New precision measurements of the strong interaction in kaonic hydrogen

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on behalf of the SIDDHARTA Collaboration
Exotic atoms – a broad research field

- Studies of fundamental interactions and symmetries
  - Low-energy QCD
    - Chiral Symmetry Breaking
  - Hadronic Atoms
    - K-p, K-d
    - \( \pi-p, \pi-d \)
  - Measurement of Particle masses
    - Pion / Kaon Mass
  - Electromagnetic Processes
    - \( \mu CF, \text{e.m. Cascade} \)
  - Weak Interaction
    - Muon Capture
  - Quantum-Electrodynamics
  - Fundamental Symmetries
    - Matter-Antimatter
Hadronic atoms

Unique laboratory for studying strong interaction at zero kinetic energy

Exotic atoms cast light on fundamental questions

A workshop in Trento explored how experiments on exotic atoms, deeply bound kaonic states and antihydrogen provide a low-energy route to addressing fundamental physics.
Motivation

- K-p simplest exotic atom with strangeness
- strong interaction shift $\varepsilon_{1s}$ and width $\Gamma_{1s}$ directly observable by X-ray spectroscopy
- kaonic hydrogen „puzzle“ solved – but: precision data missing
- K-p: Information on $\Lambda(1405) \rightarrow$ kaonic nuclear clusters
- kaonic deuterium never measured before
- atomic physics: new cascade calculations to be tested
  $\rightarrow$ see talk given by M. Faifman at this Conference
Kaonic Hydrogen - Goals

- Measurement of strong interaction shift and width of kaonic hydrogen and kaonic deuterium at the highest precision

- Determination of the isospin-dependent scattering lengths near threshold
  - no extrapolation to zero energy

- Testing chiral symmetry breaking in systems with strangeness
Experimental method

Negative kaons stopped in $\text{H}_2 \rightarrow$ initial atomic capture $\rightarrow$ electromagnetic cascade $\rightarrow$ X-ray transitions

As the kaon interacts strongly with the nucleus the 1s energy level is shifted and broadened.

$\Gamma_{1s}$

$K_\gamma$

$E_{1s}$

$E_{2p}$

$\epsilon_{1s} = E_{2p-1s}^{\text{meas.}} - E_{2p-1s}^{\text{e.m.}}$

$K_a \sim 6.3 \text{ keV}$

Shift and width of states $n>1$ negligible
Kaonic hydrogen

With \(a_0, a_1\) for the \(l=0,1\) S-wave KN scattering lengths in the isospin limit \((m_d = m_u)\), \(\mu\) being the reduced mass of the \(K^-p\) system, and neglecting isospin-breaking corrections:

\[
\epsilon + i \frac{\Gamma}{2} = 2\alpha^3 \mu^2 a_{K^-p} = 412 \frac{fm^{-1}}{eV} \cdot a_{K^-p}
\]

\[
a_{K^-p} = \frac{1}{2} (a_0 + a_1)
\]

"By using the non-relativistic effective Lagrangian approach a complete expression for the isospin-breaking corrections can be obtained; in leading order parameter-free modified Deser-type relations exist and can be used to extract scattering lengths from kaonic atom data" (Meißner, Raha, Rusetsky, 2004)

\[
\epsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu c^2 a_p \left\{ 1 - 2\alpha \mu c (\ln \alpha - 1) a_p \right\}
\]
Kaonic deuterium

For the determination of the isospin dependent scattering lengths $a_0$ and $a_1$ the hadronic shift and width of kaonic hydrogen and kaonic deuterium are necessary.

Theoretical procedures are needed to connect the observables with the isospin-dependent scattering lengths.

\[
a_{K^-p} = \frac{1}{2} [a_0 + a_1]
\]

\[
a_{K^-n} = a_1
\]

Impulse approximation term

\[
a_{K^-d} = \frac{4(m_N + m_K)}{2m_N + m_K} \cdot a^{(0)} + C
\]

\[
a^{(0)} = \frac{1}{2} [a_{K^-p} + a_{K^-n}] = \frac{1}{4} [a_0 + 3a_1]
\]
K⁻p and K⁻d atom properties

K⁻p (K⁻d) e.m. bound kaonic atoms
Bohr radius ~80 fm, binding energy ~9 keV

| Kaonic atom | e.m. position of $K_\alpha$ line (eV) | $\varepsilon$ (eV) | $\Gamma$ (eV) | X-ray Yield |
|-------------|--------------------------------------|-------------------|--------------|-------------|
| hydrogen    | 6480                                 | $\approx 200$     | $\approx 250$| ~1-3 %      |
| deuterium   | 7810                                 | $\approx 325^*$   | $\approx 630^*$| ~0.2 %      |

*) A.N. Ivanov, M. Cargnelli, M. Faber, H. Fuhrmann, V.A. Ivanova, J. Marton, N.I. Troitskaya, J. Zmeskal, Eur.Phys.J. A 23 (2005) 79
Kaonic Atoms @ DAΦNE: DEAR
DAΦNE (LN Frascati)

electron – positron collider
collision energy tuned
to the Φ resonance
at 1.02 GeV c.m.

