

Theoretical progress and future direction in kaonic nuclei



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$\Lambda(1405)$ and $\bar{K}N$ potentials

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);

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

K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018);

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)



Applications to few-body systems

- Kaonic nuclei

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, PRC95, 065202 (2017)

- Kaonic deuterium

T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)



Summary and prospect

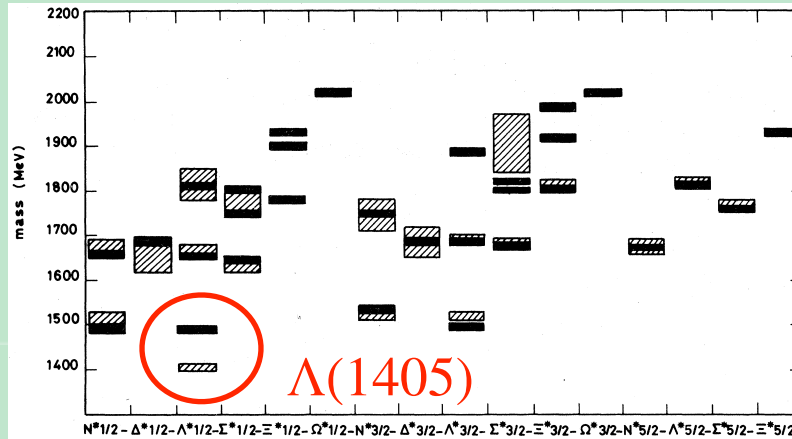
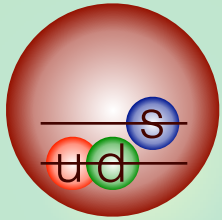
T. Hyodo, M. Niiyama, Prog. Part. Nucl. Phys. 120, 103868 (2021);

T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)

$\Lambda(1405)$ and $\bar{K}N$ scattering

$\Lambda(1405)$ does not fit in standard picture \rightarrow exotic candidate

N. Isgur and G. Karl, PRD18, 4187 (1978)

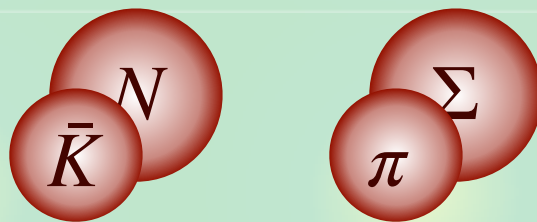


— : theory

▨ : experiment

Resonance in coupled-channel scattering

- Coupling to MB states



energy \uparrow

— $\bar{K}N$ threshold

▨ $\Lambda(1405)$

— $\pi\Sigma$ threshold

Detailed analysis of $\bar{K}N$ - $\pi\Sigma$ scattering is necessary

Strategy for $\bar{K}N$ interaction

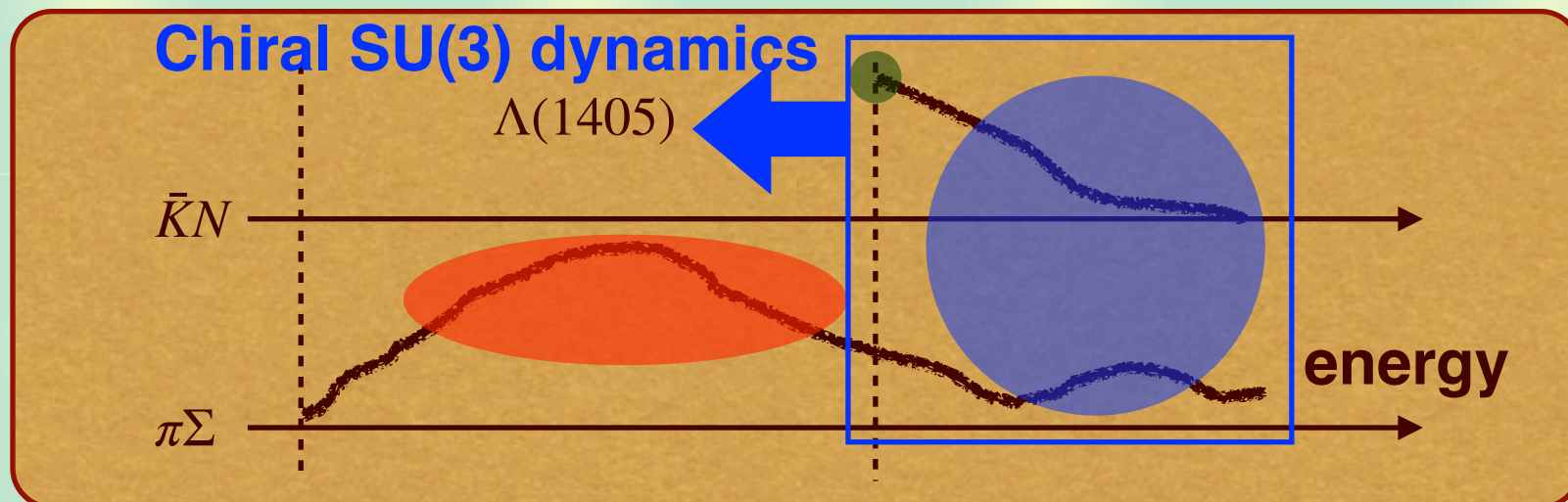
Above the $\bar{K}N$ threshold : direct constraints

