Kaonic deuterium from realistic antikaon-nucleon interaction

Tetsuo Hyodo

Yukawa Institute for Theoretical Physics, Kyoto Univ.

2018, Jun. 7th

Contents

- $\bar{K}N$ interaction and potential

  - Analysis with chiral SU(3) dynamics

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

  - Realistic $\bar{K}N$ potentials

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

    K. Miyahara, T. Hyodo, W. Weise, arXiv:1804.08269 [nucl-th]

- Application to kaonic deuterium

  - Prediction of shift and width

  - Sensitivity to $I=1$ component

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

$\bar{K}$ meson and $\bar{K}N$ interaction

Two aspects of $K(\bar{K})$ meson

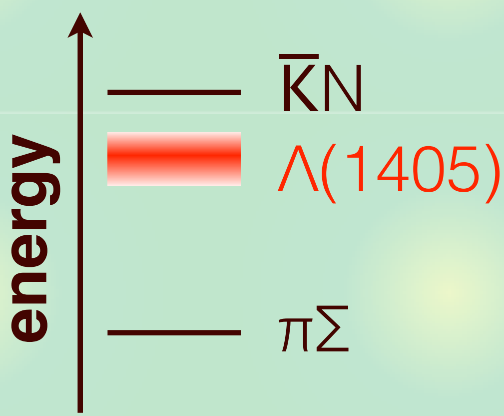
- **NG boson** of chiral $SU(3)_R \otimes SU(3)_L$ —> $SU(3)_V$
- **Massive** by strange quark: $m_K \sim 496$ MeV

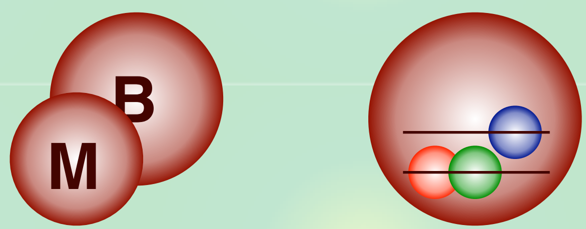
—> **Spontaneous**/**explicit** symmetry breaking

$\bar{K}N$ interaction ...

T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

- is coupled with $\pi\Sigma$ channel
- generates $\Lambda(1405)$ below threshold





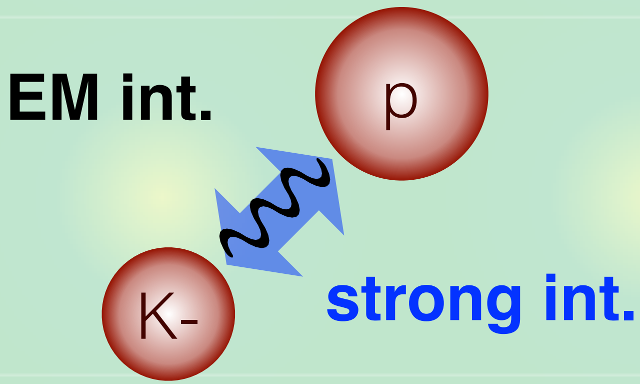
molecule three-quark

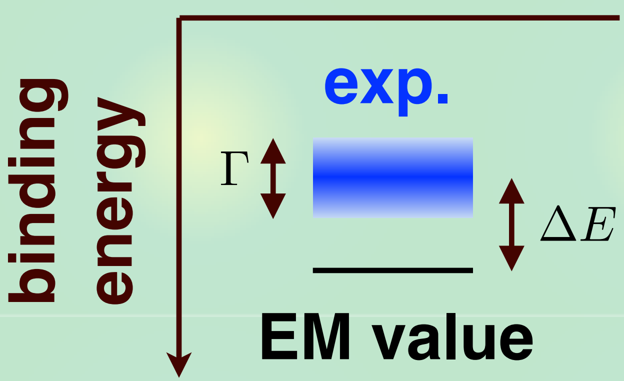
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$-atoms, ...

