Experimental Studies of kaonic atoms

Precise investigation of the strong interaction with strangeness at low energies

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Stefan Meyer Institute, Vienna

ICNFP, Crete, July 2014
SIDDHARTA collaboration

Silicon Drift Detector for Hadronic Atom Research by Timing Applications

LNF - INFN, Frascati, Italy
SMI - ÖAW, Vienna, Austria
IFIN – HH, Bucharest, Romania
Politecnico, Milano, Italy
MPE, Garching, Germany
PNSensors, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada

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Network WP9 – LEANNIS – FP7- I3HP2
Austrian Science Fund

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Content

• Exotic atoms as probes for fundamental interactions
• Results of KH, K$^3,4$He experiments
• Open issues: K$^-$D measurement, high resolution experiments
• Experimental challenges (yield, background)
• Target and Instrumentation
• Summary and Outlook
What is a exotic (kaonic) atom?

“normal” hydrogen

```
K^-
```

```
n=1
```

```
\text{p}
```

```
e^-
```

“exotic” (kaonic) hydrogen

```
K^-
```

```
n=2
```

```
n=1
```

```
K^-\text{X-ray}
```

```
2p \rightarrow 1s
```

```
K_\alpha \text{ transition}
```

```
n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e
```

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Exotic atoms

- Studies of fundamental interactions and symmetries with exotic atomic bound systems

Hadronic atoms are sensitive probes for the strong interaction at lowest energy (direct study of strong interaction at threshold)
Cascade in hadronic atoms (KH,KD)

Atomic capture in high n state → subsequent e.m. cascade

shift and width of states n > 1 are negligible

Kα ~ 6.3 keV

ε₁s = E₂p-1s (meas.) - E₂p-1s (e.m.)

Probing strong interaction at threshold

due to the strong interaction kaon-proton the 1s level is shifted and broadened
Kaonic hydrogen and deuterium

• Principal interaction = electromagnetic

• Strong interaction manifests in hadronic shift and width of the 1s state → **energy displacement** from the electromagnetic value of the 1s state and **broadening** due to $K^-$ absorption

\[ \mathcal{E}_{1s} = E_{1s}^{\text{meas.}} - E_{1s}^{\text{e.m. (calc.)}} \]

\[ E_{1s}^{\text{e.m. (calc.)}} = E_{KG} + E_{VP} + E_{FS} \]

• calculated solving the Klein-Gordon (KG) equation and taking into account vacuum polarization (VP) and final size (FS) effect (accuracy ~1eV).
• Strong interaction effect on 2p state is weak (meV) and experimentally undetermined, nevertheless has **severe consequences for the x-ray yield**.
Experiments on kaonic hydrogen

Older experiments used liquid targets which have the disadvantage of lower yields (Stark effect)

KpX, PRL1997
KEK (K beam)
Gas target
Si(Li) detectors

DEAR, PRL2005
DAFNE (e⁺ e⁻ collider)
Gas target
CCD detectors

SIDDHARTA, PLB 2011
DAFNE (e⁺ e⁻ collider)
Gas target
SDD detectors
Kaonic atoms at DAΦNE/Frascati
SIDDHARTA data overview
Beam pipe in $e^+e^-$ intersection of SIDDHARTA

SIDDHARTA used the KLOE intersection of DAFNE

Luminosity increased with new system providing a large crossing angle (crab waist system)

Kaon window

Kaon detectors sitting below and above the intersection
SIDDHARTA SDD Array
144 SDDs = 144 cm² active area
Background suppression in SIDDHARTA

Efficient background suppression by using the kaon - x-ray correlation.
Comparison kaonic $^3$He and $^4$He

$\Delta E_{2p} = -2 \pm 2(\text{sta}) \pm 4(\text{sys})$ eV

$\Delta E_{2p} = +5 \pm 3(\text{sta}) \pm 4(\text{sys})$ eV

K-$^3$He (3d-2p)

K-$^4$He (3d-2p)

