Precision spectroscopy of light kaonic atom X-rays in the SIDDHARTA experiment

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

On behalf of: The SIDDHARTA collaboration

Garching

Munich

Vienna

Bucarest

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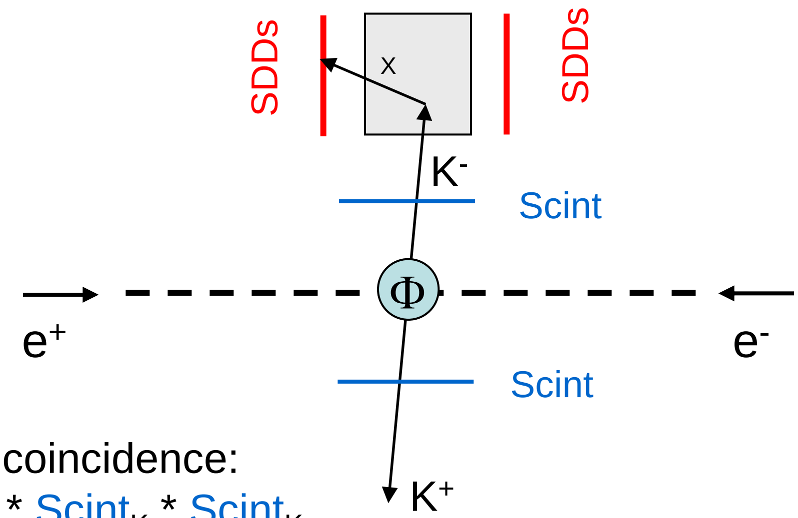
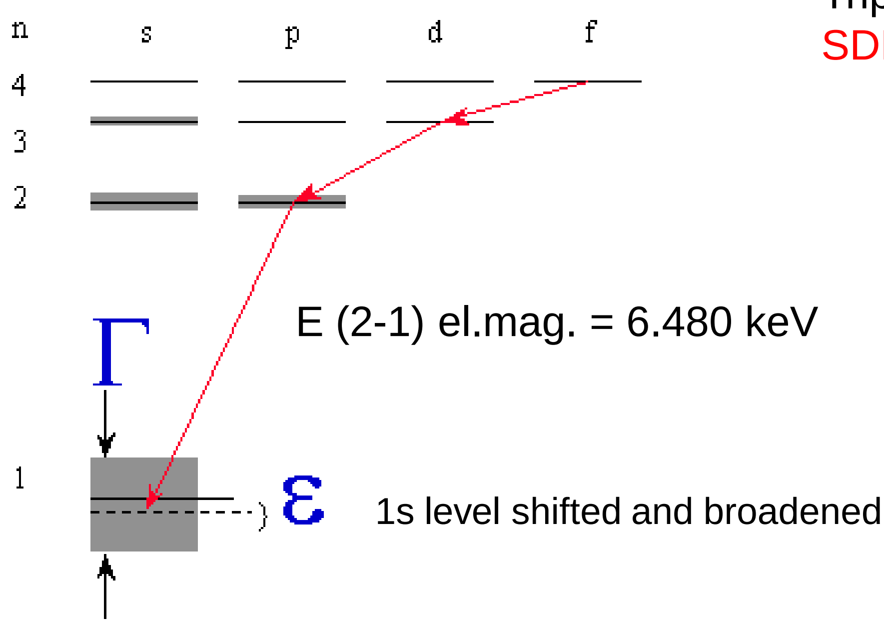
SIDDHARTA - What is it ?

Goal: measure the shift and broadening of the X ray transition of light kaonic atoms. The ground state is affected by the strong interaction of the kaon and the nucleus. Delivers input for effective theories in low energy QCD



Triple coincidence:
$SDD_X * Scint_K * Scint_K$



New X-ray detectors (SDD silicon drift detectors)

- timing capability → background suppression
- excellent energy resolution
- high efficiency, large solid angle
- performance in accelerator environment

Hadronic atoms in QCD

Objects of type ($\bar{K}$ X), (π^-, X) with X = p, d, ^{3}He, ^{4}He,.. or $\pi^+ \pi^-$ π K $\bar{p}$ He

Bound electromagnetically, binding well known
Strong interaction (mediated by QCD) $\rightarrow$ modify binding
$\rightarrow$ decay of object

in some cases: small perturbation
$\rightarrow$ energy shift and width can be related to T-matrix elements at threshold (Deser[1] type formulas)

compare to results from low energy scattering experiments[2]

Low energy phenomena in strong interaction can not be described in terms of quarks and gluons, instead *effective theories* are used (they have some degrees of freedom to accomodate experimental data)

[1] Deser relation in some cases not sufficient to compare to high precision experimental data
[2] Problems: extrapolation to E=0 and quality of old experimental data

QCD predictions

Chiral perturbation theory was extremely successful in describing systems like πH, but *can not be used for KH*. Main reason is the presence of the Λ(1405) resonance only 25 MeV below threshold.

Effective field theory ↔ scattering data
Effective field theory ↔ atomic X ray data
Effective field theory ↔ energy, width of resonances

There exist non-perturbative coupled channel techniques which are able to generate the Λ(1405) dynamically as a Kbar N quasibound state and as a resonance in the π Σ channel

Kaonic hydrogen – Deser formula

With a_0, a_1 standing for the I=0,1 S-wave $\bar{K}N$ complex scattering lengths in the isospin limit ($m_d = m_u$), μ being the reduced mass of the K^-p system, and neglecting isospin-breaking corrections, the relation reads:

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

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

… a linear combination of the isospin scattering lengths a_0 and a_1
to disentangle them, also the kaonic deuterium scattering length is needed

„By using the non-relativistic effective Lagrangian approach a complete expresson 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 lenghts from kaonic atom data“[2]

[2]Meißner,Raha,Rusetsky, 2004

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 !

Elaborate procedures needed to connect the observables with the underlaying physics parameters.

"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)

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

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

Impulse approximation term

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

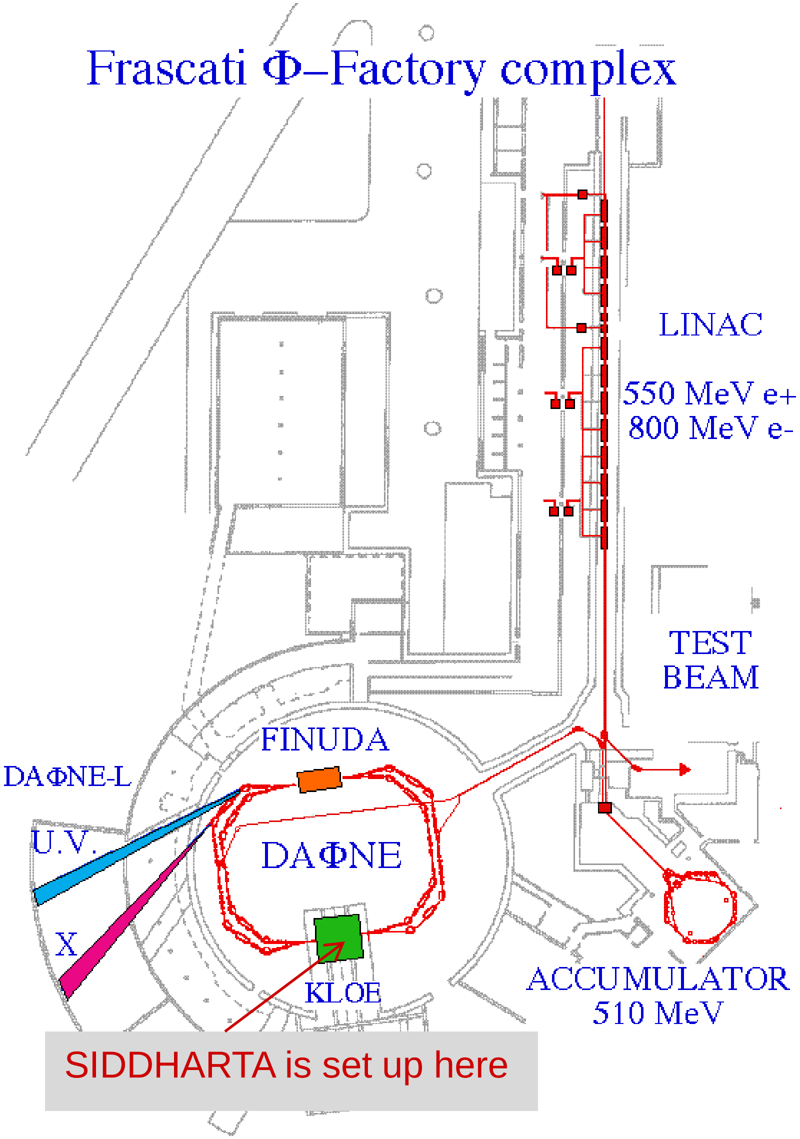
larger then leading term

$$a^{(0)} = \frac{1}{2}\left[a_{K^-p} + a_{K^-n}\right] = \frac{1}{4}[a_0 + 3a_1]$$