- K^-p total cross sections (old data)
- $\bar{K}N$ threshold branching ratios (old data)
- K^-p scattering length (new data : SIDDHARTA)

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012)

Below the $\bar{K}N$ threshold : indirect (reaction model needed)

- $\pi\Sigma$ mass spectra (LEPS, CLAS, HADES, J-PARC, ...)



Chiral SU(3) dynamics : best-fit results

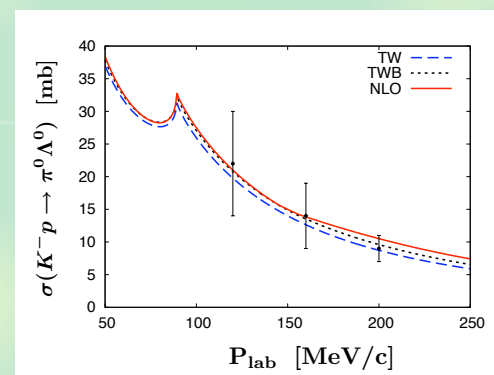
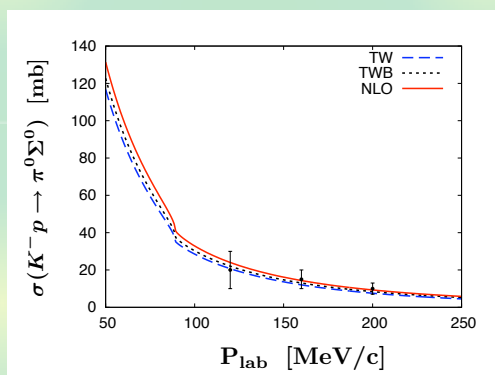
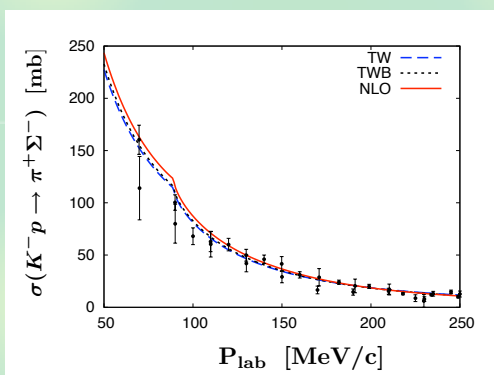
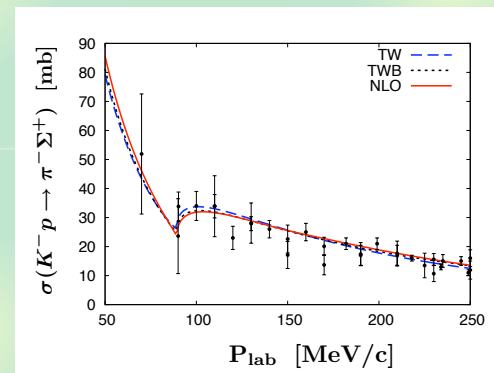
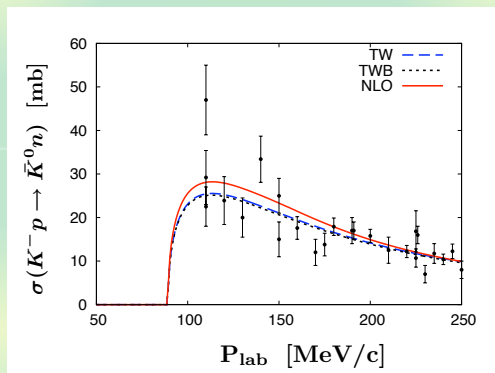
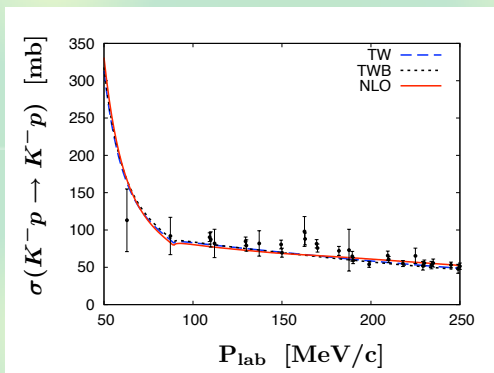
K at rest

