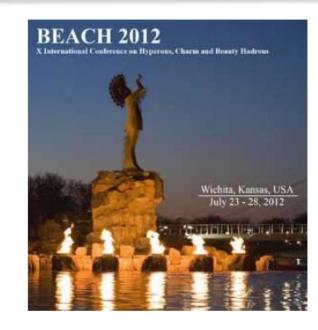# X-ray spectroscopy of light kaonic atoms:
New results and perspectives

Johann Marton, SMI, Vienna
for the SIDDHARTA Collaboration
and LEANNIS Network (EU-HP3)

Outline

- **Exotic (hadronic) atoms as probes for low-energy QCD**

- **Information sources for low-energy interaction with strangeness**

- **Solved puzzles**

  Kaonic atoms:

  - Kaonic hydrogen (strong interaction effect on the groundstate)

  - Kaonic helium isotopes He-3,4 (strong interaction on 2p)

- **Open questions and future challenges**

  Kaonic atoms

  - Precision data on kaonic deuterium

  - Precision data on kaonic atoms Z>2

  Relation kaonic nuclei:

  - Lamda(1405) related to the quest of bound strange nuclear systems (K$^-$pp, K$^-$ppn …)
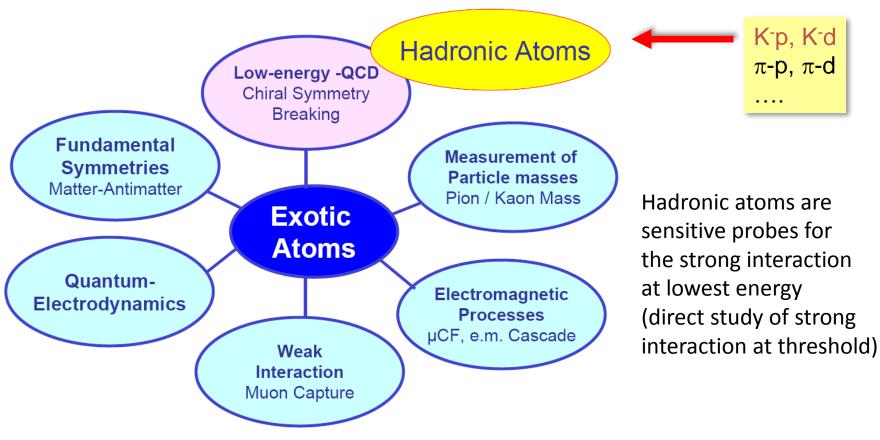
- **Summary and Outlook**

Exotic atoms

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

K⁻p, K⁻d
π-p, π-d
....

Hadronic atoms are sensitive probes for the strong interaction at lowest energy (direct study of strong interaction at threshold)

The simple(st) cases

- Hadronic atoms* like

  $\pi^+\pi^-$, π^+K^-, π^-K^+ described by
  Chiral Perturbation Theory

  data from DIRAC**

- Pionic hydrogen* → ChPT, e.g. new data from our experiment at PSI (shift, width)***

- Complicated: even simple hadronic atoms with strangeness due to resonances ChPT

*J. Gasser, V.E. Lyubovitskij and A. Rusetsky, Phys.Rep. 456 (2008) 167.
**B. Adeva et al., PL B674 (2009) 11.
*** A. Hirtl [piH Coll.] Hyp. Int. 193 (2009) 153.

The field

- Studies of atomic bound systems with strangeness (hadronic/kaonic atoms) provide unique access to strong interaction of antikaons at very low energies (i.e. in kaonic atoms).

- Search for exotic nuclei bound by antikaon(s)

- Fascinating research field involving different fields in physics (particle physics, nuclear physics, atomic physics) and energies from GeV to eV.

- Unique research infrastructures in Europe: DAFNE/LNF, GSI, Jülich.

- Opportunities at J-PARC in Japan

CERN Courier

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Jan 20, 2010

The fascinating world of strange exotic atoms

Experts and young researchers from around the world participated in a recent international workshop that focused on puzzles past and present in the study of strange hadronic atoms and nuclei. Catalina Curceanu and Johann Marton report from Trento.

Résumé

Le monde fascinant des atomes exotiques

Le domaine des atomes exotiques connaît une renaissance, du point de vue expérimental et théorique. Du côté expérimental, de nouveaux faisceaux hadroniques peuvent être obtenus, ou pourront bientôt être obtenus. De nouveaux détecteurs, ayant une performance améliorée, commencent également à fonctionner. Côté théorie, des avancées significatives ont eu lieu avec des développements récents dans les théories du champ effectif chirales et leur application aux systèmes noyau–hadron. L'atelier international sur le thème « atomes et noyaux hadroniques – énigmes résolues, problèmes en suspens et défis futurs pour la théorie et les expériences » a traité de ces questions du 12 au 16 octobre 2009, au Centre européen pour les études théoriques en physique nucléaire (ECT), à Trente.

(http://images.iop.org/objects/ccr/cern/50/1/20/CCeds1_01_10.jpg)
Participants (http://images.iop.org/objects/ccr/cern/50/1/20/CCeds1_01_10.jpg)

The field of exotic atoms has a long history and it is currently experiencing a renaissance, from both the experimental and theoretical points of view. On the experimental side, new hadronic beams are either already available, with kaons at the DAΦNE facility at Frascati, or will soon become available with the start-up of the Japan Proton Accelerator Research Complex (J-PARC). New detectors, with improved performance in energy resolution, stability, efficiency, trigger capability etc, are also starting to operate. On the theoretical side the field has advanced significantly through recent developments in chiral effective-field theories and their applications to hadron–nuclear systems. In light of these developments it was appropriate for the international workshop "Hadronic atoms and nuclei – solved puzzles, open problems and future challenges in theory and experiment" to address these topics on 12–16 October 2009, at the European Centre for Theoretical Studies in Nuclear Physics and related areas, ECT*, Trento.
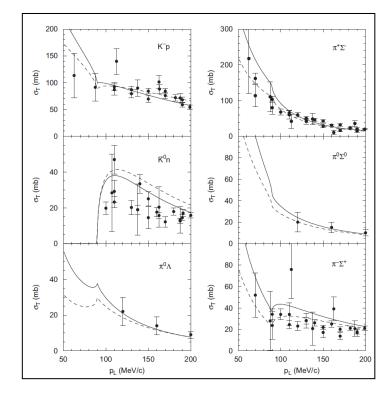
Experimental information on the low energy (anti)kaon-nucleon interaction

- Kaon-proton scattering data (old data with large errors, above threshold → extrapolation)

- πΣ mass spectrum

- Threshold decay ratios

- X-ray data of light kaonic atoms (K⁻p, K⁻d, K⁻He):

  SIDDHARTA at DAFNE

  - Kaonic hydrogen → increased precision, threshold data important constraints for theory

  - Kaonic deuterium → exploratory experimental studies

  - Kaonic helium-3 first measurement

  - Kaonic helium-3,4 → 2p shift small, „superstrong" antikaon nuclear interaction ruled out?

- Reliable theory has to be consistent with these informations

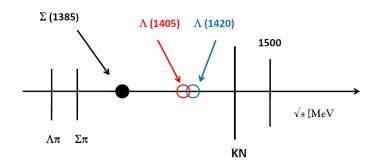|		
$\dfrac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)}$	2.37	2.36 ± 0.04
$\dfrac{\Gamma(K^-p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \to \text{all inelastic channels})}$	0.66	0.66 ± 0.01
$\dfrac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral states})}$	0.19	0.19 ± 0.02

Motivation for new studies

- The low-energy kaon-nucleon interaction is neither simple nor well understood:

- Central importance for the physics of strong interaction has the dynamics driven by chiral symmetry breaking in low-energy QCD.

