Competition between nucleon- and $\bar{K}NN$-cluster correlations in kaonic nuclear systems

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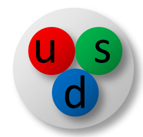
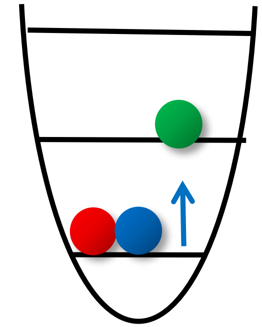
Kaonic nuclei (Nucleus with antikaon)

- $\Lambda(1405)$; $J^{\pi}=1/2^{-}$, S= -1
  - uds constituent quark model
    - Energy is too high



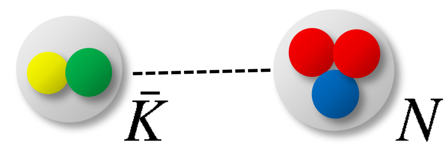


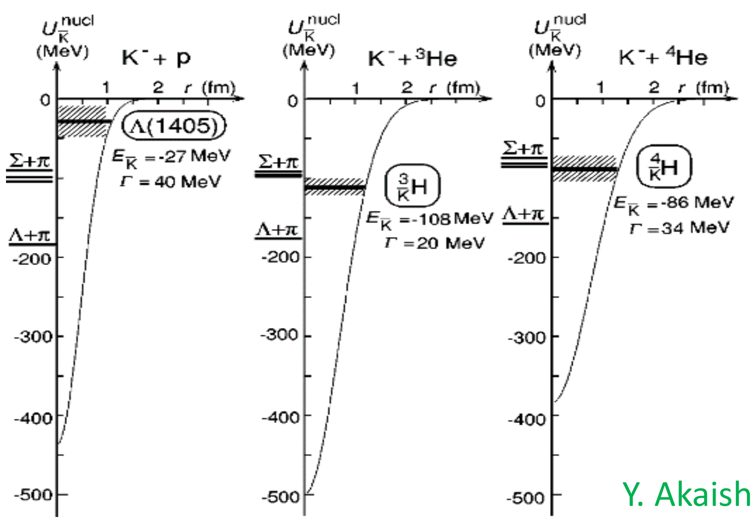
Isgur, Karl, PRD 18, 4187(1978)

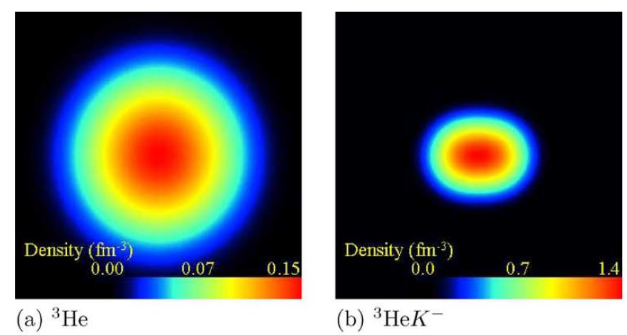
  - $\bar{K}N$ quasi-bound state

    Dalitz, Wong, Tajasekaran, PR 153, 1617 (1967)

    → strongly attractive $\bar{K}N$ interaction







(a) ${}^3He$ (b) ${}^3HeK^-$

Dote, et. al., PLB590, 51(2004).

Y. Akaishi, T. Yamazaki, PRC 65, 044005 (2002).

Does Kaonic nucleus really exist? E15 exp. Y. Sada *et al.*, Prog. Theor. Exp. Phys. **2016**, 051D01 (2016).