	TW	TWB	NLO	Experiment
ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$ [10]
Γ [eV]	495	514	591	$541 \pm 89 \pm 22$ [10]
γ	2.36	2.36	2.37	2.36 ± 0.04 [11]
R_n	0.20	0.19	0.19	0.189 ± 0.015 [11]
R_c	0.66	0.66	0.66	0.664 ± 0.011 [11]
$\chi^2/\text{d.o.f}$	1.12	1.15	0.96	

} **SIDDHARTA**

} **Branching ratios**

K^-p cross sections



Accurate description of all existing data ($\chi^2/\text{d.o.f} \sim 1$)

PDG has changed

2020 update of PDG

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012); ▲

Z.H. Guo, J.A. Oller, PRC87, 035202 (2013); ✕

M. Mai, U.G. Meißner, EPJA51, 30 (2015) ■ ○

- Particle Listing section:

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

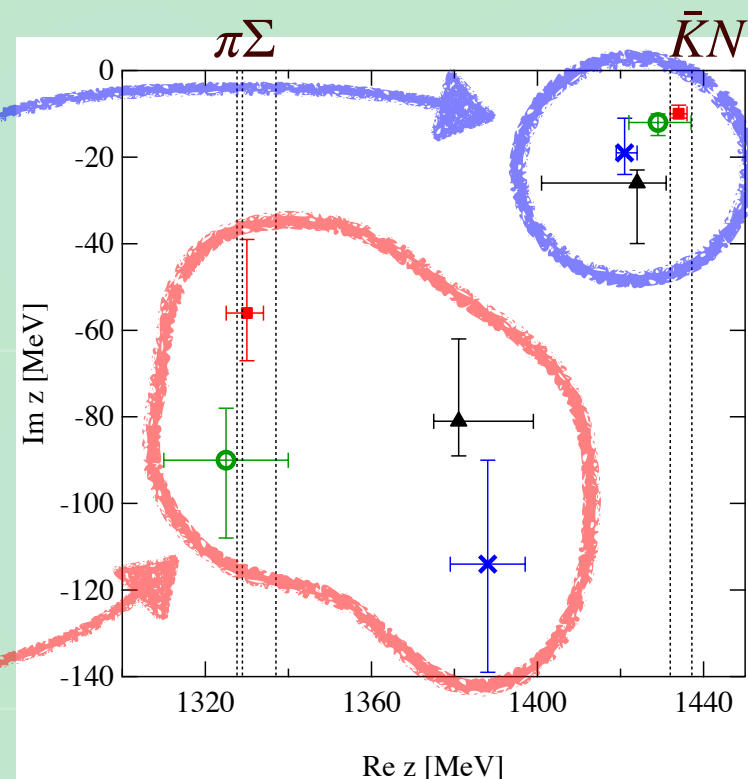
$\Lambda(1405) 1/2^-$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ****

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1380) 1/2^-$

$J^P = \frac{1}{2}^-$ Status: **
new!



