Studying strong interaction at DAΦNE and J-PARC

Johann Zmeskal

XVIII International Conference on Hadron Spectroscopy and Structure
HADRÓN 2019

August 17 – 21, 2019
Guilin Bravo Hotel, Guilin, China
OUTLINE

• Motivation
• Charged kaon production
• Status kaonic hydrogen
• Towards kaonic deuterium SIDDHARTA-2 E57
• Summary
Motivation to study hadronic atoms

- exotic hadronic atoms are bound by Coulomb force - QED
  - e.g. $\pi^+\pi^-, \pi^-p, \pi^-d, K^-p, K^-d, \ldots$
- Bohr radii > as the typical scale of strong interaction, but..
  - observable effects of QCD
    - energy shift from pure Coulomb value
    - decay width
  - access to scattering at zero energy

- these scattering lengths are sensitive to chiral and isospin symmetry breaking in QCD
- can be analysed systematically in the framework of low-energy Effective Field Theory
Forming “exotic” atoms

“normal” hydrogen

“exotic” (kaonic) hydrogen

\[ n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e \]
X-ray transitions to the 1s state

\[ E_{2p} \rightarrow 1s (e.m.) (K-p) = 6480 \pm 1 \text{ eV} \]

\[ E_{2p} \rightarrow 1s (e.m.) (K-d) = 7820 \pm 1 \text{ eV} \]

\( K_\alpha \sim 6.2 \text{ keV} \)

\[ \varepsilon_{1s} = E_{2p-1s} \text{ (meas.)} - E_{2p-1s} \text{ (e.m.)} \]

due to the strong interaction kaon-proton the 1s level is shifted and broadened
Scattering lengths

Deser-type relation connects shift $\varepsilon_{1s}$ and width $\Gamma_{1s}$ to the real and imaginary part of $a_{K-p}$

$$\varepsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu a_{K-p}$$

($\mu$ .. reduced mass of the $K^-p$ system, $\alpha$ .. fine-structure constant)

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

$$a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2} [a_{K^-p} + a_{K^-n}] + C = \frac{k}{4} [a_0 + 3a_1] + C$$

$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

➢ the measurement of kaonic deuterium
   will allow to extract antikaon-nucleon isospin dependent scattering lengths
Charged kaon production

- DAΦNE at Laboratori Nazionali di Frascati
- J-PARC - Japan Proton Accelerator Research Complex
Low energy charged kaons at DAΦNE

operates at the centre-of-mass energy of the Φ meson
mass m = 1019.413 ± 0.008 MeV
width Γ = 4.43 ± 0.06 MeV

Φ produced via e^+e^- collision
σ(e^+e^- → Φ) ~ 5 µb
→ monochromatic kaon beam (127 MeV/c)
Primary beam: 30 GeV/c protons
Repetition cycle: 5 sec
Flat top: 3 sec
Production target: Au
Kaon momentum: 1.2 GeV/c (max.)
Status kaonic hydrogen

- SIDDHARTA at DAΦNE
Kaonic hydrogen “puzzle”

KpX (KEK)
M. Iwasaki et al, 1997

\[ \epsilon = -323 \pm 63 \pm 11 \text{ eV} \]
\[ \Gamma = 407 \pm 208 \pm 100 \text{ eV} \]

Davies et al, 1979
Bird et al, 1983
Izycki et al, 1980

shift $e_{1s}$ [eV]

width $\Gamma_{1s}$ [eV]
SIDDHARTA: cryogenic target + X-ray detector

working T 25 K
working P 1.5 bar

Alu-grid

Side wall:
Kapton 50 µm

Kaon entrance
Window:
Kapton 75 µm
K^-p spectrum, BG subtracted

\[ \varepsilon_{1s} = -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \]
\[ \Gamma_{1s} = 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV} \]
Kaonic hydrogen results

\[ \varepsilon_{1s} = -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \]
\[ \Gamma_{1s} = 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV} \]
Improved constraints on chiral SU(3) dynamics from kaonic hydrogen
Y. Ikeda, T. Hyodo and W. Weise, PLB 706 (2011) 63