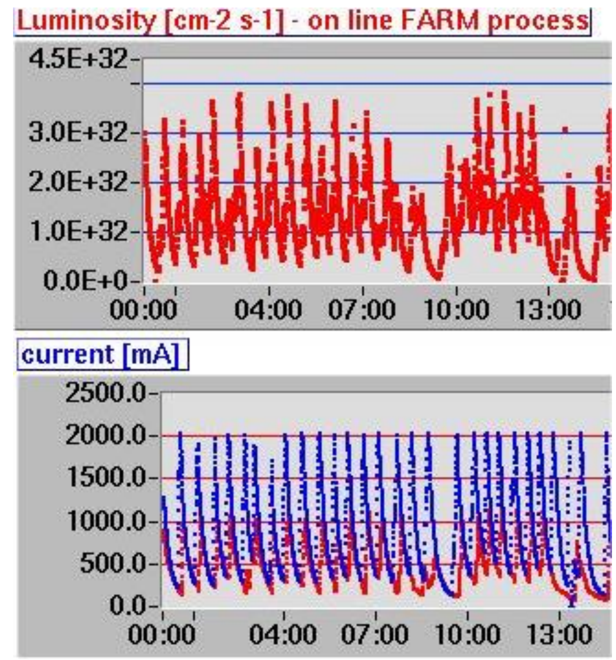
Summary of physics framework and motivation

- Exotic (kaonic) atoms – probes for strong interaction
  - hadronic shift ε_{1s} and width Γ_{1s} directly observable
  - experimental study of low energy QCD. Testing chiral symmetry breaking in strangeness systems
- Kaonic hydrogen
  - Kp simplest exotic atom with strangeness
  - kaonic hydrogen „puzzle“ solved – but: more precise experimental data important
  - kaonic deuterium never measured before
  - atomic physics: new cascade calculations (to be tested !)
- Information on Λ(1405) sub-threshold resonance
  - responsible for negative real part of scattering amplitude at threshold
  - important for the search for the controversial „deeply bound kaonic states” present / upcoming experiments (KEK,GSI,DAFNE,J-PARC)
- Determination of the isospin dependent KN scattering lengths
  - no extrapolation to zero energy

DAΦNE



electron-positron collider, energy at phi resonance
phi produced nearly at rest.
(boost: 55 mrad crossing angle → 28 MeV/c)
charged kaons from phi decay: E_k = 16 MeV
degrade to < 4MeV to stop in gas target



Φ production cross section ~ 3000 nb (loss-corrected)
Integr. luminosity 2009 **~ 6 pb^{-1} per day** [1] (~ 10^7 $K^\pm$)
(increased by crabbed waist scheme)
Peak luminosity ~ 3 × 10^{32} cm^{-2} s^{-1} = 450 Hz $K^\pm$
[1] we can not use kaons produced during injections.

compare situation during DEAR data taking **(2002)**
currents ~ 1200/800 ~ 1 pb^{-1} per day, peak ~ 3×10^{31} cm^{-2} s^{-1}

The challenge

to do low energy X ray spectroscopy at an accelerator !

The radiation environment produces **a lot of charge** in Si detectors

„Beam background“ Touschek scattering – stray 510 MeV $e^{\pm}$ - **e.m. showers.**
$e^{\pm}$ from Babha scattering – Showers.
not correlated to charged kaon pairs; „accidentals“

μ, π, e from K decay; **Λ, π,..** from K- absorption, kaonic X rays from K^- wallstops
synchronous background – has trigger signal – remains in triggered setup
„hadronic background“

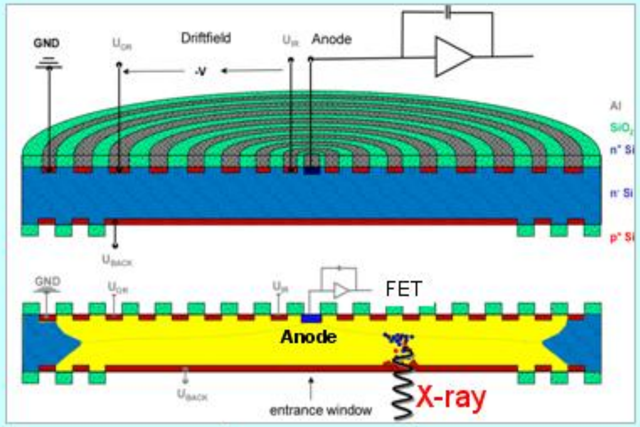
S: Signal, B: background,
T: trigger rate,
S_T : signal per trigger
Δt: coincidence width,
A: accidental rate,
H_T: hadronic background in ROI, per trigger

$$S / B = \frac{T \cdot S_T}{T \cdot (\Delta t \cdot A + H_T)}$$

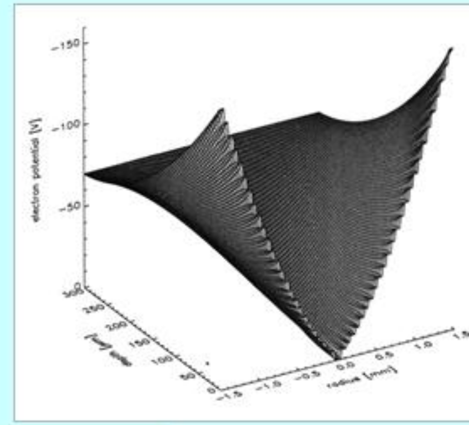
Function principle

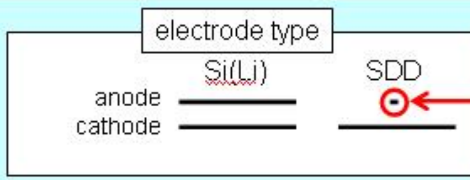
SDD (Silicon Drift Detector)

Schematic drawing



potential distribution





$$Q = CV$$
$$= (\varepsilon_0 S / d)\, V$$

Small capacitance

The small capacitance results in a large amplitude and a short rise time of the signal

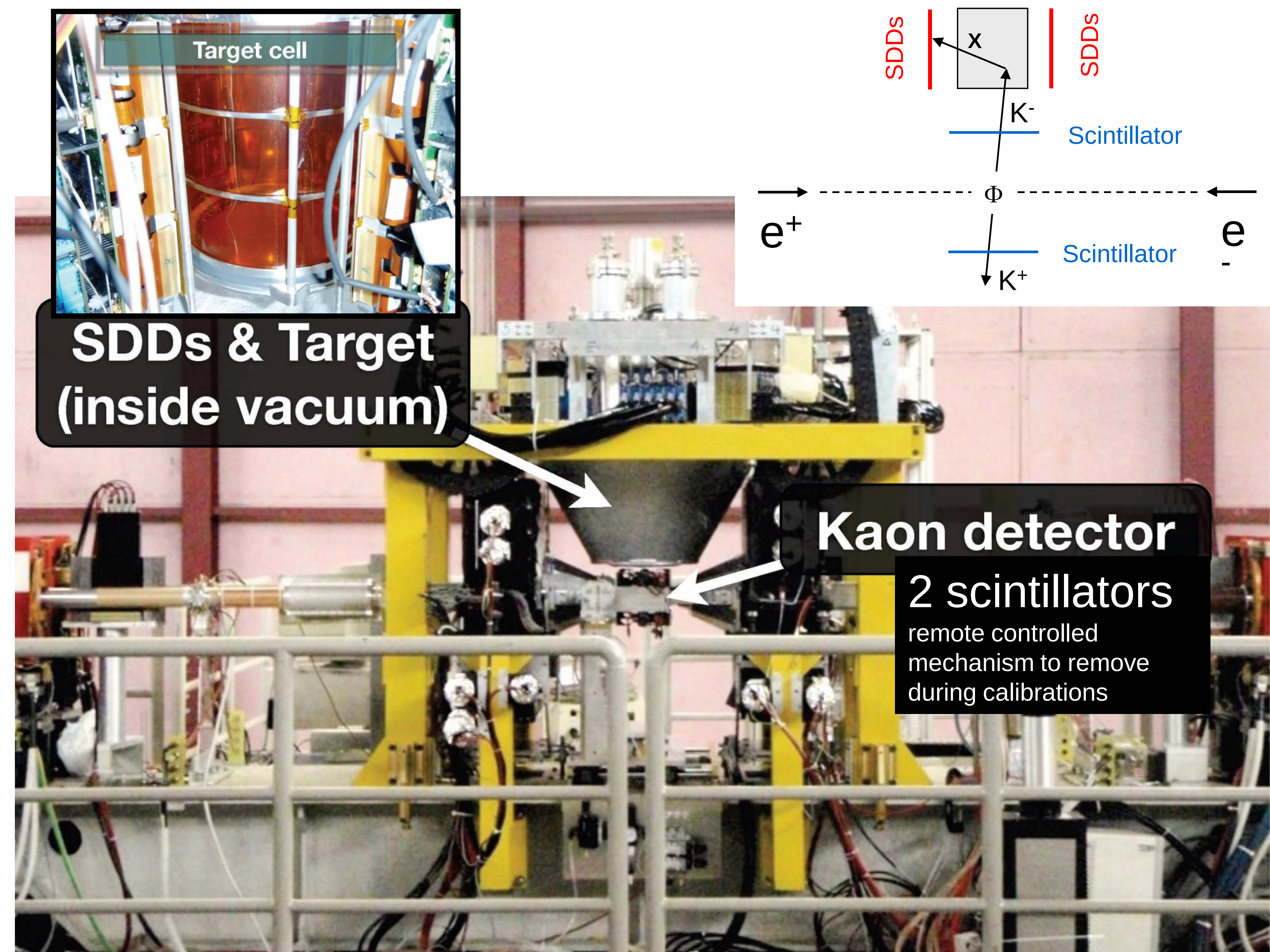
Compared to conventional photodiodes SDDs can be operated at higher rates and have better energy resolution.