- Problems arise from the existence of sub-threshold resonances like the famous Λ(1405)

Interesting question:
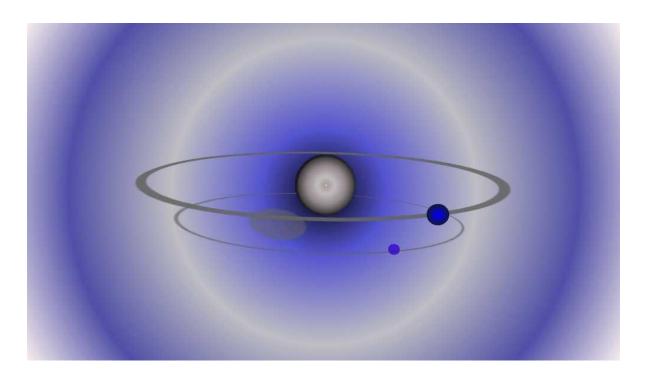Two-pole structure??
Λ(1405) & Λ(1420) and
their impact

- The development of reliable theories is asking for precision data on the threshold observables (e.g. shift/width of kaonic atom states).

Kaonic Hydrogen
A key experiment in $K_{bar}N$ interaction

Exotic atoms
as probes for
strong interaction
at threshold

and an experimental challenge ...
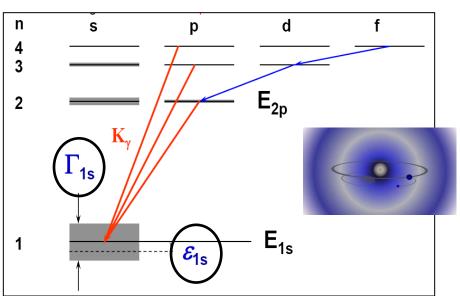
Kaonic hydrogen and deuterium

- 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

$$\varepsilon_{1s} = E_{1s}^{meas.} - E_{1s}^{e.m.(calc.)}$$

$$E_{1s}^{e.m(calc.)} = E_{KG} + E_{VP} + E_{FS}$$

- 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.

Energy scales involved

Particle physics meets atomic physics

Example: Kaonic hydrogen at DAFNE/LNF

- Phi-meson formation   1.020.000.000 eV
- K- energy (Phi decay)   16.000.000 eV
- K_α transition energy in K^-p 6.500 eV
- Strong interaction shift   280 eV
- Accuracy of shift determination   few 10 eV

Challenge: Precision x-ray spectroscopy
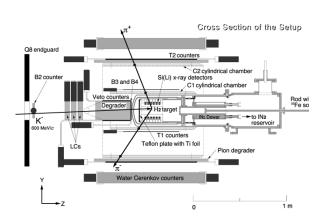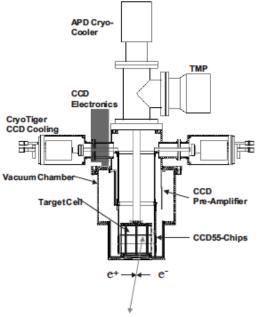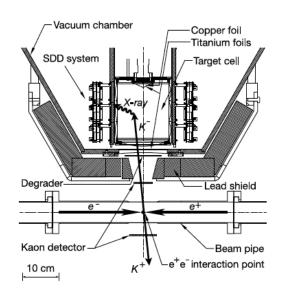in a particle accelerator environment

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

X-ray detectors for exotic atom spectroscopy

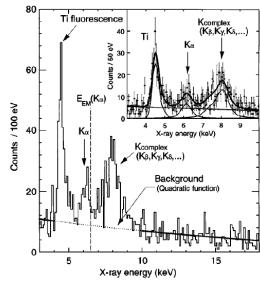| X-ray detector	Si(Li)	CCD	SDD
Effective area [mm^2]	<300	724	100
Thickness of depletion [mm]	4	0.03	0.26
Energy resolution [eV] at 6 keV	~300	~150	~150
Time resolution [ns]	~280	–	~700
Experiment	KpX	DEAR	SIDDHARTA
Number of detectors	60	16	200
Application	K^-p, $K^{-4}He$	K^-p	K^-p, $K^{-3,4}He$

Kaonic hydrogen "puzzle"

The K⁻p scattering lengths determined from kaonic hydrogen X-ray measurements and those from scattering analyses

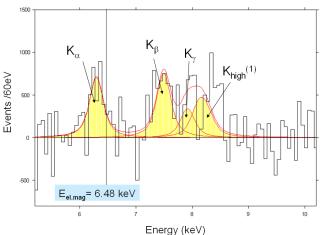| Method	Reference	a_{K^-p} (fm)
Kaonic hydrogen X-ray measurements	Davies et al. (1979)	$(0.10\pm0.14) + i(0.00^{+0.28}_{-0.00})$
	Izycki et al. (1980)	$(0.65\pm0.19) + i(0.68\pm0.31)$
	Bird et al. (1983)	$(0.47\pm0.14) + i(0.10^{+0.27}_{-0.10})$
K⁻p scattering analyses	Sakitt et al. (1965)	$(-0.91\pm0.05) + i(0.48\pm0.03)$
	Kim et al. (1967)	$(-0.87\pm0.04) + i(0.69\pm0.03)$
	von Hippel et al. (1968)	$(-0.89\pm0.02) + i(0.62\pm0.02)$
	Martin & Ross (1970)	$(-0.89\pm0.03) + i(0.66\pm0.03)$
	Martin et al. (1981)	$(-0.66\pm0.05) + i(0.64\pm0.04)$

X-ray experiments gave a positive energy shift of the 1s state by strong interaction in kaonic hydrogen.

in disagreement to scattering experiments which indicated a negative energy shift.

This puzzling situation was clarified in the KpX experiment and later by our group with DEAR.

KpX @ KEK

DEAR@LNF

Kaonic hydrogen: extraction of a_{K-p}

With a_0, a_1 for the I=0,1 S-wave KN scattering lengths in the isospin limit ($m_d = m_u$), μ being the reduced mass of the K$^-$p system one gets in lowest order:

$$\varepsilon + i\frac{\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\, fm^{-1}\cdot eV \cdot a_{K^-p}$$

Deser-type formula

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

„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)

$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2\, a_p\left\{1 - 2\alpha\mu_c(\ln\alpha - 1)\, a_p\right\}$$
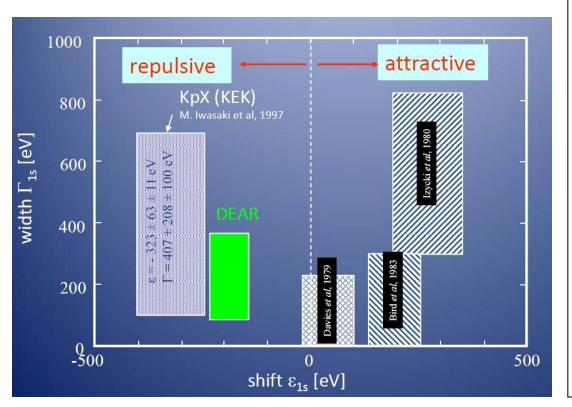
Accuracy ~10%

Kaonic hydrogen: before SIDDHARTA

❖Most precise values for shift and width from DEAR experiment (CCDs)
❖But still precision limited (e.g. error bar of width > 50%)
❖shift vs. width (1 σ errors) see below

DEAR (2005)
ε_{1s} = - 193 ± 37 (stat.) ± 6 (syst.) eV
Γ_{1s} = 249 ± 111 (stat.) ± 30 (syst.) eV

a_{K-p} = (-0.468 ± 0.090 ± 0.015) +
i(0.302 ± 0.135 ± 0.036) fm

KpX (1998)
ε_{1s} = - 323 ± 63 (stat.) ± 11 (syst.) eV
Γ_{1s} = 407 ± 208 (stat.) ± 100 (syst.) eV

a_{K-p} = (-0.78 ± 0.15 ± 0.03) +
i(0.49 ± 0.25 ± 0.12) fm
using Deser-Trueman (i.e. lowest order)

Solved puzzles – Status before SIDDHARTA

- Kaonic hydrogen puzzle was qualitatively solved (sign of the shift) but precision was limited, furthermore the case of kaonic deuterium was unexplored

- Kaonic helium-4 puzzle was quantitatively solved but verification was asked for and the strong interaction in helium-3 was unexplored → this was solved by SIDDHARTA.

