Plan of lectures

- 1 15.04.2015 Preliminary Discussion / Introduction

- 2 22.04.2015 Experiments (discovery of the positron, formation of antihydrogen, ...)
- 3 29.04.2015 Experiments (Lamb shift, hyperfine structure, quasimolecules and MO spectra)
- 4 06.05.2015 Theory (from Schrödinger to Dirac equation, solutions with negative energy)
- 5 13.05.2015 Theory (bound-state solutions of Dirac equation, quantum numbers)
- 6 20.05.2015 Theory (bound-state Dirac wavefunctions, QED corrections)

- 7 27.05.2015 Experiment (photoionization, radiative recombination, ATI, HHG...)
- 8 03.06.2015 Theory (description of the light-matter interaction)
- 9 10.06.2015 Experiment (Kamiokande, cancer therapy, ….)
- 10 17.06.2015 Theory (interaction of charged particles with matter)

- 11 24.06.2015 Experiment (Auger decay, dielectronic recombination, double ionization)
- 12 01.06.2015 Theory (interelectronic interactions, extension of Dirac (and Schrödinger) theory for the description of many-electron systems, approximate methods)
- 13 08.07.2015 Theory (many-electron atoms)

- 14 15.07.2015 Experiment (Atomic physics PNC experiments (Cs,...), heavy ion PV research)

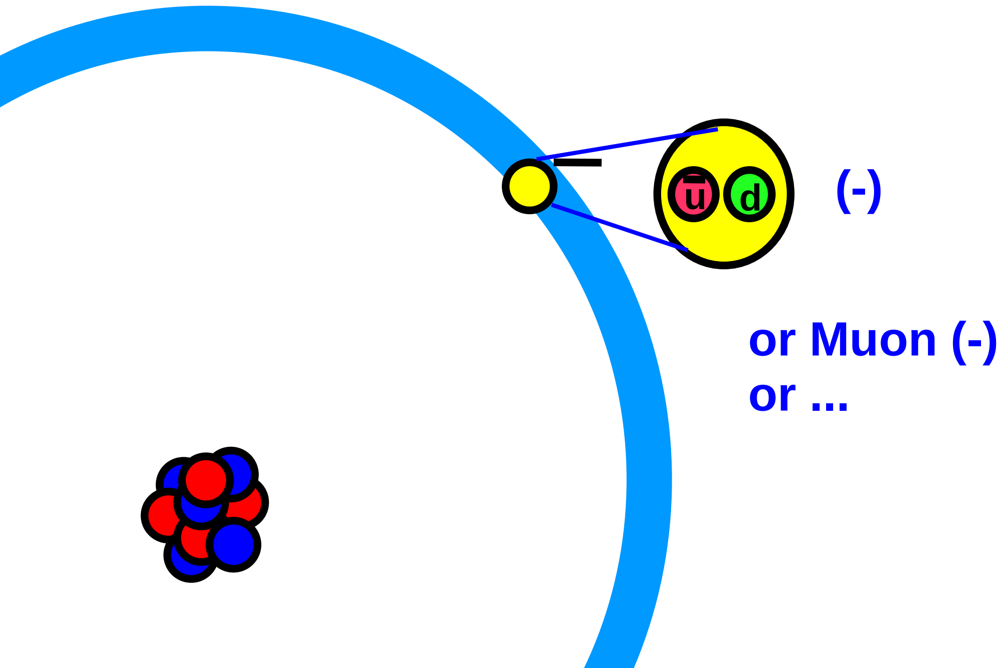
Exotic atoms

What are exotic atoms

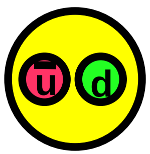
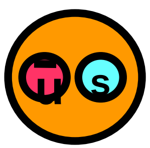
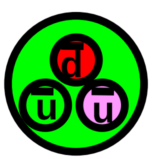
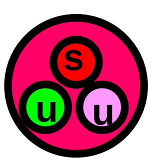
• Atoms which--instead of electrons--have another negatively charged particle

• Lifetime of the particle is sufficient to have a bound system (lifetime >> fs)

• Requirements for accelerators for the production of the particle



Possible ingredients ...

•	**Electron**	Lepton	τ = infinite	m = 0.51 Mev/c^2
●	**Muon (μ^-)**	Lepton	τ = 2.19 µs	m = 106 Mev/c^2
	**Pion (π^-)**	Meson (anti-u, d)	τ = 26 ns	m = 119 Mev/c^2
	**Kaon (K^-)**	Meson (anti-u, s)	τ = 12 ns	m = 494 Mev/c^2
	**Antiproton ($\bar{p}$)**	Barion (2 anti-u, anti-d)	τ = "infinite"	m = 931 Mev/c^2
	**Sigma (Σ^-)**	Barion (2 u, s)	τ = 0.08 ns	m = 1189 Mev/c^2

Exotic atoms history

- Prediction

1947 $\tau_{capture} << \tau_{particle}$ (E. Fermi and E. Teller)

- First X-ray experiment

1952	π^- C	NaI (scintillator)
1953	..., μ^- Pb ,...	NaI (scintillator)
1965	K^- He	prop. counter
1969/70	Σ^- S, Σ^- K	Ge(Li) (solid state det.)
1970	$\bar{p}$Tl	Ge(Li) (solid state det.)

