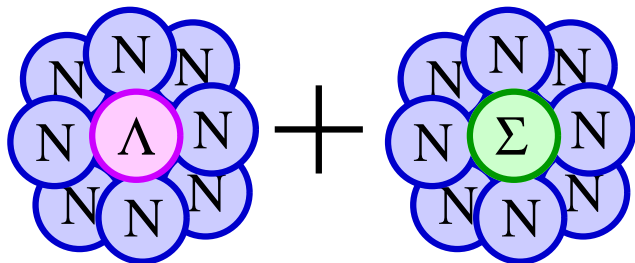
assuming  $\alpha$  cluster or  $^{16}\text{O}$  core

- Cluster model
- Shell model

⋮

**Research plan**

*ab initio* calculation for neutron-rich hypernuclei  
 with **realistic interactions**  
 taking into account  **$\Lambda N$ - $\Sigma N$  coupling explicitly**



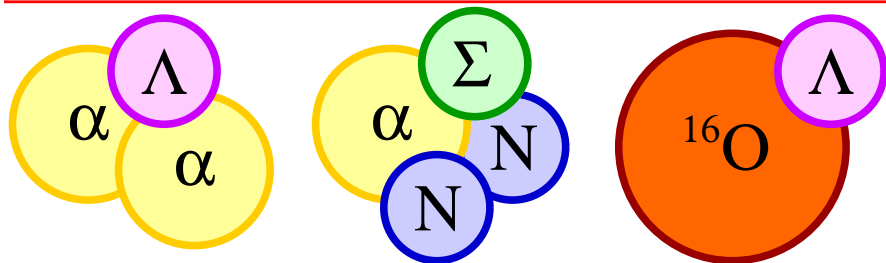
$\Lambda$  channel +  $\Sigma$  channel

- great many configurations
- difficult and challenging calculation

**Method: Tensor-Optimized Shell Model (TOSM)**

*T. Myo et al., Prog. Theor. Phys. 117, 257 (2007).*