- On the other hand precision data are requested for reliable theoretical description of the low-energy anti-kaon nucleon interaction and in the context of the existence of kaonic nuclear bound states
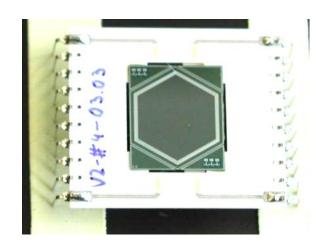
New experiments - new (x-ray) detectors

- Silicon Drift Detectors with large active area
  active area → 100 mm²

- Excellent energy resolution, timing capability

- Compact design, arrangement in array

- 2 different SDD types for exotic atom research

  ❖ SDD with external FET
    (commercial product, KETEK)
    system studied:
    $K^-{}^4He$ (E570/KEK)

  ❖ SDD with on chip integrated FET
    → SIDDHARTA (JRA10/EU-FP6)
    systems studied: K^-p, K^-d ….

New precision X-ray spectroscopy of kaonic H/D/He (SIDDHARTA)
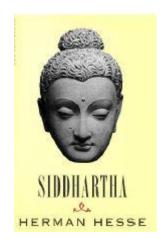
SIDDHARTA Collaboration
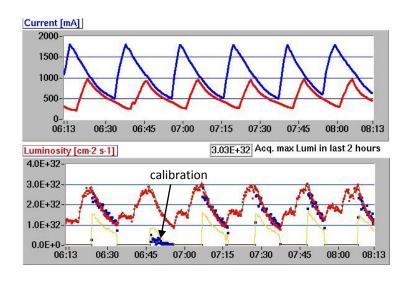

Garching   Munich   Vienna

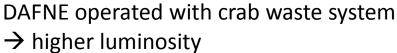Bucarest

Electron-positron collider DAFNE at LNF

- $\Phi \rightarrow K^- K^+$ (49.1%)

- Monochromatic low-energy K^- (~127MeV/c)

- Less hadronic beam background

Excellent for low-energy kaon physics: kaonic atoms

DAFNE Luminosity
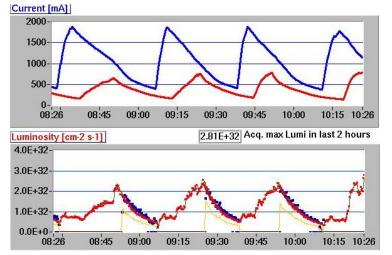

DAFNE operated with crab waste system → higher luminosity

SIDDHARTA is taking data only between injections (blue dots, yellow line)

Under good conditions during
SIDDHARTA DAQ
L ~ 2.8 10^{32} – 1.0 10^{32} cm^{-2} s^{-1}

Comparison to 2002 DEAR experiment:
~ 3.0 10^{31} cm^{-2} s^{-1}
now up to 10 times higher !

SIDDHARTA: L_{int} up to ~ 8 pb^{-1} per day
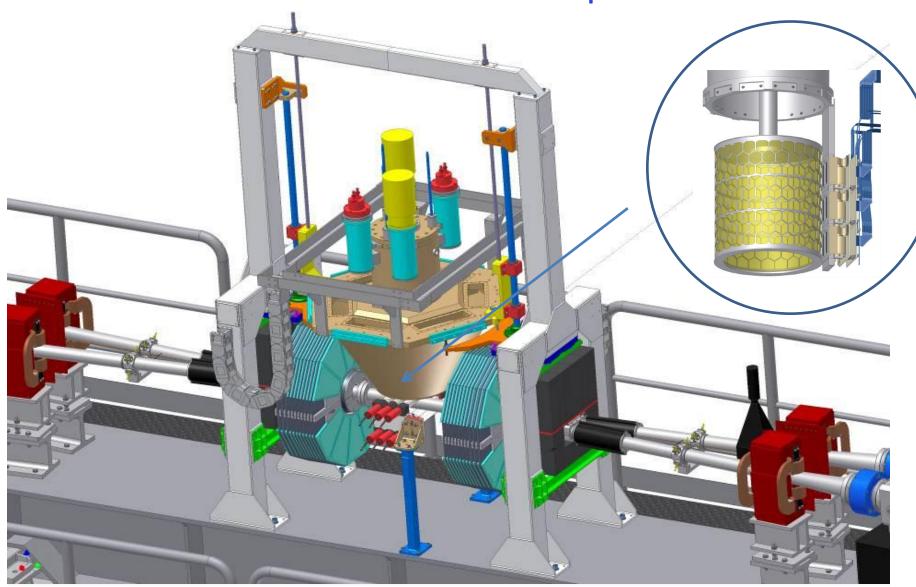
SIDDHARTA SDD Array
144 SDDs =144 cm^2 active area

SIDDHARTA Setup

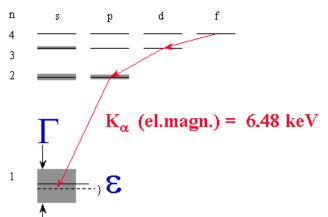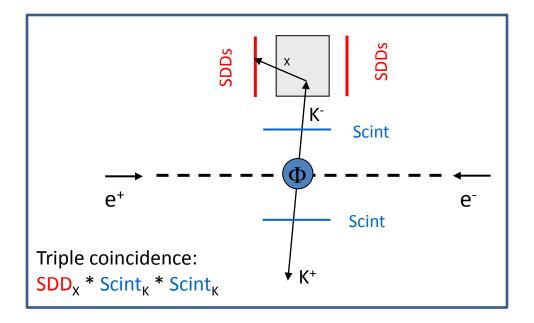# Scheme of SIDDHARTA

Goal: measure the shift and broadening of the X ray transition of kaonic atoms With high precision.

K_{α} (el.magn.) = 6.48 keV

Triple coincidence:
SDD_X * $Scint_K$ * $Scint_K$

New X-ray detectors (SDD silicon drift detectors)

- timing capability → background suppression

  by using the kaon - X ray time correlation

- excellent energy resolution

- high efficiency, large solid angle
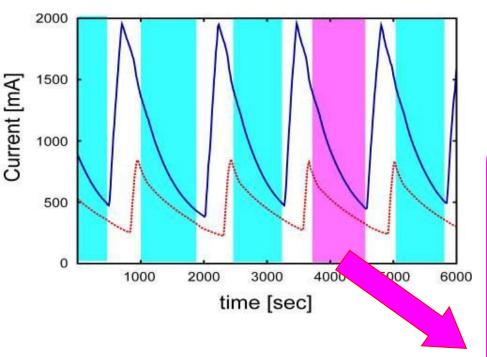
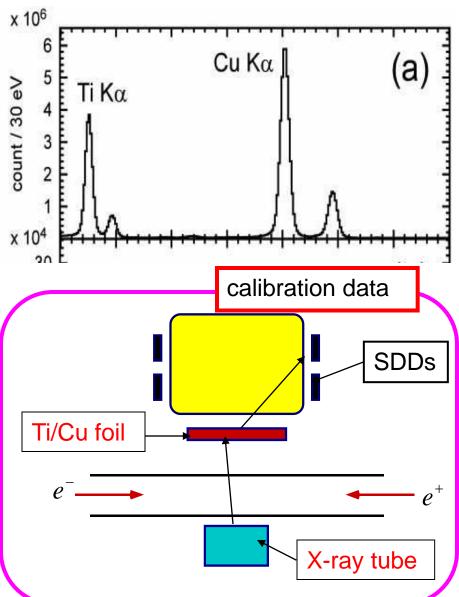- performance in accelerator environment