Real part and imaginary part of the $K^− p \rightarrow K^− p$ forward scattering amplitude extrapolated to the subthreshold region, deduced from the SIDDHARTA kaonic hydrogen measurement.
Chiral EFT motivated K-N approaches

Kyoto-Munich

Murcia (MI , MII )

Bonn (B2, B4)

Prague

Barcelona
$K^-p \rightarrow K^-p$ forward scattering amplitude

- subthreshold amplitudes not yet well determined

![Graph showing subthreshold amplitudes](image.png)
$K^- n \rightarrow K^- n$ forward scattering amplitude

![Graph showing the real and imaginary parts of the forward scattering amplitude as a function of $s^{1/2}$ for different groups: Kyoto-Munich, Murcia 1, Murcia 2, Prague, Bonn 2, Bonn 4, Barcelona.](image-url)
Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
  - Kaonic hydrogen pilot run
The scientific goal of SIDDHARTA-2 and E57

- **a first measurement of kaonic deuterium**
  - to extract the $\bar{K}N$ isospin dependent scattering lengths

---

**INPUT**

- **signal:** shift $-800$ eV
  - width $800$ eV
- **density:** 5% (LHD)
- **detector area:** $246 \text{ cm}^2$
- **K$\alpha$ yield:** 0.1%
  - with the yield ratio as in $K^-p$
- **$S/B \sim 1:4$**

---

**achievable precision:**
- **shift:** $30$ eV
- **width:** $75$ eV

---

**Geant4 simulated $K^-d$ X-ray spectrum**
E57 / SIDDHARTA-2 targeted precision

Theory – SIDDHARTA-2

- Oset 2001
- Shevchenkov 2012
- Weise 2017
- Mizutani 2013
- Meißner 2011
- Gall 2007
Experimental challenges towards $K^-d$

- **X-ray yield:**  
  - $K^-p \sim 1\%$  
  - $K^-d \sim 0.1\%$

- **1s state width:**  
  - $K^-p \sim 540\text{ eV}$  
  - $K^-d \sim 800 - 1000\text{ eV}$

**BG sources:**  
- asynchronous BG $\rightarrow$ timing  
- synchronous BG $\rightarrow$ spatial correlation
SIDDHARTA-2
Silicon Drift Detector for Hadronic Atom Research by Timing Applications

LNF - INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN – HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University
CERN, Switzerland

Croatian Science Foundation, research project 8570
SIDDHARTA-2
The new 4x2 SDD array for $K^{-d}$

SDD-chip back side with bonding pads

SDD-chip glued to ceramic board, bonded to CUBE preamplifier

9 holes for bondings

CUBE preamplifier

connector
X-ray detector for SIDDHARTA-2 and E57

New SDD technology with CUBE preamplifier

$^{55}$Fe spectrum

![Image of X-ray detector](image)

**Energy [KeV]**

- **Counts**
- **123.0 eV FWHM**
SIDDHARTA – 2 successfully installed at DAΦNE in April 2019

more details: Session 4, Aug. 20 at 9:15
Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
  - Kaonic hydrogen pilot run
K-d collaboration

LNF - INFN, Frascati, Italy
SMI - ÖAW, Vienna, Austria
IFIN - HH, Bucharest, Romania
Politecnico, Milano, Italy
RIKEN, Japan
Tokyo Univ., Japan
Victoria Univ., Canada
KEK, Tsukuba, Japan
RCNP, Osaka, Japan
Seoul Univ., South Korea
Zagreb Univ., Croatia
INFN, Torino, Italy
Osaka Univ., Japan
TUM, Garching, Germany
Kyoto Univ., Japan
Jagiellonian Univ., Poland
RCJ, Juelich, Germany
Santiago de Compostela Univ., Spain
Tohoku Univ., Japan
KIRAMS, Seoul, South Korea
E57 within E15 spectrometer (CDS)