International Conference on Muon Catalyzed Fusion 2007
Setup at ДАФНЕ
Array of 16 CCD55-30
- 1242 x 1152 pixels / chip
- pixel size 22.5 x 22.5 µm
- total area per chip 7.24 cm²
- depletion depth ~30 µm
- read-out time per CCD 2 min.
- energy resolution ~150 eV @ 6keV
- temperature stabilized at 165 K
Resulting K⁻p X-ray Spectrum

\[ \varepsilon_{1s} = -193 \pm 37 \text{ (stat.)} \pm 6 \text{ (syst.) eV} \]

\[ \Gamma_{1s} = 249 \pm 111 \text{ (stat.)} \pm 30 \text{ (syst.) eV} \]
DEAR Results

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DEAR – Comparison with theory

B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94, 213401 (2005)

A.N. Ivanov et al., Eur. Phys. J. A21 (2004) 11
J. Phys. G 31 (2005) 769
Eur. Phys. J. A25 (2005) 329

FIG. 1. Real (solid line) and the imaginary part (dashed line) of the strong $K^- p \rightarrow K^- p$ amplitude, $f_{K^- p \rightarrow K^- p}^{\text{str}}$, as defined in the text. The data points represent the real and imaginary parts of the $K^- p$ scattering length, derived from the DEAR experiment [1] with inclusion of isospin breaking corrections according to Ref. [18].

FIG. 4. Results for the strong-interaction shift and width of kaonic hydrogen from our approach, both by using the Deser-Tneman formula [28] (empty circle) and by including isospin breaking corrections [18] (full circle). The DEAR data are represented by the shaded box [1], and the KEK data by the light gray box [20]. The fit restricted to the DEAR data is represented by the small full rectangle (empty rectangle without isospin breaking corrections).
Precision data are urgently needed
From DEAR to SIDDHARTA

- Precision of the DEAR result limited by high soft X-ray background (S/N ~ 1:70)

- Next step: background reduction by using kaon – X-ray time correlation (S/N ~ 10:1 for kaonic hydrogen)

→ New X-ray detectors SDDs: JRA in I3HP (EU FP6) in cooperation with LNF, MPG, PNSensor, Politecnico Milan, IFIN-HH and new dedicated target-detector set-up
Silicon Drift Detectors for Hadronic Atom Research by Timing Application

Work supported by I3 HadronPhysics

Contract No. RII3-CT-2004-506078
Silicon Drift Detector SDD

- SDD has small capacitance → low noise
- Good energy resolution - comparable with CCD
- But most important: timing capability

Large area SDD with 1 cm² active area
3 SDDs on 1 chip
SIDDHARTA Setup

Cryogenic setup

Triple coincidence:
\[ \text{SDD}_x \cdot \text{Scint}_K \cdot \text{Scint}_K \]

SDD array (~200 SDDs)
Target cell – SDD array assembly

Cryogenic target cell
50 µm Kapton within a pure aluminum grid
$P_{\text{work}} \approx 2\text{ bar}$

Carefully selected structure materials analyzed by PIXE
Cryogenic target cell

Temperature 22 K
Working pressure 2 bar

Alu-grid

Side wall:
Kapton 50 µm

Kaon entrance
Window:
Kapton 50 µm
SDD unit (2x3x3 SDDs)

$\Delta E_{FWHM} \sim 138 \text{ eV} @ 5.9 \text{ keV}$
Layout of the kaon trigger

PMT Hamamatsu R4998
anode pulse rise time
~ 0.7 ns

Scintillator Material
BC420
(200mm x 35mm x 1.5 mm)
SIDDHARTA apparatus

Target cooling

SDD cooling

HV- and voltage supply for SDDs and readout electronics

TMP
SIDDHARTA setup @ DAΦNE

Bruno Dulach
Cesidio Capoccia

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SIDDHARTA: Schedule

- Tuning of setup / optimization 100 pb$^{-1}$
- Precision measurement of kaonic hydrogen 400 pb$^{-1}$
- Measurement of kaonic deuterium 600 pb$^{-1}$
- **Further options:**
  - Kaonic helium studies ($^{3}$He and $^{4}$He)
Monte Carlo Simulations

Monte Carlo simulated X-ray spectra
Measurement with SDD array and kaon trigger

$K^{-}p$:
- $\epsilon_{1s} = 193$ eV, $\Gamma_{1s} = 249$ eV, $Y(K_\alpha) = 2\%$
- $\Delta \epsilon_{1s} \sim \pm 2$ eV, $\Gamma_{1s} \sim \pm 4.5$ eV

$K^{-}d$:
- $\epsilon_{1s} = 325$ eV, $\Gamma_{1s} = 630$ eV, $Y(K_\alpha) = 0.2\%$
- $\Delta \epsilon_{1s} \sim \pm 15$ eV, $\Gamma_{1s} \sim \pm 40$ eV
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Summary

DEAR finished successfully: most precise data on KH shift and width up to now

Theoretical studies continue

SIDDHARTA is well under way: KH, KD, …
Thank you for your attention
Spare
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Discovery of the kaon (K meson). 'Strange' long lived particles discovered in cosmic ray events by Clifford Butler and George Rochester.