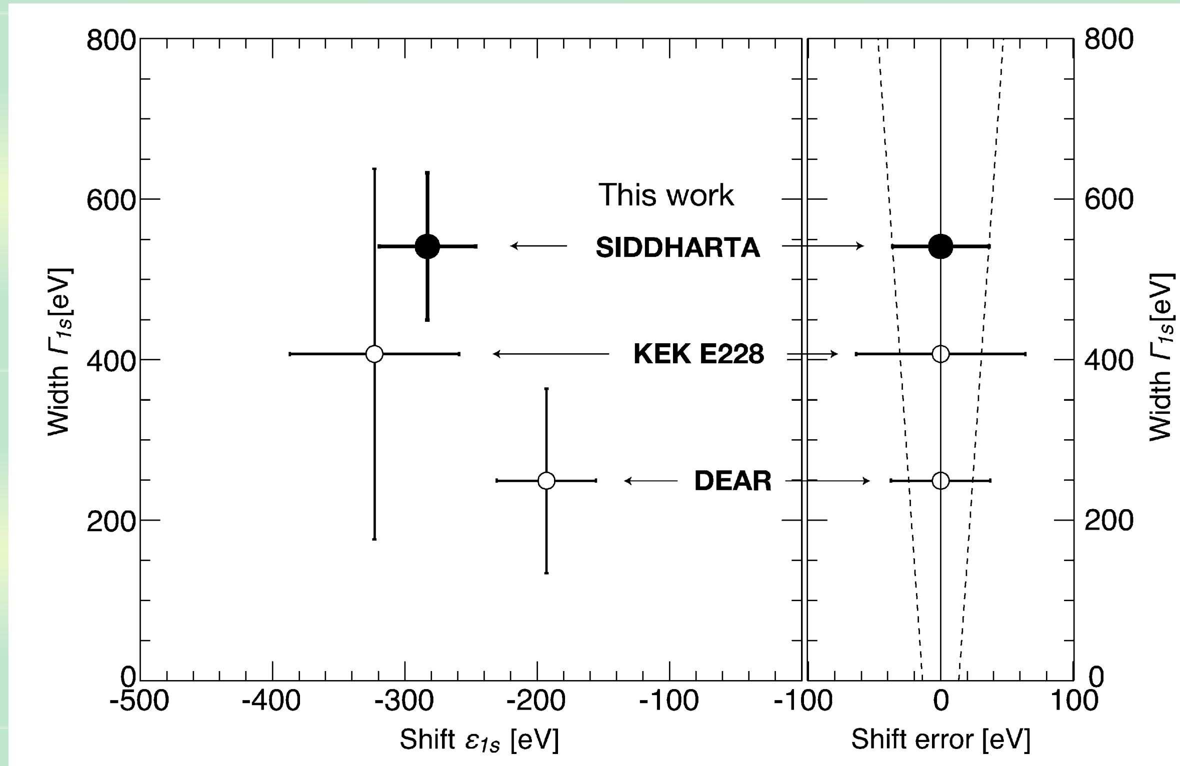
SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011); Nucl. Phys. A881, 88 (2012)