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Kaonic helium results

<table>
<thead>
<tr>
<th></th>
<th>Shift [eV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK E570</td>
<td>+2±2±2</td>
<td>PLB653(2007)387</td>
</tr>
<tr>
<td>SIDDHARTA (He4 with 55Fe)</td>
<td>+0±6±2</td>
<td>PLB681(2009)310</td>
</tr>
<tr>
<td>SIDDHARTA (He4)</td>
<td>+5±3±4</td>
<td>arXiv:1010.4631,</td>
</tr>
<tr>
<td>SIDDHARTA (He3)</td>
<td>-2±2±4</td>
<td>PLB697(2011)199</td>
</tr>
</tbody>
</table>

➢ calibration under control within several eV

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Yields in kaonic helium atoms

- Study of the x-ray pattern in kaonic helium atoms (transitions to the 2p state)
- First determination of the absolute yields
- Indications of weak molecular Stark mixing
- Data are calling for improved cascade calculations

### L-series X-ray yields of kaonic $^3\text{He}$ targets

The SIDDHARTA Collaboration

<table>
<thead>
<tr>
<th>Transition</th>
<th>$^3\text{He}$ (0.96 g/l)</th>
<th>$^4\text{He}$ (1.65 g/l)</th>
<th>$^4\text{He}$ (2.15 g/l)</th>
<th>$^4\text{He}$ (Liquid) [1]</th>
<th>$^4\text{He}$ (Liquid) [3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L\alpha$</td>
<td>$25.0^{+6.7}_{-5.8}$</td>
<td>$23.1^{+6.0}_{-4.2}$</td>
<td>$17.2^{+2.6}_{-0.5}$</td>
<td>$9.2 \pm 2.4$</td>
<td>$8.9 \pm 4.5$</td>
</tr>
<tr>
<td>$L\beta$</td>
<td>$3.6^{+1.8}_{-0.7}$</td>
<td>$4.2 \pm 1.1$</td>
<td>$3.1^{+0.6}_{-1.0}$</td>
<td>$5.2 \pm 1.3$</td>
<td>$2.3 \pm 1.2$</td>
</tr>
<tr>
<td>$L\gamma$</td>
<td>$1.3^{+0.5}_{-0.4}$</td>
<td>$1.3 \pm 0.6$</td>
<td>$0.7^{+0.3}_{-0.8}$</td>
<td>$2.4 \pm 0.7$</td>
<td>$1.6 \pm 0.8$</td>
</tr>
<tr>
<td>$L_{\text{high}}$</td>
<td>$5.2 \pm 2.1$</td>
<td>$6.9^{+2.9}_{-1.9}$</td>
<td>$4.1^{+1.1}_{-2.1}$</td>
<td>–</td>
<td>$0.4 \pm 0.3^*$</td>
</tr>
</tbody>
</table>

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K-p result SIDDHARTA

\[ \varepsilon_{1S} = -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \]

\[ \Gamma_{1S} = 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV} \]

Physics Letters B704 (2011) 113
Kaonic atoms with deuterium gas (SIDDHARTA)

fit for shift about 500 eV, width about 1000eV, $K\alpha / K_{\text{complex}} = 0.4$

First exploratory $K\cdot d$ x-ray experiment
Upper limits (90 C.L.) for the x-ray yield (SIDDHARTA)

\[ Y (K_{\text{tot}}) < 0.0143 \]
\[ Y (K\alpha) < 0.0039 \]
Results of SIDDHARTA

**Kaonic Hydrogen:** 400 pb$^{-1}$, most precise measurement, Physics Letters B704 (2011) 113

**Kaonic deuterium:** 100 pb$^{-1}$, exploratory first measurement ever, Nucl. Phys. A907 (2013) 69


- **Kaonic helium 3:** 10 pb$^{-1}$, first measurement, published in Phys. Lett. B 697 (2011) 199
Sources of experimental information on $K_{\text{bar}}N$ interaction

K-p scattering data for threshold data extrapolation necessary

Threshold branching ratios

Kaonic atom data

<table>
<thead>
<tr>
<th>Kaonic hydrogen</th>
<th>Kaonic deuterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s state shift</td>
<td>1s state width</td>
</tr>
</tbody>
</table>