Can such a high density system be produced in laboratory? → $\bar{K}N$ **interaction is essential!**

Outline

- Precise few-body calculations for kaonic nuclear systems S. Ohnishi, WH, T. Hoshino, K. Miyahara, T. Hyodo, Phys. Rev. C 95, 065202 (2017)
  - Modern $\bar{K}N$ interaction K. Miyahara, T. Hyodo, PRC93 (2016)
  - Structure of kaonic nuclei
    - $\bar{K}NN$ to $\bar{K}NNNNNN$ (7-body)
    - **Clustering**: competition between $4N$ and $\bar{K}NN$ correlations

Variational calculations with correlated Gaussian method

Choice of $\overline{K}N$ interaction

Kyoto $\overline{K}N$ potential

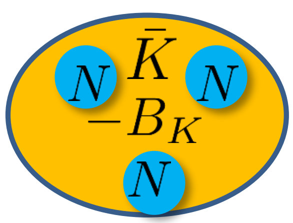
K.Miyahara, T.Hyodo, PRC 93, 015201 (2016)

- Energy-dependent $\overline{K}N$ single-channel potential
- Chiral SU(3) dynamics at NLO
- Pole energy: 1424 - 26i and 1381 – 81i MeV Y.Ikeda, T.Hyodo, W.Weise, NPA881 (2012) 98
- Consistent with the recent kaonic hydrogen data SIDDHARTA: Bazzi+2012, NPA881

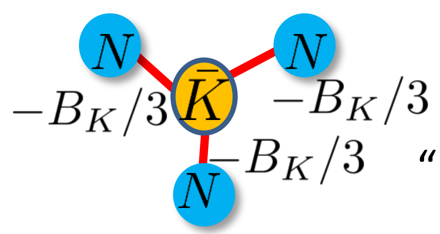
$\overline{K}N$ two-body energy in an *N*-body system are determined as:

$$\sqrt{s} = m_N + m_{\bar{K}} + \delta\sqrt{s} \quad , \quad -B_K \equiv \langle\Psi|H|\Psi\rangle - \langle\Psi|H_N|\Psi\rangle \quad ,$$

Type I: $\delta\sqrt{s} = -B_K$, Type II: $\delta\sqrt{s} = -B_K/(N-1)$, for *N-body*



"Field picture"



"Particle picture"

A. Dote, T. Hyodo, W. Weise, NPA804, 197 (2008).

Akaishi-Yamazaki (AY) potential

Akaishi, Yamazaki, PRC65, 04400(2002).

- Energy-independent
- Reproduce $\Lambda(1405)$ as $\overline{K}N$ quasi-bound state

Kaonic nuclear systems (3 to 7-body)

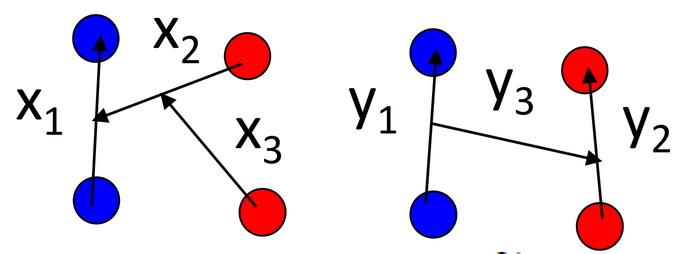
- Hamiltonian $$H = \sum_{i=1}^{\mathcal{N}} T_i - T_{\rm cm} + \sum_{i<j}^{\mathcal{N}-1} V_{ij}^{(NN)} + \sum_{i=1}^{\mathcal{N}-1} V_{i\mathcal{N}}^{(\bar{K}N)} + \sum_{i<j}^{\mathcal{N}} V_{ij}^{\rm Coul.}$$
- Basis expansion with correlated Gaussian basis:

Formulation for N-particle system

Functional form unchanged under any coordinate trans.