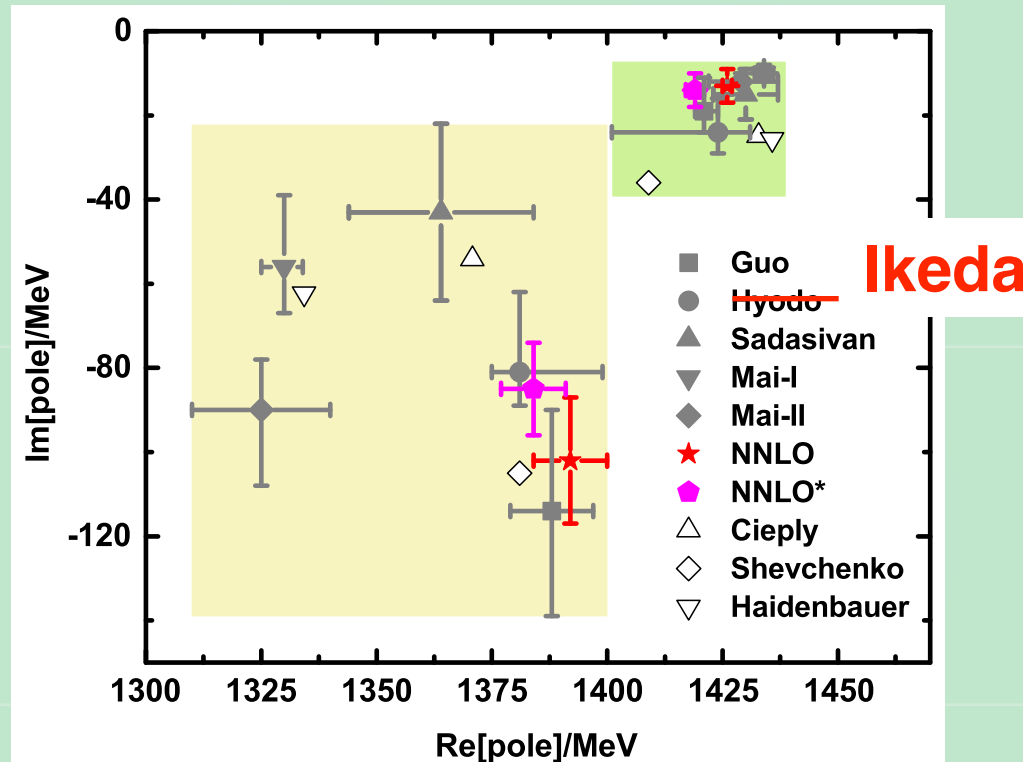
T. Hyodo, M. Niyama, Prog. Part. Nucl. Phys. 120, 103868 (2021)

- “ $\Lambda(1405)$ ” is no longer at 1405 MeV but ~ 1420 MeV.
- Lower pole : two-star resonance $\Lambda(1380)$

NNLO analysis

New analysis at **NNLO!** ($\bar{K}N$ and πN included)

J.-X. Lu, L.S. Geng, M. Doering, M. Mai, PRL130, 071902 (2023)



Pole positions (MeV)

$\Lambda(1380)$	$1392 \pm 8 - i(102 \pm 15)$
$\Lambda(1405)$	$1425 \pm 1 - i(13 \pm 4)$

Construction of $\bar{K}N$ potentials

Local $\bar{K}N$ potential is useful for various applications

meson-baryon amplitude
(chiral SU(3) EFT)

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

Kyoto $\bar{K}N$ potential
(single-channel, complex)

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

Kyoto $\bar{K}N$ - $\pi\Sigma$ - $\pi\Lambda$ potential
(coupled-channel, real)