**Suited for a systematic investigation of nuclei with  $A = 3-10$   
 without assuming an  $\alpha$  cluster**



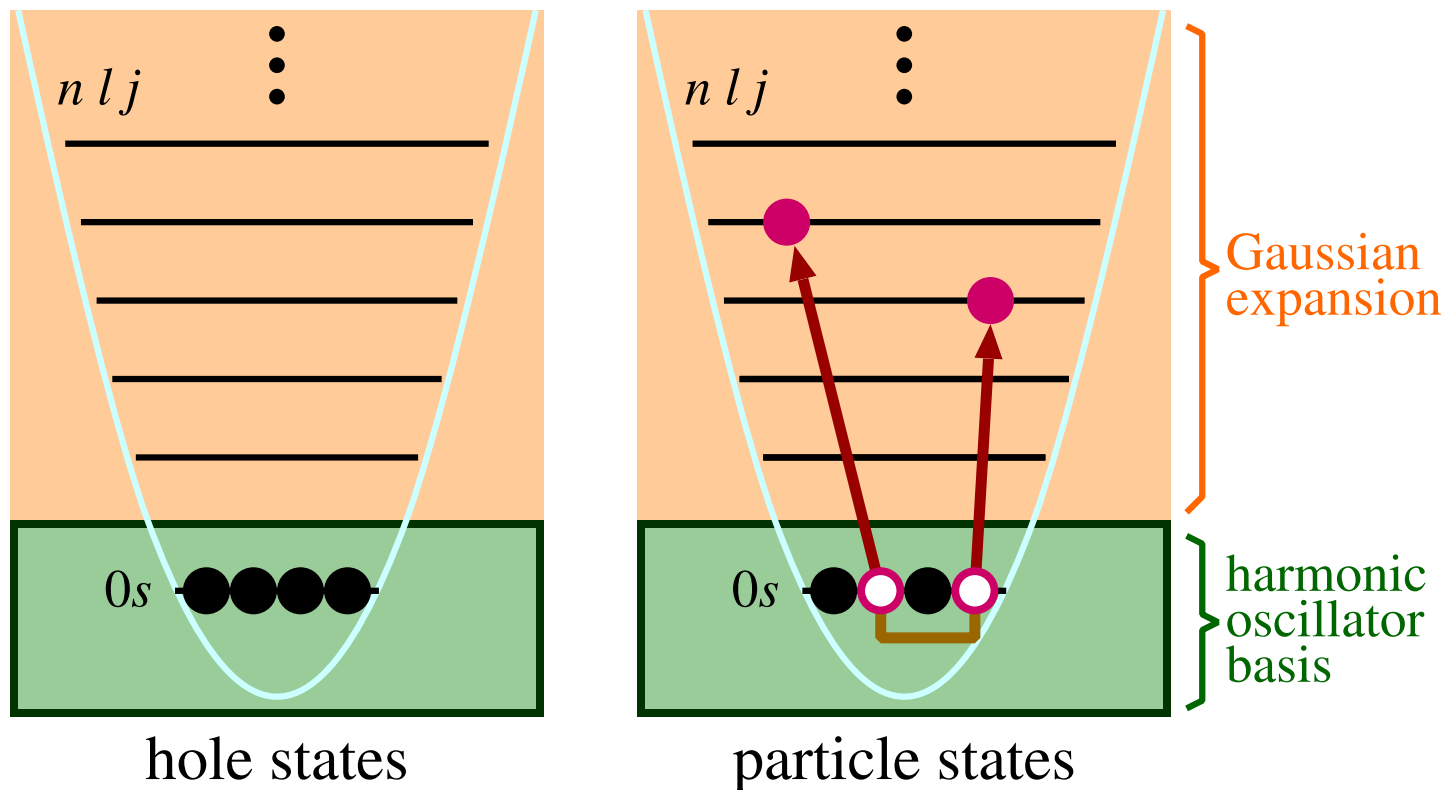
**Accuracy: a few MeV**

- Cluster model
- Shell model
- $\vdots$

# Tensor-Optimized Shell Model (TOSM)

T. Myo *et al.*, Prog. Theor. Phys. 117, 257 (2007).

Case of  ${}^4\text{He}$



taking into account high-momentum components

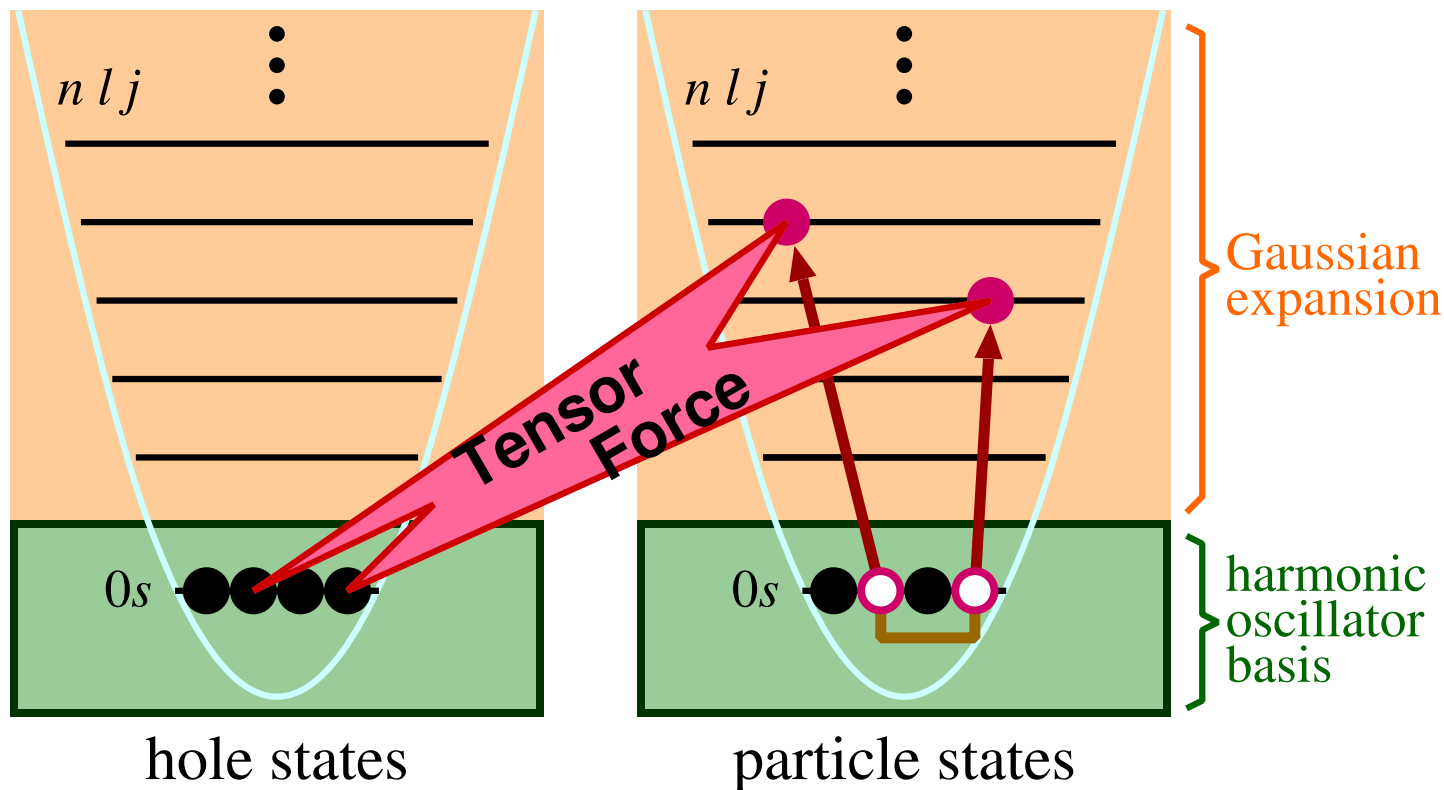
described by  $1p-1h$  and  $2p-2h$  excitations



