Updated experimental insight into the ŊN interaction.

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KbarN interaction: building block of non-perturbative regime of QCD

**KN and KbarN strong interactions are very different**
The presence of the strange quark has dramatic consequences
- Strong attractiveness in KbarN gives rise to bound states

Sub-threshold: \(\Lambda(1405)\) is an “old object” not fitting in the standard 3-quark picture
- Molecular state with two poles KbarN-\(\Sigma\pi\)
- Strong coupled channel dynamics
Theoretical framework

Theoretical approaches:
• meson exchange
• phenomenological
• chiral SU(3) dynamical
• Lattice QCD
Theoretical framework

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Data is crucial to test (+feed) this approaches.
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- meson exchange
- phenomenological
- **chiral SU(3) dynamical**
- Lattice QCD

Data is crucial to test (+feed) these approaches.

**Data fitting by chiral SU(3)**
- Going to NLO (N$^2$LO?), s+p waves ⇒ more parameters to be fixed (by data)
- Adding **new data** helps to improve the model
- Adding **more precise data** helps to improve the model
- Adding **data at different energies** helps to improve the model
Available experimental data

Lorentz-invariant formulation of chiral effective field theory (LO)

Ren, Epelbaum, Gegelia, Meißner, EPJC (2021)

Extension to higher energies (LO+NLO):

Feijoo, Magas, Ramos, PRC 2019
Bruns, Cieplý, NPA 2022

and higher partial waves:

Feijoo, Gazda, Magas, Ramos, Symmetry 2021

A. Ramos @ QNP2022
Available experimental data

- B and Γ of kaonic nuclear states
- Single vs Multi-nucleonic absorption rates
- K-pp three body femtoscopy

Antikaonic atoms

- SIDDHARTA constraint on $a_0^{K-p}$

Scattering data

- $\sigma_{K^-p \rightarrow K^-p}$
- $\sigma_{K^-p \rightarrow \bar{K}^0n}$

Femtoscopy

- $\Lambda(1405)$ mass shape in different channels
- Threshold branching ratios
- Scattering amplitudes below threshold

image courtesy of Y. Kamiya
Available experimental data

- **Antikaonic atoms**
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- **Scattering data**
  - $\sigma_{K^-p\rightarrow K^-p}$
  - $\sigma_{K^-p\rightarrow K^0n}$

- **Femtoscopy**
  - $\Lambda(1405)$ mass shape in different channels
  - Threshold branching ratios
  - $K^-p$ correlation

- **B and $\Gamma$ of kaonic nuclear states**
- **Single vs Multi-nucleonic absorption rates**
- **K-pp three body femtoscopy**

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*Image courtesy of Y. Kamiya*
Measurement of the **shift**($\epsilon$) and **width**($\Gamma$) induced by the **strong interaction** in the lowest level atomic transition.

Translated via Desser-type Formula into a $K^-p$ scattering length that is an average of the KbarN scattering lengths for $I=0$ and $I=1$

$$\epsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst}) \text{ eV}$$

$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst}) \text{ eV},$$

$$\epsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu_c^2 a_p (1 - 2\alpha \mu_c (\ln \alpha - 1) a_p)$$

$$a_{K^-p} = \frac{a_0 (I = 0) + a_1 (I = 1)}{2}$$
KbarN Femtoscopy with ALICE

Nucleus-Nucleus (pp, Pb-Pb) collisions at the LHC recorded by ALICE

![Diagram showing proton-proton collision and kaon production](https://www.nature.com/articles/d41586-020-03393-z)

M. Lorenz https://www.nature.com/articles/d41586-020-03393-z
Observable: **Correlation function of two final-state particles**

\[
C(k^*) = \frac{\xi(k^*)}{N_{\text{mixed}}(k^*)} \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}
\]
Femtoscopy: Theoretical correlation function

\[
C(k^*) = \int d^3 r^* S(r^*) |\psi(k^*, r^*)|^2
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Femtoscopy: Theoretical correlation function

\[ C(k^*) = \int d^3r^* S(r^*) |\psi(k^*, r^*)|^2 \]

theory

source wave function

The overlap of the kaon wavefunction with the nucleon delivers insight into the effects of the strong interaction, competing with Coulomb effects.
SIDDHARTA: antiKaonic Hydrogen

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* for antikaonic hydrogen
the K- p distance is ~100 times the Bohr radius

Sensitive to near surface potential shape

Small collision systems $r \sim 1$ fm
⇒ effect of the interaction is enhanced

$$C(k^*) = \int S(r^*) \left| \Psi(k^*, \vec{r}^*) \right|^2 d^3r^*$$
KbarN at threshold and low momentum

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**ALICE: \( K^- p \) femtoscopy**

Gaussian Source Function (\( r_G = 1.25 \text{ fm} \))

Typical short-range nuclear potential

Deliver different observables ⇔ scattering lengths can be obtained from both
(via approximations: Deser-type and Lednický–Lyuboshitz formulae)
K⁻p Femtoscopy with ALICE in pp collisions