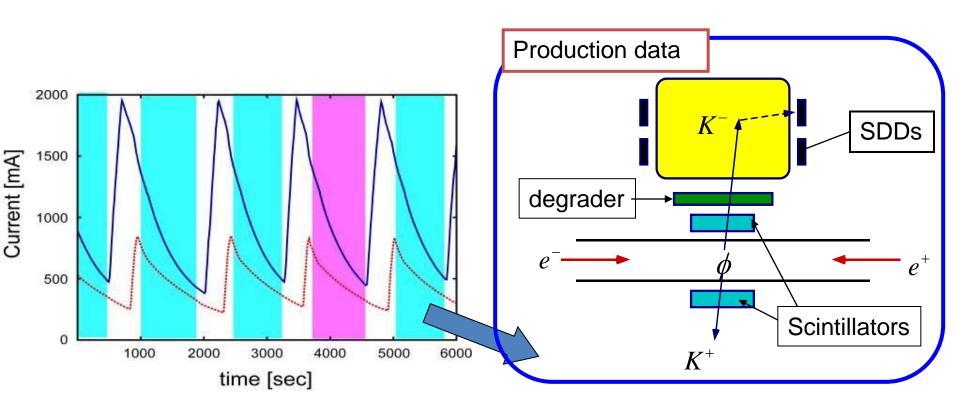# Data taking at DAFNE -Calibration

Estimated
systematic error ~ 3-4 eV

calibration data

SDDs

Ti/Cu foil

e^- e^+

X-ray tube

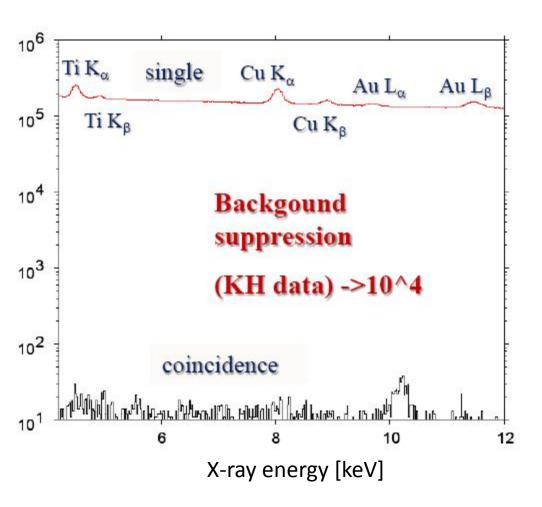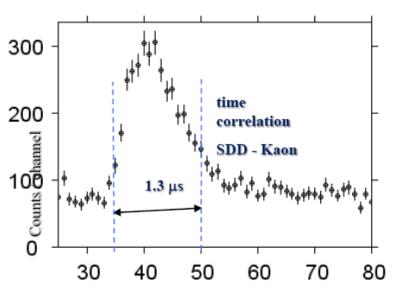# Data taking at DAFNE - Production

Background suppression

Efficient background suppression by using the kaon - x-ray correlation

X-ray energy [keV]
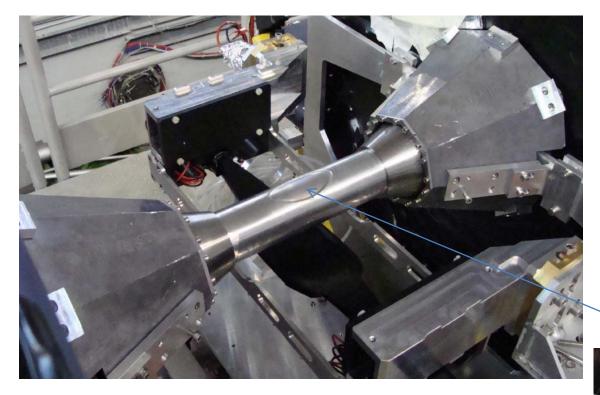

time [83 ns/ch]

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
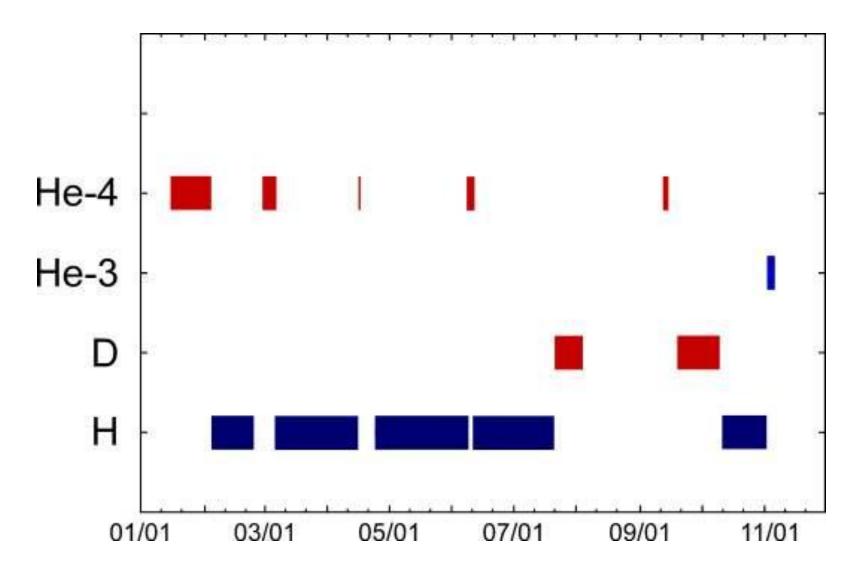
Kaon detectors sitting below and above the intersection

OAW
Austrian Academy of Sciences

Study of Strongly Interacting Matter
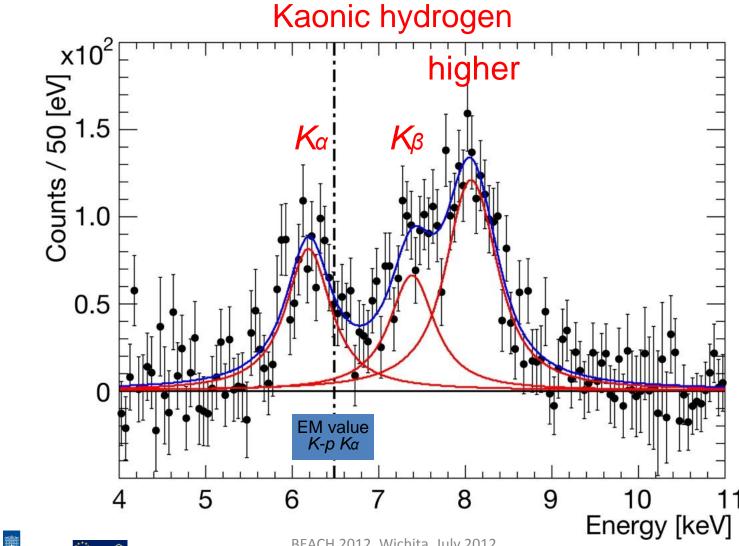HadronPhysics

SIDDHARTA data overview

Residuals of K-p x-ray spectrum
after subtraction of fitted background

KAONIC HYDROGEN results

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

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

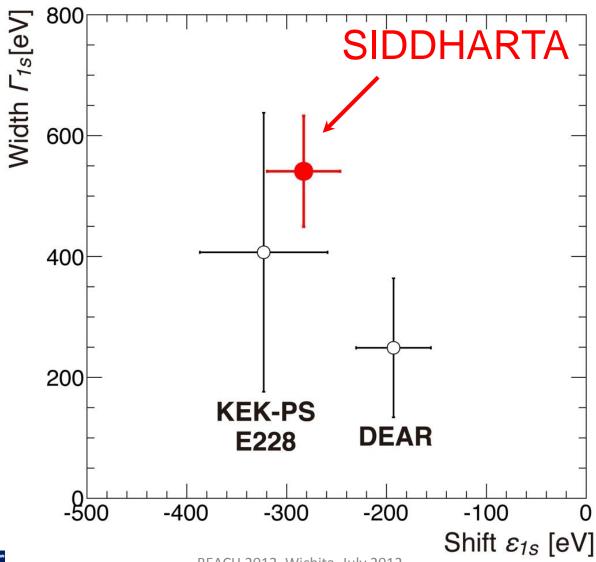With relative yields of K lines known
→ Error in position < 20-25 eV

Kaonic hydrogen result (2011)

EXOTIC ATOMS

Kaonic hydrogen casts new light on strong dynamics

Hadronic bound systems with strange quarks, such as kaonic hydrogen, are well suited for testing chiral dynamics, especially in view of the interplay between spontaneous and explicit symmetry breaking. Effective field theories with coupled channels based on chiral meson–baryon Lagrangians have become well established as a framework for describing $\bar{K}$–nucleon interactions at threshold, including much disputed $\Lambda(1405)$ resonances and deeply bound antikaonic nuclear clusters lying just below the respective thresholds.