# Tensor-Optimized Shell Model (TOSM)

T. Myo *et al.*, Prog. Theor. Phys. 117, 257 (2007).

Case of  ${}^4\text{He}$



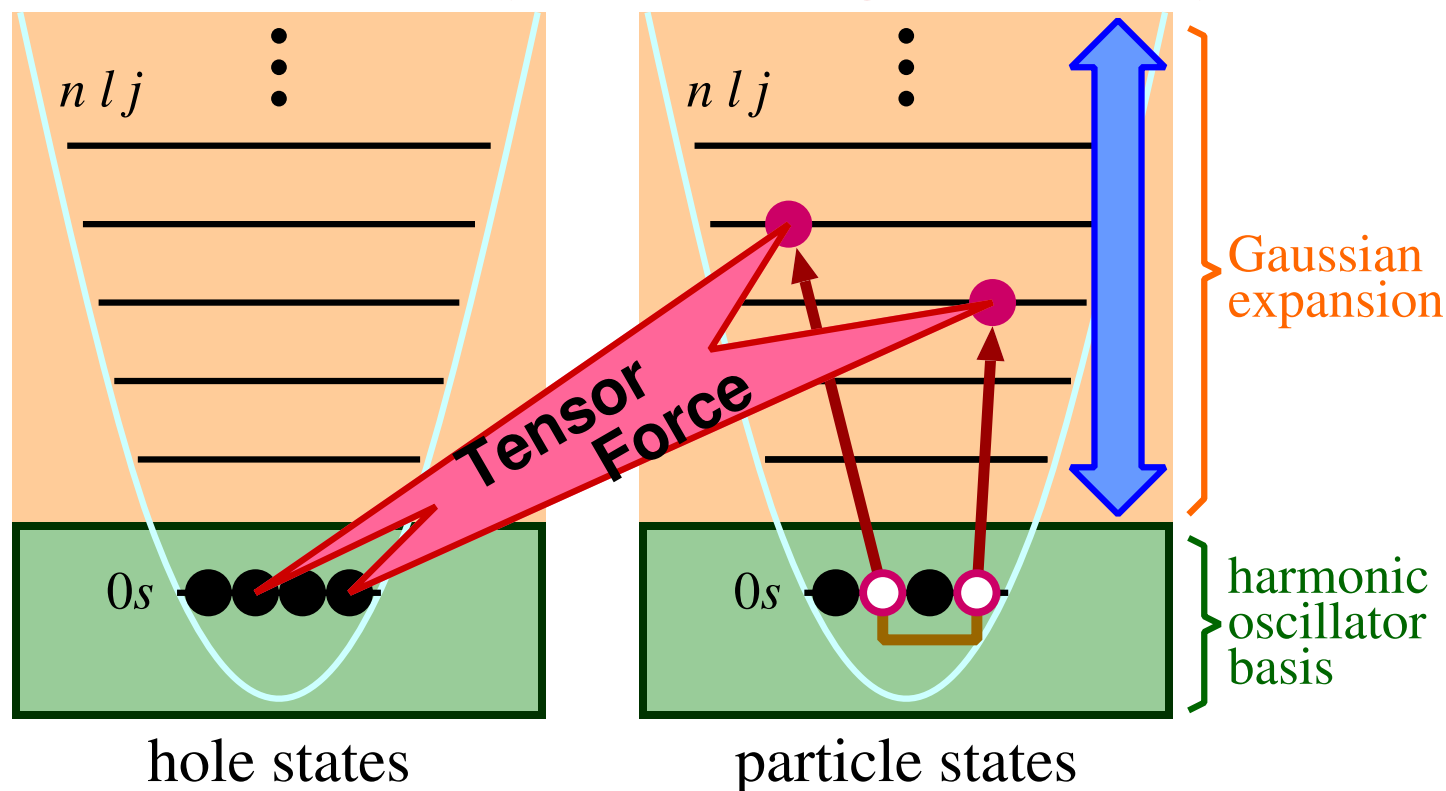
taking into account high-momentum components

described by  $1p-1h$  and  $2p-2h$  excitations

# Tensor-Optimized Shell Model (TOSM)

T. Myo *et al.*, Prog. Theor. Phys. 117, 257 (2007).

Case of  ${}^4\text{He}$



taking into account high-momentum components

described by  $1p-1h$  and  $2p-2h$  excitations

- Model space ← given by maximum number of angular momentum  $l$
- Particle states ← described by several Gaussians

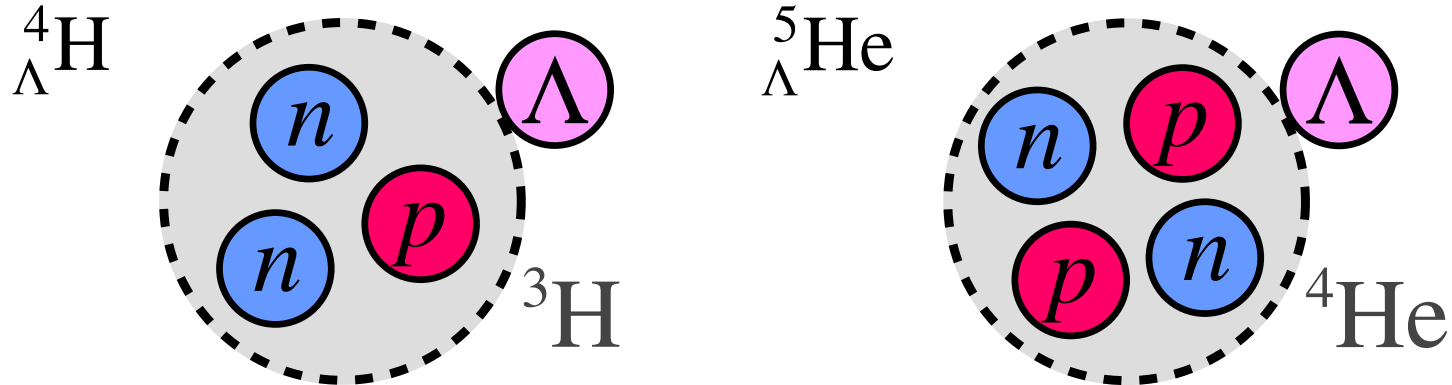
In this talk...

Focus on ***s*-shell**  $\Lambda$ -hypernuclei

In this talk...