$$\Phi_{SM_SM_T}(x, A) = \mathcal{A}\{\exp(-\tilde{x}Ax)\chi_{SM_S}\eta_{M_T}\},$$

$$\tilde{x}Ax = \sum_{i,j=1}^{N-1} A_{ij} x_i \cdot x_j$$

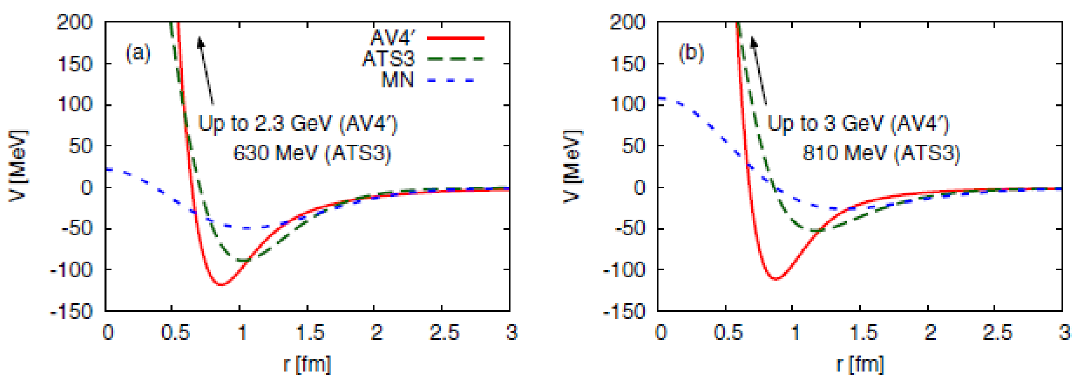


$$y = Tx \quad \Longrightarrow \quad \tilde{y}By = \tilde{x}\tilde{T}BTx$$

  - Many parameters ～(N-1)(N-2)/2 × (# of basis)

    → Stochastically selected K. Varga and Y. Suzuki, PRC52, 2885 (1995).

- Choice of *NN* potential (AV4', ATS3, MN)