A lateral field makes the produced charge drift to the collecting anode.

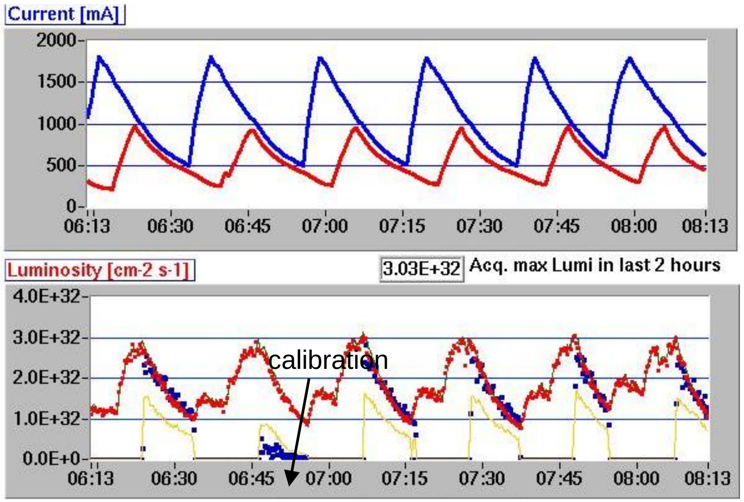
different from standard electronic devices:

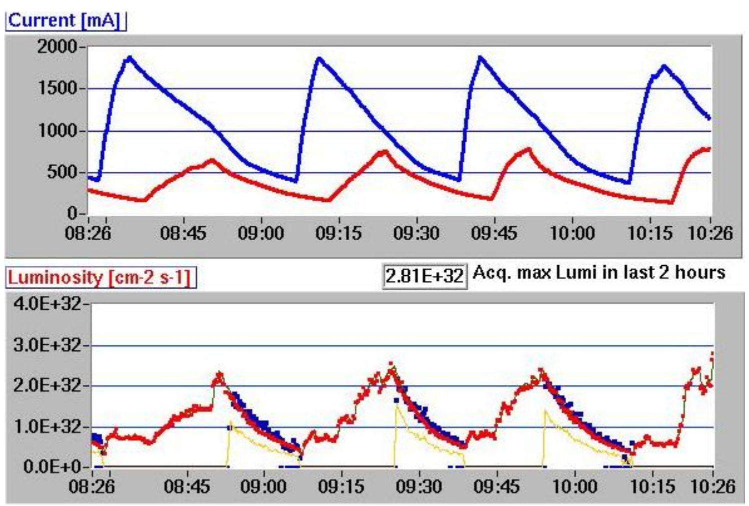
- double sided structure
- not passivated
- large area chips
- arrangement of bond pads in the center

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


Target cell
SDDs & Target
(inside vacuum)
SDDs
x
SDDs
K-
Scintillator
e+
Φ
e-
Scintillator
K+
Kaon detector
2 scintillators
remote controlled
mechanism to remove
during calibrations

Luminosity





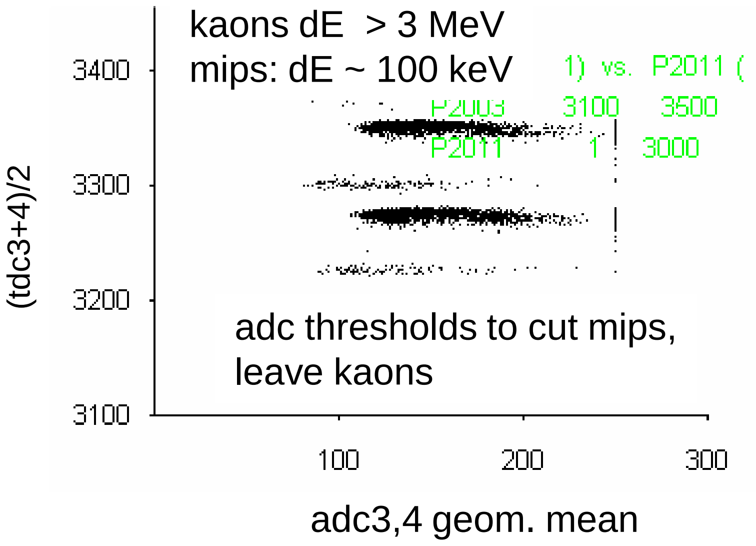
siddharta can work only between injections (blue dots, yellow line)

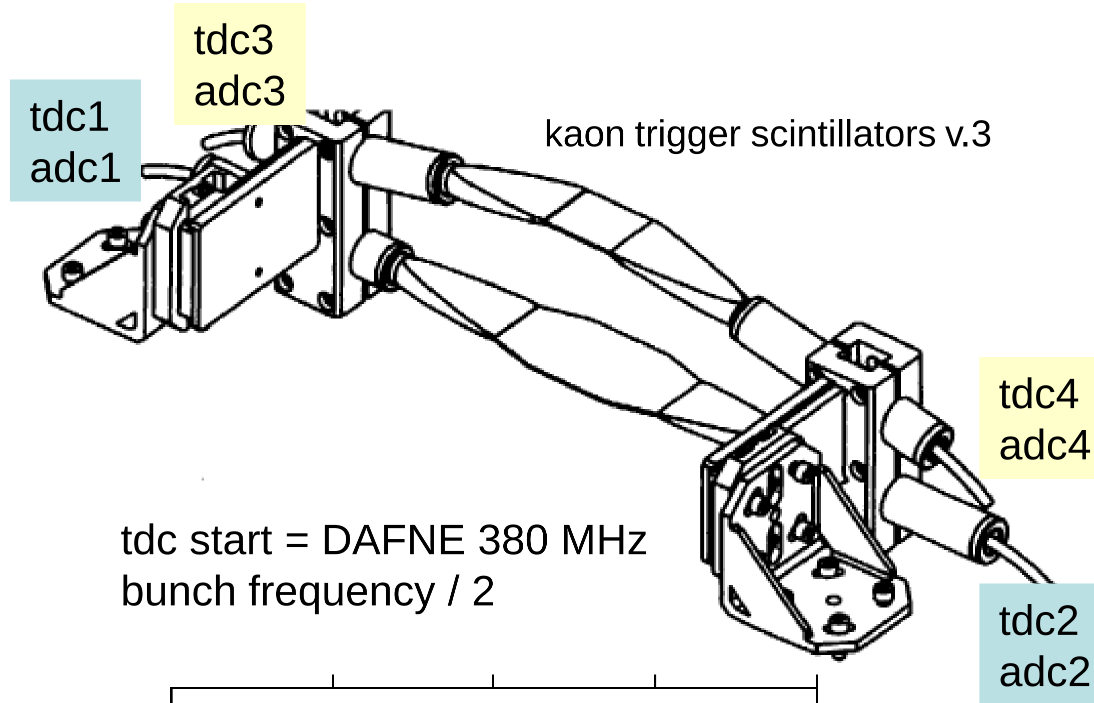
under good conditions during siddharta DAQ ~ 2.8e32 – 1.0e32 $cm^{-2}\ s^{-1}$ luminosity

compare to 2002 DEAR experiment:
~ 3.0e31 $cm^{-2}\ s^{-1}$
now up to 10 times higher !

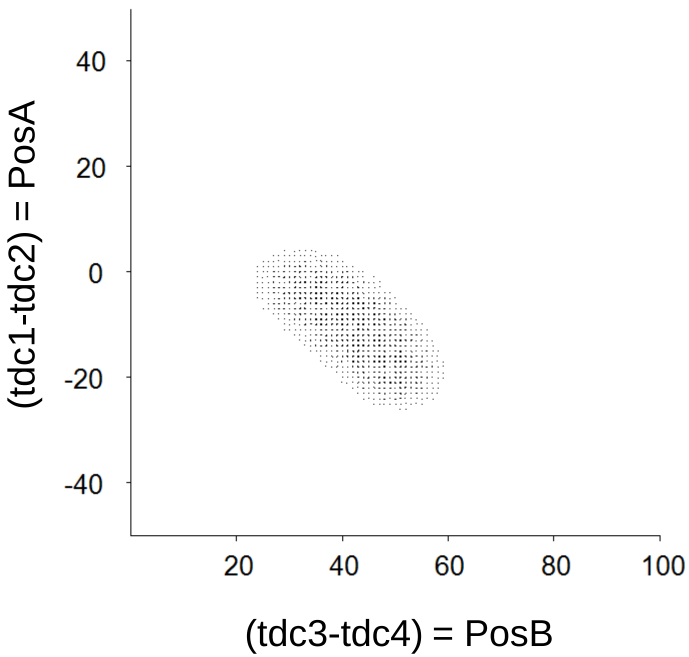
siddharta integrated luminosity
on 23 Oct 2009: ~ 8 pb^{-1} !