A recent precision measurement at the Laboratori Nazionali di Frascati of the strong-interaction-induced shift and width of the 1s level in kaonic hydrogen sheds new light on these basic problems in strong-interaction binding and dynamics. Kaonic hydrogen, in which a $\bar{K}$ replaces the electron, is produced by the capture of

The SIDDHARTA collaboration with the apparatus. (Image credit: C Curceanu.)

stopped $\bar{K}$ from the decay of ϕ mesons in hydrogen gas. The ϕ mesons are generated nearly at rest at the DAΦNE e^+e^- collider, operating in a new, high-luminosity collision mode.

The shift and width of the kaonic 1s state is deduced from precision X-ray spectroscopy of the K-series transitions in the kaonic hydrogen. The emitted K-series X-rays, with energies of 6–9 keV, were detected by the

recently developed Silicon Drift Detector for Hadronic Atom Research by Timing Application (SIDDHARTA) experiment, which performs X-ray–kaon coincidence spectroscopy using microsecond timing and the excellent energy resolution of about 180 eV FWHM at 6 keV of 144 large-area (1 cm²) silicon drift detectors that surround the hydrogen target cell. This method reduces the large X-ray background from beam losses by orders of magnitude. It has led to the most precise values for the 1s level shift, $\varepsilon_{1s} = -283 \pm 36$ (stat.) ± 6 (syst.) eV, and width $\Gamma_{1s} = 541 \pm 89$ (stat.) ± 22 (syst.) eV for kaonic hydrogen (Bazzi et al. 2011).

A recent study using next-to-leading-order chiral dynamics calculations of the shift and the width has shown excellent agreement with these measurements (Ikeda et al. 2011). Further measurements with similar accuracy are planned for the K-series X-rays from kaonic deuterium, using an improved SIDDHARTA-2 set-up to disentangle the isoscalar and isovector scattering lengths.

● **Further reading**
M Bazzi et al. Phys. Lett. **B704** (2011) 113.
Y Ikeda, T Hyodo and W Weise 2011
arXiv:1109.3005 [nucl-th].

Results of SIDDHARTA

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

Kaonic deuterium: 100 pb^{-1}, exploratory first measurement ever, to be published

- Kaonic helium 4: first measurement ever in gaseous target; published in Phys. Lett. B 681 (2009) 310; NIM A628 (2011) 264 and Phys. Lett. B 697 (2011)

- Kaonic helium 3: 10 pb^{-1}, first measurement, published in Phys. Lett. B 697 (2011) 199

A new measurement of kaonic hydrogen X-rays

SIDDHARTA Collaboration

M. Bazzi [a], G. Beer [b], L. Bombelli [c], A.M. Bragadireanu [a,d], M. Cargnelli [e,*], G. Corradi [a], C. Curceanu (Petrascu) [a], A. d'Uffizi [a], C. Fiorini [c], T. Frizzi [c], F. Ghio [f], B. Girolami [a], C. Guaraldo [a], R.S. Hayano [g], M. Iliescu [a,d], T. Ishiwatari [e], M. Iwasaki [h], P. Kienle [e,i], P. Levi Sandri [a], A. Longoni [c], V. Lucherini [a], J. Marton [e], S. Okada [a,*], D. Pietreanu [a,d], T. Ponta [d], A. Rizzo [a], A. Romero Vidal [a], A. Scordo [a], H. Shi [g], D.L. Sirghi [a,d], F. Sirghi [a,d], H. Tatsuno [g,1], A. Tudorache [d], V. Tudorache [d], O. Vazquez Doce [a], E. Widmann [e], J. Zmeskal [e]

Kaonic hydrogen casts new light on strong dynamics – CERN Courier   26.10.11 17:10

CERN Courier

CERN COURIER

Oct 25, 2011

Kaonic hydrogen casts new light on strong dynamics

(http://images.iop.org/objects/ccr/cern/51/9/6/CCnew3_09_11.jpg)
SIDDHARTA (http://images.iop.org/objects/ccr/cern/51/9/6/CCnew3_09_11.jpg)
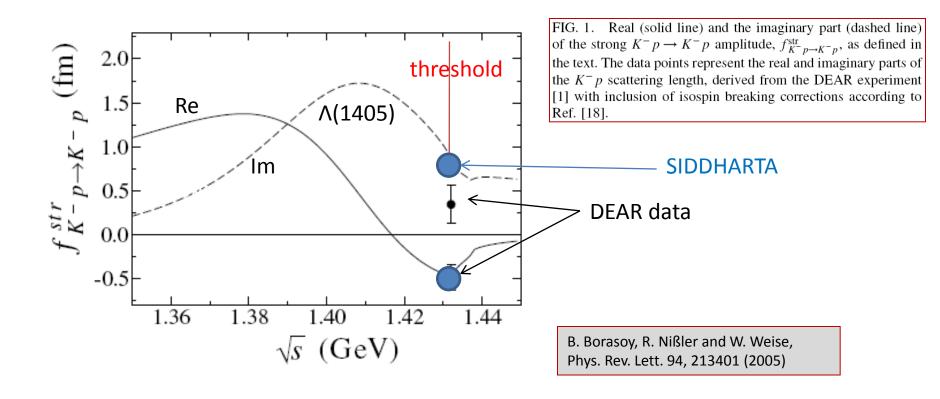
$\overline{\text{K}}$N interaction at threshold

K-p: repulsive character at threshold, attractive below threshold

FIG. 1. Real (solid line) and the imaginary part (dashed line) of the strong $K^- p \rightarrow K^- p$ amplitude, $f^{str}_{K^- p \rightarrow K^- p}$, 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].

B. Borasoy, R. Nißler and W. Weise,
Phys. Rev. Lett. 94, 213401 (2005)
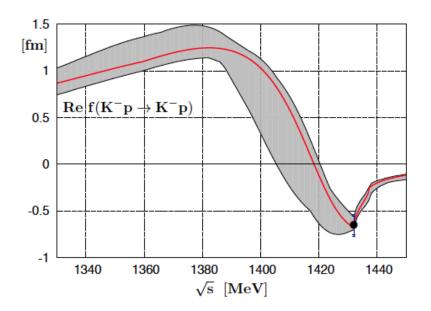
Improved constraints on chiral SU(3) dynamics from kaonic hydrogen
Y. Ikeda, T. Hyodo and W. Weise, arXiv 1109.3005v1v1 (2011)
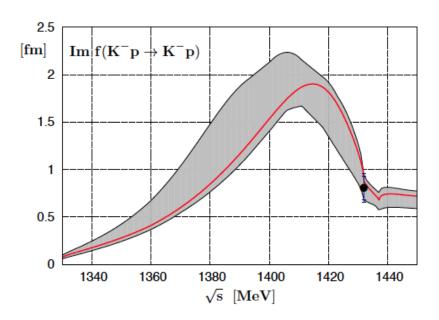PLB 706 (2011) 63

Fig. 3. Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude 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 [7]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.
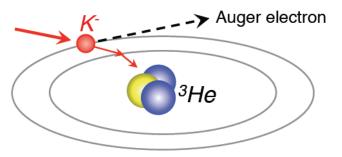
Kaonic helium @ SIDDHARTA