Focus on ***s*-shell**  $\Lambda$ -hypernuclei

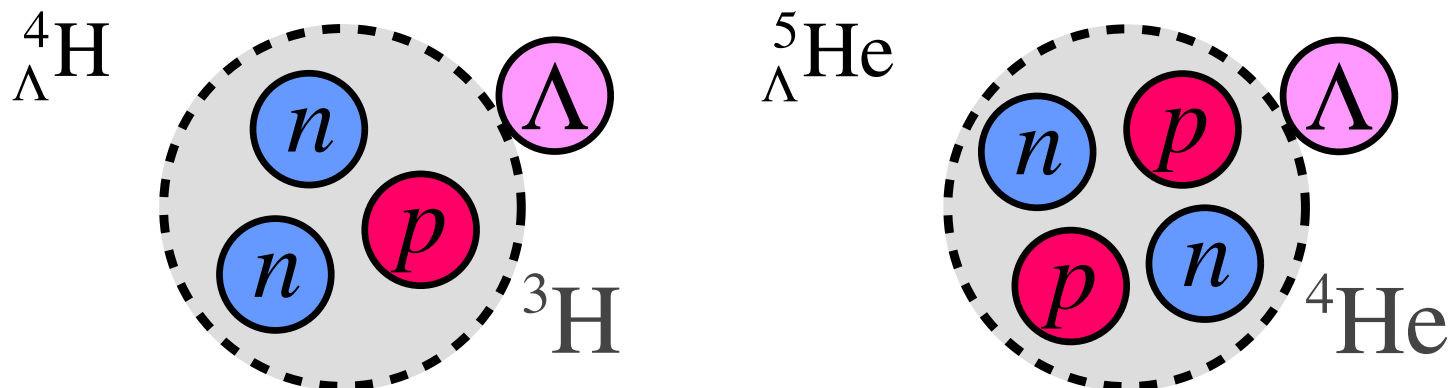
Calculations of energy levels of  ${}^4_{\Lambda}\text{H}$  and  ${}^5_{\Lambda}\text{He}$



In this talk...

Focus on ***s*-shell**  $\Lambda$ -hypernuclei

Calculations of energy levels of  ${}^4_{\Lambda}\text{H}$  and  ${}^5_{\Lambda}\text{He}$

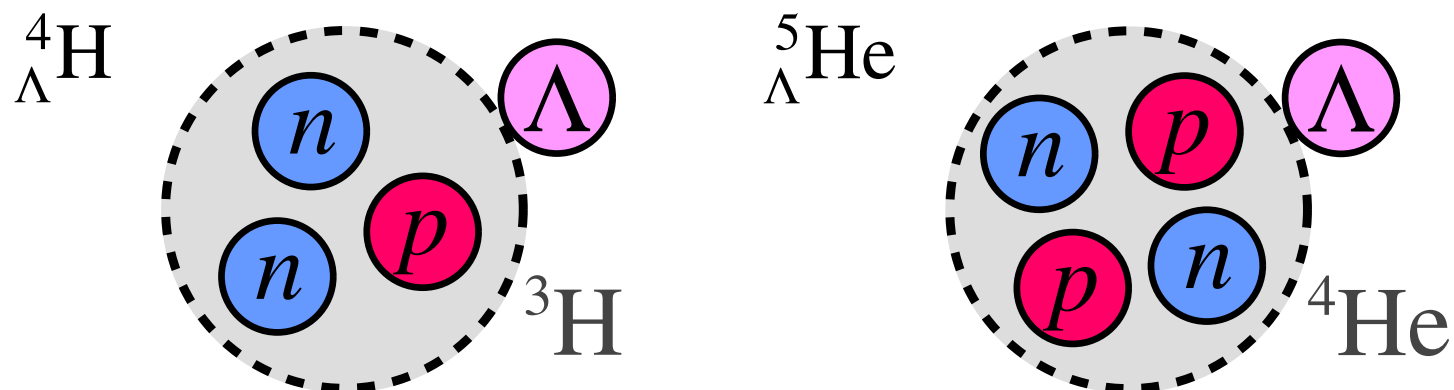


**First TOSM calculations of hypernuclei**

In this talk...

Focus on ***s*-shell**  $\Lambda$ -hypernuclei

Calculations of energy levels of  ${}^4_{\Lambda}\text{H}$  and  ${}^5_{\Lambda}\text{He}$



**First TOSM calculations of hypernuclei**

Comparison with other *ab initio* calculations

checking the accuracy of TOSM for an application  
to neutron-rich hypernuclei

## Application to $s$ -shell $\Lambda$ -hypernuclei

### Model space

- $\Sigma$  hyperon state in the TOSM wave functions
- $l_{\max} = 14$  in the energy variation

## Application to $s$ -shell $\Lambda$ -hypernuclei

### Model space

- $\Sigma$  hyperon state in the TOSM wave functions
- $l_{\max} = 14$  in the energy variation

### Interactions

- $NN$  interaction

**AV8'** B.S. Pudliner *et al.*, Phys. Rev. C 56, 1720 (1997).

- $YN$  interaction ( $\Lambda N$ ,  $\Sigma N$ ,  $\Lambda N$ - $\Sigma N$  coupling)

$$V_{YN} = V_0^{YN} + \sigma \cdot \sigma V_{\sigma}^{YN} + \ell \cdot s V_{\ell s}^{YN} + S_{12} V_{\text{tensor}}^{YN}$$