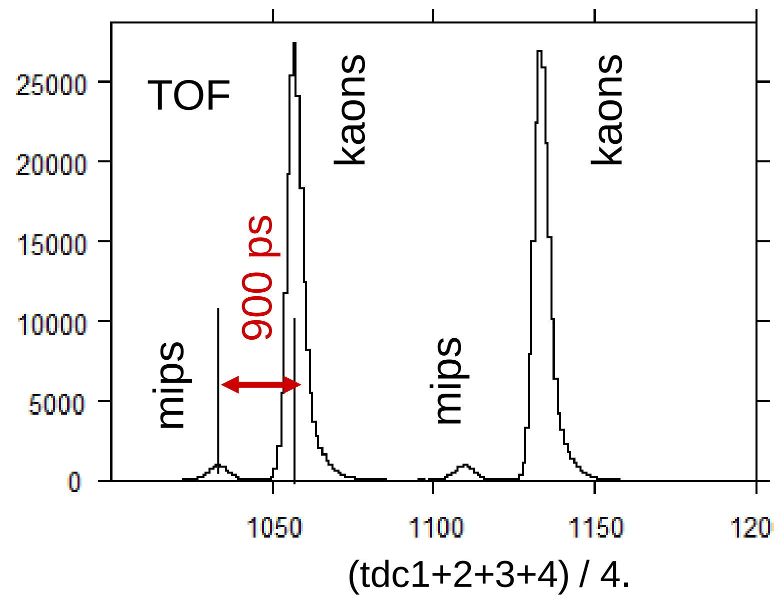
Kaon trigger





tdc start = DAFNE 380 MHz
bunch frequency / 2





Data analysis

What the Data Aquisition System stores:

- Energies and detector numbers of X ray hits
- event id-number, time-tag

if a kaontrigger happend:
- the time correlation between X-ray and kaon
- the kaon detector parameters

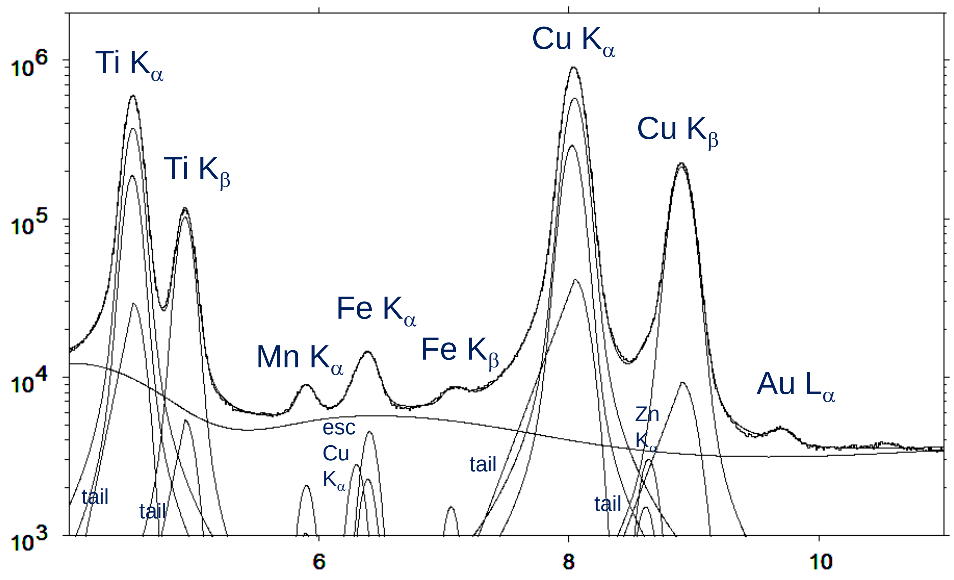
- DAFNE current values

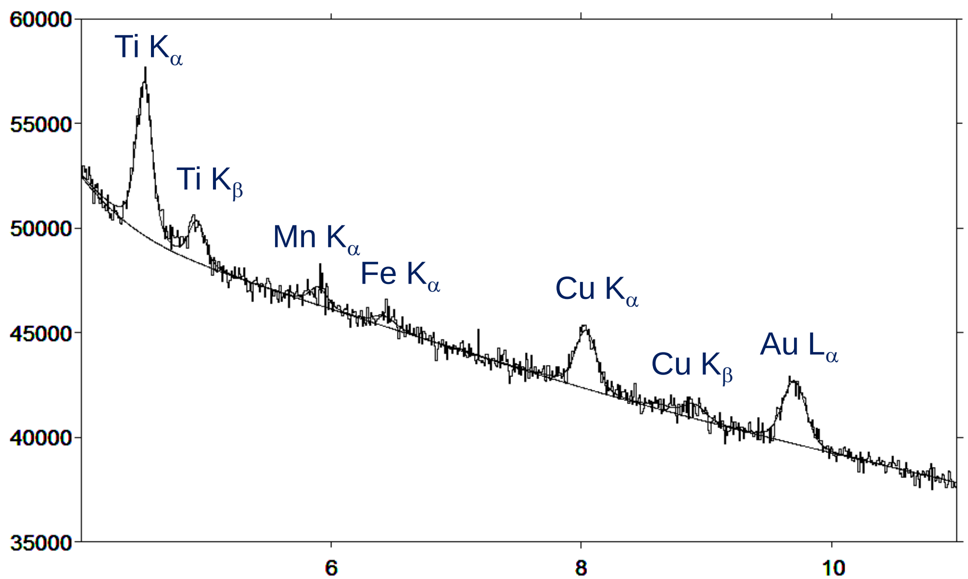
From this we can derive in off-line analysis:

- the kaondetector TOF to discriminate against MIPS
- kaondetector position information from the timedifference of the PMs at both ends
- sdd rates (e.g. counts during last second)
- kaon rates (-- „ --)
- number of hits without vs. hits with kaon coincidence
- multiplicity of hits
- kaons per Xray

Analysis task:
select cuts on above listed parameters
periodically update calibration and selection of best sdds

Energy calibration





Calibration: periodic xray-tube switch on <u>during beam</u>
Ti + Cu K_α lines

line shape to fit detector response (sum of 100 sdds with individual resolution, small asymmetry effect)

compare selftrigger spectrum without Xtube - fluorescense lines excited by background

Published results

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Physics Letters B ••• (••••) •••–•••

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Kaonic helium-4 X-ray measurement in SIDDHARTA

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[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], V. Lucherini[a], J. Marton[e], S. Okada[a], D. Pietreanu[a], 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], A. Tudorache[d], V. Tudorache[d], O. Vazquez Doce[a], E. Widmann[e], J. Zmeskal[e]

[a] INFN, Laboratori Nazionali di Frascati, Frascati (Roma), Italy
[b] Dep. of Phys. and Astro., Univ. of Victoria, Victoria B.C., Canada
[c] Politechno di Milano, Sez. di Elettronica, Milano, Italy
[d] IFIN-HH, Magurele, Bucharest, Romania
[e] Stefan-Meyer-Institut für subatomare Physik, Vienna, Austria
[f] INFN Sez. di Roma I and Inst. Superiore di Sanita, Roma, Italy
Japan

- Kaonic Helium-4 publication
confirming the KEK E570 result using a gaseous target

- KHe4 publication concerning yields of the transitions: under preparation

- KHe3 paper: work in progress

Table 1
Energy shift of the kaonic helium 2*p* state [4]

ΔE_{2p} (eV)	Ref.
-41 ± 33	Wiegand *et al.* [1]
-35 ± 12	Batty *et al.* [2]
-50 ± 12	Baird *et al.* [3]
-43 ± 8	Average of above [3,4]
$+2 \pm 2$ (stat) ± 2 (syst)	Okada *et al.* [5]
0 ± 6 (stat) ± 2 (syst)	This work

[1,2,3] liquid He, [5] liq. He, Compton scattering corrected,
[This] gaseous He, Compton negligable