- Shift and width of atomic state <—> K-p scattering length

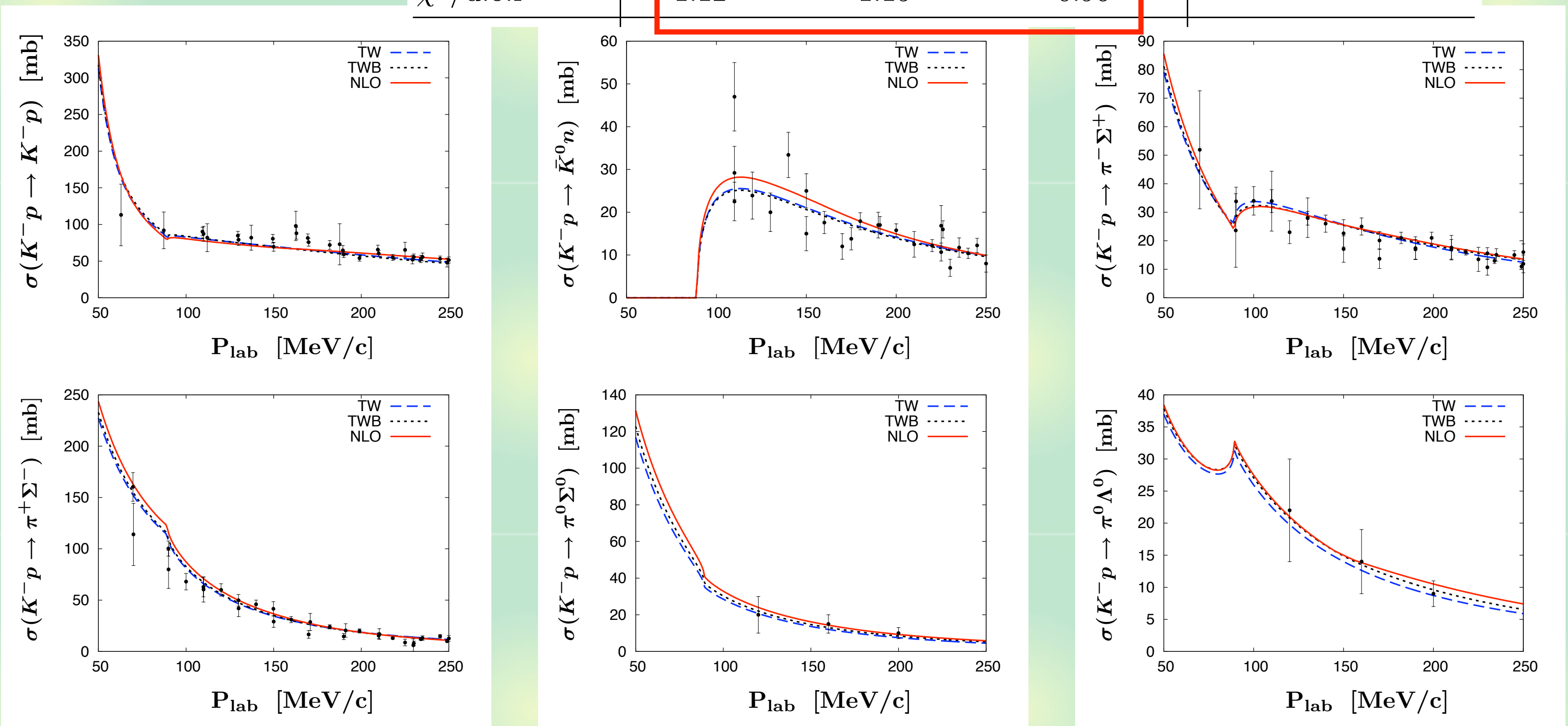
U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)

Quantitative constraint on the $\bar{K}N$ interaction at fixed energy

Best-fit results of chiral SU(3) dynamics

		TW	TWB	NLO	Experiment	
SIDDHARTA	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
Branching ratios	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		