Kaonic Helium

Coulomb-bound system of K⁻ and He nucleus

Result on K⁴He 2p shift (E570 @ KEK)
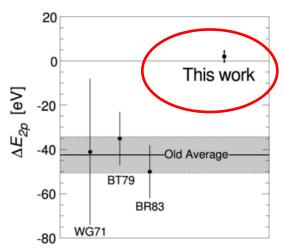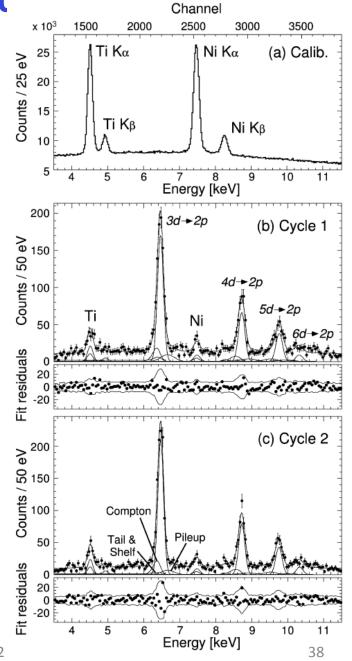
- **Clarification of a puzzle**

Precision measurement of the $3d \rightarrow 2p$ x-ray energy in kaonic ^{4}He

S. Okada [a,*], G. Beer [b], H. Bhang [c], M. Cargnelli [d], J. Chiba [e], Seonho Choi [c], C. Curceanu [f],
Y. Fukuda [g], T. Hanaki [e], R.S. Hayano [h], M. Iio [a], T. Ishikawa [h], S. Ishimoto [i], T. Ishiwatari [d],
K. Itahashi [a], M. Iwai [i], M. Iwasaki [a,g], B. Juhász [d], P. Kienle [d,j], J. Marton [d], Y. Matsuda [a],
H. Ohnishi [a], H. Outa [a], M. Sato [g,l], P. Schmid [d], S. Suzuki [i], T. Suzuki [a], H. Tatsuno [h], D. Tomono [a],
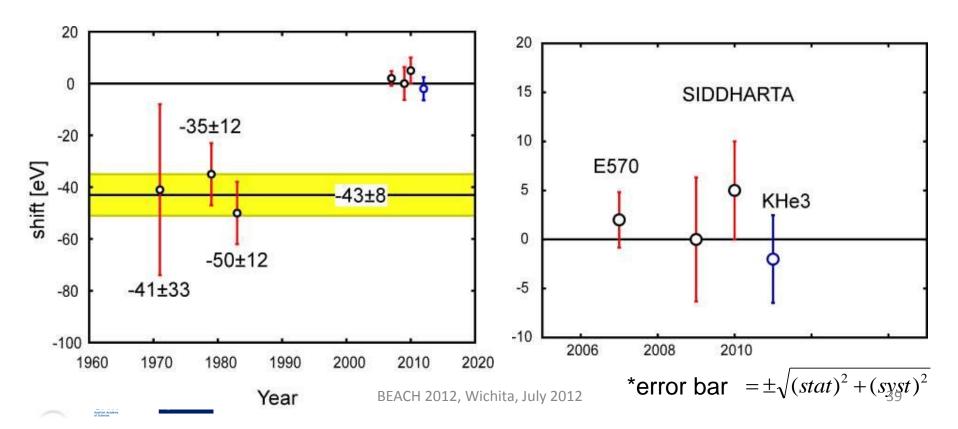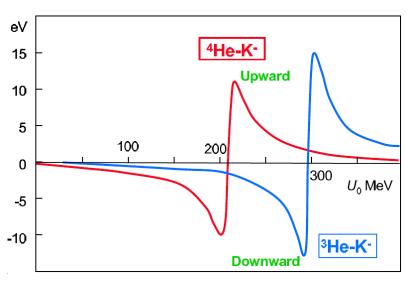E. Widmann [d], T. Yamazaki [a,h], H. Yim [c], J. Zmeskal [d]

Comparison of results

	Shift [eV]	Reference
KEK E570	**+2±2±2**	**PLB653(07)387**
SIDDHARTA (He4 with 55Fe)	**+0±6±2**	**PLB681(2009)310**
SIDDHARTA (He4)	**+5±3±4**	**arXiv:1010.4631,**
SIDDHARTA (He3)	**-2±2±4**	**PLB697(2011)199**

*error bar $= \pm\sqrt{(stat)^2 + (syst)^2}$

K^{4}He vs. K^{3}He
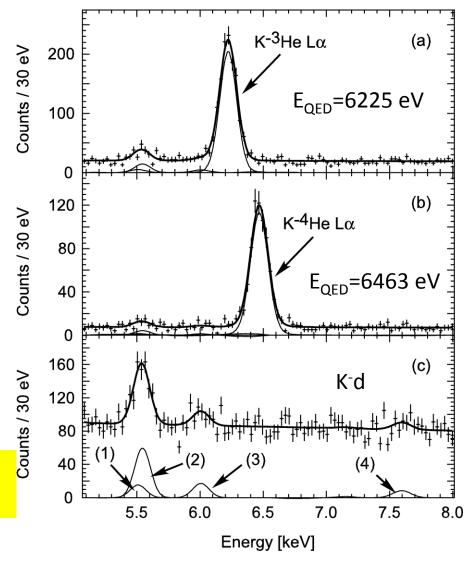

Y. Akaishi, Proc. EXA05, Austrian Academy of Science Press,
eds. A. Hirtl, J.M., E. Widmann, J. Zmeskal

SIDDHARTA

K^{4}He ε_{2p} = +5 $\pm$ 3(stat) $\pm$ 4(syst)
K^{3}He ε_{2p} = -2 $\pm$ 2(stat) $\pm$ 4(syst)

Isotope shift seems to be rather small
but isotopic effect difficult to detect
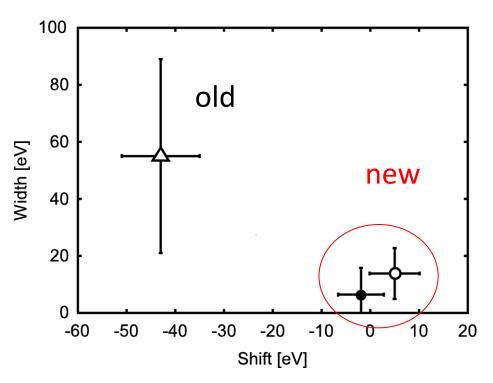
Kaonic helium (^{3}He, ^{4}He) 2p state width

SIDDHARTA Collaboration, Phys. Lett. B714 (2012) 40.

Measurements of the strong-interaction widths of the kaonic ^{3}He and ^{4}He 2p levels

SIDDHARTA Collaboration

M. Bazzi[a], G. Beer[b], L. Bombelli[c], A.M. Bragadireanu[a,d], M. Cargnelli[e], C. Curceanu (Petrascu)[a], A. d'Uffizi[a], C. Fiorini[c], T. Frizzi[c], F. Ghio[f], C. Guaraldo[a], R.S. Hayano[g], M. Iliescu[a,d], T. Ishiwatari[e,*], M. Iwasaki[h], P. Kienle[e,i], P. Levi Sandri[a], A. Longoni[c], J. Marton[e], S. Okada[h], D. Pietreanu[a,d], T. Ponta[d], A. Rizzo[a], A. Romero Vidal[a], E. Sbardella[a], A. Scordo[a], H. Shi[g], D.L. Sirghi[a,d], F. Sirghi[a,d], H. Tatsuno[a], A. Tudorache[d], V. Tudorache[d], O. Vazquez Doce[i], B. Wünschek[e], E. Widmann[e], J. Zmeskal[e]

The determined width of kaonic ^{3}He 2p state is:

$$\Gamma_{2p}\left(^3\text{He}\right) = 6 \pm 6 \text{ (stat.)} \pm 7 \text{ (syst.) eV,}$$

and the width of kaonic ^{4}He 2p state is

$$\Gamma_{2p}\left(^4\text{He}\right) = 14 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.) eV.}$$

Some open questions

- Precision data on antikaon-nucleon interaction requires study of KD to extract scattering lengths a_0 and a_1, important input for theory.

- $\Lambda(1405)$ – pole structure ? Consequences?

- Strength of antikaon-nucleon interaction below threshold.

Goals of SIDDHARTA2

❖ Kaonic atom x-ray spectroscopy taking advantage of DAFNE as ideal kaon source (low energy, monoenergetic...)