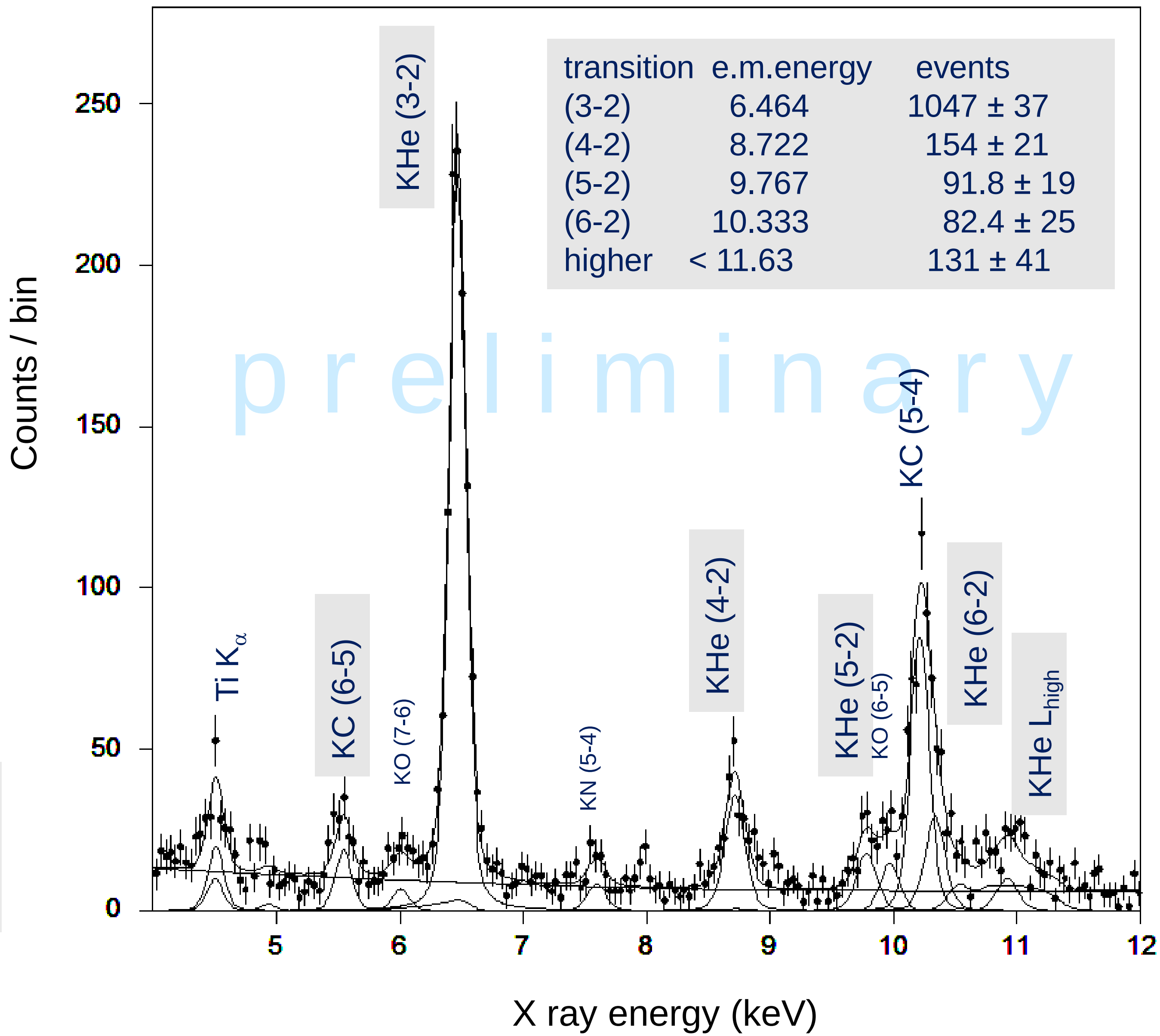
Fit of Kaonic Helium 4

KHe used for **gasstop optimization** + physics interest[1])

data from setup 2
(no Fe55 source)

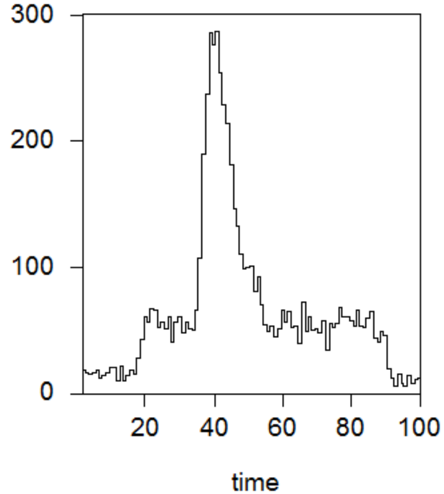
shift = + 2.1 eV
+- 2.9 eV (stat.)
+- 4 eV (syst.)

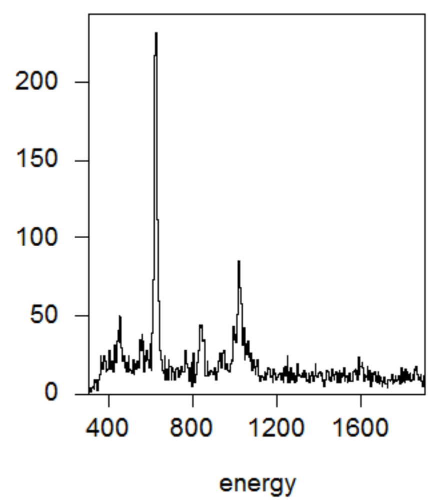
[1]) compare KEK E570
KHe L lines in liquid He,
consistent result,
first measurement in gas



Kaonic Helium 3 data

time correlation
(83 ns per chan.)

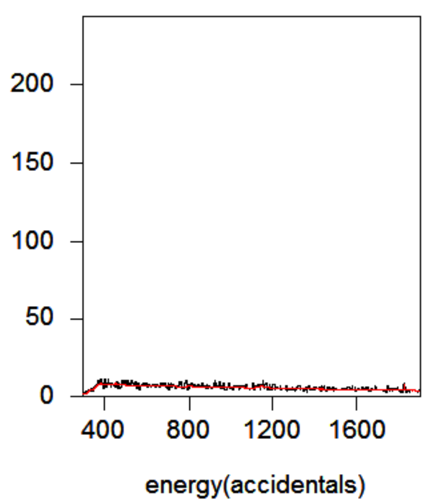


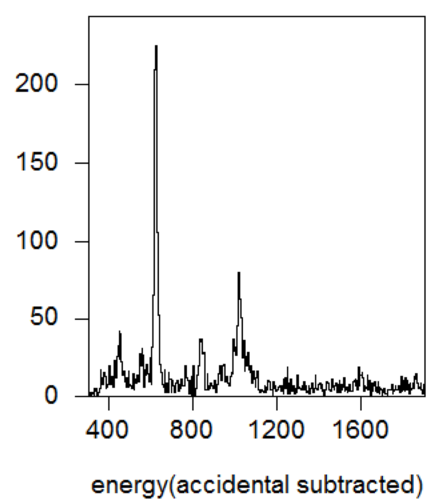


energy spectrum
for timewindow
ch. 37-46 (830 ns)

10 eV per chan.

energy spectrum
for timewindow
out of correlation





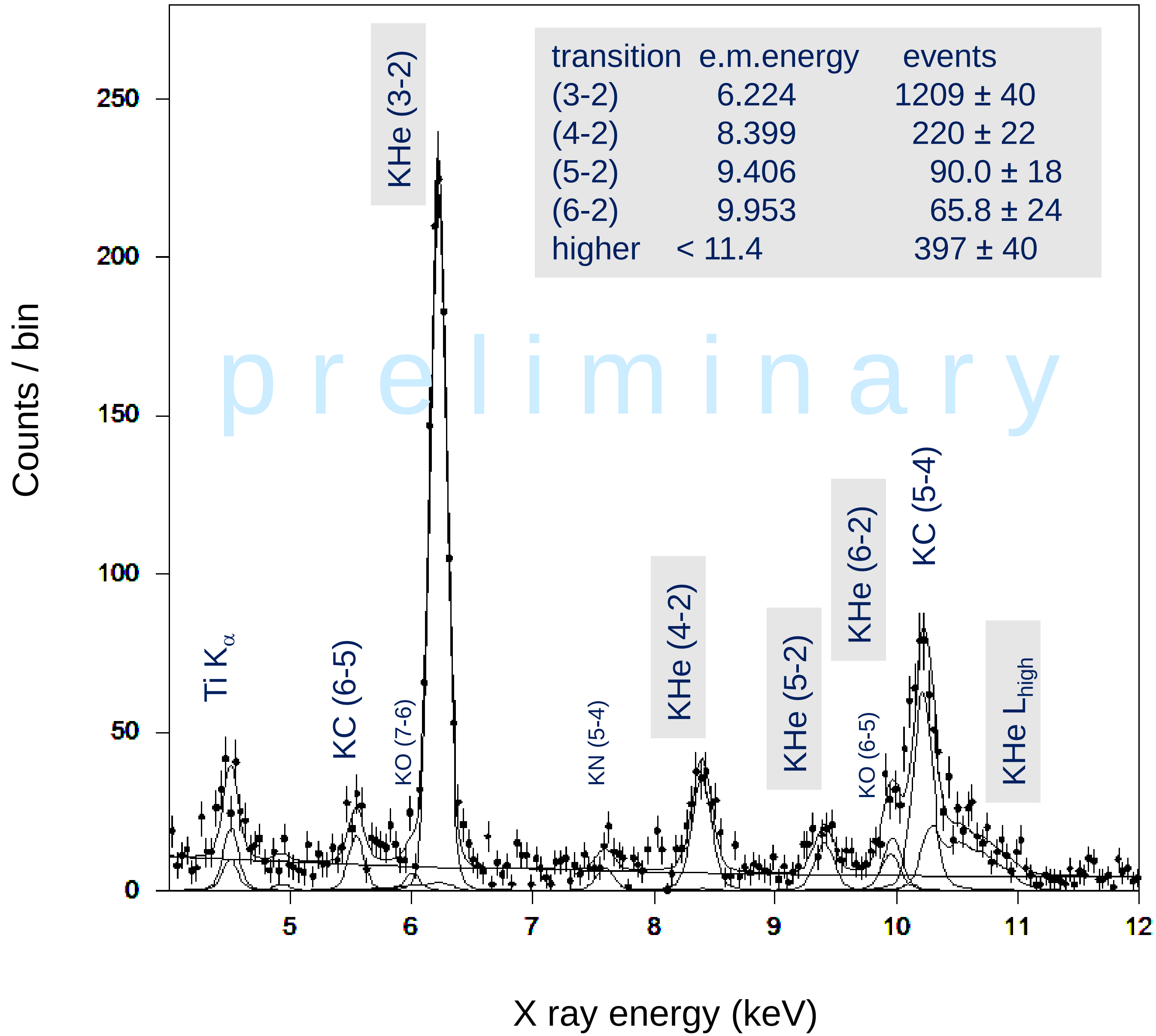
subtracted spectrum
only correlated
background remains