cross sections

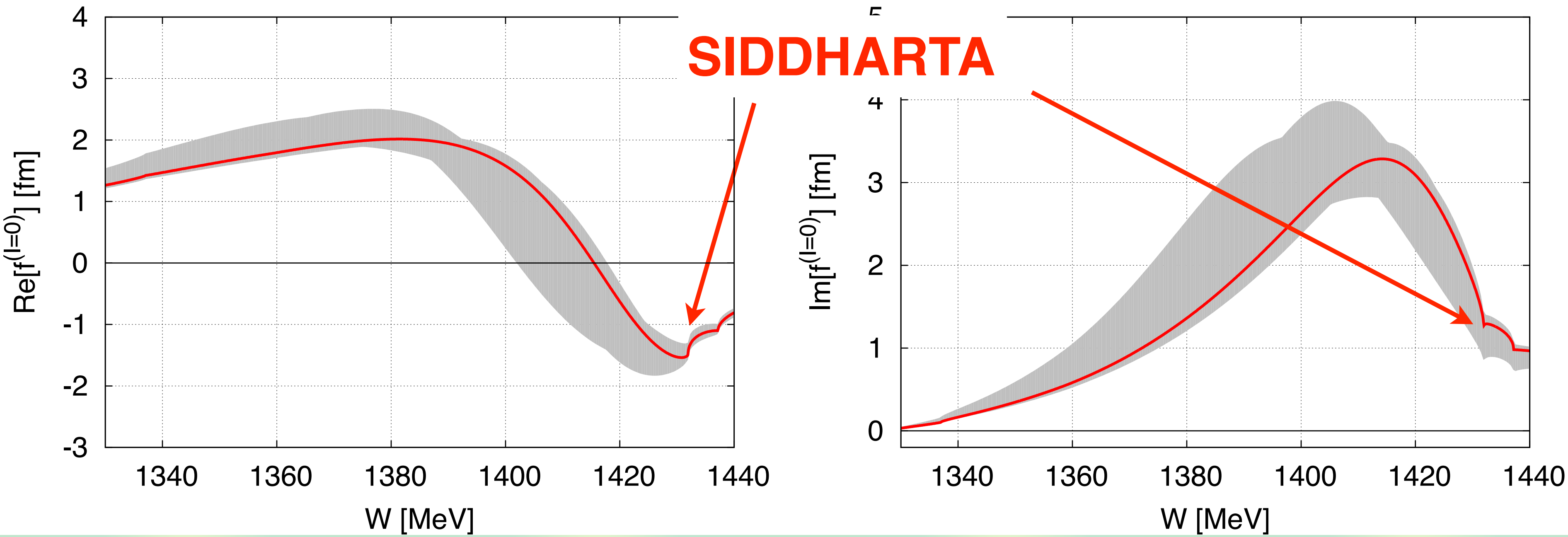


Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

Accurate description of all existing data (χ^2/d.o.f. ~ 1)

Subthreshold extrapolation

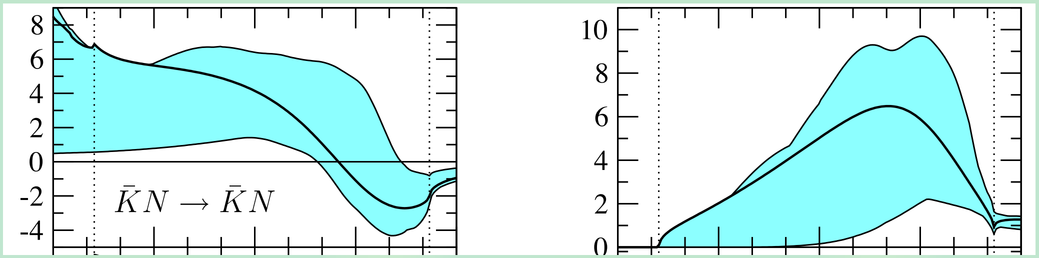
Uncertainty of $\bar{K}N \longrightarrow \bar{K}N$ (I=0) amplitude below threshold



Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise, Nucl. Phys. A954, 41 (2016)

- c.f. without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)

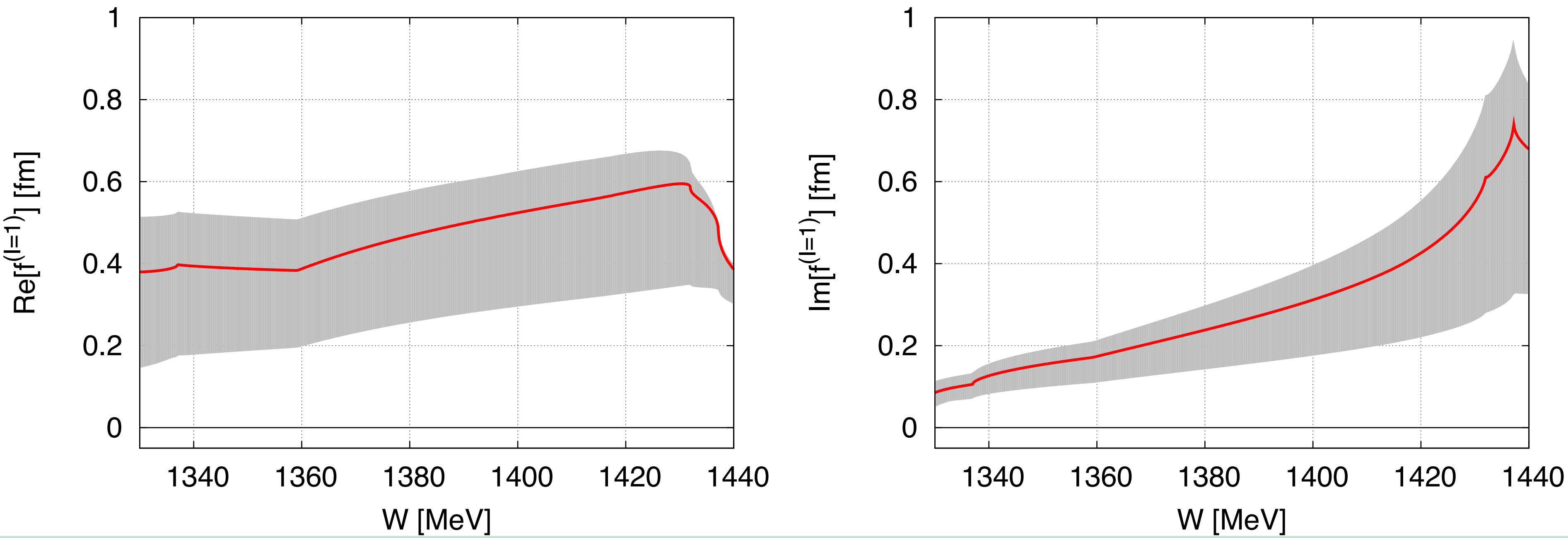


Accurate data is essential to reduce theoretical uncertainty.