❖ Determination of the 1s state shift/width of kaonic deuterium

  ▪ Precision constraints from K- nucleon threshold measurements
  ▪ Important input for the quest of kaonic nuclear clusters

❖ Investigation of the K (np $\rightarrow$ 1s) transitions in kaonic helium

❖ Measurement of other kaonic atoms (gas and solid targets)

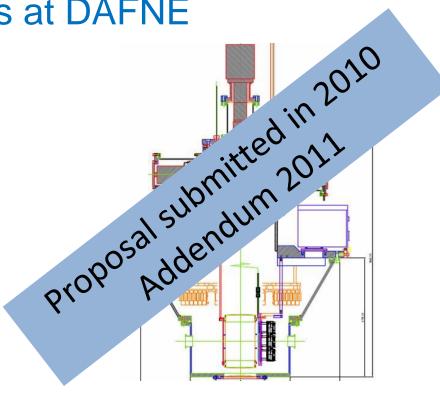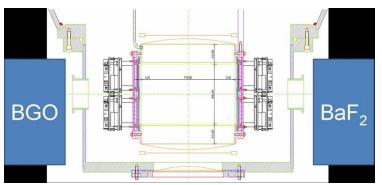❖ Radiative kaon capture study with pure hydrogen (K-p $\rightarrow$ Λ(1405) + γ)

New precision studies of the strong interaction in kaonic atoms at DAFNE

DAFNE 2012?

KLOE setup

Proposal submitted in 2010
Addendum 2011

Enriched physics case (keV-MeV γ detection):

BGO

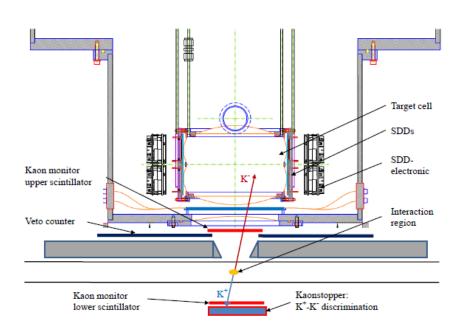BaF$_2$

SIDDHARTA-2 setup improvements

- new target design

- new SDD arrangement

- vacuum chamber

- more cooling power

- improved trigger scheme
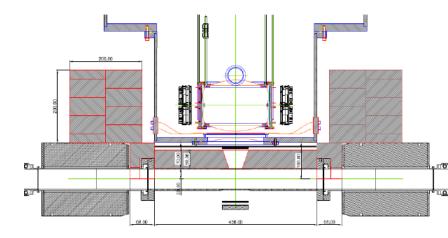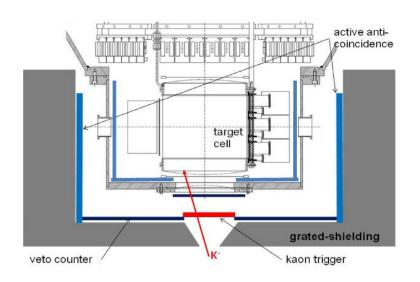
- shielding and anti-coincidence
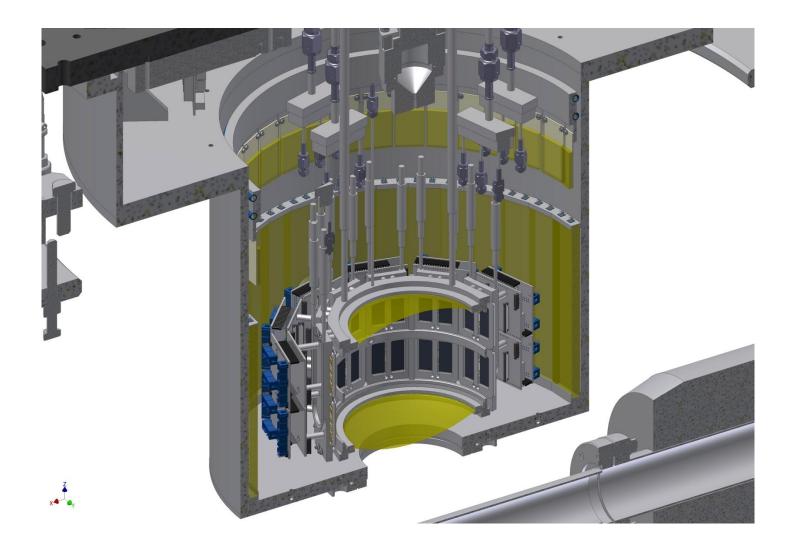
Trigger scheme, shielding

SIDDHARTA2 x-ray detector array inside the insulation vessel

Kaonic deuterium

Once the shift and width of the 1s level for kaonic hydrogen and kaonic deuterium are measured → **scattering lengths a_0, a_1**

$$\varepsilon_{1s} + i\Gamma_{1s} \rightarrow a_{K^- p} \ eV \ fm^{-1}$$

$$\varepsilon_{1s} + i\Gamma_{1s} \rightarrow a_{K^- d} \ eV \ fm^{-1}$$

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

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

"To summarize, one may expect that the combined analysis of the forthcoming high-precision data from DEAR/SIDDHARTA collaboration on kaonic hydrogen and deuterium will enable one to perform a stringent
test of the framework used to describe low–energy kaon deuteron scattering, as well as to extract the values of a0 and a1 with a reasonable accuracy. However, in order to do so, much theoretical work related to the systematic calculation of higher-order corrections within the non-relativistic EFT is still to be carried out." *(from: Kaon-nucleon scattering lengths from kaonic deuterium, Meißner, Raha, Rusetsky, 2006, arXiv:nucl-th/0603029)*
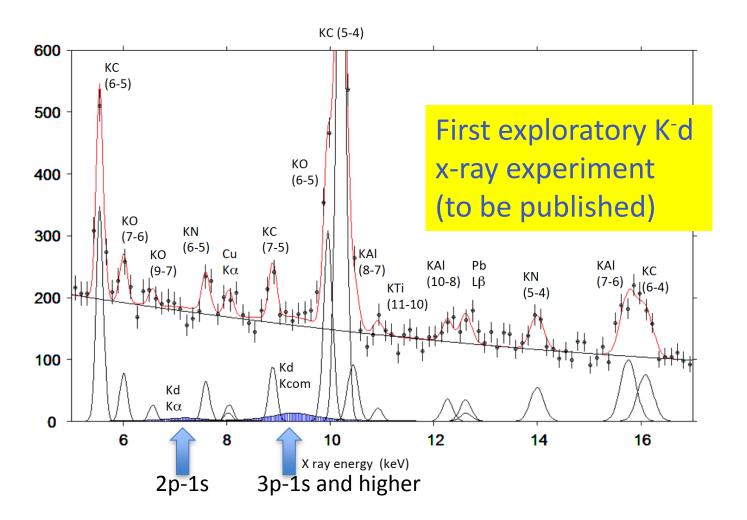
Kaonic deuterium spectrum (SIDDHARTA preliminary)

fit for shift about 500 eV, width about 1000eV, Kα / Kcomplex = 0.4

First exploratory K⁻d x-ray experiment (to be published)
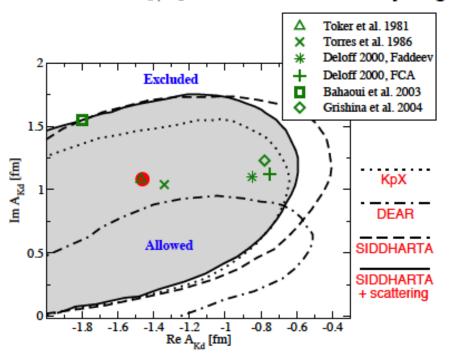
2p-1s   3p-1s and higher

$\bar{K}d$ scattering length

Area, where solutions for a_0, a_1 are consistent with hydrogen data:

M. Döring, U.-G. Meißner, PLB 704 (2011) 663.

Prediction for the scattering length: $A_{Kd} = (-1.46 + i\,1.08)\,\text{fm}$

Predicted uncertainty $\simeq 25\%$ both in real and imaginary parts
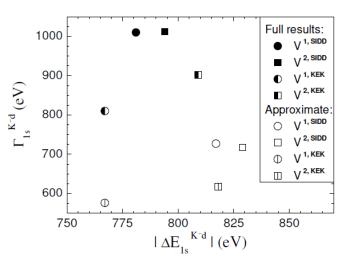
Kaonic deuterium: expected values

Compilation of predicted K⁻ d scattering lengths a_d and corresponding experimental values ε_{1s} and Γ_{1s} calculated from eq. 1.