K. Miyahara, T. Hyodo, W. Weise,
PRC 98, 025201 (2018)

Kaonic nuclei

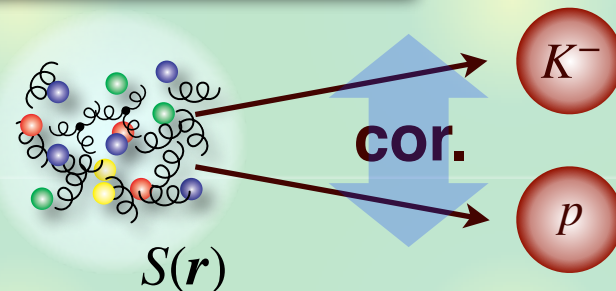
Kaonic deuterium

K^-p correlation function

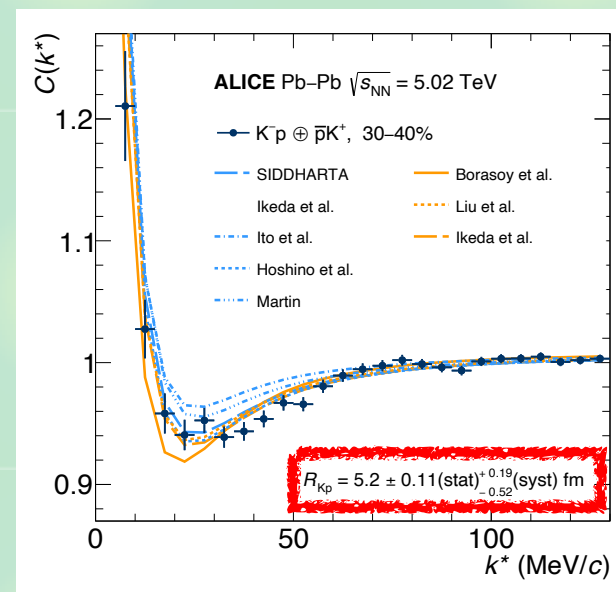
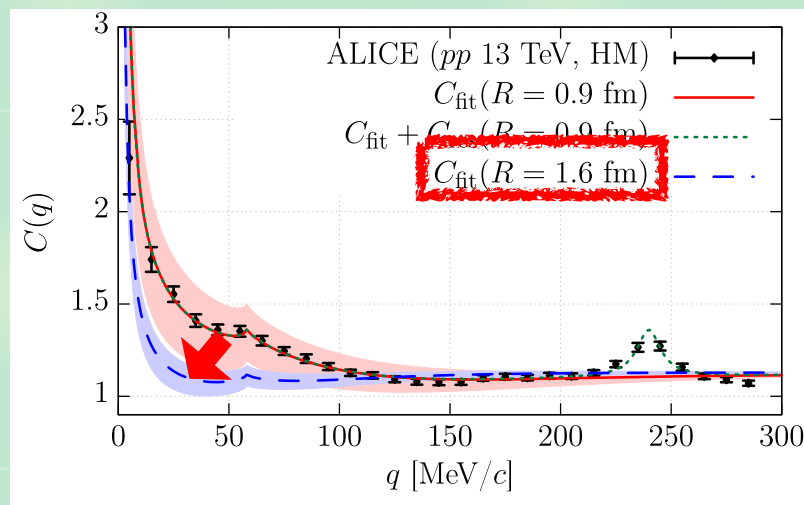
Correlation function and femtoscopy

K^-p correlation function $C(q)$

$$C(q) = \frac{N_{K^-p}(\mathbf{p}_{K^-}, \mathbf{p}_p)}{N_{K^-}(\mathbf{p}_{K^-})N_p(\mathbf{p}_p)} \simeq \int d^3\mathbf{r} S(\mathbf{r}) |\Psi_q^{(-)}(\mathbf{r})|^2$$



- Wave function $\Psi_q^{(-)}(\mathbf{r})$: Kyoto $\bar{K}N-\pi\Sigma-\pi\Lambda$ potential



S. Acharya *et al.* (ALICE), PRL 124, 092301 (2020)

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)

S. Acharya *et al.* (ALICE), PLB 822, 136708 (2021)

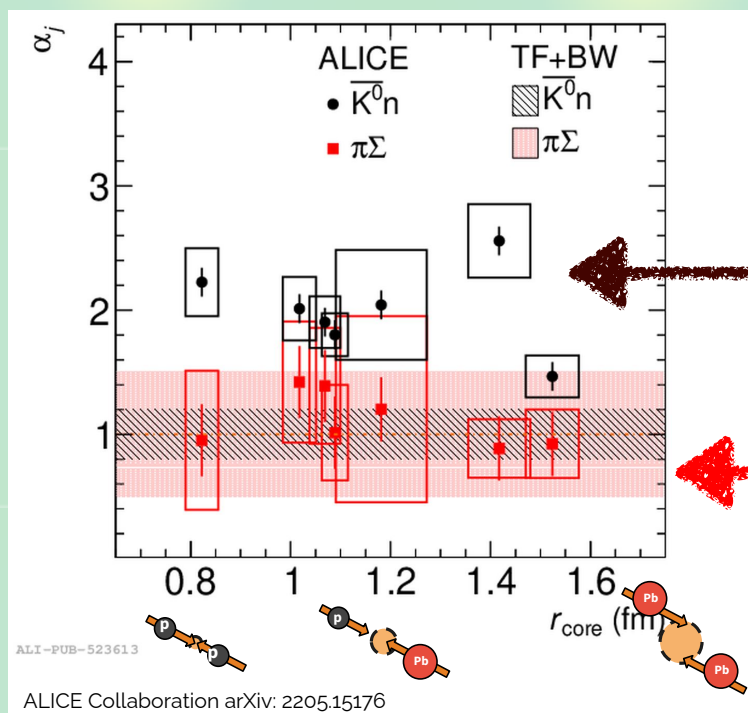
Correlation functions are well reproduced and predicted