Remaining ambiguity

$\bar{K}N$ interaction has two isospin components (I=0, I=1).

$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \ldots, \quad a(K^-n) = a(I=1) + \ldots$$



Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise, Nucl. Phys. A954, 41(2016)

Relatively large uncertainty in I=1 sector

- More constraints required (<— kaonic deuterium?)

PDG changes

PDG particle listing of Λ(1405)

M. Tanabashi, *et al.*, Phys. Rev. D98, 030001 (2018), http://pdg.lbl.gov/

2014

Λ(1405) 1/2⁻ $I(J^P) = 0(\frac{1}{2}^-)$ Status:

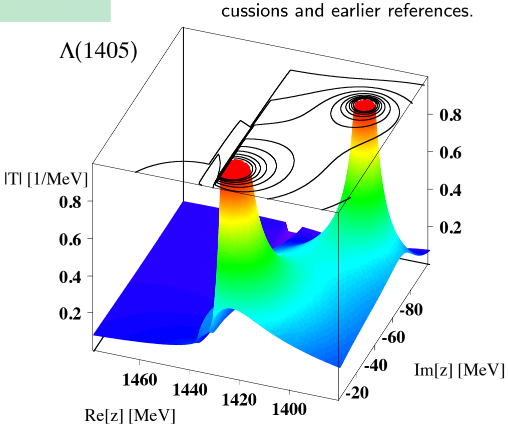
The nature of the Λ(1405) has been a puzzle for decades: t... quark state or hybrid; two poles or one. We cannot here survey the rather extensive literature. See, for example, CIEPLY 10, KISSLINGER 11, SEKIHARA 11, and SHEVCHENKO 12A for discussions and earlier references.

...of the chiral-unitary community ...400-MeV region. ZYCHOR 08 ...inst the two-pole model, but this ...REVAI 09, which finds little basis ...wo-pole models; and IKEDA 12,

...1405) fits nicely into a J^P = ...her members are the $\Lambda_c(2595)^+$, ...Fig. 1 of our note on "Charmed

MASS

... TECN COMMENT



105. Pole Structure of the Λ(1405) Region

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The Λ(1405) resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and

2018

Λ(1405) 1/2⁻ $I(J^P) = 0(\frac{1}{2}^-)$ S

In the 1998 Note on the Λ(1405) in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the N-$\bar{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the Σ(1385), has no such threshold distortion because its N-$\bar{K}$ coupling is P-wave. For Λ(1405) this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the Λ(1405). The experiment produced the Λ(1405) spin-polarized in the photoproduction process $\gamma p \to K^+ \Lambda(1405)$ and measured the decay of the Λ(1405)(polarized) $\to \Sigma^+$(polarized)π^-. The observed isotropic decay of Λ(1405) is consistent with spin $J = 1/2$. The polarization transfer to the Σ^+(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

See the related review(s):
Pole Structure of the Λ(1405) Region

Λ(1405) REGION POLE POSITIONS

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1429^{+8}_{-7}	[1] MAI	15	DPWA
1325^{+15}_{-15}	[2] MAI	15	DPWA
1434^{+2}_{-2}	[3] MAI	15	DPWA
1330^{+4}_{-5}	[4] MAI	15	DPWA
1421^{+3}_{-2}	[5] GUO	13	DPWA
1388^{+9}	[6] GUO	13	DPWA
1424^{+7}_{-23}	[7] IKEDA	12	DPWA
1381^{+18}_{-6}	[8] IKEDA	12	DPWA

