Theory of (few-body) kaon-nuclear systems

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Clusters & Hierarchies

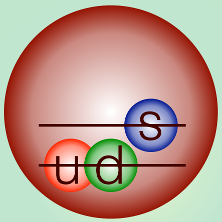
2022, Oct. 3rd

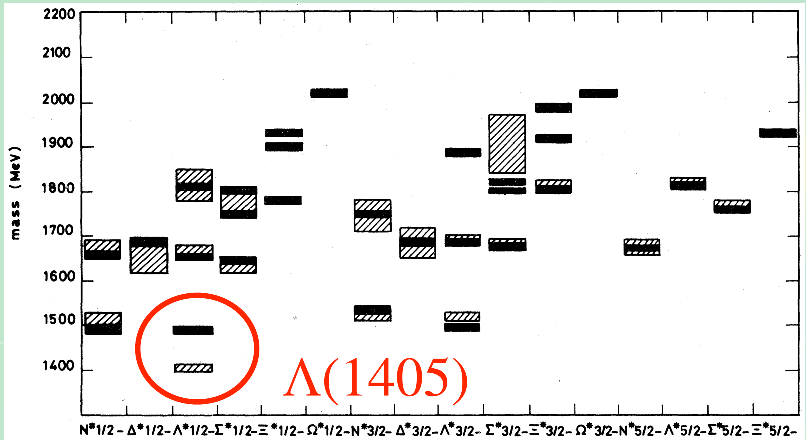
Contents

Λ(1405) and $\bar{K}N$ scattering

Λ(1405) does not fit in standard picture —> exotic candidate

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



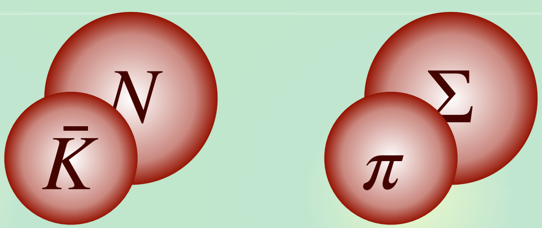


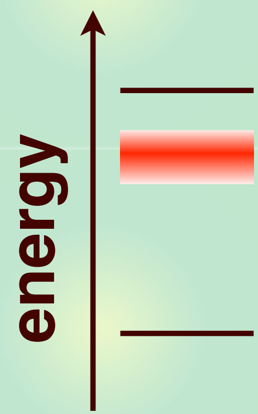
: theory

: experiment

Resonance in coupled-channel scattering

- Coupling to MB states





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

Strategy for $\bar{K}N$ interaction

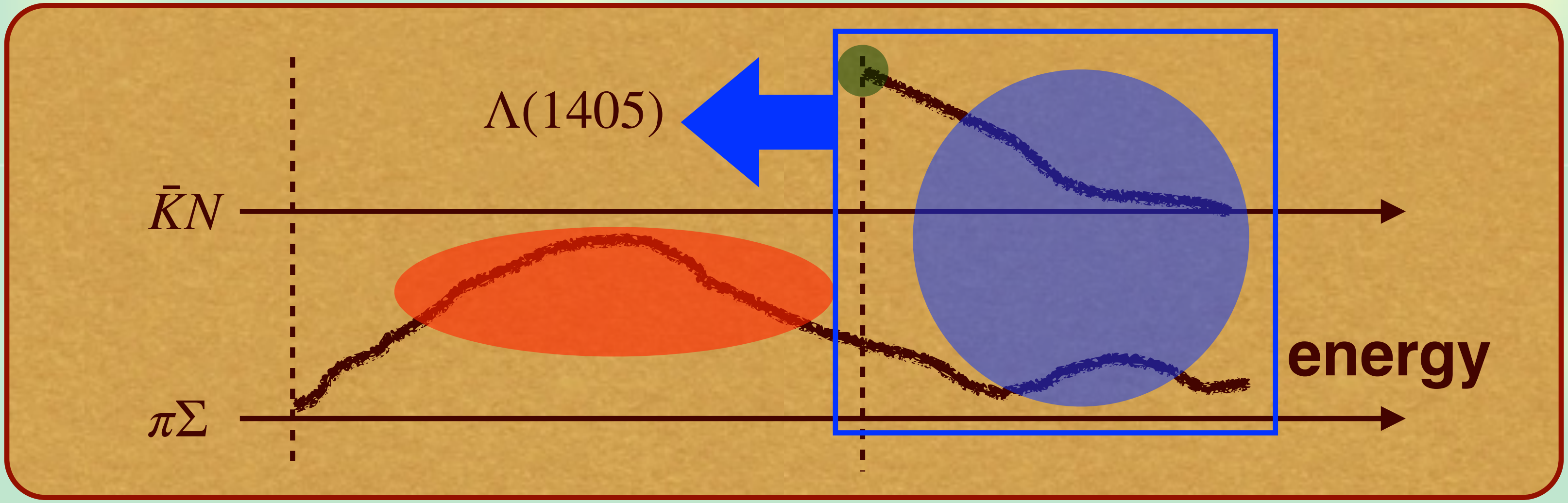
Above the $\bar{K}N$ threshold : direct constraints