- FACILITIES

1974 ...	pions, muons	Paul-Scherrer-Institut PSI, TRIUMF,LAMPF
1983 ...	antiprotons	Low-Energy-Antiproton-Ring LEAR, AD, (FAIR)
---	kaons	KEK, DAΦNE

Characteristics (1)

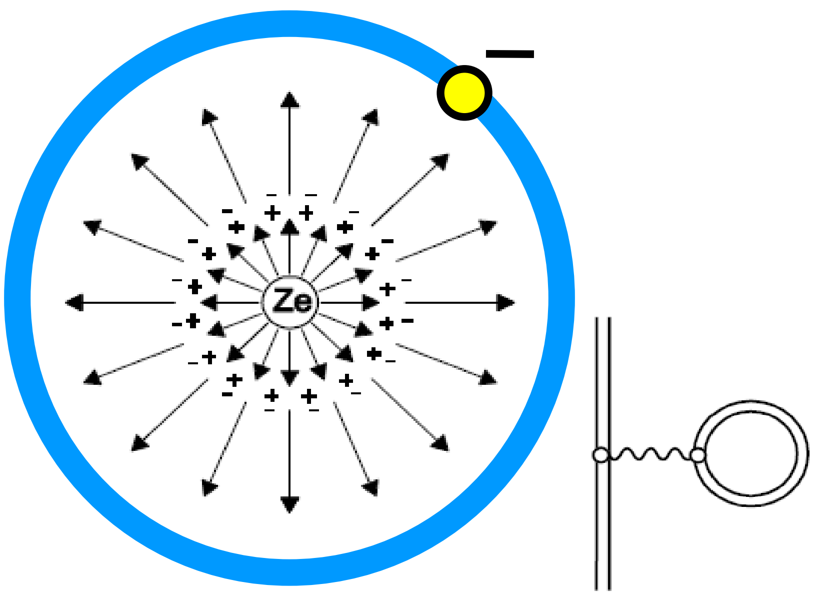
$$r_0 = \frac{\hbar}{Z\alpha m c}$$

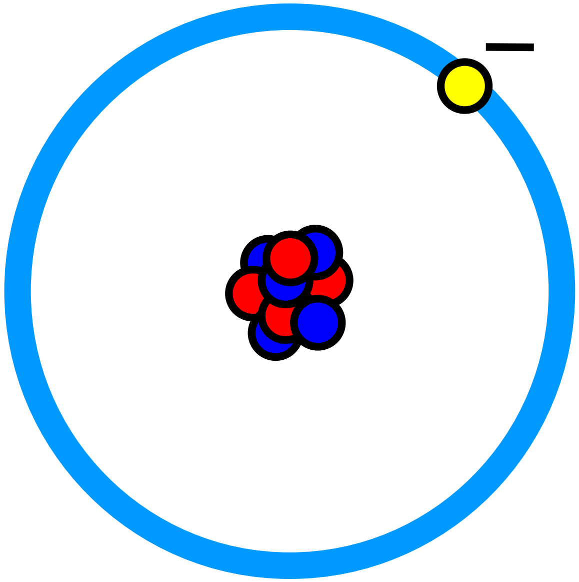
Z = atomic number,
m =reduced mass,
h = Planck constant,
c = light velocity,
α = fine structure constant.

Small radius

- Sensibility to the Quantum Electrodynamics effects like vacuum polarization

- Influence of the nuclear finite size





Characteristics (2)

$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2}$$

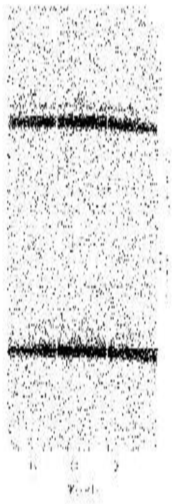
Z = atomic number,
m =reduced mass,
h = Planck constant,
c = light velocity,
α = fine structure constant.

Increasing of the atomic level energies

- Emitted photons in the X-rays range (1-100 keV)

Hydrogen spectrum

Visible light



Hydrogenlike pionic nitrogen

X-rays

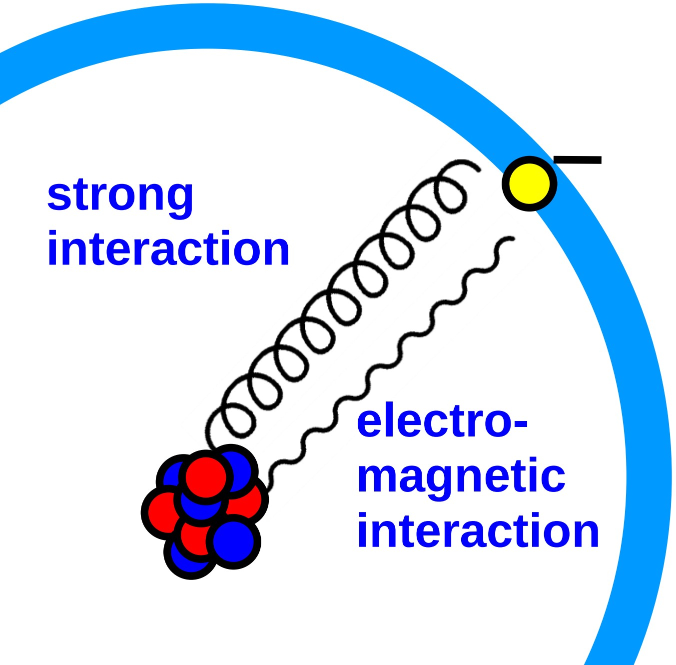
Characteristics (3)

- Electromagnetic interaction -> bound system
- **Strong interaction!!** (except muonic atoms)