$\rightarrow$ x-ray spectroscopy

Threshold branching ratios

$\frac{\Gamma(K^-p \rightarrow \pi^+\Sigma^-)}{\Gamma(K^-p \rightarrow \pi^-\Sigma^+)}$

$\frac{\Gamma(K^-p \rightarrow \pi^+\Sigma^- , \pi^-\Sigma^+)}{\Gamma(K^-p \rightarrow \text{all inelastic channels})}$

$\frac{\Gamma(K^-p \rightarrow \pi^0\Lambda)}{\Gamma(K^-p \rightarrow \text{neutral states})}$

Constraints from precise kaonic hydrogen measurements $\rightarrow$ sub-threshold extrapolations of the KbarN amplitude with strongly reduced uncertainties
Chiral SU(3) theory of antikaon-nucleon interactions with improved threshold constraints

Fig. 4. Real part (left) and imaginary part (right) of the $K^- p \rightarrow K^- p$ forward scattering amplitude obtained from the NLO calculation and extrapolated to the subthreshold region. The empirical real and imaginary parts of the $K^- p$ scattering length deduced from the recent kaonic hydrogen measurement (SIDDHARTA [15]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.
Predictions

Real and imaginary part of the $K\cdot n \rightarrow K\cdot n$ forward scattering amplitude in the sub-threshold region

Imaginary part of the $I=0$ $K\bar{N}$ and $\Sigma\pi$ amplitudes

Error bands due to constraints by SIDDHARTA
Motivation for new experiments

• SIDDHARTA – K-p strong interaction observables
• SIDDHARTA – First exploratory experiment on K-D

But: No data on hadronic shift and width of 1s state of kaonic deuterium
→ still to be measured

➢ Study of K-n interaction: Isospin-dependent scattering lengths from KH and KD → K-p interaction at low energy is well understood, but the case of K-d represents the most important missing information

➢ High resolution studies of kaonic atoms (e.g. K-He, heavier kaonic atoms)
Modified Deser formula next-to-leading order in isospin breaking (Meißner, Raha, Rusetsky 2004 [3])
($\mu_c$ reduced mass of K-d, $\alpha$ finestructure constant )

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

<table>
<thead>
<tr>
<th>$a_d$ [fm]</th>
<th>$\epsilon_{1s}$ [eV]</th>
<th>$\Gamma_{1s}$ [eV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.58 + i 1.37</td>
<td>-887</td>
<td>757</td>
<td>Mizutani 2013 [4]</td>
</tr>
<tr>
<td>-1.48 + i 1.22</td>
<td>-787</td>
<td>1011</td>
<td>Shevchenko 2012 [5]</td>
</tr>
<tr>
<td>-1.46 + i 1.08</td>
<td>-779</td>
<td>650</td>
<td>Meißner 2011 [1]</td>
</tr>
<tr>
<td>-1.42 + i 1.09</td>
<td>-769</td>
<td>674</td>
<td>Gal 2007 [6]</td>
</tr>
<tr>
<td>-1.66 + i 1.28</td>
<td>-884</td>
<td>665</td>
<td>Meißner 2006 [7]</td>
</tr>
</tbody>
</table>

Expected shift and width

$\Rightarrow$

shift = -800 eV  
width = 800 eV

used in simulation
Isospin scattering lengths

• The isospin scattering lengths $a_0$ and $a_1$ for $I=0,1$ cannot be determined from $\varepsilon_{1s}$ and $\Gamma_{1s}$ from kaonic hydrogen.