- $K^- p$ **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, ...)**



Best-fit results

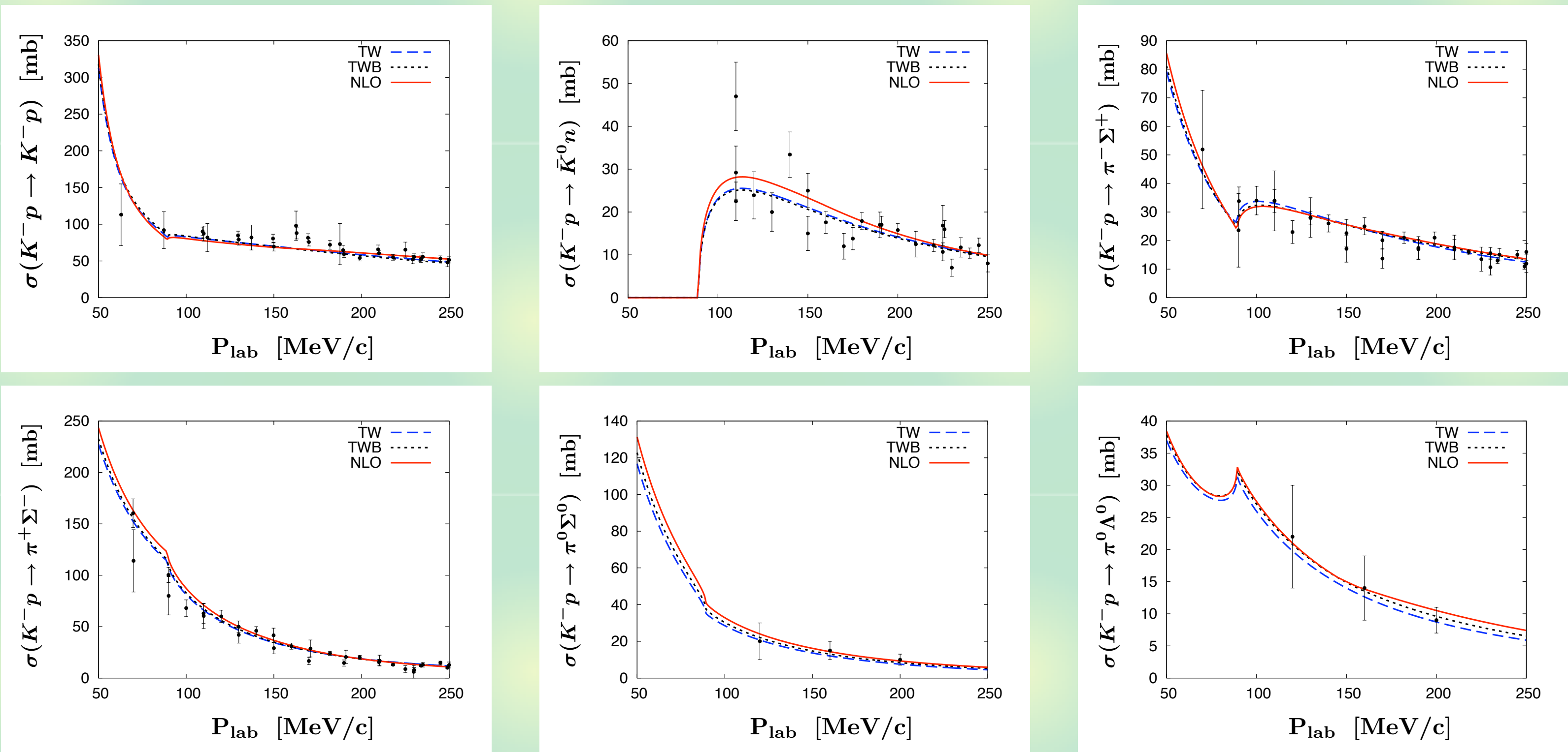
K at rest

	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]
χ^2/d.o.f	1.12	1.15	0.96		

} **SIDDHARTA** (ΔE, Γ)