made by S. Shinmura

simulated the scattering phase shifts given by NSC97f

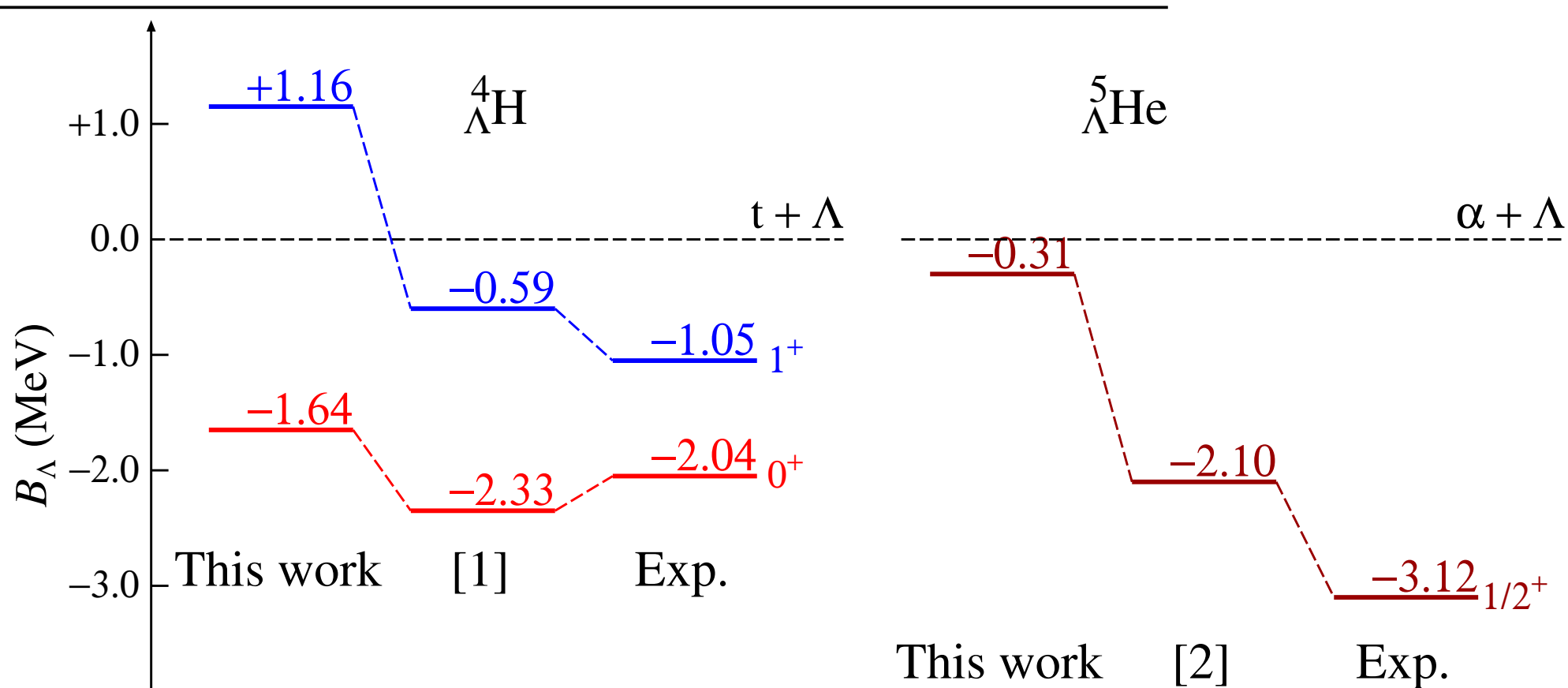
used in few-body calculations

E. Hiyama *et al.*, Phys. Rev. C 65, 011301(R).

H. Nemura *et al.*, Phys. Rev. Lett. 89, 142504 (2002).



## Numerical results of energy levels of ${}^4_{\Lambda}\text{H}$ and ${}^5_{\Lambda}\text{He}$



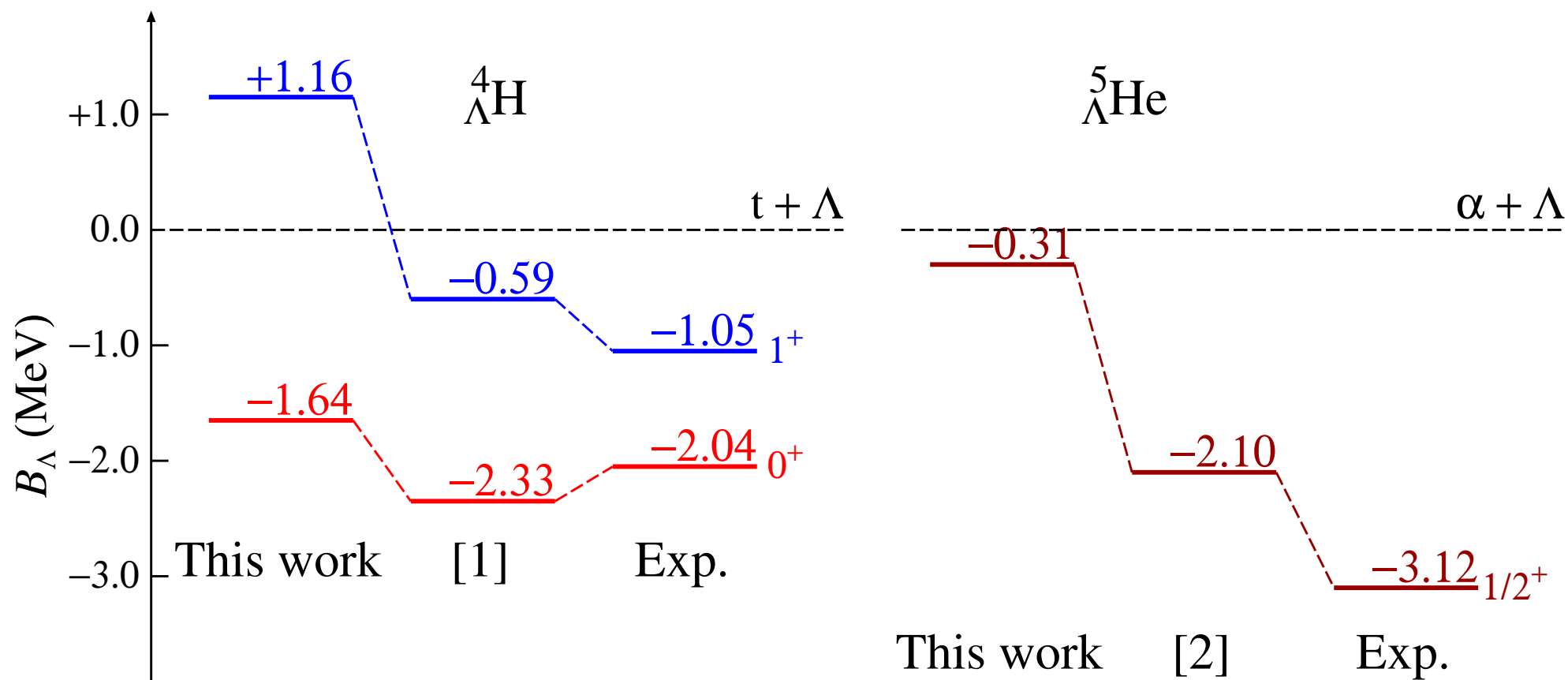
[1] E. Hiyama *et al.*, Phys. Rev. C 65, 011301(R) (2001).

