X-rays of light kaonic atoms: SIDDHARTA and future

Michael Cargnelli, Stefan Meyer Institute, Austrian Academy of Sciences, Vienna

On behalf of: The SIDDHARTA collaboration

2015 European Nuclear Physics Conference
Kaonic atoms X-rays

SIDDHARTA experiment at DAFNE: (.e+ e- collider tuned to the energy of the Φ resonance, Frascati)
Kaonic atoms X-rays

Goal: learn about antikaon-nucleon interaction at lowest energies

Technique: measure the shift and broadening of X-ray transition energies in light kaonic atoms.
The lowest states are measureably affected by the strong interaction between the kaon and the nucleus. $\varepsilon, \Gamma$ connect to theories in low energy QCD.
**Theory and experiment**

Kp, Kd, KHe bound electromagnetically, binding well known

Strong interaction (mediated by QCD) \( \rightarrow \) modifies binding
\( \rightarrow \) causes absorption

if ‘small perturbation’
\( \rightarrow \) energy shift and width can be related to T-matrix elements at threshold
(Deser type formulas)

Description of antikaon nucleon interaction: chiral effective field theory

ChEFT \( \rightarrow \) scattering data
\( \rightarrow \) atomic X ray data
\( \rightarrow \) energy, width of resonances

.. needs input from experimental data
.. aims at accommodating all experimental evidence

Test validity of the *description of the antikaon-nucleon interaction* at low energies
Scattering lengths

Deser-type relation \(^1\) connect the observables shift \(\epsilon_{1s}\) and width \(\Gamma_{1s}\) of transitions to the ground-state with the real and imaginary part of the scattering length \(a\) (\(\mu_c\) reduced mass of the K'd system, \(\alpha\) finestructure constant, similar relation for K'p):

\[
\epsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu_c^2 a_{K-d} (1 - 2\alpha \mu_c (\ln \alpha - 1) a_{K-d})
\]

\[\begin{align*}
    a_{K-p} &= \frac{1}{2} [a_0 + a_1] \\
    a_{K-n} &= a_1 \\
    a_{K-d} &= \frac{4[m_N + m_K]}{[2m_N + m_K]} Q + C \\
    Q &= \frac{1}{2} [a_{K-p} + a_{K-n}] = \frac{1}{4} [a_0 + 3a_1]
\end{align*}\]

\(a_{K-p}\) and \(a_{K-d}\) are linear combination of the KN isospin scattering lengths \(a_0\) and \(a_1\). To extract \(a_0\) and \(a_1\), both scattering lengths \(a_{K-p}\) and \(a_{K-d}\) are needed (contain different combination of \(a_0, a_1\))


next-to-leading order in isospin breaking

Note: sign-reversed definition of the shift
... „Double Annular Phi-factory for Nice Experiments“

at Laboratory Nazionali di Frascati dell'INFN
Experimental setup
SIDDHARTA 2009

Figure 1: A schematic view of the SIDDHARTA setup installed at the $e^+e^-$ interaction region of DAΦNE.
The small capacitance results in a large amplitude and a short rise time of the signal.

Compared to conventional photodiodes, SDDs can be operated at higher rates and have better energy resolution.

A lateral field makes the produced charge drift to the collecting anode, different from standard electronic devices:
- double sided structure
- not passivated
- large area chips
- arrangement of bond pads in the center

I3 Hadron Physics EU FP6 – Joint Research Activity: SIDDHARTA - in cooperation with LNF, MPG, PNSensor, Politecnico Milano, IFIN-HH.
## Data analysis

### Data aquisition:
- **energies** and detector numbers of X ray hits
- event id-number, time-tag

If a kaon trigger happened:
- the **time correlation** between X-ray and kaon
- the kaon detector parameters

### Analysis tasks:
- periodically calibrate the >100 individual detectors (**gain alignment**), discard 'bad' ones
- determine the energy resolution (**response shape**) of the summed detectors
- **fit** the spectrum with signal-components, background lines and continuous background

### Background:

**Beam background**
- Touschek- Babha- and beam-gas-scattering,
- stray high-energy $e^\pm$ => **e.m. showers. not correlated** to charged kaon pairs:
  1. **accidentals**