Attraction or repulsion -> shift of the energy transition ε

Reaction with the nucleus -> ground state instable

- lifetime of the atom not infinite
- lifetime measurement from the width of the transition line width Γ



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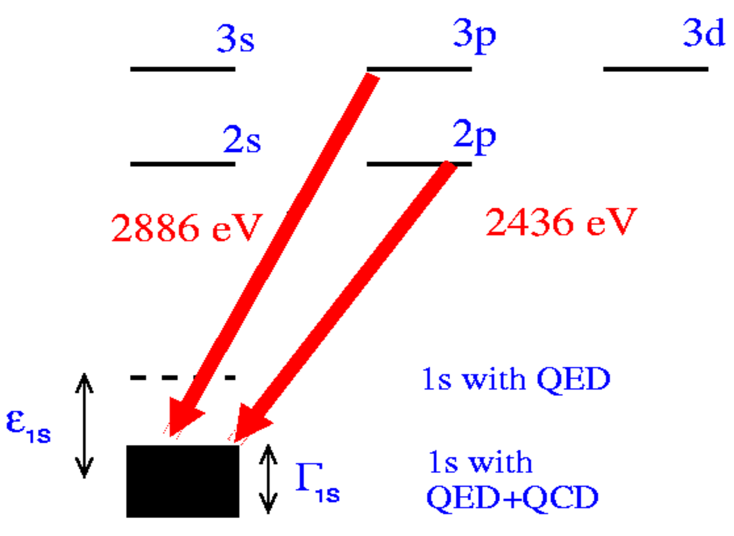
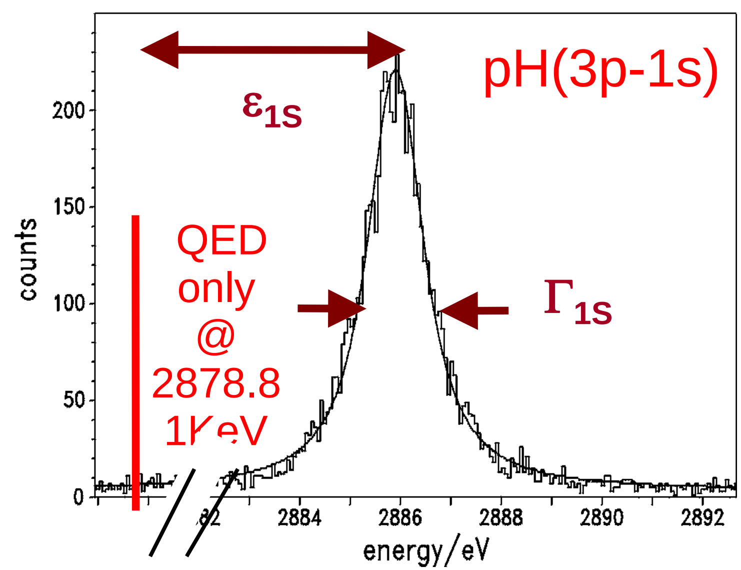




$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2}$$

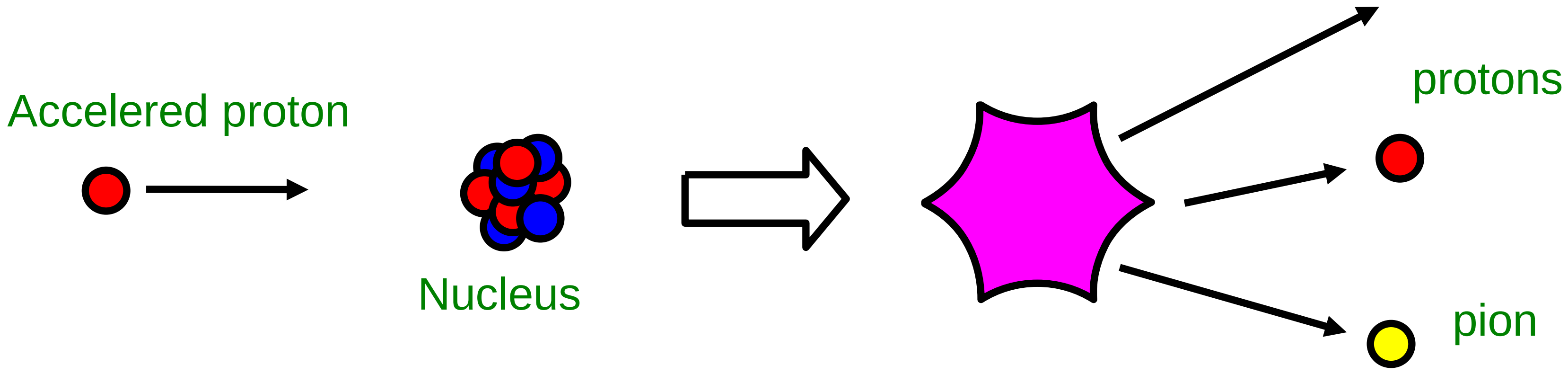
What for?