Systematic study of source size dependence

Correlations in pp , p -Pb, Pb-Pb by Kyoto $\bar{K}N$ - $\pi\Sigma$ - $\pi\Lambda$ potential

S. Acharya et al. (ALICE), arXiv:2205.15176 [nucl-ex]

$$C_{K^-p}(\mathbf{q}) \simeq \int d^3\mathbf{r} S_{K^-p}(\mathbf{r}) |\Psi_{K^-p,q}^{(-)}(\mathbf{r})|^2 + \sum_{i \neq K^-p} \omega_i \int d^3\mathbf{r} S_i(\mathbf{r}) |\Psi_{i,q}^{(-)}(\mathbf{r})|^2$$



enhancement needed to explain data

Expected weight ω_i by Thermal Fist + Blast Wave

More strength is needed in the \bar{K}^0n channel

Contents



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Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)



Applications to few-body systems

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- Kaonic deuterium

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Summary and prospect

T. Hyodo, M. Niiyama, Prog. Part. Nucl. Phys. 120, 103868 (2021);

T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)

$\bar{K}NN$ system : simplest \bar{K} -nucleus

Theoretical calculation with **realistic $\bar{K}N$ interaction**

- Fit to K^-p cross sections and branching ratios
- **SIDDHARTA constraint of kaonic hydrogen**

[1] J. Revai, N.V. Shevchenko, PRC 90, 034004 (2014)

[2] S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, PRC95, 065202 (2017)

Potential	$\Lambda(1405)$ [MeV]	$\Lambda(1380)$ [MeV]	$B_{\bar{K}NN}$ [MeV]	$\Gamma_{\bar{K}NN \rightarrow \pi YN}$ [MeV]
$V_{\bar{K}N-\pi\Sigma}^{1,SIDD}$	1426 - 48 <i>i</i> [3]	-	53.3 [1]	64.8 [1]
$V_{\bar{K}N-\pi\Sigma}^{2,SIDD}$	1414 - 58 <i>i</i> [3]	1386 - 104 <i>i</i> [3]	47.4 [1]	49.8 [1]
$V_{\bar{K}N-\pi\Sigma-\pi\Lambda}^{chiral}$	1417 - 33 <i>i</i> [4]	1406 - 89 <i>i</i> [4]	32.2 [1]	48.6 [1]
Kyoto $\bar{K}N$	1424 - 26 <i>i</i> [5]	1381 - 81 <i>i</i> [5]	25.3-27.9 [2]	30.9-59.4 [2]

[3] N.V. Shevchenko, NPA 890-891, 50 (2012)

[4] N.V. Shevchenko, J. Revai, PRC 90, 034003 (2014)

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

- **Caution: $2N$ absorption (Γ_{YN}) is **NOT** included!!**

Kaonic nuclei

Rigorous few-body approach up to $A = 6$ systems

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, PRC95, 065202 (2017)

- Stochastic variational method with correlated gaussians

$$\hat{V} = \hat{V}^{\bar{K}N}(\text{Kyoto } \bar{K}N) + \hat{V}^{NN}(\text{AV4}') \quad (\text{single channel})$$

Results for kaonic nuclei with $A = 2, 3, 4, 6$

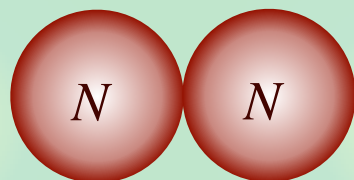
	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNN$
$I(J^P)$	$1/2(0^-)$	$0(1/2^-)$	$1/2(0^-)$	$1/2(0^-, 1^-)$
B [MeV]	25.3-27.9	45.3-49.7	67.9-75.5	69.8-80.7
$\Gamma_{\text{mes.}}$ [MeV]	30.9-59.4	25.5-69.4	28.0-74.5	23.7-75.6