} **Branching ratios** (γ, R_n, R_c)

$K^- p$ cross sections



Accurate description of all existing data (χ^2/d.o.f ~ 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) ■ ○

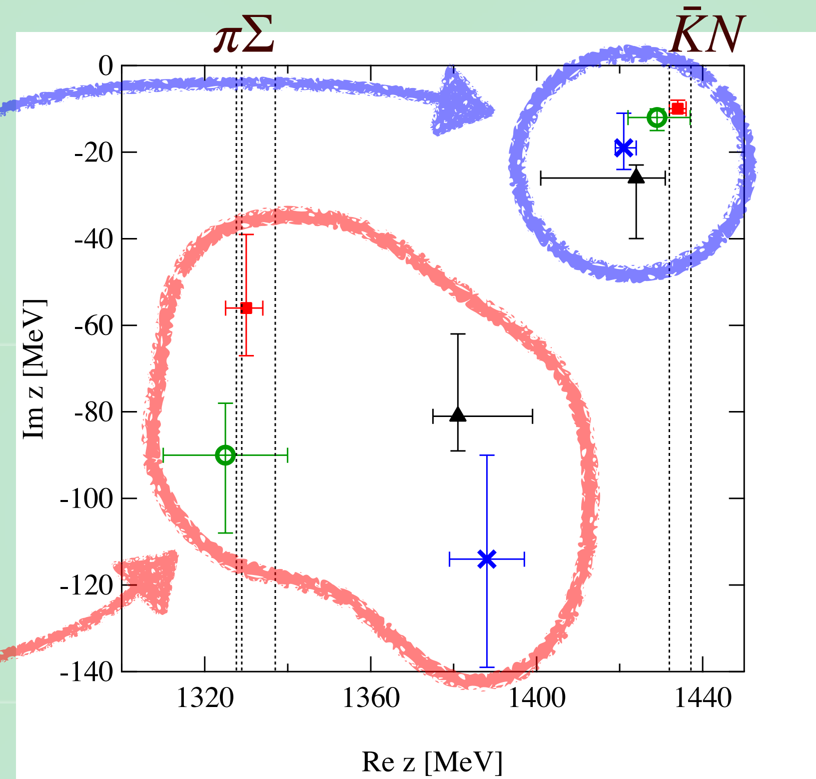
- **Particle Listing section:**

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)

$\Lambda(1380)\ 1/2^-$ **new!** $J^P = \frac{1}{2}^-$ Status: ∗∗



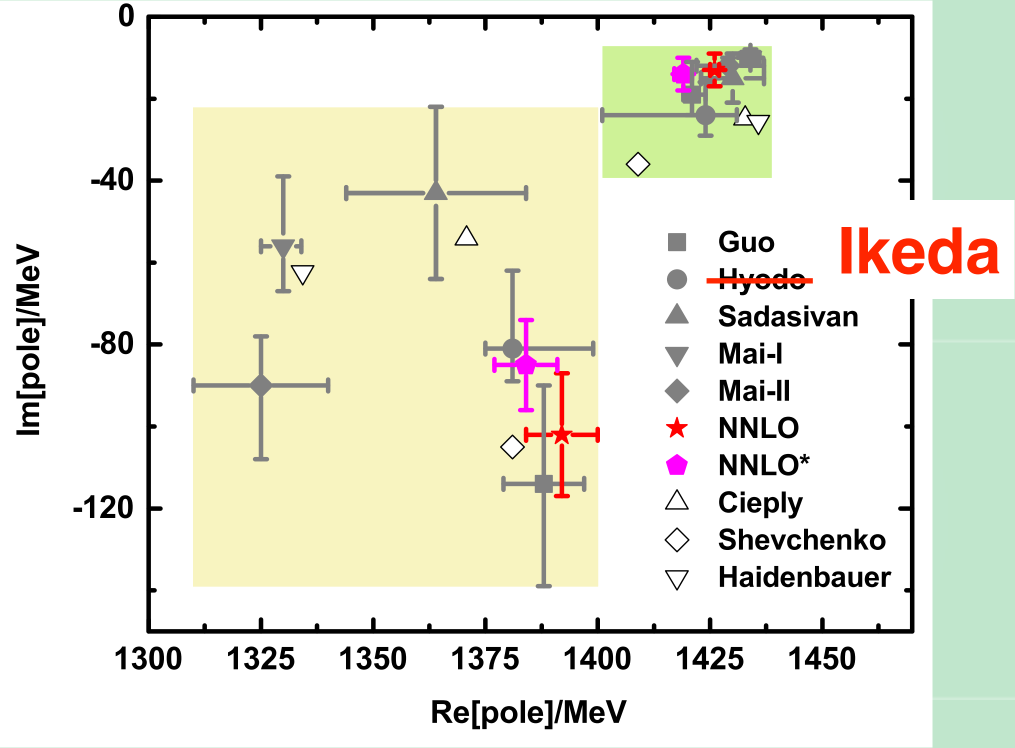
T. Hyodo, M. Niiyama, Prog. Part. Nucl. Phys. 120, 103868 (2021)