data of ~ 15 pb^{-1}
taken 3.-7.11.2009

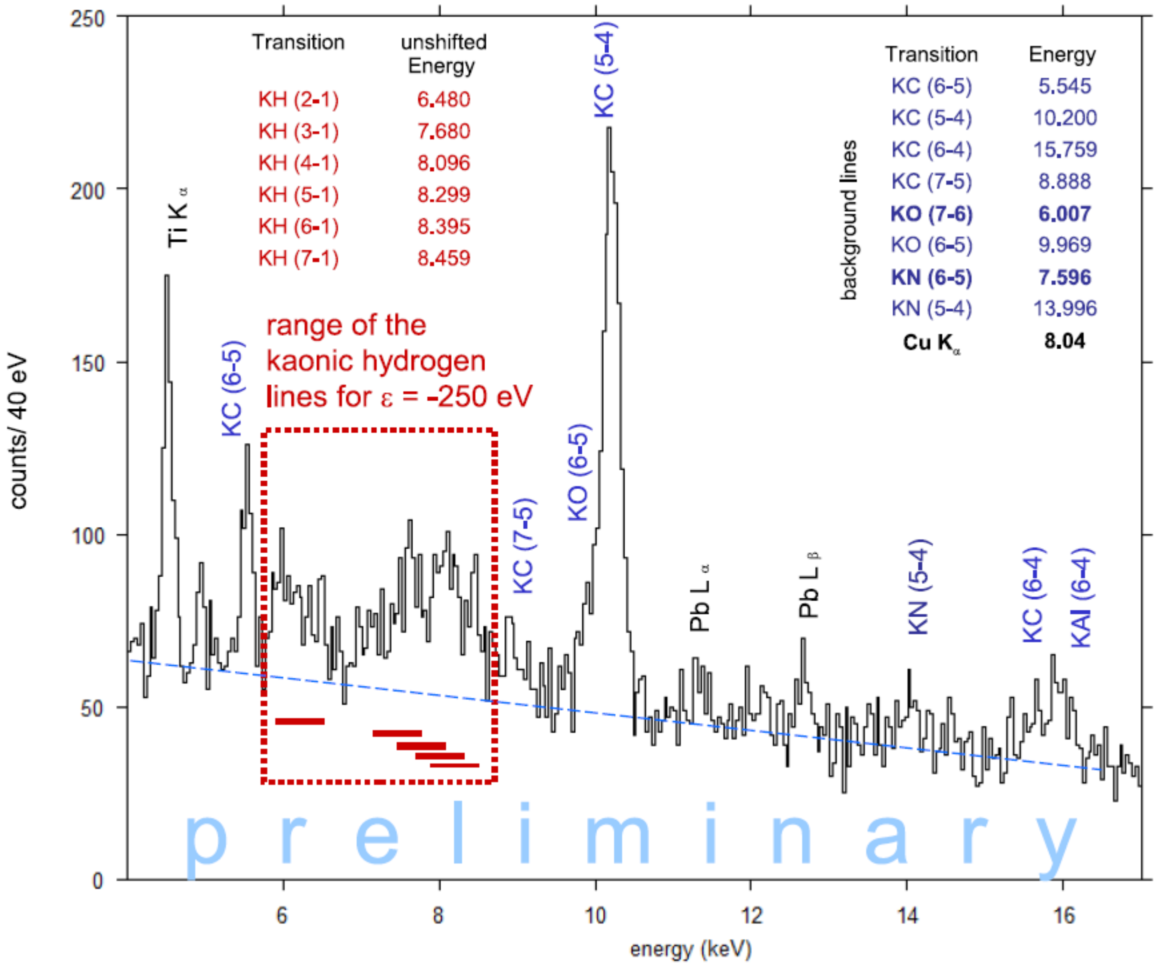
Fit of Kaonic Helium 3

KHe3
never measured
before !

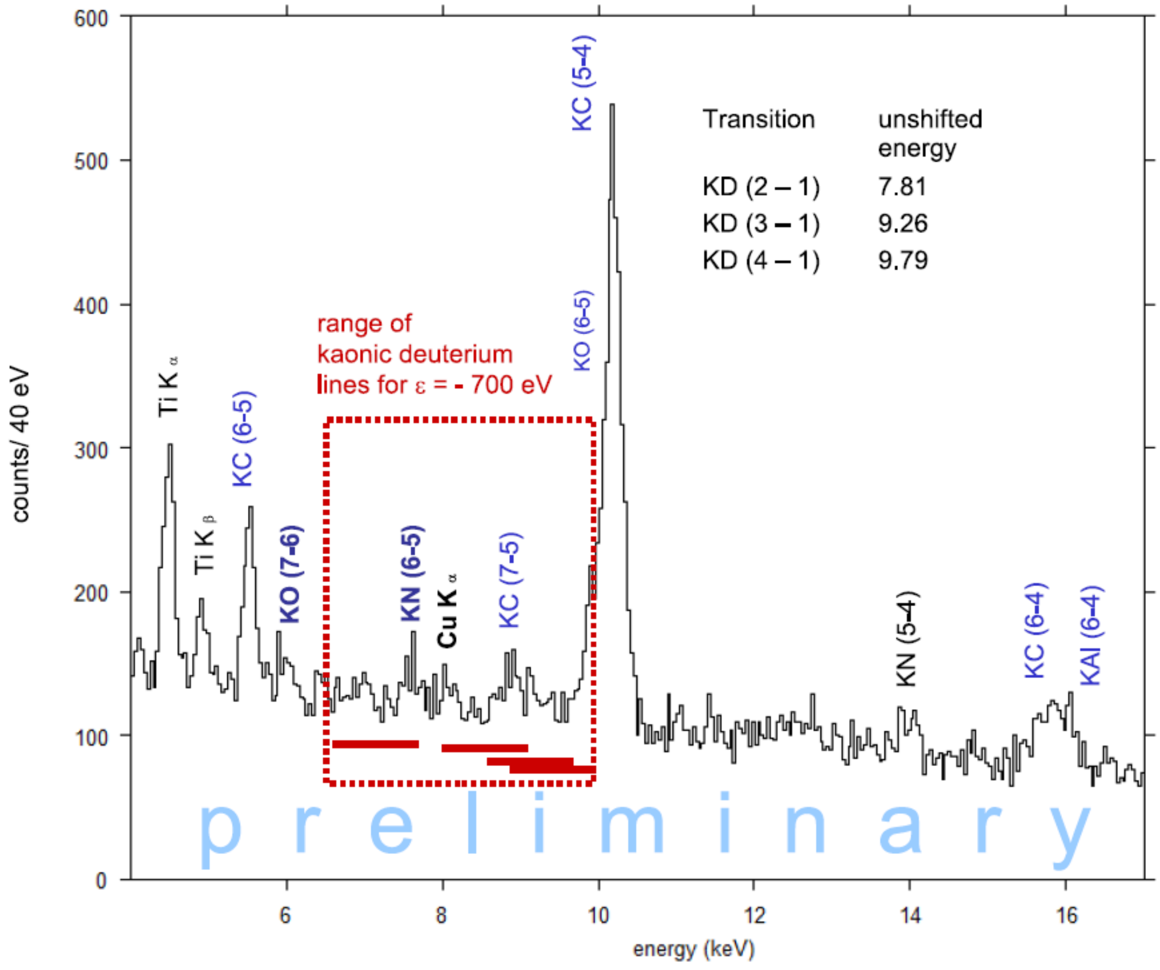
shift = - 1.7 eV
+- 2.7 eV (stat.)
+- 4 eV (syst.)