• The (modified) Deser-type formula

\[ \varepsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu_c^2 a_p \left( 1 - 2\alpha \mu_c (\ln \alpha - 1) a_p \right) \]

\[ a_p = \frac{1}{2}(a_0 + a_1) \]

• Kaonic deuterium provides the lacking information

\[ a_n = a_1 \]

\[ a_{K-p} = \frac{1}{2} [a_0 + a_1] \]
\[ a_{K-n} = a_1 \]
\[ a_{K-d} = [a_0 + 3a_1]Q + C \]
\[ Q = \frac{[m_N + m_K]}{[2m_N + m_K]} \]
Goal of K-D experiment

- Measurement of the shift $\epsilon_{1s}$ and width (broadening) $\Gamma_{1s}$ of the ground state $1s$
- Since only the $1s$ state is measurably affected by strong interaction $\rightarrow$ measured K line energies compared to calculated e.m transition energies yield $\epsilon_{1s}$ and $\Gamma_{1s}$

<table>
<thead>
<tr>
<th>Transition</th>
<th>e.m. energy (keV) (calculated, without strong interaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KD (2-1)</td>
<td>7.808</td>
</tr>
<tr>
<td>KD (3-1)</td>
<td>9.255</td>
</tr>
<tr>
<td>KD (4-1)</td>
<td>9.765</td>
</tr>
<tr>
<td>KD (5-1)</td>
<td>9.994</td>
</tr>
<tr>
<td>KD (6-1)</td>
<td>10.119</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>KD (∞)</td>
<td>10.41</td>
</tr>
</tbody>
</table>
## Comparison KH-KD

<table>
<thead>
<tr>
<th></th>
<th>Kaonic hydrogen</th>
<th>Kaonic deuterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (Kα) estimates</td>
<td>3%</td>
<td>0.3% (depending on 2p state width)</td>
</tr>
<tr>
<td>Energy (Kα) e.m.</td>
<td>6.5 keV</td>
<td>7.8 keV</td>
</tr>
<tr>
<td>Shift (1s)</td>
<td>-283±36(stat)±6(syst)</td>
<td>-800 ? (estimate)</td>
</tr>
<tr>
<td>Width (1s)</td>
<td>541±89(stat)±22(syst)</td>
<td>800 ? (estimate)</td>
</tr>
</tbody>
</table>

**Graphs:**

- **KH:**
  - KEK-PS E228
  - DEAR
  - SIDDHARTA

- **KD:**
  - **????**

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X-ray yields in K-D


K-D experiments employing new instrumentation
From SIDDHARTA to SIDDHARTA2

Changes

- Factor 2 in density of deuterium gas
- Kaon trigger geometry and arrangement
- Discrimination $K^+/K^-$ by lifetime detector
- Active shielding of apparatus
- Higher timing resolution of SDDs by cooling

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Lightweight cryogenic target (used for KH)

working $T$ 22 K
working $P$ 1.5 bar

Alu-grid

Side wall:
Kapton 50 $\mu$m

Kaon entrance window:
Kapton 75 $\mu$m
Plans for SIDDHARTA2 at DAFNE

- new target design
- new SDD arrangement
- vacuum chamber
- more cooling power
- improved trigger scheme
- shielding and anti-coincidence (veto)
New x-ray detectors

- JFET integrated on the SDD
  - lowest total anode capacitance
  - limited JFET performances
  - sophisticated SDD+JFET technology

- external CUBE preamplifier (MOSFET input transistor)
  - larger total anode capacitance
  - better FET performances
  - standard SDD technology

Used in Siddharta

Proposed for kaonic deuterium measurement

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New SDDs for x-ray detection (FBK and Politecnico Milano)

Excellent active to total area 85% → Large solid angle

Very good energy resolution

Very good timing at low T

Test with Fe-55 source
Mn Kα 127 eV (FWHM)
SDD Characterization

• Extremely important for precision x-ray spectroscopy

  – Stability
    • Long term monitoring gain and offset
    • Stability under small temperature variations
    • Gain stability at different x-ray rates

  – Linearity
  – SDD time response at various temperatures
  – SDD operation at low temperatures
  – Radiation hardness
Kaonic deuterium with SIDDHARTA2 at DAFNE

Monte Carlo Simulation for KD in SIDDHARTA2:
Shift: -805 eV
Width: 750 eV
Yield (Kα)=0.001
Luminosity: 800 pb^{-1}