- for $A = 6$ system, 0^- and 1^- are almost degenerated
- **quasi-bound** state below the lowest threshold
- decay width (**without multi- N absorption**) \sim binding energy₁₃

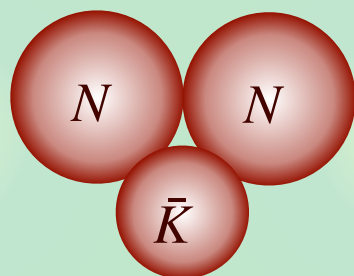
Interplay between NN and $\bar{K}N$ correlations 1

Two-nucleon system

$${}^1S_0(I_{NN} = 1)$$



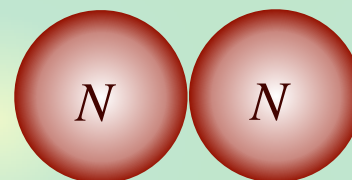
unbound



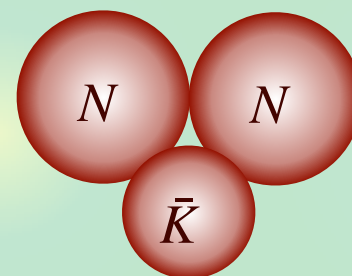
(quasi-)bound

$$\frac{\bar{K}N(I = 0)}{\bar{K}N(I = 1)} = 3$$

$${}^3S_1(I_{NN} = 0)$$



bound (d)