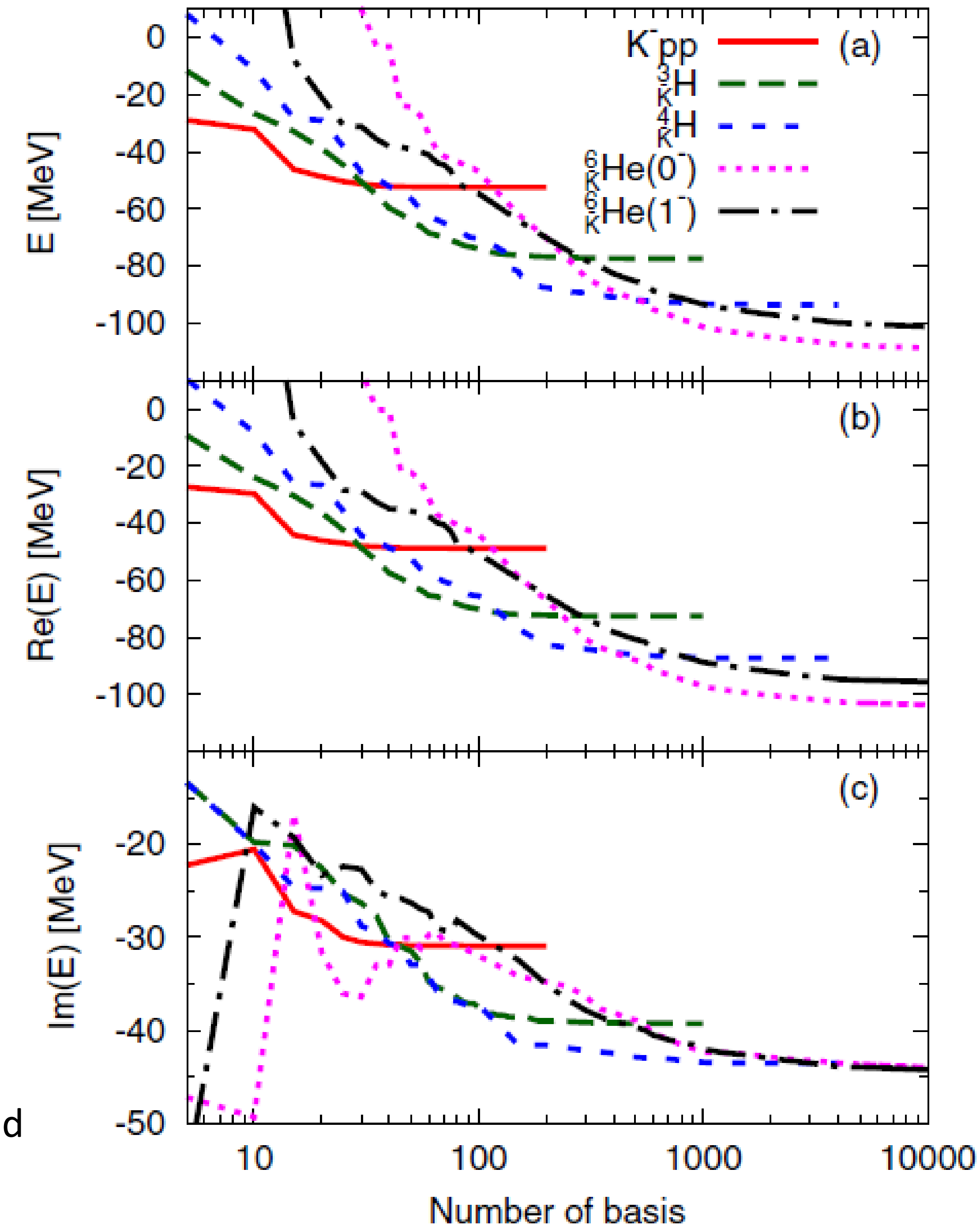


All *NN* interaction models reproduce the binding energy of *s*-shell nuclei

Energy curves

- Optimization only with a real part of the $\overline{K}N$ pot.
- Two-body $\overline{K}N$ energy is self-consistently determined
- AV4' NN pot. is employed

Full energy curves



Validity of this approach is confirmed in the three-body (K^-pp) system

Properties of $K^{-}pp$ (AV4' pot.)

Model	Kyoto		AY
	Type I	Type II	
B (MeV)	27.9	26.1	48.7
Γ (MeV)	30.9	59.3	61.9
$\delta\sqrt{s}$ (MeV)	$-61.0 - i25.0$	$-30.2 - i23.7$	
P_{K^-}	0.65	0.65	0.64
$P_{\bar{K}^0}$	0.35	0.35	0.36
$\sqrt{\langle r_{NN}^2 \rangle}$ (fm)	2.16	2.07	1.84
$\sqrt{\langle r_{\bar{K}N}^2 \rangle}$ (fm)	1.80	1.73	1.55
$\sqrt{\langle r_{N}^2 \rangle}$ (fm)	1.12	1.08	0.958
$\sqrt{\langle r_{\bar{K}}^2 \rangle}$ (fm)	1.14	1.10	0.988

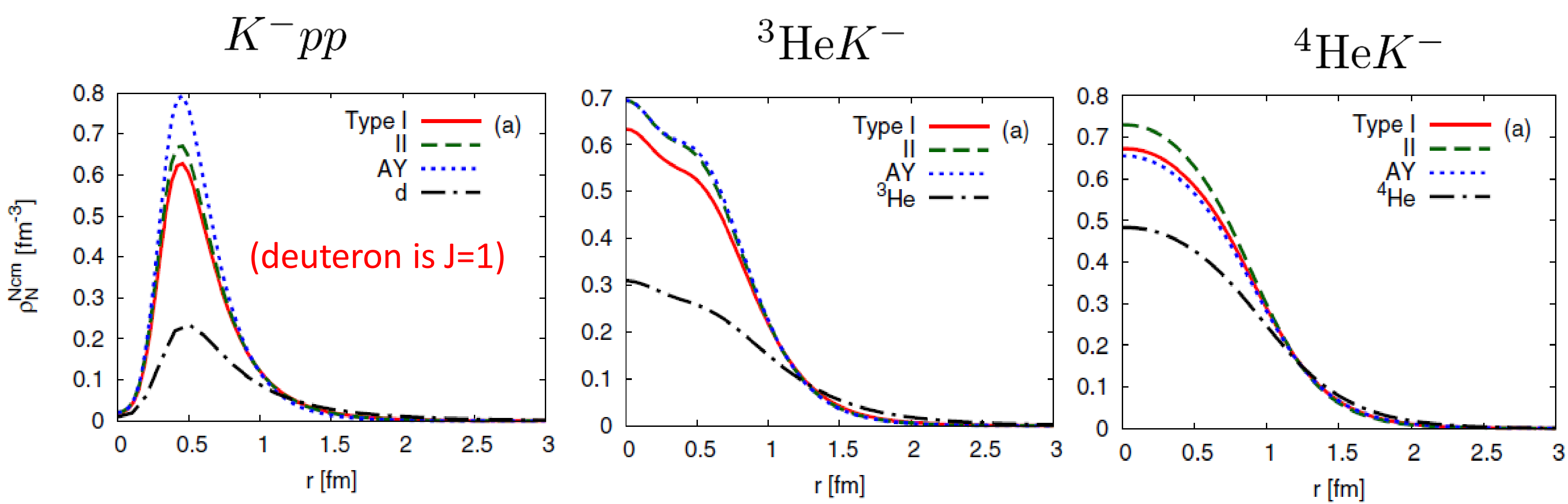
Kyoto $\overline{K}N$ pot.
Similar binding energies with Types I and II B～26-28 MeV
Γ～30-60 MeV