[2] H. Nemura *et al.*, Phys. Rev. Lett. 89, 142504 (2002).

(G3RS potential is used for  $NN$  interaction in [2].)

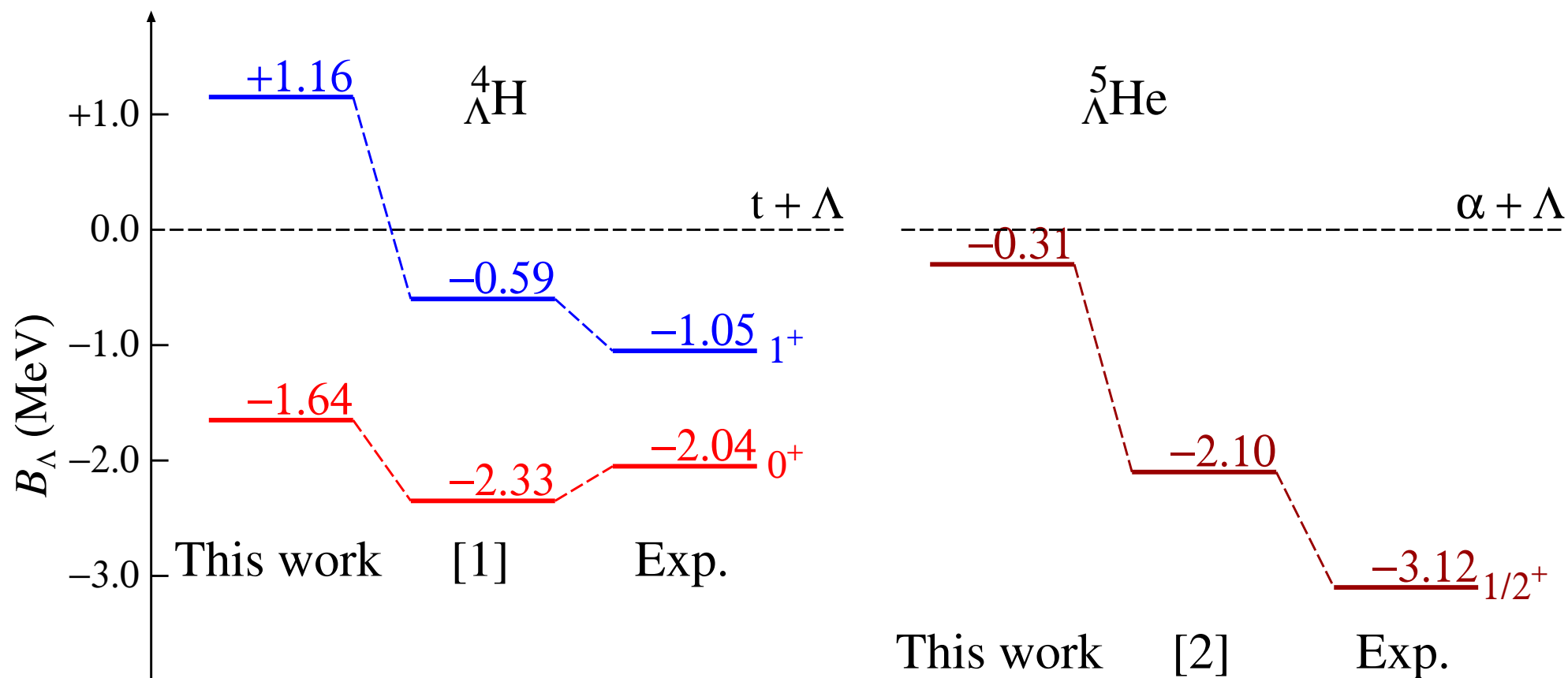
**R. Tamagaki, Prog. Theor. Phys. 39, 91 (1968).**