$\Lambda(1405)$

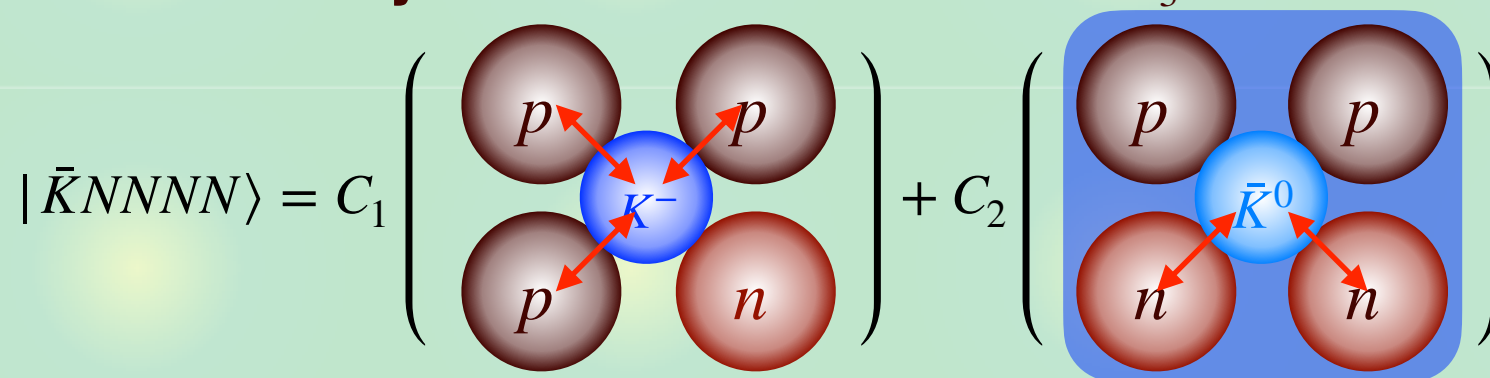
unbound

$$\frac{\bar{K}N(I = 0)}{\bar{K}N(I = 1)} = \frac{1}{3}$$

NN correlation $<$ $\bar{K}N$ correlation

Interplay between NN and $\bar{K}N$ correlations 2

Four-nucleon system with $J^P = 0^-, I = 1/2, I_3 = +1/2$



- $\bar{K}N$ correlation

$I = 0$ pair in K^-p (3 pairs) or \bar{K}^0n (2 pairs) : $|C_1|^2 > |C_2|^2$

- NN correlation

$ppnn$ forms α : $|C_1|^2 < |C_2|^2$

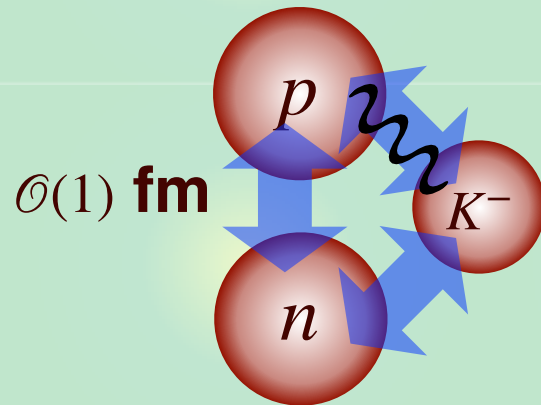
- Numerical result

$$|C_1|^2 = 0.08, \quad |C_2|^2 = 0.92$$

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

Kaonic deuterium

K^-pn system with **strong** + Coulomb interaction



Potential	$\Delta E - i\Gamma/2$ [eV]
$V_{\bar{K}N-\pi\Sigma}^{1,\text{SIDD}}$	$767 - 464i$ [1]
$V_{\bar{K}N-\pi\Sigma}^{2,\text{SIDD}}$	$782 - 469i$ [1]
$V_{\bar{K}N-\pi\Sigma-\pi\Lambda}^{\text{chiral}}$	$835 - 502i$ [1]
Kyoto $\bar{K}N$	$670 - 508i$ [2]

Theoretical requirements :

- **Rigorous** three-body treatment of strong + Coulomb
- Inclusion of SIDDHARTRA constraint (**realistic** $\bar{K}N$)

[1] J. Revai, PRC 94, 054001 (2016)

[2] T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)

- Experiments : J-PARC E57, SIDDHARTA-2

$I = 1$ dependence**Study sensitivity to $I = 1$ interaction**

- introduce parameter β to control potential strength

$$\text{Re } \hat{V}^{\bar{K}N(I=1)} \rightarrow \beta \times \text{Re } \hat{V}^{\bar{K}N(I=1)}$$

Vary β within SIDDHARTA uncertainty of K^-p

- allowed region : $-0.17 < \beta < 1.08$

(negative β may contradict with scattering data)

β	K^-p		K^-d	
	ΔE	Γ	ΔE	Γ
1.08	287	648	676	1020
1.00	283	607	670	1016
-0.17	310	430	506	980

~ 170 eV deviation

- Planned precision: 60 eV (30 eV) at J-PARC (SIDDHARTA-2)

Measurement of K^-d will provide **strong constraint** on $I = 1$

Summary



Experimental data constrain pole structure of the $\Lambda(1405)$ region : “ $\Lambda(1405)$ ” \rightarrow $\Lambda(1405) + \Lambda(1380)$

$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****



$\bar{K}N$ potentials are useful to calculate kaonic nuclei and kaonic deuterium

Potential	$\Lambda(1405)$ [MeV]	$\Lambda(1380)$ [MeV]	$B_{\bar{K}NN}$ [MeV]	$\Gamma_{\bar{K}NN \rightarrow \pi YN}$ [MeV]	$\Delta E - i\Gamma/2$ [eV]
$V_{\bar{K}N-\pi\Sigma}^{1,SIDD}$	$1426 - 48i$	-	53.3	64.8	$767 - 464i$
$V_{\bar{K}N-\pi\Sigma}^{2,SIDD}$	$1414 - 58i$	$1386 - 104i$	47.4	49.8	$782 - 469i$
$V_{\bar{K}N-\pi\Sigma-\pi\Lambda}^{chiral}$	$1417 - 33i$	$1406 - 89i$	32.2	48.6	$835 - 502i$
Kyoto $\bar{K}N$	$1424 - 26i$	$1381 - 81i$	25.3-27.9	30.9-59.4	$670 - 508i$

T. Hyodo, M. Niyama, Prog. Part. Nucl. Phys. 120, 103868 (2021);

T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)

Future directions



$\bar{K}N$ system

- Determination of $\Lambda(1380)$
- $\pi\Sigma$ scattering length, correlation functions,...
- $l=1$ $\bar{K}N$ interaction \leftarrow kaonic deuterium



$\bar{K}NN$, kaonic nuclei

- Evaluation of $2N$ absorption decay
- Reaction study : spectrum \leftrightarrow eigenstate
- Quantum numbers $I(J^P)$ of $\bar{K}NN$
- Internal structure : $\bar{K}NN$? Λ^*N ? others?