AY pot.
Deeper binding energy ～49MeV
→ Smaller rms radii

Systematics of $\bar{K}XN$ (X=2-6) systems

	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNNN$
B (MeV)	26-28	45-50	68-76	70-81
Γ (MeV)	31-59	26-70	28-74	24-76

Bound states appear below subthresholds: B∼Γ

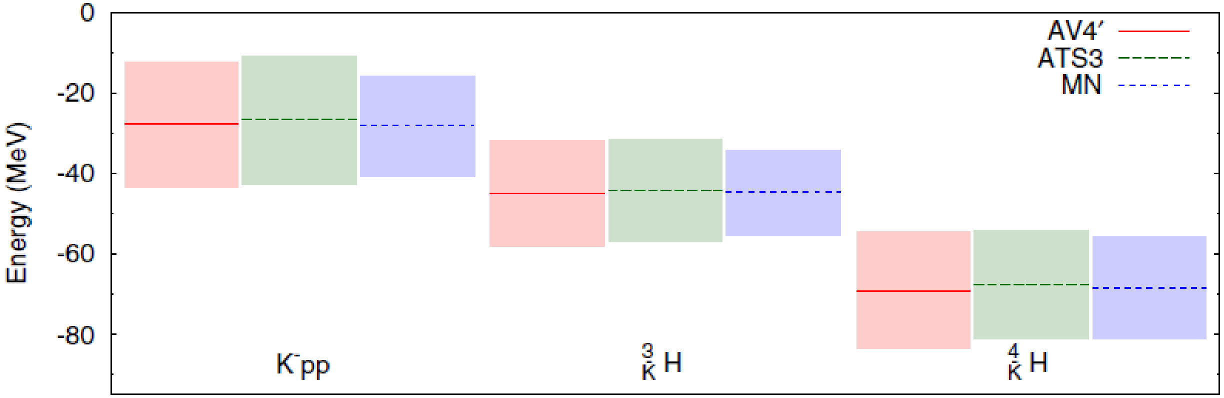


- Central nucleon density ρ(0) is enhanced by kaon
- Not always proportional to B → tail of w.f.
- ρ(0)~0.7fm^{-3} at maximum, ∼2 times higher than that without $\bar{K}$

(∼4 times higher than the saturation dens.)