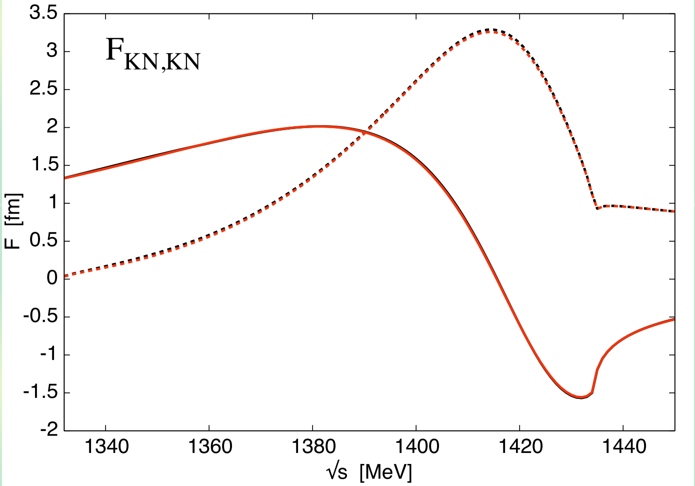
- **Our analysis** (+ 2 other groups) included
- **Pole positions** are now tabulated, prior to mass/width.

Construction of $\bar{K}N$ potential

Accurate scattering amplitude is now available.

- local $\bar{K}N$ potential in Schrödinger eq.

—> device to be used in few-body calculations



Construction of equivalent potential

- single-channel $\bar{K}N$ potential

K. Miyahara. T. Hyodo, Phys. Rev. C93, 015201 (2016)

- coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

K. Miyahara, T. Hyodo, W. Weise, arXiv:1804.08269 [nucl-th]

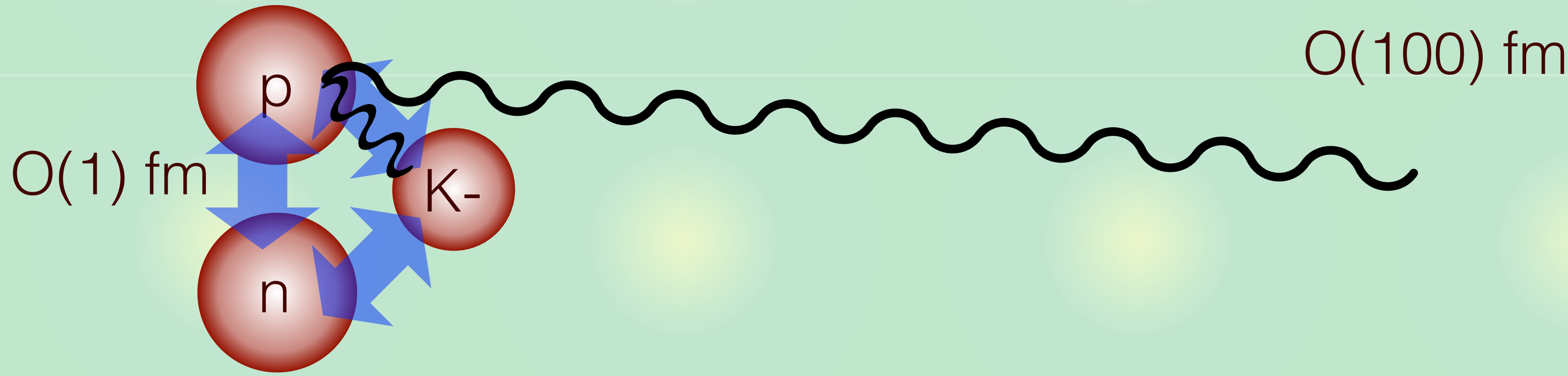
- original (black) v.s. potential (red)

These potentials accurately reproduces data (χ^2/d.o.f. ~ 1)

—> realistic $\bar{K}N$ potential

Kaonic deuterium: background

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



- Experiments are planned at J-PARC E57, SIDDHARTA-2

Theoretical requirements:

- Rigorous three-body treatment of strong + Coulomb

- Inclusion of SIDDHARTRA constraint (realistic $\bar{K}N$**)**

- c.f. advanced Faddeev calculations

P. Doleschall, J. Revai, N.V. Shevchenko, Phys. Lett. B 744, 105 (2015);
J. Revai, Phys. Rev. C 94, 054001 (2016)

Check of kaonic hydrogen

Kaonic hydrogen (K-p) in the present setup?

- **Deser-type formula is based on (systematic) expansion.**
- $\bar{\mathrm{K}}$N **potential is formulated with isospin symmetry.**

Two-body calculation with physical masses

$$\begin{pmatrix} \hat{T} + \hat{V}^{\bar{K}N} + \hat{V}^{\mathrm{EM}} & \hat{V}^{\bar{K}N} \\ \hat{V}^{\bar{K}N} & \hat{T} + \hat{V}^{\bar{K}N} + \Delta m \end{pmatrix} \begin{pmatrix} |K^- p\rangle \\ |\bar{K}^0 n\rangle \end{pmatrix} = E \begin{pmatrix} |K^- p\rangle \\ |\bar{K}^0 n\rangle \end{pmatrix}$$

Result:

- **consistent with SIDDHARTA constraint**
- **Ressumed Deser-type formula works reasonably for** K-p.