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

NNLO analysis

New analysis at NNLO! (KN and πN included)

J.-X. Lu, L.S. Geng, M. Doering, M. Mai, arXiv:2209.02471 [hep-ph]



	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

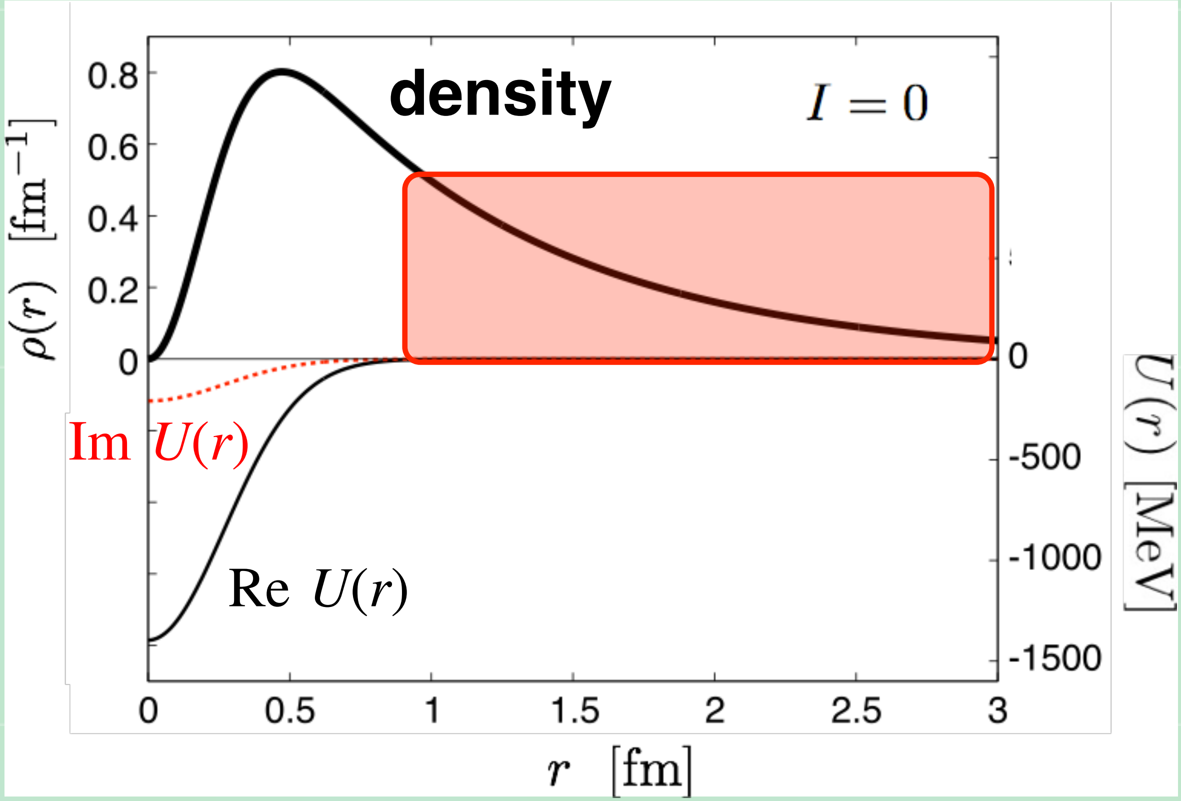
Kaonic deuterium

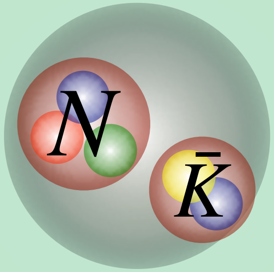
$K^{-}p$ correlation function

Spatial structure of $\Lambda(1405)$

$\bar{K}N$ wave function at $\Lambda(1405)$ pole

K. Miyahara. T. Hyodo, PRC93, 015201 (2016)





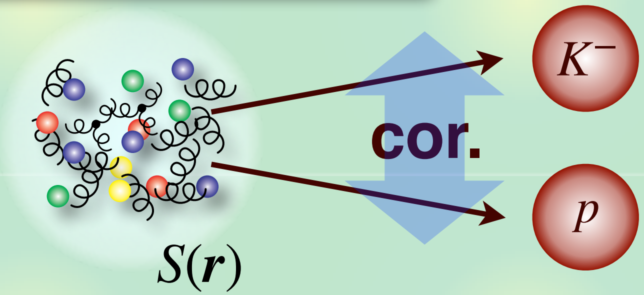
- substantial distribution at $r > 1$ fm
- root mean squared radius $\sqrt{\langle r^2 \rangle} = 1.44$ fm

The size of $\Lambda(1405)$ is much larger than ordinary hadrons

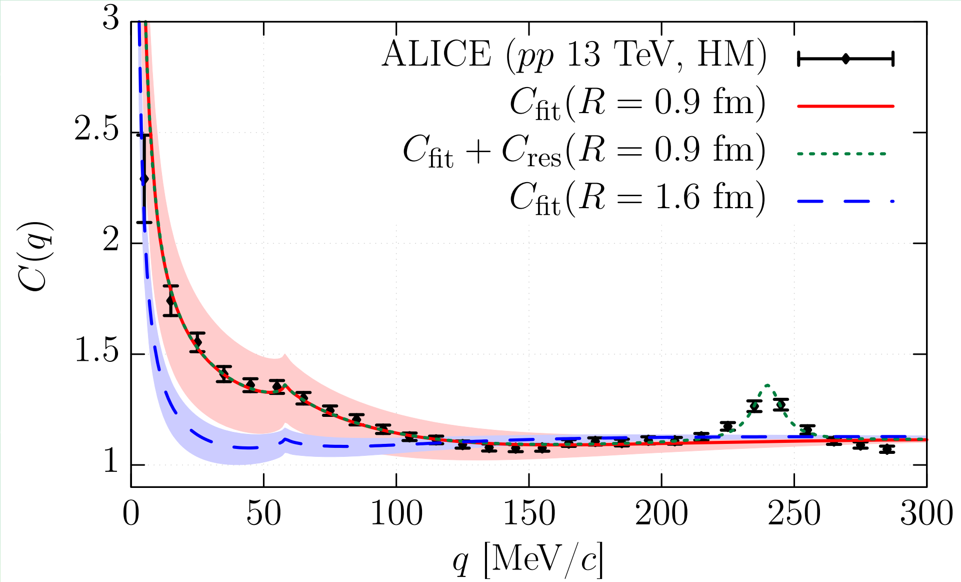
Correlation function and femtoscopy

K^-p **correlation function** $C(\boldsymbol{q})$

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



- Wave function $\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})$ **: coupled-channel** $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ **potential**



—> Talks by R. Lea and Y. Kamiya tomorrow

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

Correlation function is well reproduced

Contents

$\Lambda(1405)$ 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

T. Hyodo, M. Niiyama, Prog. Part. Nucl. Phys. 120, 103868 (2021);
T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th]

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

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

- Fit to K^-p cross sections and branching ratios
- SIDDHARTRA 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]	$\Gamma_{\bar{K}NN\to\pi YN}$ [MeV]
$V^{1,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$1426-48i$ [3]	-	53.3 [1]	64.8 [1]
$V^{2,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$1414-58i$ [3]	$1386-104i$ [3]	47.4 [1]	49.8 [1]
$V^{\mathrm{chiral}}_{\bar{K}N\text{-}\pi\Sigma\text{-}\pi\Lambda}$	$1417-33i$ [4]	$1406-89i$ [4]	32.2 [1]	48.6 [1]
Kyoto $\bar{K}N$	$1424-26i$ [5]	$1381-81i$ [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