$$r_0 = \frac{\hbar}{Z\alpha mc}$$

Three ingredients: exotic particle, nucleus, interaction

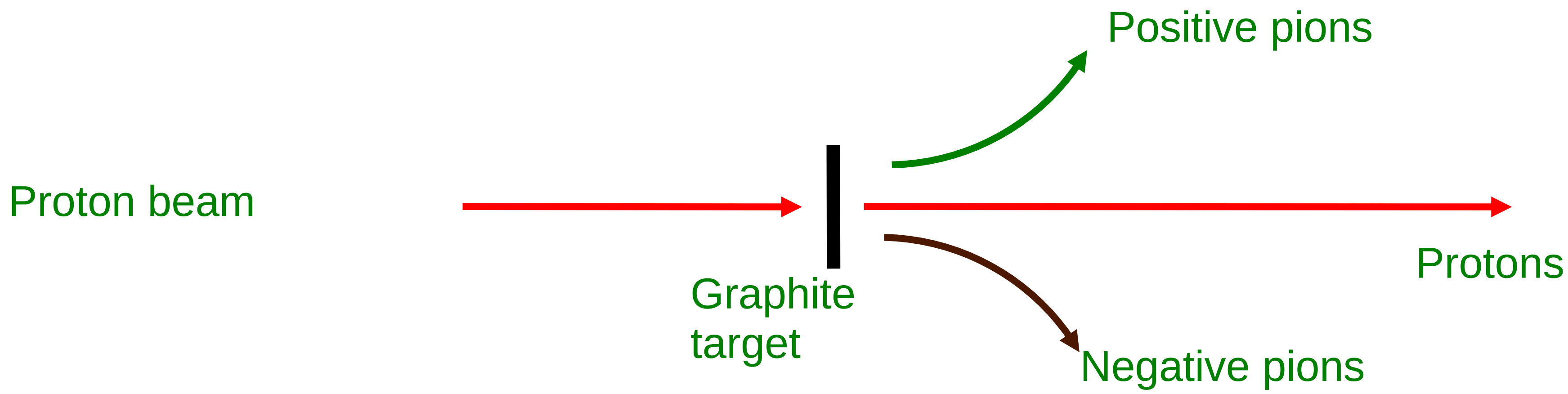
- Study of the particle
  - mass of the exotic particle (pion, kaon, antiproton, sigma)
- Study of the nucleus
  - exotic particle as nuclear probe (muon, pion, antiproton)
  - nuclear dimension (muon, pion, antiproton)
  - proton and neutron distribution (pion, antiproton)
- Study of the interaction
  - QED effects (Vacuum Polarization, self energy)
  - Test of Klein-Gordon (spin 0) and Proca (spin 1) relativistic equations (pion, kaon, sigma)
  - Strong interaction at (very) low energy (pion, kaon, antiproton, sigma)

Exotic Particles production

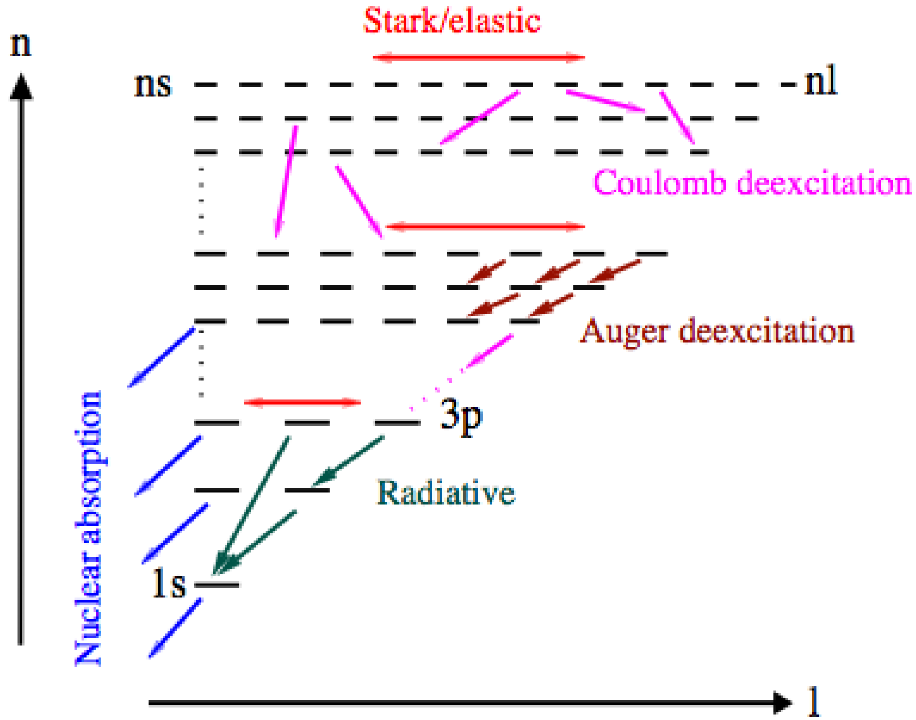


Ex: Production of pions at the Paul Scherrer Institut:

- Proton beam :E_{kin}=590 Mev/c, I=1.9 mA
- Graphite target
- 10^8 pions/sec, E_{kin}=110 Mev/c



Exotic atoms production



- Deceleration and stop particle in target
  E_{kin}~10 eV

- Capture at radii of outmost electrons

$$n_i = n_{el}\sqrt{\frac{m_{part}}{m_{el}}}$$

n_{pion} ~17
$n_{antiproton}$ ~ 43

Highly excited state!