# Numerical results of energy levels of ${}^4_{\Lambda}\text{H}$ and ${}^5_{\Lambda}\text{He}$



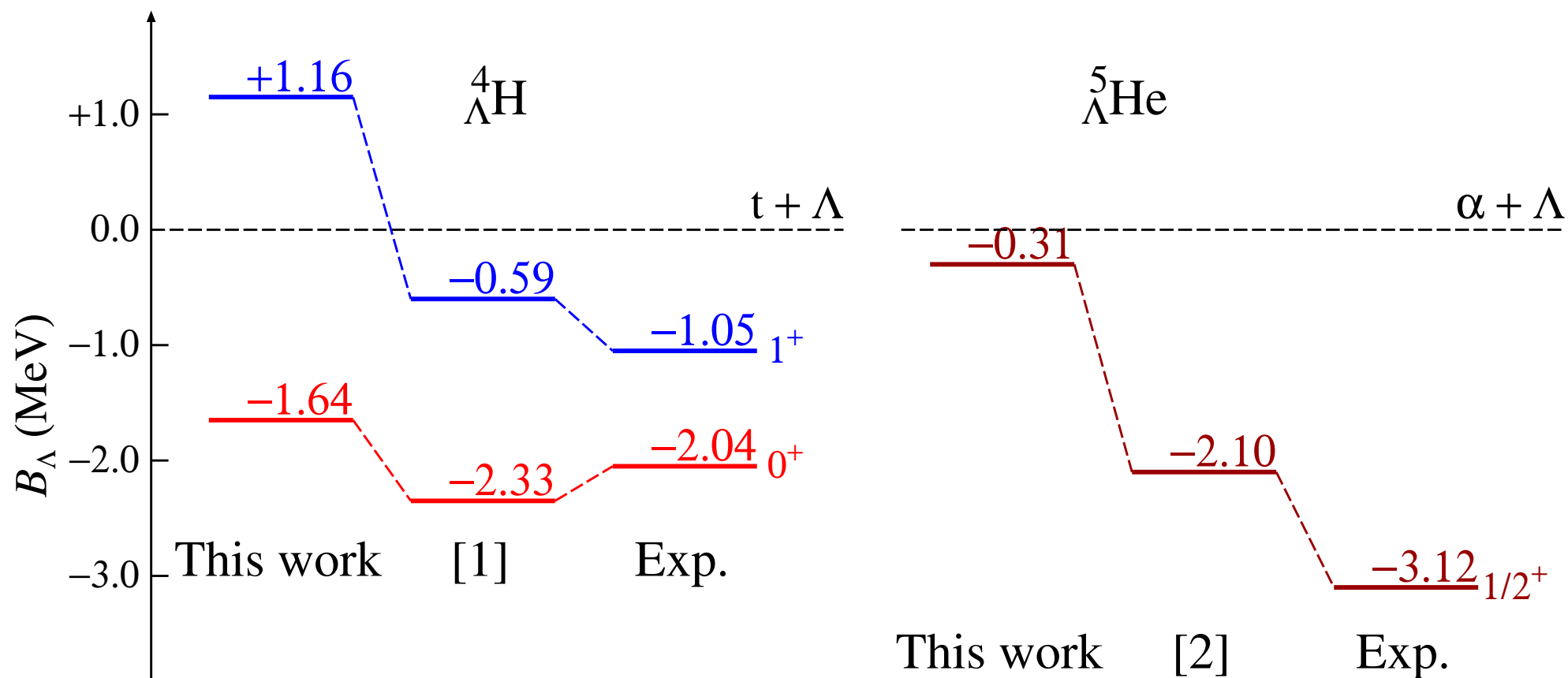
• not get sufficient binding energies

# Numerical results of energy levels of ${}^4_{\Lambda}\text{H}$ and ${}^5_{\Lambda}\text{He}$



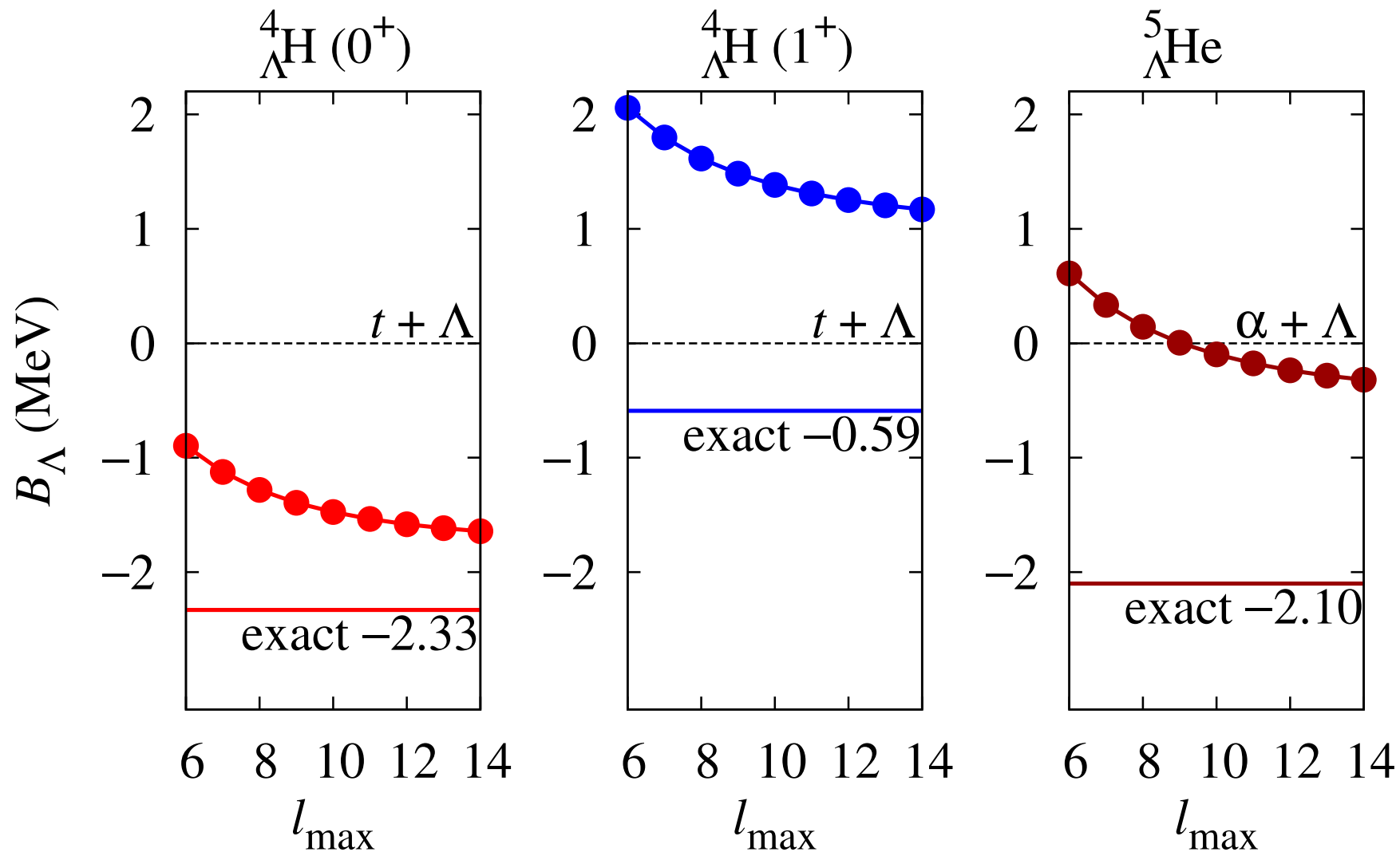
- not get sufficient binding energies
- ${}^4_{\Lambda}\text{H}$  ( $1^+$ ) is unbound