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

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

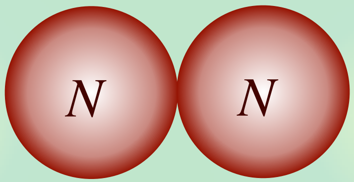
	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNNN$
$I(J^P)$	$1/2(0^-)$	$0(1/2^-)$	$1/2(0^-)$	$1/2(0^-, 1^-)$
B [MeV]	25.3-27.9	45.3-49.7	67.9-75.5	69.8-80.7
$\Gamma_{\text{mes.}}$ [MeV]	30.9-59.4	25.5-69.4	28.0-74.5	23.7-75.6

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

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

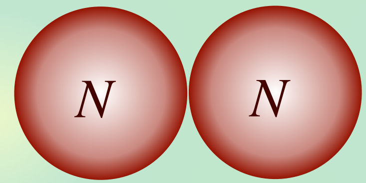
Two-nucleon system

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

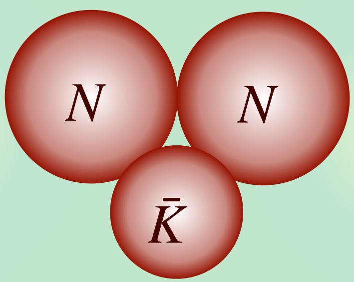


unbound

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

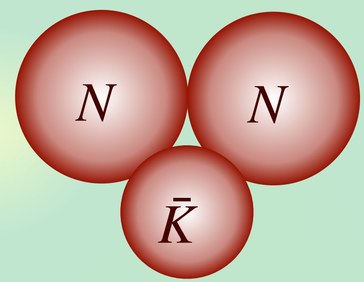


bound (d)



(quasi-)bound

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



$\Lambda(1405)$

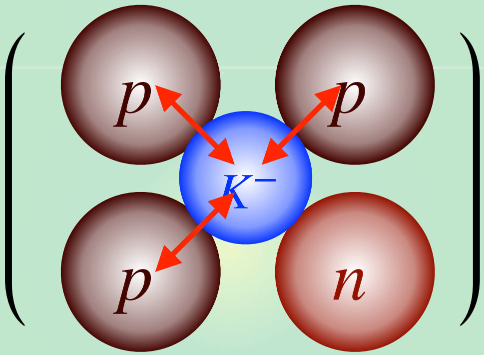
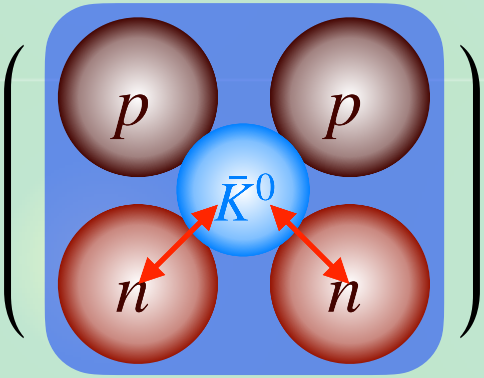
unbound

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

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

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

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

$|\bar{K}NNNN\rangle = C_1$  $+ C_2$ 

- **$\bar{K}N$ correlation**

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

- **NN correlation**

  $ppnn$ **forms** α **:** $|C_1|^2 < |C_2|^2$

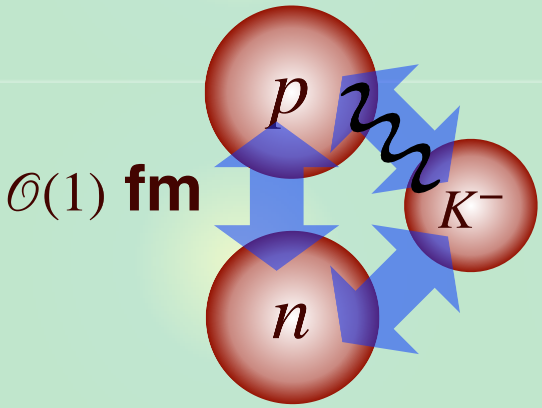
- **Numerical result**

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

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

Kaonic deuterium

K^-pn system with strong + Coulomb interaction



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

Summary

- Experimental data constrain pole structure of the $\Lambda(1405)$ region : "$\Lambda(1405)$" —> $\Lambda(1405)$ + $\Lambda(1380)$

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

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

Potential	$\Lambda(1405)$ [MeV]	$\Lambda(1380)$ [MeV]	$B_{\bar{K}NN}$ [MeV]	$\Gamma_{\bar{K}NN\to\pi YN}$ [MeV]	$\Delta E - i\Gamma/2$ [eV]
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