C-degrader: ~ 500 mm

Solenoid

Cylindrical drift chamber

Cylindrical detector hodoscope

Cryogenic target cell surrounded by SDDs

Refrigerator for target and SDDs

HADRON 2019
K-d cryogenic target and SDD setup

- 2-stage closed cycle cryo-cooler
- 16-channel amplifier boards
- Analogue signal and HV-LV cables
- Ultra-pure Al cooling lines
- Line driver boards
- Cryo target + SDDs
Combined target and SDD design

target cell: \( l = 160 \text{ mm} \), \( d = 65 \text{ mm} \)
target pressure max.: 0.35 MPa
target temperature: 23 – 30 K
SDD active area: 246 cm\(^2\)
density: 5% LHD
(29K/0.35 MPa)
Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
  - Kaonic hydrogen pilot run
Kaonic hydrogen/helium pilot run

K1.8BR area February 2019

E15 CDS

H2/D2 gas target
Kaonic hydrogen/helium pilot run
Feb. - April 2019 for a total of 6 days

E57 pilot run geometry
Kaonic hydrogen/helium pilot run
Feb. - April 2019 for a total of 6 days

K^+ stopping tune: Range curve
kaon momentum 0.7 GeV/c

Graph: # of stopped kaons (arbitrary) vs. thickness of adjustable degrader [mm]

- Blue circles: with wedge after D3
- Orange circles: without wedge

➤ successfully optimized kaon stop density
K+ run: Vertex (BPC&CDC)

Target cell & SDDs

-130<Z<-70
-60<Z<60
70<Z<130
Helium-4, Stopped Kaon trigger

Counts / 80 eV

Energy (keV)

T. Hashimoto

HADRON 2019
Kaonic Helium-4 spectrum
6 hour data taking

Counts / 80 eV

Energy (keV)

K•He
Cu-Kα
Zn-Kα
KC/KO/KAl
KAl

Kaon trigger
DEF cut
DEF & CDC cut

T. Hashimoto
HADRON 2019
Kaonic Helium-4 spectrum
6 hour data taking

~80 K⁻He (3d → 2p) events to be compared with MC → S/BG ~100/1
Kaonic Hydrogen

Kaon trigger
DEF cut
DEF & CDC cut

Counts / 80 eV

Energy (keV)
Kaonic hydrogen spectrum
90 hour data taking

- Higher X-ray transitions are observed
- $K\alpha$ events less than expected, analysis ongoing
Summary

- A first measurement of kaonic deuterium is urgently needed and will be performed at DAΦNE and J-PARC

- **SIDDHARTA-2**
  - Apparatus installed at DAΦNE in April 2019
  - Commissioning until Nov. 2019
  - Data taking planned for 2020

- **E57**
  - Kaonic hydrogen/helium pilot run (Feb.-April 2019)
  - Data analysis ongoing, together with improvements on the dedicated MC
The modern era of light kaonic atom experiments

Catalina Curceanu, Carlo Guaraldo, Mihai Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marion, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Accepted 8 March 2019

ABSTRACT

This review article covers the modern era of experimental kaonic atoms studies, encompassing twenty years of activity, defined by breakthroughs in technological developments which allowed performing a series of long-awaited precision measurements. Kaonic atoms are atomic systems where an electron is replaced by a negatively charged kaon, containing the strange quark, which interacts in the lowest orbits with the nucleus also by the strong interaction. As a result, their study offers the unique opportunity to perform experiments equivalent to scattering at vanishing relative energy. This allows to study the strong interaction between the antikaon and the nucleon or the nucleus "at threshold", namely at zero relative energy, without the need of extrapolation to zero energy, as in scattering experiments. The fast progress achieved in performing precision light kaonic atoms experiments, which also solved

Thanks for your attention

Rev. Mod. Phys. 91, 025006 – Published June 2019