Modified Deser formula next-to-leading order in isospin breaking (Meißner, Raha, Rusetsky 2004[a])
(μ_c reduced mass of K⁻d)

$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_d\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_d\right) \quad (1)$$
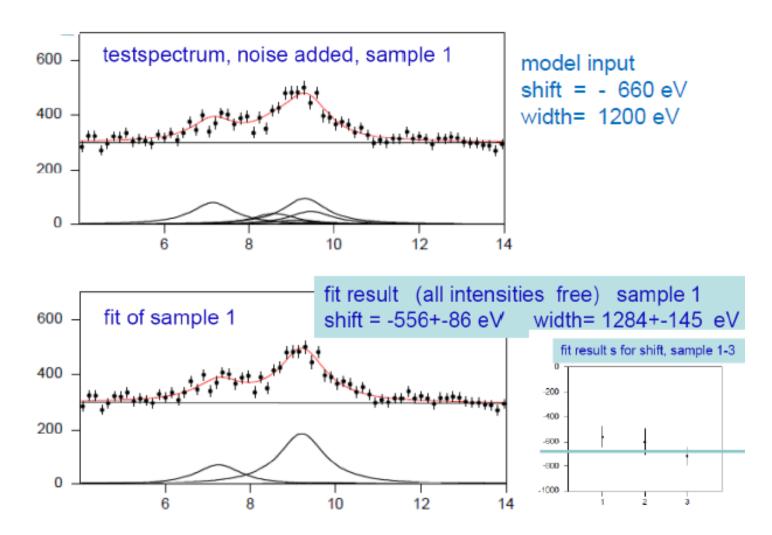
[a] U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
[b] The precision of a_d is quoted to be ~25%

[1] M. Döring, U.-G. Meißner, Phys. Lett. B 704 (2011) 663
[4] N.V. Shevchenko, arXiv:1103.4974v2 [nucl-th] (2011)
[5] A. Gal, Int. J. Mod. Phys. A22 (2007) 226
[6] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. phys. J. C47 (2006) 473
[7] N.V. Shevchenko, arXiv:1201.3173v1 [nucl-th] (2012)

| a_d [fm]	ε_{1s} [eV]	Γ_{1s} [eV]	Reference
-1.48 + i 1.22	818	724	Shevchenko 2012 „one-pole" [7]
-1.51 + i 1.23	829	715	Shevchenko 2012 „two-pole" [7]
-1.46 + i 1.08	779	650	Meißner 2011 [b] [1]
-1.49 + i 0.98	767	578	Shevchenko 2011 „one-pole" [4]
-1.57 + i 1.11	818	618	Shevchenko 2011 „two-pole" [4]
-1.42 + i 1.09	769	674	Gal 2007 [5]
-1.66 + i 1.28	884	665	Meißner 2006 [6]
-1.48 + i1.22	781	1010	Shevchenko 2011 „one-pole"-full [4]
-1.51 + i 1.23	794	1012	Shevchenko 2011 „two-pole"- full [4]

Kaonic deuterium with SIDDHARTA
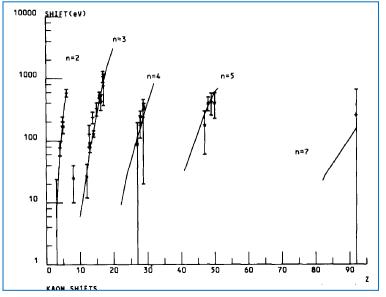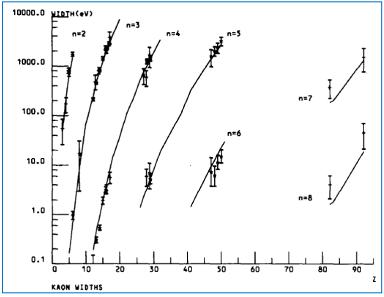
New experiments

- Spectroscopy of kaonic atoms with Z>2 improving the precision of the data set

C.J. Batty , E. Friedmann, A. Gal, Phys. Rep. 287 (1997) 385, E. Friedmann and A. Gal, Phys. Rep. 452 (2007) 89

The main source of error in the energy measurements comes from the statistics on the peak position in the data. In general the calibration peaks were determined much more precisely and hence have little effect on the overall error. Exceptions are the
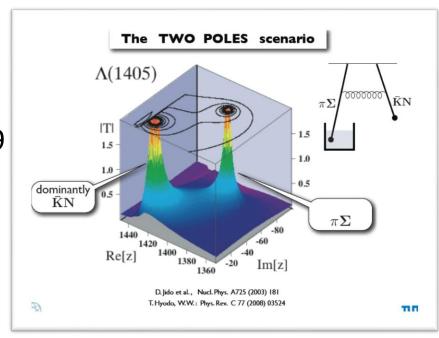
The Lambda(1405) Resonance

- Generated by the attractive Kbar-N interaction

- Quasi-bound state decaying into $\Sigma\pi$

- Predicted by Dalitz and Tuan in 1959

- After more than 50 years still a challenging object in experiment and theory

- Relation to nuclear bound states mediated by the attractice Kbar-N interaction (K-p bound state?)

- New idea by S. Wycech: $K^-p\rightarrow\Lambda(1405)+\gamma$

The TWO POLES scenario

$\Lambda(1405)$

dominantly $\bar{K}N$

$\pi\Sigma$

D. Jido et al., Nucl. Phys. A725 (2003) 181
T. Hyodo, W.W.: Phys. Rev. C 77 (2008) 03524

Review

The nature of the $\Lambda(1405)$ resonance in chiral dynamics

Tetsuo Hyodo [a], Daisuke Jido [b,*]

Summary

- SIDDHARTA – a key experiment for $\overline{K}$-N interaction at low energy

- Final data analyses $\rightarrow$ most precise data on K^-p x-ray transitions

- SIDDHARTA final data on K^-p, K^-d, $K^{-3}He$, $K^{-4}He$

- SIDDHARTA data $\rightarrow$ Impact for theory

- Agreement between scattering data and atom-spectroscopic data

- Close collaboration of experimentalists and theoreticians extremely important $\rightarrow$ LEANNIS (HP3)

Thank you for your attention

If you haven't found something strange during the day, it hasn't been much of a day.
(John Wheeler)

Spare

SIDDHARTA2

New ideas
SIDDHARTA-2

	SIDDHARTA autumn 2009	SIDDHARTA-2 new - geometry - gas density - timing resolution	improve-ment factor
gas cell: diameter x height (cm)	13.9 x 15.5	17 x 14	
entrance distance from IP (cm)	20	15	
gas density rel. LHD	< 1.5 %	3 %	
upper trigger scint.	4.9 x 6 cm^2	diameter 9 cm	
dist. from IP (cm)	6	13	
triggers per kaonpair	9.4 %	5.3 %	
K$^-$ gasstops per kaonpair (triggered)	0.78 %	1.94 %	
Signal	827 /pb^{-1}	2035 /pb^{-1}	**2.5**
trigger per signal	188	39	**4.8**
synchr. continous backgr. /Signal /keV at ROI	0.3 %	0.08 %	**3.8**
KC / Signal (kaonic lines from wall stops)	4 %	0.2 %	**20**
SDD timing resolution (ns)	750	500	**1.5**
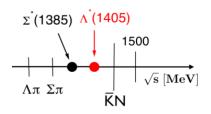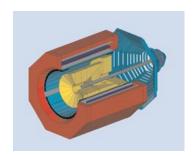
EU-FP7

Joint work of theoreticians and experimentalists extremely important

L ow

E nergy

A ntikaon

N ucleus

N uclei

I nteraction

S tudies