- De-excitation by competing Auger and X-ray emission

$$\Gamma_{\text{Auger}} \propto \Delta E^{1/2}$$

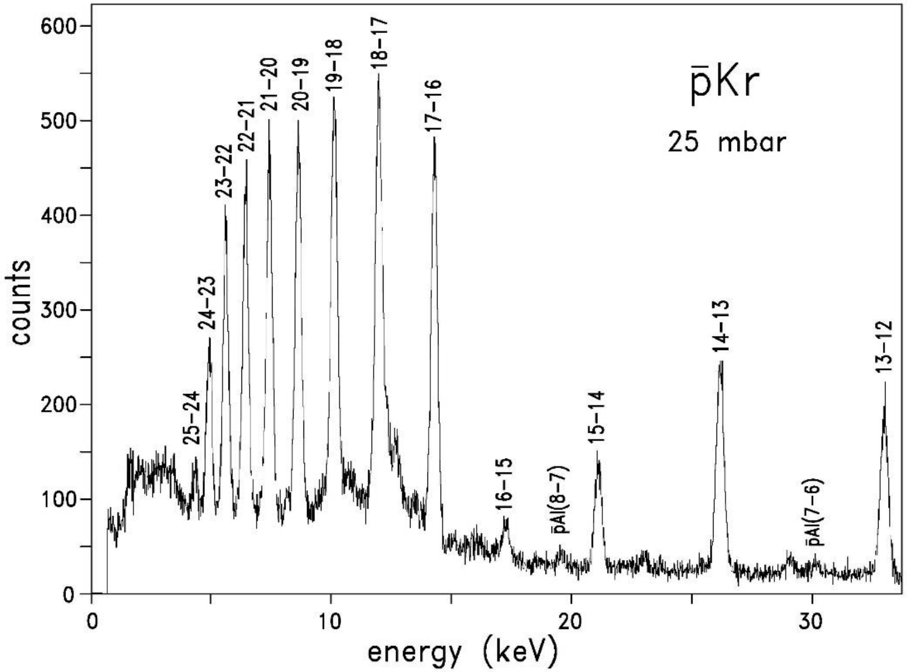
Dominates for large n

$$\Gamma_{\text{X-ray}} \propto \Delta E^{3}$$

Dominates for small n

Low Z + dilute targets => no electrons remaining!!

Exotic atoms production



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Pionic atoms

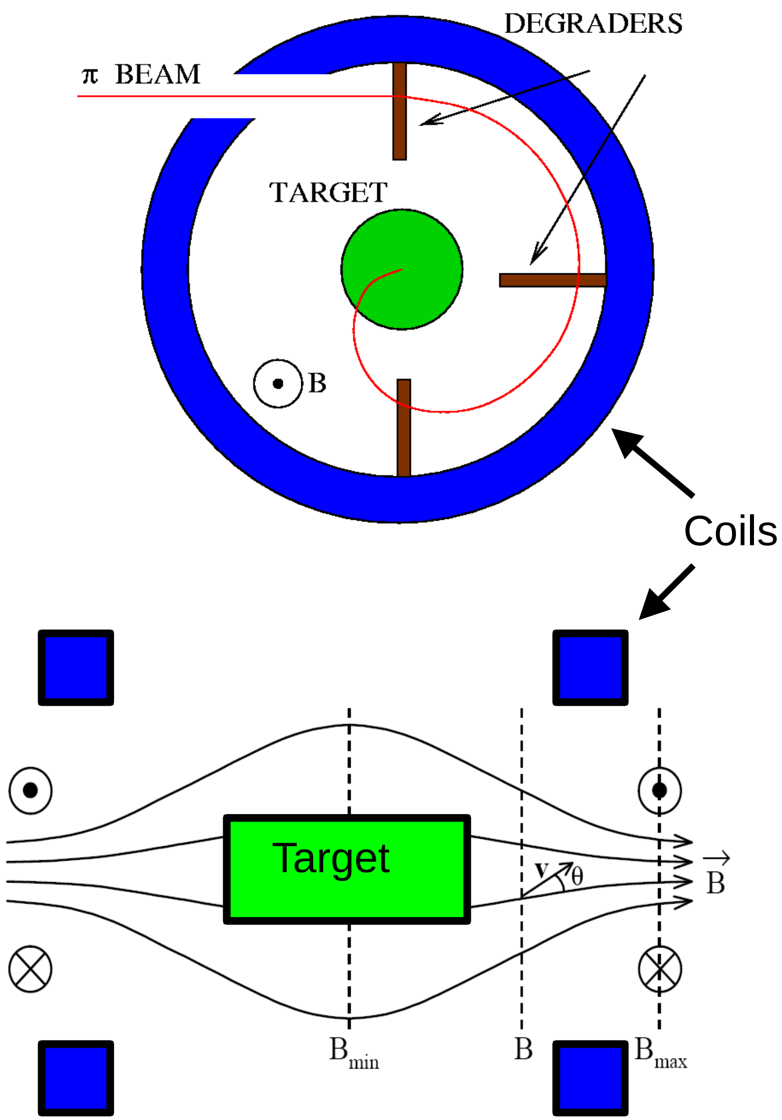
Pionic atoms production

- Pions produced at the Paul Scherrer Institut (Villigen, Suisse)
(10^{8} pions/sec, E_{kin}=110 Mev/c)

- Cyclotron trap
- Maximal magnetic field: B= 3.5 T

- Gaseous or liquid target: T: from 14 K to room temperature, effective pressure: from ~0 to 40 bars