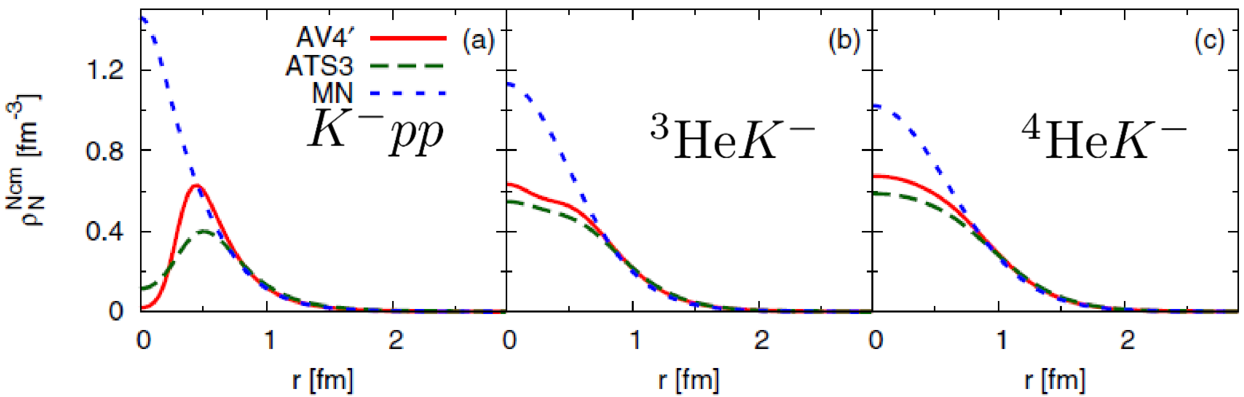
NN interaction dependence

Binding energy and decay width with different NN potential models



Not sensitive to the *NN* interaction models

Nucleon density distributions



AV4' and ATS3 potential: strong short-range repulsion

MN: weak short-range repulsion

Strong $\bar{K}N$ correlation in $\bar{K}XN$ systems: Structure of $\bar{K}NN$ & $\bar{K}NNNNNN$

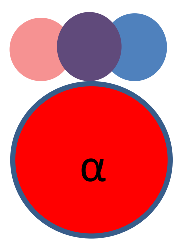
X=2

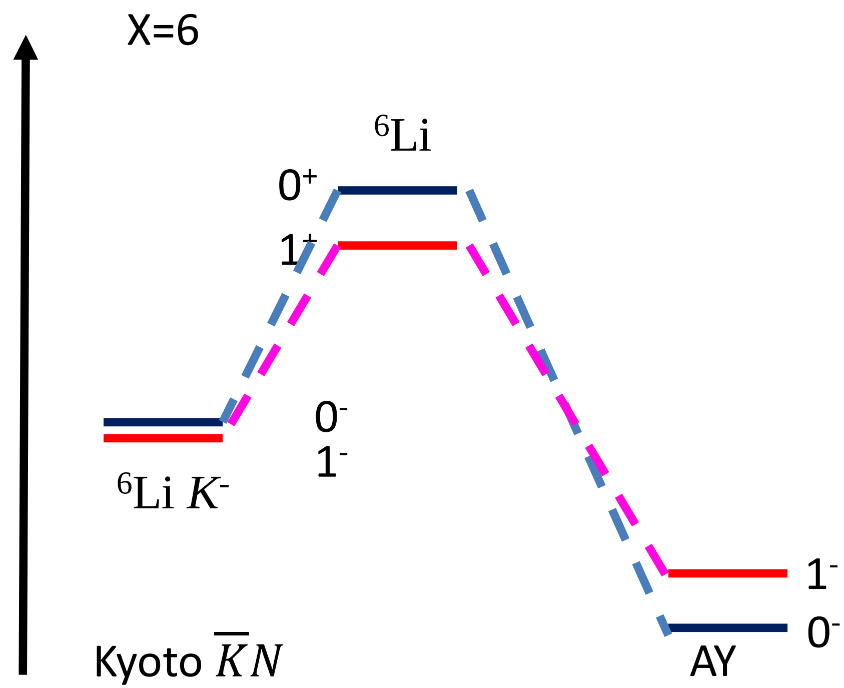
	NN	$\bar{K}NN$
J=0	unbound	bound
J=1	bound (d)	unbound