Kaonic hydrogen data

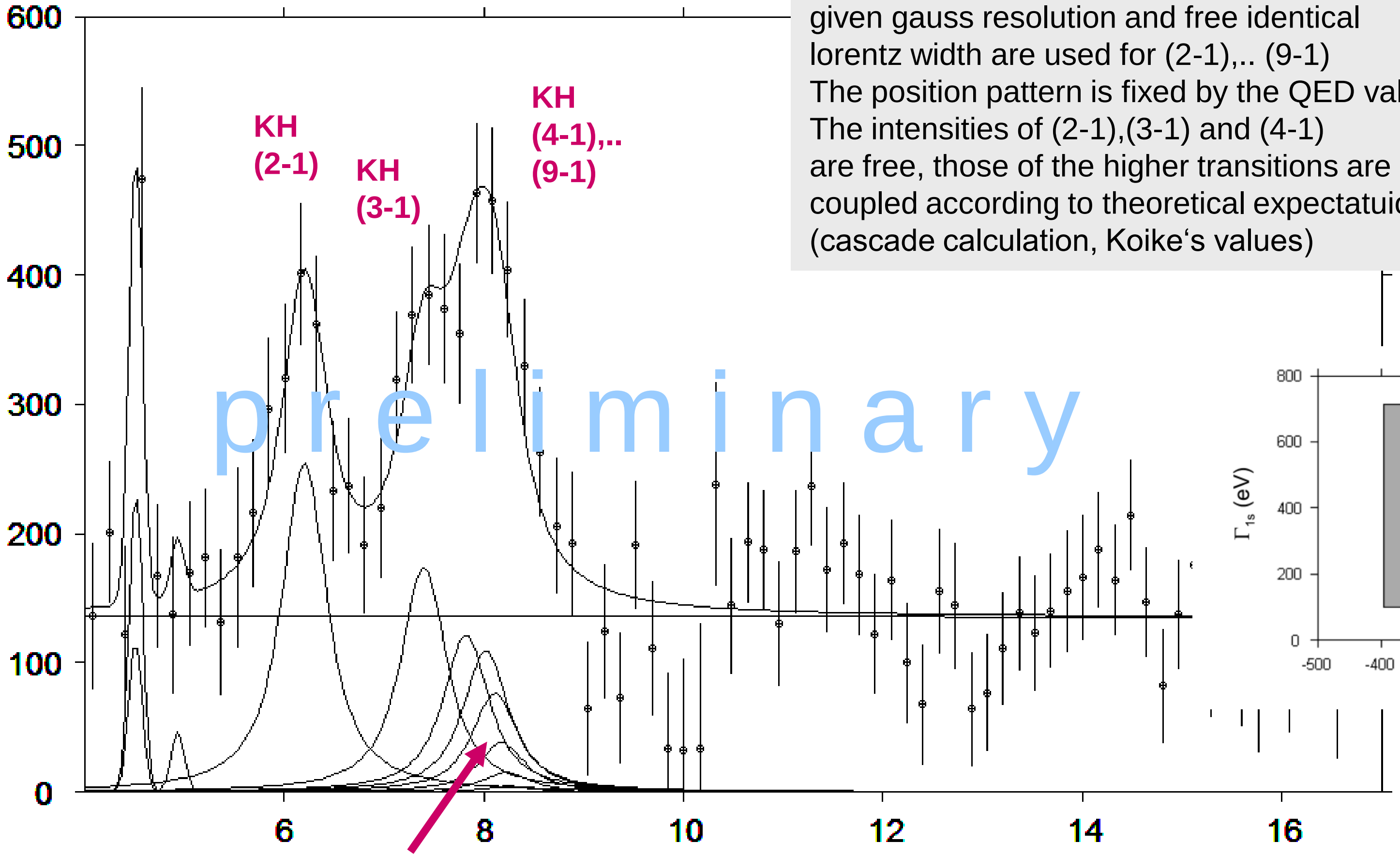


Kaonic deuterium data



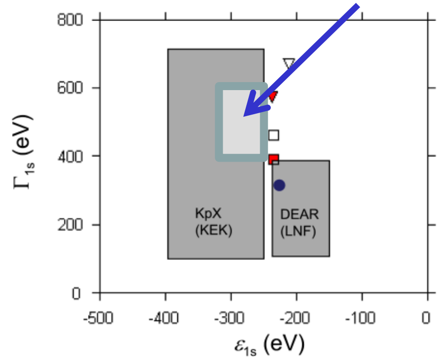
Kaonic hydrogen fit

from the kaonic hydrogen spectrum the KD specturm was subtracted to get rid of the kaonic background lines KO, KN. 290 pb^{-1} KH



For the signal 8 voigtians with given gauss resolution and free identical lorentz width are used for (2-1),.. (9-1)
The position pattern is fixed by the QED values.
The intensities of (2-1),(3-1) and (4-1) are free, those of the higher transitions are coupled according to theoretical expectatuions (cascade calculation, Koike's values)

siddharta preliminary



In the final analysis the backgound can be determined from fitting the KD data and then include the pattren in the KH fit.

MENU 2010, Cargnelli

Summary and Outlook

SIDDHARTA data taking finished Nov 2009. *Preliminary results:*

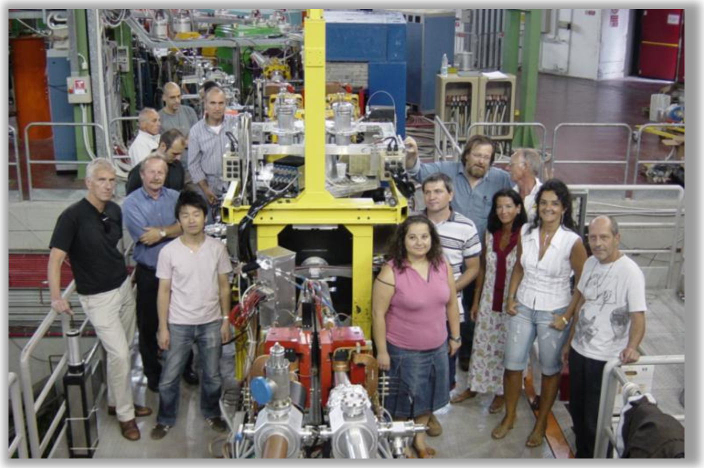
KHe4 measured in gaseous target, shift zero within errors (confirming E570)

KHe3 first time measurement, shift zero within errors (σ = 2.7 eV stat. 4 eV syst.)

K^-p shift ~ 270 eV, width ~500 eV higher precision then in DEAR

K^-d first measurement ever, exploratory measurement, small signal, significance ~ 2σ

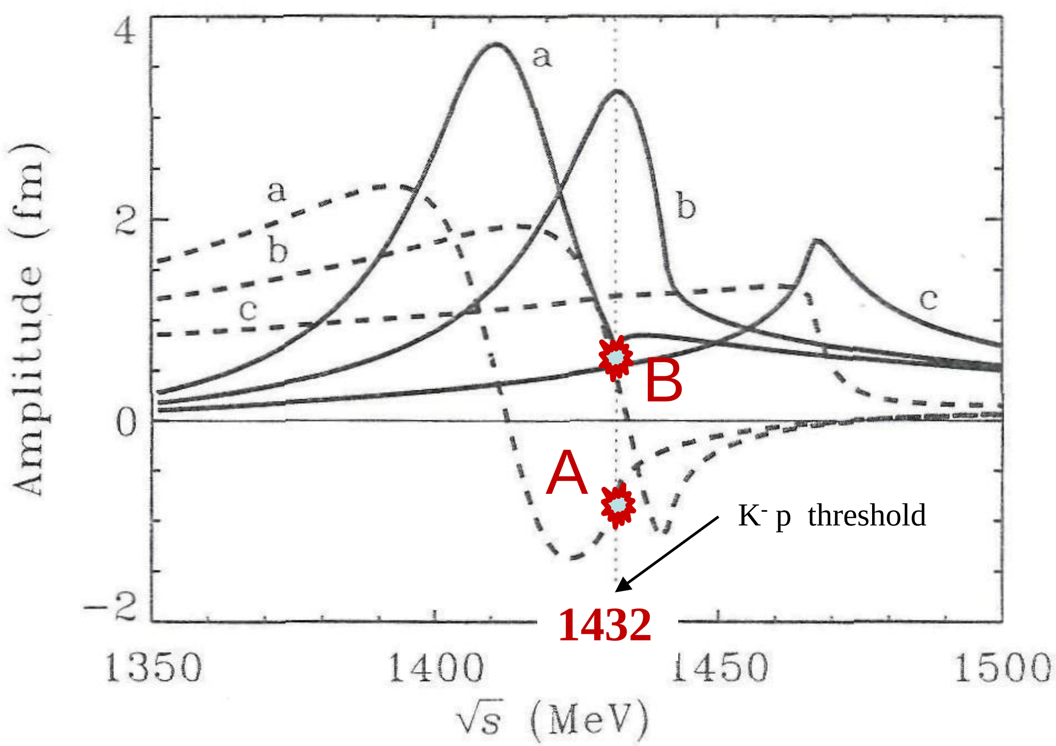
hopefully extension of the experimental program ~2012-
with improved technique - remeasure Kd, other light atoms, heavys, Kp $\rightarrow \gamma\ \Lambda^*$



Thanks for your attention !

Kbar N interaction may cause kaon-nucleon clusters ?

T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 365 (1996) 12



Kpp, Kppn,.. „deeply bound" ?
- highly controversial
- new experiments planned

understanding of KN at theshoild essential !

In free space, at threshold,

real part of $\mathbf{a_{K^-p} < 0}$ (point A)

→ **repulsive interaction**

In nuclear matter at rather low density (~0.2 ρ_0), at threshold, point B, real $\mathbf{a_{K^-p} > 0}$

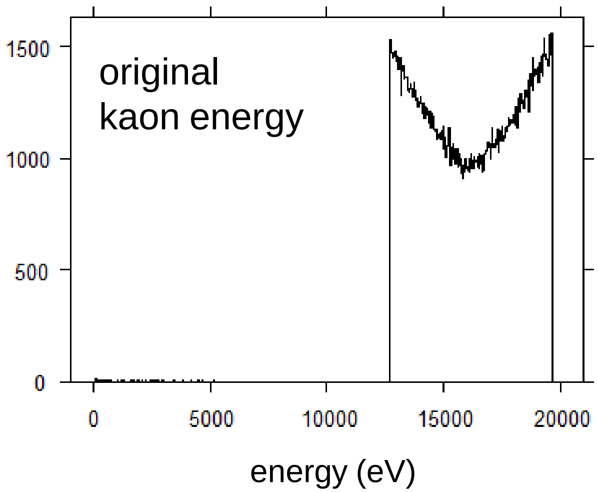
→ **attractive interaction**

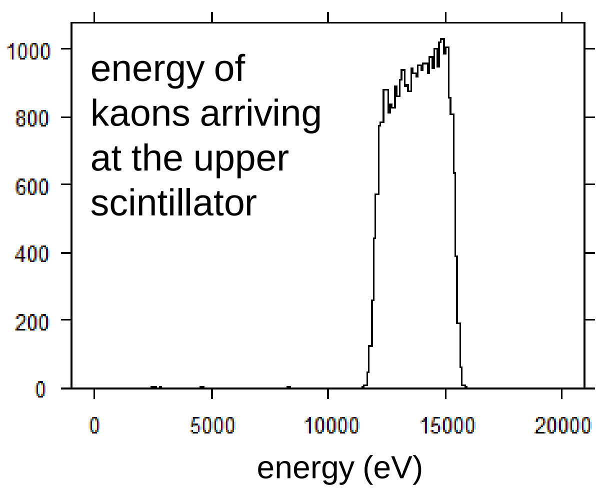
Real (dashed lines) and imaginary parts (solid lines) of the K^- p scattering amplitude in nuclear matter at different values of the Fermi momentum $\boldsymbol{p_F = (3\pi^2 \rho/2)^{1/3}}$, as a function of the total c.m. energy $\sqrt{s}$

a) free space, $p_F = 0$; **b) ~ 0.2 ρ_0**, p_F = 150 MeV/c; **c) ~ 1.4 ρ_0**, p_F = 300 MeV/c;