Precision from MC
Shift: 70 eV
Width 150 eV

M. Bazzi et al. (SIDDHARTA Coll.),

We expect to measure shift and width of kaonic deuterium with a similar relative precision like kaonic hydrogen.
Option: kaonic deuterium @ J-PARC

Proposal for J-PARC 50 GeV Proton Synchrotron

Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium at J-PARC

submitted on April 13, 2014

J-PARC K1.8BR spectrometer, for E15, E17

Proposal for J-PARC
Submitted and presented 2014
SIDDHARTA2 @ DAFNE

DAFNE – ideal for kaonic atoms

Kaon source ($\Phi$ decay in $K^-K^+$)

Low-energy kaons (127 MeV/c) ideal for stopping

No tracking

Kaonic deuterium @ J-PARC?

Kaon beam

Kaons at higher momentum (660-1000 MeV/c)

needs degrader

Tracking

With 10 pb$^{-1}$ per day

1.5 $10^7$ K- per day isotropically

2% per kaon pair stopping in gas

144 SDDs from SIDDHARTA

With 30 kW beam power

430 $10^7$ K- per day

0.03% per kaon pair stopping in gas (660 MeV/c)

340 SDDs
Cryogenic target and SDDs

target cell: $l = 160$ mm, $d = 65$ mm
target pressure max.: $0.35$ MPa
target temperature: $23 - 30$ K
SDD active area: $246$ cm$^2$
density: $5\%$ LHD
$(29K/0.35$ MPa$)$
Setup at J-PARC K1.8BR

CDH...cylindrical detector hodoscope
CDC...cylindrical drift chamber

main degrader

SDD and deuterium target

T0.......beam line counter
T1.......beam line counter
BLC....beam line chamber
Monte Carlo results Kd@J-PARC

signal to background ~ 1:4
precision: shift ~56 eV, width ~139 eV

signal: shift - 800 eV
width 750 eV
density: 5% (LHD)
detector area: 246 cm²

Kα yield: 0.1 %
yield ratio as in Kβ

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Outlook: New precision studies with new technologies

- Kaonic helium 2p state shift/width
- 2 level studies in kaonic atoms
Study of 2 transitions in the same kaonic atom for separating one-nucleon (1N) from multi-nucleon (mN) processes using micro-calorimeters

Rms radii of potentials are characteristic features:

<table>
<thead>
<tr>
<th></th>
<th>$r_m$</th>
<th>Re(full)</th>
<th>Re(1N)</th>
<th>Re(mN)</th>
<th>Im(full)</th>
<th>Im(1N)</th>
<th>Im(mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>3.72</td>
<td>3.34</td>
<td>3.82</td>
<td>2.86</td>
<td>3.73</td>
<td>4.46</td>
<td>3.12</td>
</tr>
<tr>
<td>Pb</td>
<td>5.56</td>
<td>5.21</td>
<td>5.71</td>
<td>4.78</td>
<td>5.46</td>
<td>6.23</td>
<td>5.00</td>
</tr>
</tbody>
</table>

(values in fm).

Radius difference 1N-mN real terms = 0.95 fm.

Radius difference 1N-mN imag. terms = 1.2-1.3 fm.

Further applications of microcalorimeters for precision x-ray studies:

- K-He-3,4 2p-shift/width
- Charged kaon mass

Feasibility of new experiments

Microcalorimeter detectors based on Transition Energy Sensors (TES) achieved 53 eV resolution for 100 keV X-rays for an array of 5 cm$^2$.

Resolution stays constant in the linear region (up to 400 keV).

To model less favorable conditions we adopted also increase of energy spread with $\sqrt{E_X}$.

Summary

• SIDDHARTA – important results on light kaonic atoms

• Strong impact for $K_{\bar{b}ar}N$ theory

• SIDDHARTA – first exploratory experiment on $K\cdot d$

• SIDDHARTA2 with improved apparatus aiming at a first extraction of 1s state shift and width in kaonic deuterium

• SIDDHARTA2 at DAFNE/J-PARC

• Close collaboration of experimentalists and theoreticians extremely important $\rightarrow$ LEANNIS (HadronPhysics3 in EU FP7)
Thank you