- 1-5% of the incoming pions are stopped into the target



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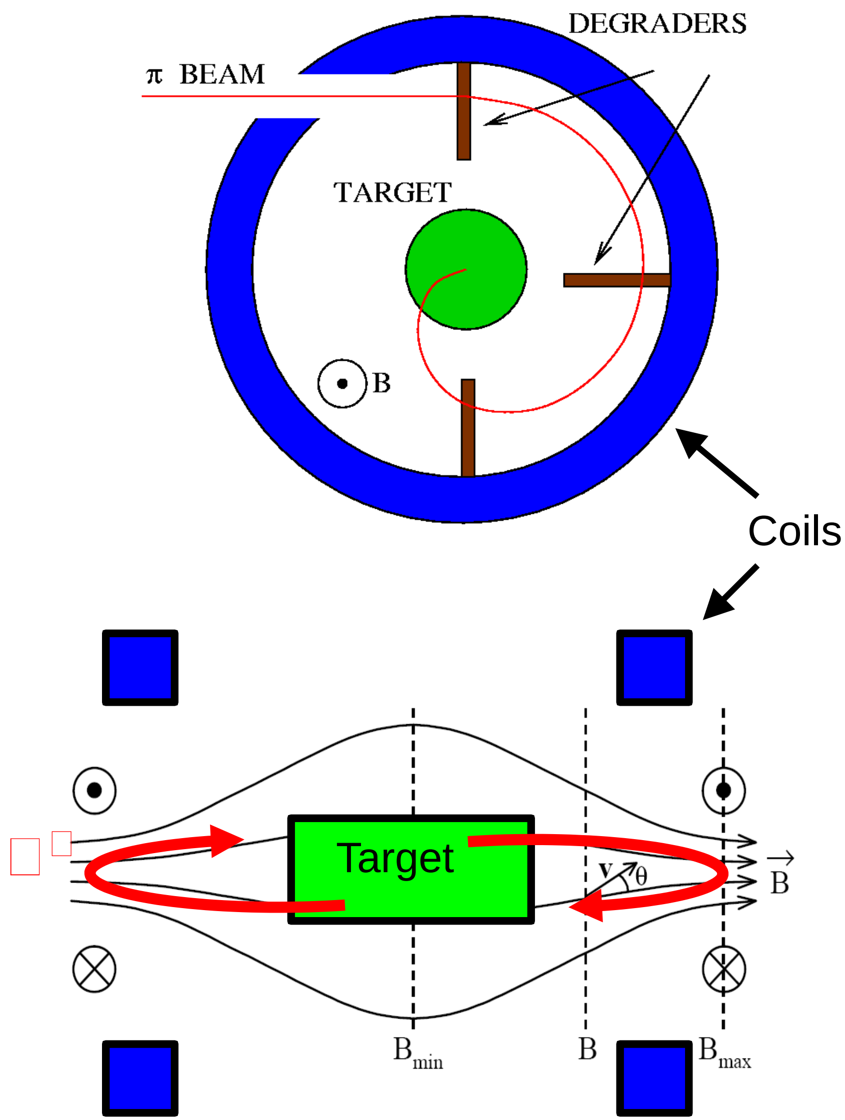
- Cyclotron trap
- Maximal magnetic field: B= 3.5 T

- Gaseous or liquid target:
T: from 14 K to room temperature,
effective pressure: from ~0 to 40 bars

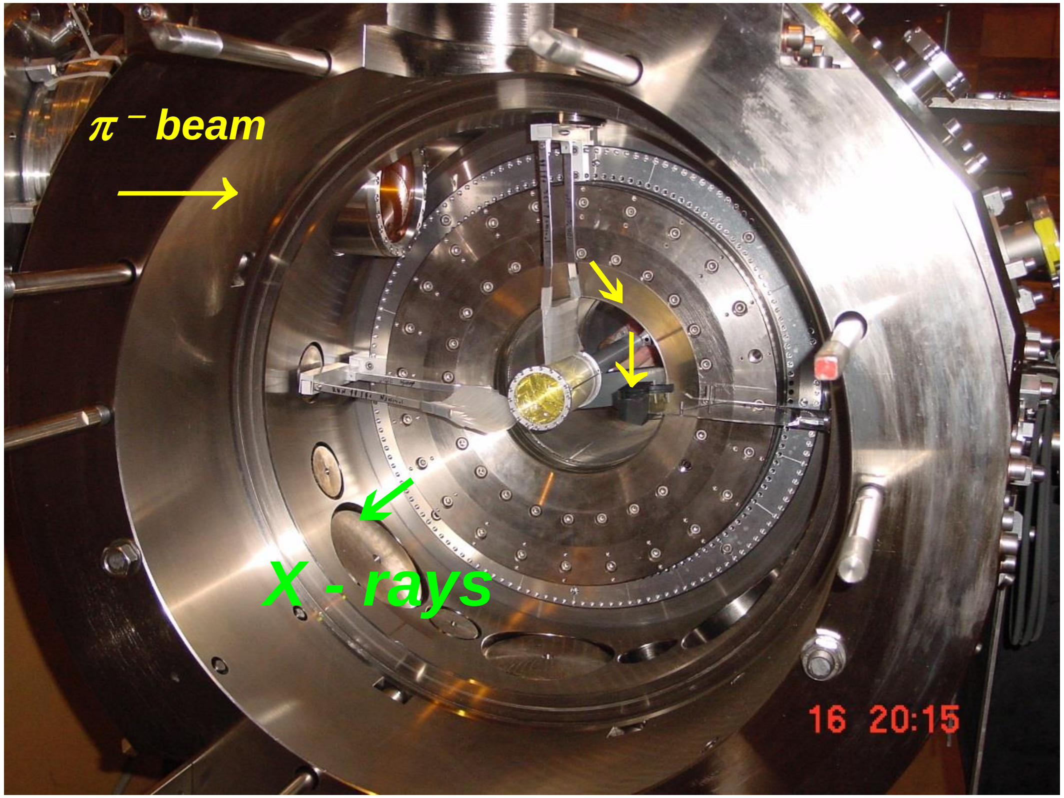
- 1-5% of the incoming pions are stopped into the target
- Production and trapping of the muons