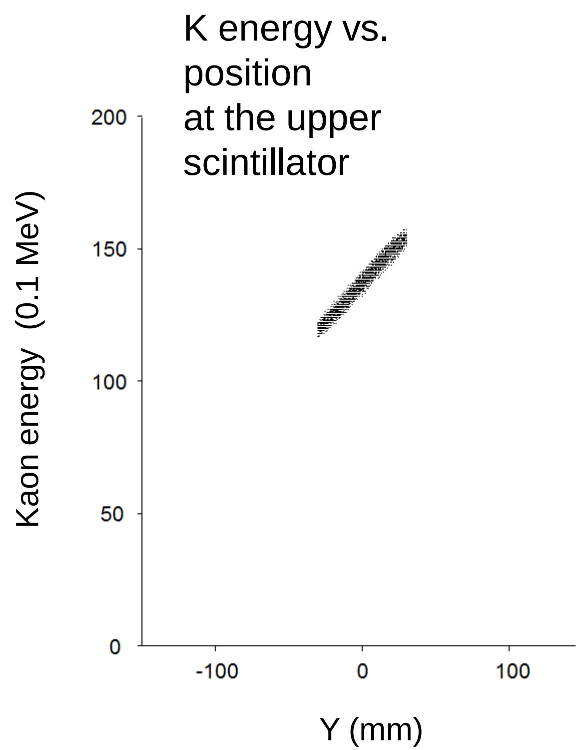
$\rho_0 = 0.17\ \text{fm}^{-3}$

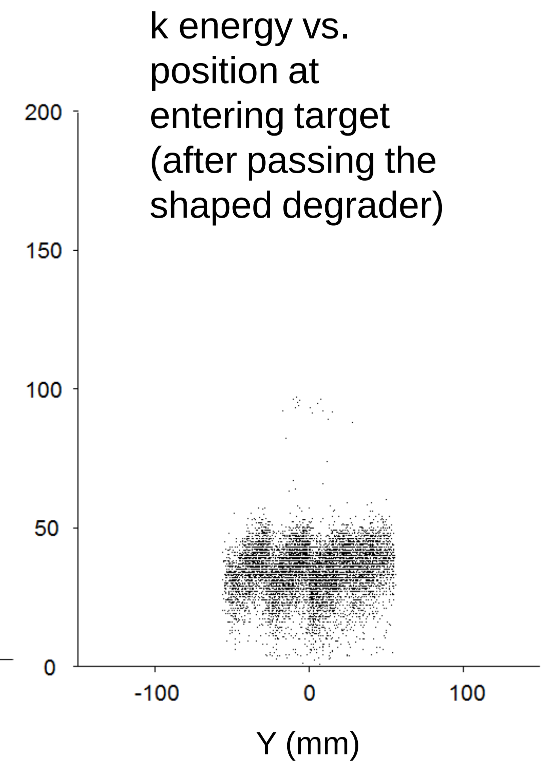
Simulation of kaon stopping

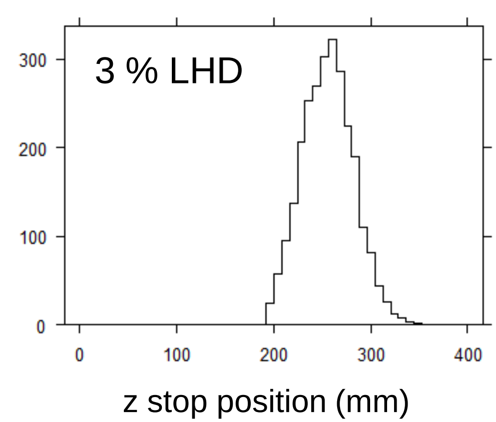


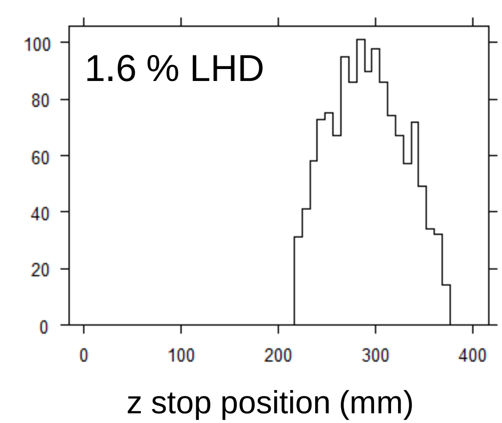


degrader optimization needs experimental fine tune ± 100 μm: material budget and dafne tune known with limited accuracy.



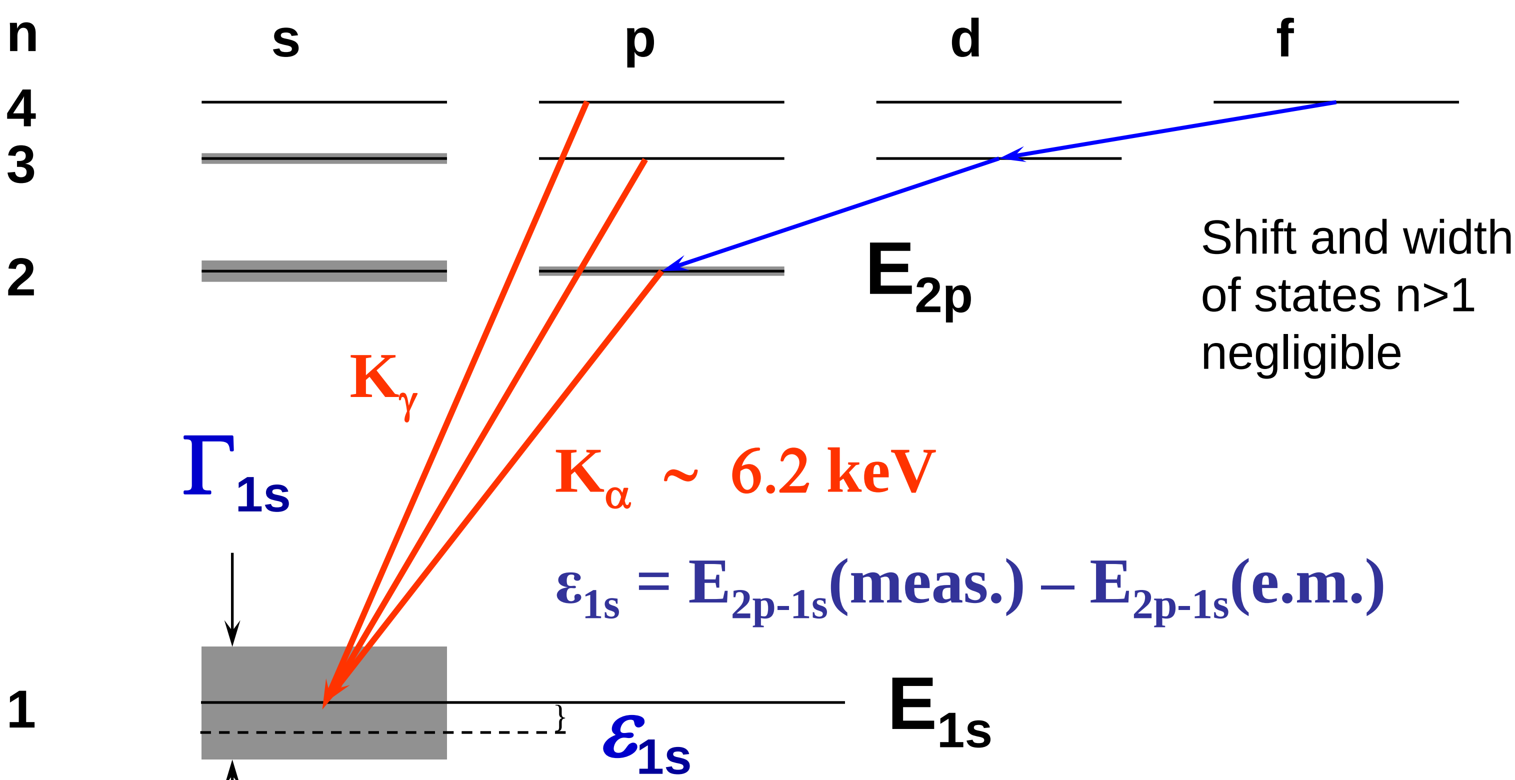






Kaonic hydrogen: formation, level transitions

Negative kaons stopped in H_2 → initial atomic capture (n ~ 25) →
→ electromagnetic cascade → X-ray transitions



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

Note: radiationless transitions: KH(n,l) + H → KH(n',l') + H + E_{kin}
Doppler broadening is a correction in the πH case where the width ~1 eV, in KH width= 300-500 eV