$\bar{K}N_{I=0} : \bar{K}N_{I=1}$

$\sim 3:1 \ (J=0^-)$

$\sim 1:3 \ (J=1^-)$





- $\bar{K}N$ interaction in I=0 is more attractive than in I=1
  → Energy gain in J=0 is larger than that in J=1
- AY potential in I=0 is strongly attractive
  → J=0 ground state

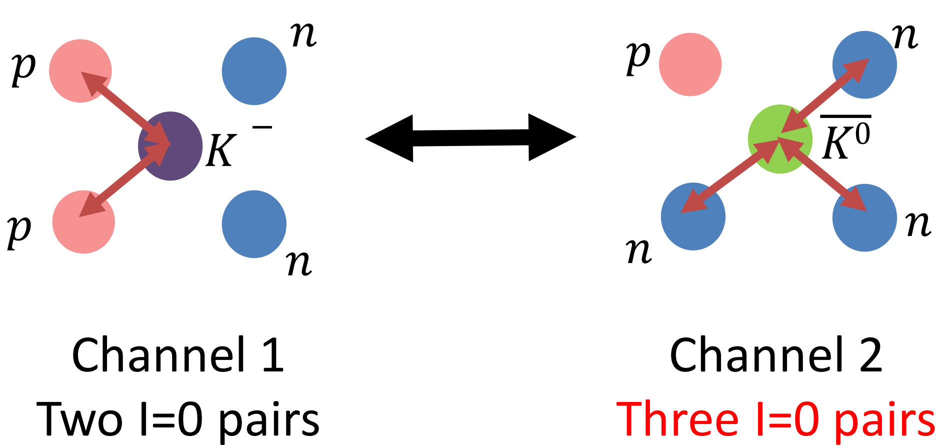
$\bar{K}N$ correlations > NN correlations

$\bar{K}N$ interaction plays a decisive role to determine the structure.

Strong NN correlations: α cluster in $\overline{K}NNNN$

- $J^{\pi}=0^{-}$, $I=1/2$, $I_z=-1/2$

  Mixture of $K^{-}ppnn$ and $\overline{K^0}pnnn$ states



- P_1:P_2=0.93:0.07
  - Channel 1 can form α cluster
  - $\overline{K}N$ correlations < NN correlations

Summary & perspectives

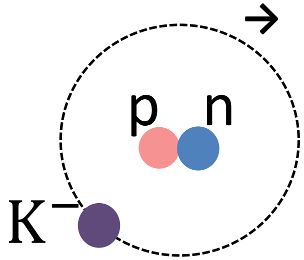
Precise few-body calculations for kaonic nuclear systems

– **Kaonic nucleus** (3- to 7-body) S. Ohnishi, WH, T. Hoshino, K. Miyahara, T. Hyodo, Phys. Rev. C95, 065202 (2017)

- Central density is increased by ∼2 times higher (4 times than ρ_0)
  - Soft *NN* interaction induces too high central densities
  - Possible extensions
    - » Explicit inclusion of the tensor and three-body forces
    - » Explicit coupling of πΣ and πΛ channels K. Miyahara, T. Hyodo, W. Weise, arXiv: 1804.08269
- Competition between $\bar{K}NN$ and $4N$ correlations
  - Strong NN correlations in $\bar{K}NNNN$ systems (α correlation)
  - Spin-parity of the g.s, of ^{6}Li $\bar{K}$ (degenerate?, inverted?)

Strength and its isospin dependence of $\bar{K}N$ interaction is essential

→ **Kaonic deuterium** (3-body) T. Hoshino, S. Ohnishi, WH, T. Hyodo, W. Weise, Phys. Rev. C 96, 045204 (2017)



Kaonic deuterium

- Prediction of the energy shift of the kaonic deuterium

$$\Delta E - i\frac{\Gamma}{2} = (670 - i\,508)\,\mathrm{eV},$$

Promising observable to constraint the I=1 component of the $\bar{K}N$ interaction complimentary to the kaonic hydrogen data (SIDDHARTA: Bazzi+2012, NPA881)