## Numerical results of energy levels of ${}^4_{\Lambda}\text{H}$ and ${}^5_{\Lambda}\text{He}$



- not get sufficient binding energies
  - ${}^4_{\Lambda}\text{H}$  ( $1^+$ ) is unbound
- ⇒ several improvements to get the sufficient binding energies

## Convergence of $B_\Lambda$



**Model space with  $L_{\max} = 14$  is not enough to get a sufficient energy convergence.**

## Role of $\Lambda N$ - $\Sigma N$ coupling

## Contributions to the binding energies

$\langle V_{YN} \rangle$ in ${}^4_{\Lambda}\text{H}; 0^+$	(MeV)		
	Central	Tensor	$LS$
$N\Lambda$ - $N\Lambda$	-5.02	-1.26	-0.23
$N\Lambda$ - $N\Sigma$	-3.18	<b>-9.29</b>	0.32
$N\Sigma$ - $N\Sigma$	0.62	-2.03	-0.14

$\langle V_{YN} \rangle$ in ${}^4_{\Lambda}\text{H}; 1^+$	(MeV)		
	Central	Tensor	$LS$
$N\Lambda$ - $N\Lambda$	-1.47	-0.64	-0.05
$N\Lambda$ - $N\Sigma$	-1.33	<b>-9.65</b>	0.13
$N\Sigma$ - $N\Sigma$	0.75	-0.23	-0.19

$\langle V_{YN} \rangle$ in ${}^5_{\Lambda}\text{He}$	(MeV)		
	Central	Tensor	$LS$
$N\Lambda$ - $N\Lambda$	-3.08	-0.67	-0.04
$N\Lambda$ - $N\Sigma$	-1.39	<b>-11.03</b>	0.12
$N\Sigma$ - $N\Sigma$	0.82	0.00	-0.23

**The tensor component of the  $\Lambda N$ - $\Sigma N$  coupling interaction strongly contributes to the binding energy.**

**These results are qualitative agreement with the few-body calculation by H. Nemura.**

**H. Nemura *et al.*, Phys. Rev. Lett. 89, 142504 (2002).**

## Summary

We have calculated the energy spectra of  $s$ -shell  $\Lambda$ -hypernuclei,  ${}^4_{\Lambda}\text{H}$  and  ${}^5_{\Lambda}\text{He}$  by using TOSM which includes the  $\Lambda N$ - $\Sigma N$  coupling explicitly.

**First TOSM calculations of hypernuclei**

## Summary

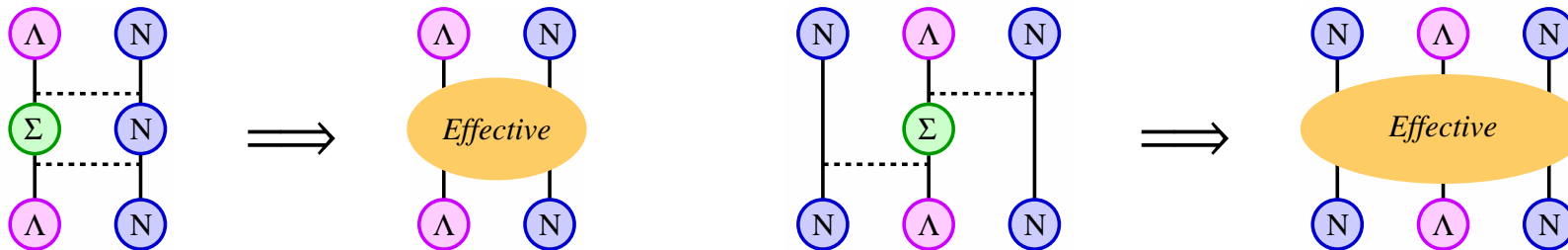
We have calculated the energy spectra of  $s$ -shell  $\Lambda$ -hypernuclei,  ${}^4_{\Lambda}\text{H}$  and  ${}^5_{\Lambda}\text{He}$  by using TOSM which includes the  $\Lambda N$ - $\Sigma N$  coupling explicitly.

### First TOSM calculations of hypernuclei

## Future plan

⇒ the TOSM calculation will be improved

- the results which are close to *ab initio* calculation
- quantitative discussion on role of the  $\Lambda N$ - $\Sigma N$  coupling interaction



- *ab initio* like calculations for  $p$ -shell hypernuclei  
 → prediction of energy levels of  ${}_{\Lambda}\text{He}$  isotope up to  $A = 9$