$$\pi^- \rightarrow \mu^- + \nu$$

- Formation of muonic (and pionic) atoms

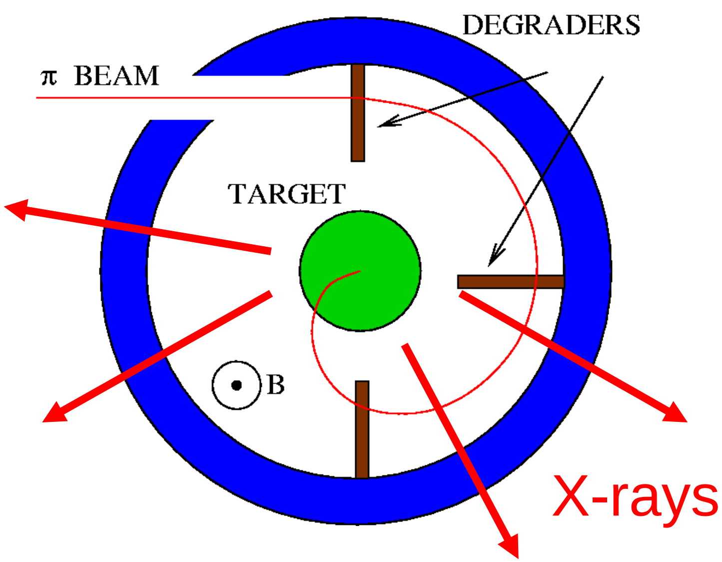


(Anti)-Cyclotron trap

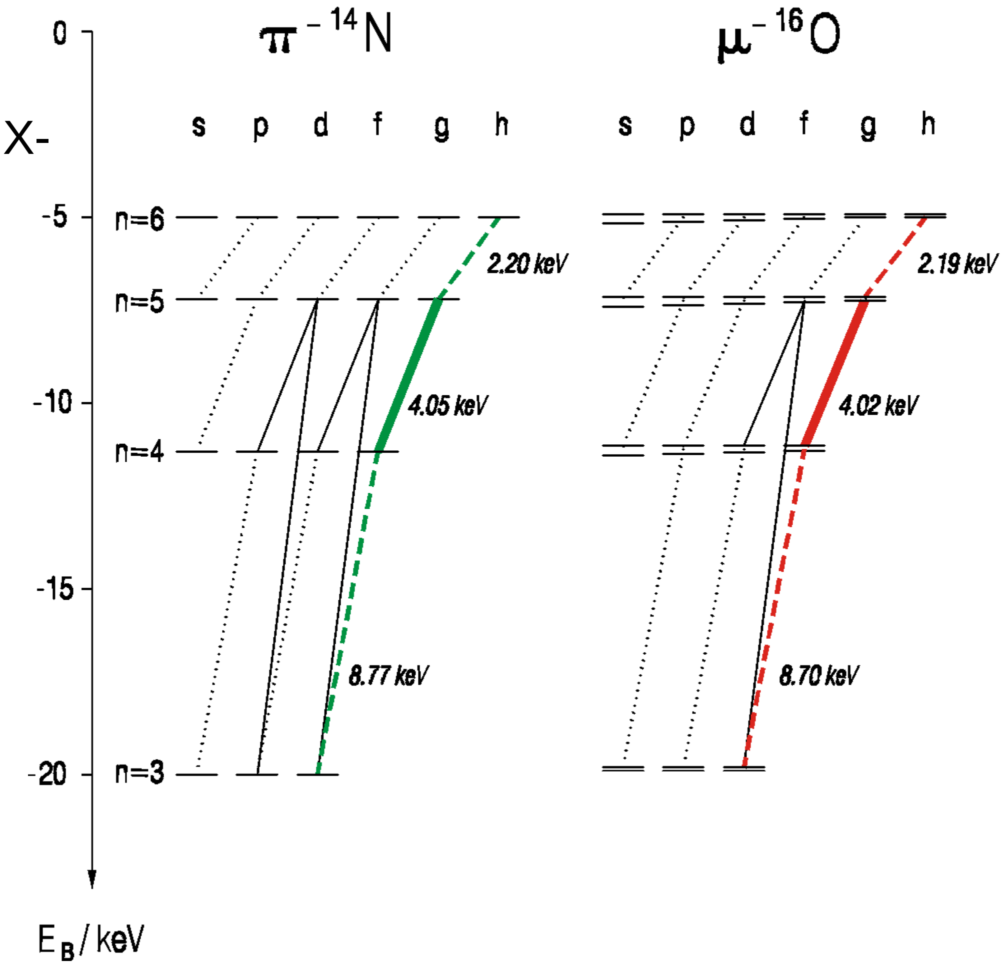


X-ray emission from the pionic atoms

- Pionic atoms produced in an excited state
- Radiative cascade with the emission of X-rays