Mass	E dependence	ΔE (eV)	Γ (eV)
Physical	Self-consistent	283	607
Isospin	Self-consistent	163	574
Physical	$E_{\bar{K}N} = 0$	283	607
Expt. [31,32]		$283 \pm 36 \pm 6$	$541 \pm 89 \pm 22$

	ΔE (eV)	Γ (eV)
Full Schrödinger equation	283	607
Improved Deser formula (18)	293	596
Resummed formula (19)	284	605

Formulation

Three-body calculation of K-d with physical masses

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

$$\begin{pmatrix} \hat{H}_{K^-pn} & \hat{V}_{12}^{\bar{K}N} + \hat{V}_{13}^{\bar{K}N} \\ \hat{V}_{12}^{\bar{K}N} + \hat{V}_{13}^{\bar{K}N} & \hat{H}_{\bar{K}^0nn} \end{pmatrix} \begin{pmatrix} |K^-pn\rangle \\ |\bar{K}^0nn\rangle \end{pmatrix} = E \begin{pmatrix} |K^-pn\rangle \\ |\bar{K}^0nn\rangle \end{pmatrix}$$

$$\hat{H}_{K^-pn} = \sum_{i=1}^{3} \hat{T}_i - \hat{T}_{\rm cm} + \hat{V}_{23}^{NN} + \sum_{i=2}^{3} (\hat{V}_{1i}^{\bar{K}N} + \underline{\hat{V}_{1i}^{\rm EM}})$$ **Coulomb**

$$\hat{H}_{\bar{K}^0nn} = \sum_{i=1}^{3} \hat{T}_i - \hat{T}_{\rm cm} + \hat{V}_{23}^{NN} + \sum_{i=2}^{3} \hat{V}_{1i}^{\bar{K}N} + \underline{\Delta M}$$ **threshold difference**

- **(single-channel) realistic $\bar{\rm K}$N potential**

K. Miyahara. T. Hyodo, Phys. Rev. C93, 015201 (2016)

Few-body technique

- **stochastic variational method + correlated gaussian basis**

Y. Suzuki, K. Varga, Lect. Notes Phys. M54, (1998)

Kaonic deuterium: shift and width

Results of the three-body calculation

- energy convergence

<— large number of basis

N	Re[E] (MeV)
1677	−2.211689436
2194	−2.211722964
2377	−2.211732072
2511	−2.211735493
2621	−2.211737242
2721	−2.211737609
2806	−2.211737677
2879	−2.211737682

keV eV!

Shift-width of the 1S state:

$$\Delta E - i\Gamma/2 = (670 - i508)\ \mathrm{eV}$$

- No shift in 2P state is shown by explicit calculation.
- Deser-type formula does not work accurately for K-d

c.f.) J. Revai, Phys. Rev. C 94, 054001 (2016)

	ΔE (eV)	Γ (eV)
Full Schrödinger equation	670	1016
Improved Deser formula (18)	910	989
Resummed formula (19)	818	1188

I=1 dependence

Study sensitivity to I=1 **interaction**

- introduce parameter β **to control the potential strength**

$$\mathrm{Re}\ \hat{V}^{\bar{K}N(I=1)}(r) \rightarrow \beta[\mathrm{Re}\ \hat{V}^{\bar{K}N(I=1)}(r)]$$

Vary β **within SIDDHARTA uncertainty of** K-p

- allowed region: -0.17< β < 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

- deviation of ΔE **of** K-d **~ 170 eV**

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

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

Summary: Λ(1405)

- **Realistic $\bar{K}N$ potentials (χ^2/d.o.f. ~ 1) based on NLO chiral SU(3) dynamics are now available, thanks to precise kaonic hydrogen data.**

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
K. Miyahara. T. Hyodo, PRC93, 015201 (2016)
K. Miyahara, T. Hyodo, W. Weise, arXiv:1804.08269 [nucl-th]

- **We study kaonic dueterium as**
  - **Prediction of shift and width**

$$\Delta E - i\Gamma/2 = (670 - i508)\ \text{eV}$$

  - **sensitive to I=1 component**

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