- $\mu, \pi, e$ from $K$ decay; $\Lambda, \pi,...$ from $K$- absorption, kaonic X rays from $K$- wallstops
  => **synchronous background** – has trigger signal

2. **kaonic X-ray lines**
3. **continuous kaon correlated background**
Fit of the KH data

 kaonic hydrogen:  
 shift = -283 ± 36 ± 6 eV  width = 541 ± 89 ± 22 eV

SIDDHARTA collaboration, "A new measurement of kaonic hydrogen X-rays",  
Physics Letters B 704 (2011), p. 113

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.
Kaonic helium spectra from SIDDHARTA

L-series lines prominently seen!

note S/B!
Kaonic helium

Summary of experimental results on the kaonic helium 4 L-series X-ray transition shift

SIDDHARTA confirmed the KEK KHe4 result and was the first measurement of KHe3

Table 1
Energy shifts ($\Delta E_{2p}$) and widths ($\Gamma_{2p}$) of the kaonic helium $^3$He and $^4$He $2p$ states.

<table>
<thead>
<tr>
<th>Target</th>
<th>$\Delta E_{2p}$ (eV)</th>
<th>$\Gamma_{2p}$ (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4$He</td>
<td>$-41 \pm 33$</td>
<td>-</td>
<td>Wiegand et al. [1]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$-35 \pm 12$</td>
<td>$30 \pm 30$</td>
<td>Batty et al. [2]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$-50 \pm 12$</td>
<td>$100 \pm 40$</td>
<td>Baird et al. [3]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$-43 \pm 8$</td>
<td>$55 \pm 34$</td>
<td>Average of above [3,4]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$+2 \pm 2$ (stat.) $\pm 2$ (syst.)</td>
<td>-</td>
<td>Okada et al. [12]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$0 \pm 6$ (stat.) $\pm 2$ (syst.)</td>
<td>-</td>
<td>SIDDHARTA [8]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$+5 \pm 3$ (stat.) $\pm 4$ (syst.)</td>
<td>$14 \pm 8$ (stat.) $\pm 5$ (syst.)</td>
<td>SIDDHARTA [9,10]</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$-2 \pm 2$ (stat.) $\pm 4$ (syst.)</td>
<td>$6 \pm 6$ (stat.) $\pm 7$ (syst.)</td>
<td>SIDDHARTA [9,10]</td>
</tr>
</tbody>
</table>
**Table 1.** Compilation of SIDDHARTA results. The errors given in this table are the sum of the statistical and the systematic component; in case of asymmetric errors, the larger one is quoted here. The upper limits of the yields are for CL 90%. The yields for H and He are preliminary values. Gas densities: H: 14.5 $\rho_{STP}$, D: 13.9 $\rho_{STP}$, $^3$He: 5.38 $\rho_{STP}$, $^4$He: 9.24 $\rho_{STP}$. For kaonic carbon etc. see [6].

<table>
<thead>
<tr>
<th></th>
<th>shift [eV]</th>
<th>width [eV]</th>
<th>transition yields in % per stopped $K^-$</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$\epsilon_{1s} = -283\pm42$</td>
<td>$\Gamma_{1s} = 541\pm111$</td>
<td>$Y(K_{tot}) = 4.5\pm1.2$ $Y(K_\alpha) = 1.2\pm0.4$</td>
<td>[7–9]</td>
</tr>
<tr>
<td>D</td>
<td>$\epsilon_{2p} = -2\pm6$</td>
<td>$\Gamma_{2p} = 6\pm13$</td>
<td>$Y(K_{tot}) &lt; 1.43$ $Y(K_\alpha) &lt; 0.39$</td>
<td>[10]</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$\epsilon_{2p} = 5\pm7$</td>
<td>$\Gamma_{2p} = 14\pm13$</td>
<td>$Y(L_\alpha) = 25.0\pm6.7$</td>
<td>[11, 13, 14]</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$\epsilon_{2p} = 5\pm7$</td>
<td>$\Gamma_{2p} = 14\pm13$</td>
<td>$Y(L_\alpha) = 23.1\pm6.0$</td>
<td>[12–14]</td>
</tr>
</tbody>
</table>