Small systems: pp collisions $r \sim 1$ fm

⇒ Provides a quantitative test of coupled channels in the theory

Strong interaction: Kyoto model
K⁻p Femtoscopy with ALICE in pp collisions

**Small systems**: pp collisions $r \sim 1$fm

⇒ Provides a **quantitative test of coupled channels in the theory**

**Effects of coupled channels** enhanced by small source
- less important for large sources of HIC

Strong interaction: Kyoto model
Large systems (HIC): Pb-Pb collisions, up to $r \sim 9$ fm

Strength of coupled channels significantly reduced

- Kyoto model
- Fit to the scattering parameters  
  

\[ R_{kp} = 5.2 \pm 0.11 \text{(stat)} ^{+0.19}_{-0.52} \text{(syst)} \text{ fm} \]
**K^−p Femtoscopy with ALICE in Pb-Pb collisions**

**Large systems (HIC):** Pb-Pb collisions, up to $r \sim 9$ fm

- Strength of coupled channels significantly reduced
  - Kyoto model
  - Fit to the scattering parameters

⇒ Antikaonic-hydrogen and K-p femtoscopy scattering parameters compatible
Upcoming: Accessing KbarN I=1 interaction

**Full isospin dependence** needs K^−d interaction measurements:

\[ a_{K^−d} = \frac{1}{2} \left( \frac{m_N + m_K}{m_N + m_N} \right) \left( 3a_1 + a_0 \right) + C \]
Upcoming: Accessing KbarN $I=1$ interaction

**Full isospin dependence** needs $K^-d$ interaction measurements:

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**SIDDHARTA-2** with new experimental setup
→ measurement of antikaonic deuterium
→ very challenging! low yield of signal
→ Complete upgrade of SIDDHARTA setup
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Beam tuning April – May 2022, He measurement

➢ Deuterium measurement started begin of June 2022 at DAΦNE
Accessing KbarN I=1 interaction with ALICE

Access to I=1 KbarN interaction via femtoscopy

\[ C_{K_S^0p} = \frac{1}{2} \left( C_{\bar{K}^0p} + C_{K^0p} \right) \]

\[ |K_S^0p\rangle = \left( |\bar{K}^0p\rangle - |K^0p\rangle \right)/\sqrt{2} \]

- \( \bar{K}N, I = 1 \)
- \( KN, I = 0, 1 \)

- \( I = 1 \) component only
- Well determined with scat. exp.

On the horizon: \( K^0d \) femtoscopy

Femtoscopy with deuterons (K\(^+\)d, pd) by ALICE in small systems and by STAR in HIC [H. Zbroszczyk @ HYP2022]
Kaonic nuclei
AMADEUS: $K^-$ absorption in $^4$He and $^{12}$C

Multi-nucleon absorption processes dominate

$K^- + A \rightarrow Yp + A'$

AMADEUS Coll. PLB 758 (2016) 134
AMADEUS Coll. PLB 782 (2018) 339
Below threshold (-33 MeV)  
$K^- n \to \Lambda \pi^-$ amplitude, non resonant $I=1$

$|A_{K^- n \to \Lambda \pi^-}| = (0.334 \pm 0.018 \text{ stat}^{+0.034}_{-0.058 \text{ syst}}) \text{ fm}$.

Above threshold  
$K^- p \to \Lambda \pi^0, \Sigma^0 \pi^0$ cross sections (preliminary)

- $\sigma_{K^- p \to \Sigma^0 \pi^0} = 42.8 \pm 1.5 (\text{stat.})^{+2.4}_{-2.0} (\text{syst.}) \text{ mb}$
- $\sigma_{K^- p \to \Lambda \pi^0} = 31.0 \pm 0.5 (\text{stat.})^{+1.2}_{-1.2} (\text{syst.}) \text{ mb}$

th. calculation  
Y. Ikeda, T. Hyodo, W. Weise,  
In-flight $^3\text{He}(K^-,n)\Lambda p$ reaction @ 1.0 GeV/c

\[ B_K = 42 \pm 3\text{(stat.)}^{+3}_{-4}\text{(syst.)} \text{ MeV} \]
\[ \Gamma_K = 100 \pm 7\text{(stat.)}^{+19}_{-9}\text{(syst.)} \text{ MeV} \]
3-Body femtoscopy by ALICE

\[ Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2} \]

ALICE Preliminary

pp $\sqrt{s} = 13$ TeV

High Mult. (0-0.17% INEL)

$(p-pK^-) \oplus (\bar{p}-\bar{K}^+)$

ALI-PREL-513597
Isolation of the three-body effects in the correlation function:

\[
c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2
\]

2-body correlations experimentally determined

Genuine three-body correlations (cumulant)

Measured triplets

Lower-order correlations

ppK\(^{-}\) cumulant

⇒ ppK\(^{-}\) cumulant is compatible with zero.
ppK\(^-\) cumulant

⇒ ppK\(^-\) cumulant is compatible with zero.

⇒ Suggest that three-body effects are not relevant for the description of the K\(^-\)pp system.

In p-p-p correlations significant 3-body effect (pauli blocking? FSI?)
⇒ relevant for the description of the K-NNN system?
We are collecting new data (e.g. ALICE run 3 with x500 stats and improved tracking, SIDDHARTA-2 running)

In the near future:
- new experimental apparatus
- new facilities

In the KbarN field a boost similar to the precise measurement of antikaonic hydrogen is expected

…still on the search for a description of the KbarN interaction that can accommodate all the data from above to below threshold