SIDDHARTA-2 at DAFNE

changed **geometry and gas-density:**
- closer, doubled gas density, upper kaon trigger DIRECTLY in front of target, smaller then entry window

added **kaon livetime detector** for K⁺⁻ discrimination:
- identify K⁺ by delayed secondaries ($\tau_K=12.8$ ns)

added surrounding **scintillators:**
- „active shielding“, anticoincidence during SDDs time window (~500 ns), except
  coincidence during „gas-stop-time (≈5 ns, K⁻ absorption secondaries)“, but not „behind X ray hit“ (MIPS veto)

SDDs operated at lower temp. to improve timing resolution, make use of drift-time/risetime correlation

---

**Experimental schemes for future Kd**

for a Kd yield ~ 1/10 of Kp yield and Kd width up to 2 times Kp width we need
~ 20 times reduction of background to get similar S/B as in kaonic hydrogen
~ 600 pb⁻¹ to get 1500 events in Kd (2-1) if efficiency of the setup is doubled

---

SIDHARTA SIDDHARTA-2 Kd.J-PARC
**SIDDHARTA-2 at DAFNE**

600 pb⁻¹ => with 8 pb⁻¹ per day ~75 days

1.5e6 K⁺ per pb⁻¹
=> 1.5e7 K⁺ per day ~ isotropically
p = 127 MeV/c

Target stops: ~ 2 % per kaonpair (gas 3% dens.)
due to solid angle. Intrinsic ~ 100%
=> 18e6 stops

SDDs: 144 cm² devices from SIDDHARTA
active/module = 0.22
possibly: 246 cm² new SDDs from Milano /FBK

**source**

**low energy kaons**

**tracking not necessary**

**preparation in advanced state**

---

**… at J-PARC**

at 30 kW proton beam,
35 days

at  p = 0.7 GeV/c
~ 40e7 kaons per day

Target stops for 5% dens.
~ 0.6e-3 per beam kaon  => 7.8e6 stops

SDDs: 246 cm² new devices from Milano /FBK
active/module = 0.84

**beam**

**high energy kaons**
>90% lost in degrader, wide energy range at
entering target
in the target: absorption in flight relevant

**tracking**
fiducial volume cut

**feasibility study, proposal submitted**
Figure 8: Sketch of the proposed setup for the kaonic deuterium measurement

Figure 11: Design of the cryogenic target and X-ray detector system. The target cell, with a diameter of 65 mm and a length of 160 mm, is closely surrounded by SDDs, about 5 mm away from the target wall.
Achievable precision

<table>
<thead>
<tr>
<th>events kaonic deuterium $K_\alpha$</th>
<th>S/B</th>
<th>precision of shift result (eV)</th>
<th>precision of width result (eV)</th>
<th>experiment 600 pb$^{-1}$ at DAFNE resp. 100 shifts with 40 kW p-beam at J-PARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>1 : 3</td>
<td>47</td>
<td>123</td>
<td>SIDDHARTA-2</td>
</tr>
<tr>
<td>3000</td>
<td>1 : 3</td>
<td>32</td>
<td>83</td>
<td>SIDDHARTA-2 using the new SDDs</td>
</tr>
<tr>
<td>1500</td>
<td>1 : 5</td>
<td>70</td>
<td>160</td>
<td>J-PARC</td>
</tr>
<tr>
<td>2000</td>
<td>10 : 3</td>
<td>12</td>
<td>24</td>
<td>kaonic hydrogen test (few days)</td>
</tr>
</tbody>
</table>

Monte Carlo test spectrum with relative yield distribution similar to kaonic hydrogen. 1500 Kd K\(\alpha\) events Fit with free intensities
Results on shift, width and yields from measurements of kaonic He-3, He-4, C and hydrogen (Kp) published. Strong impact for K-N theory!

K'd first experiment, exploratory measurement, signal hints, significance ~ 2σ upper limit for K-series yield published.

Proposed extension of the experimental program: SIDDHARTA-2 with improved technique - measure Kd shift and width, other light atoms, Kp → γ Λ*
Preparations under way. Timescale: “after KLOE experimental period” ... 2017?

„Plan B“: Kd experiment at J-PARC, proposal submitted.

Future: microcalorimeter detectors with few eV resolution at 6 keV