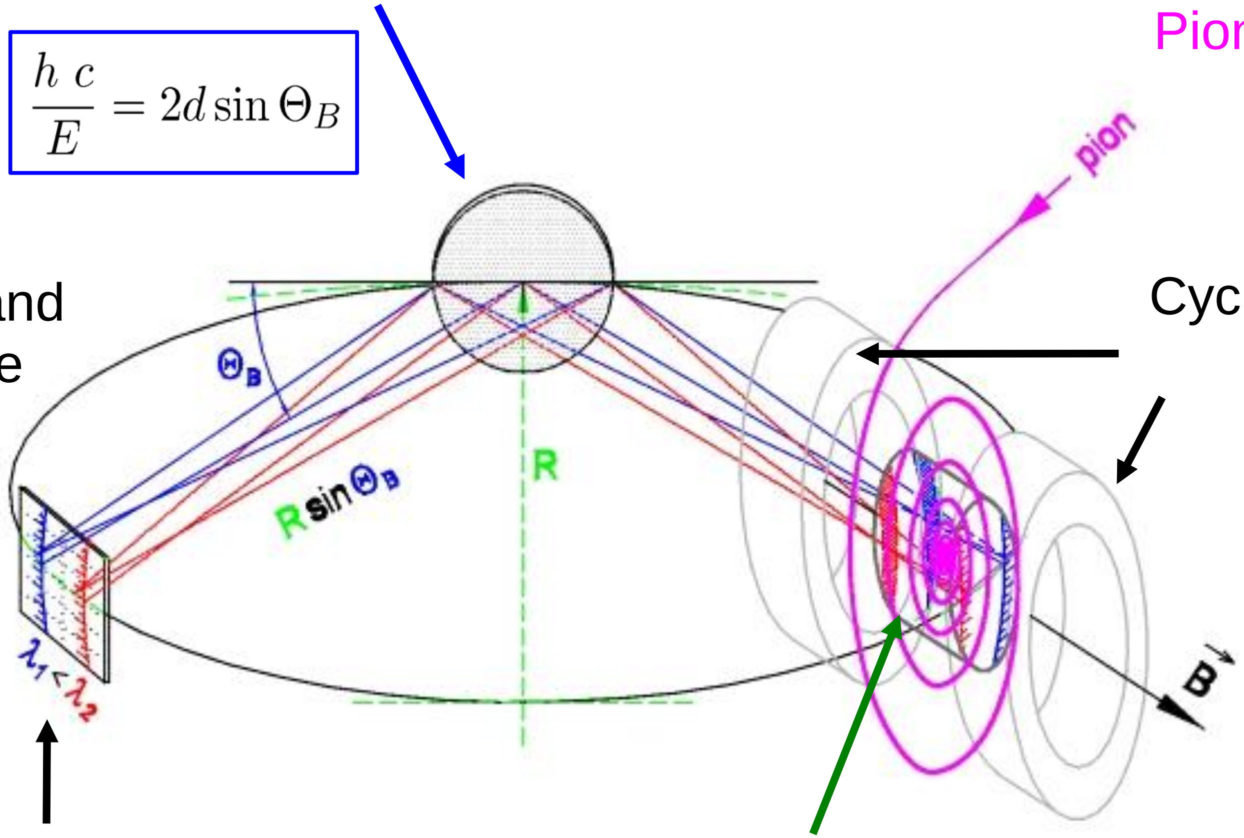
Transitions on pionic nitrogen and muonic oxygen



Johann-type Bragg spectrometer

d = distance between crystal planes

$$\frac{h\,c}{E} = 2d\sin\Theta_B$$



D.Gotta et al.Nucl. Phys. A 660, 283 (1999)

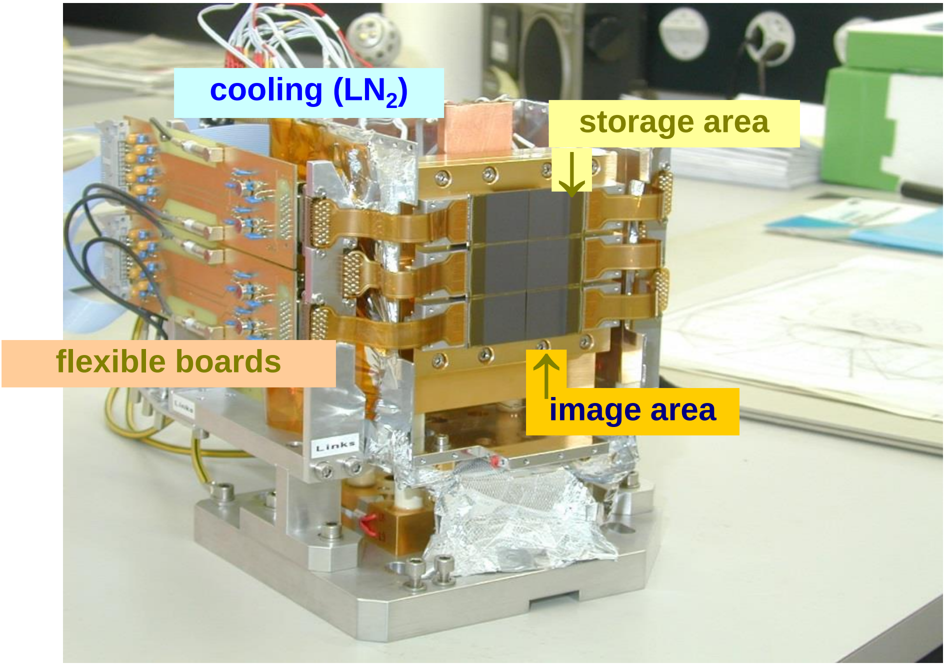
Spherically curved crystals

Radius of curvature 2985.4 mm

Produced by Zeiss

Large area focal plane detector

2 × 3 CCD 22 array with frame buffer
(Marconi technology)



pixel size 40 μm × 40 μm

600 × 600 pixels per chip

frame transfer ≈ 10 ms

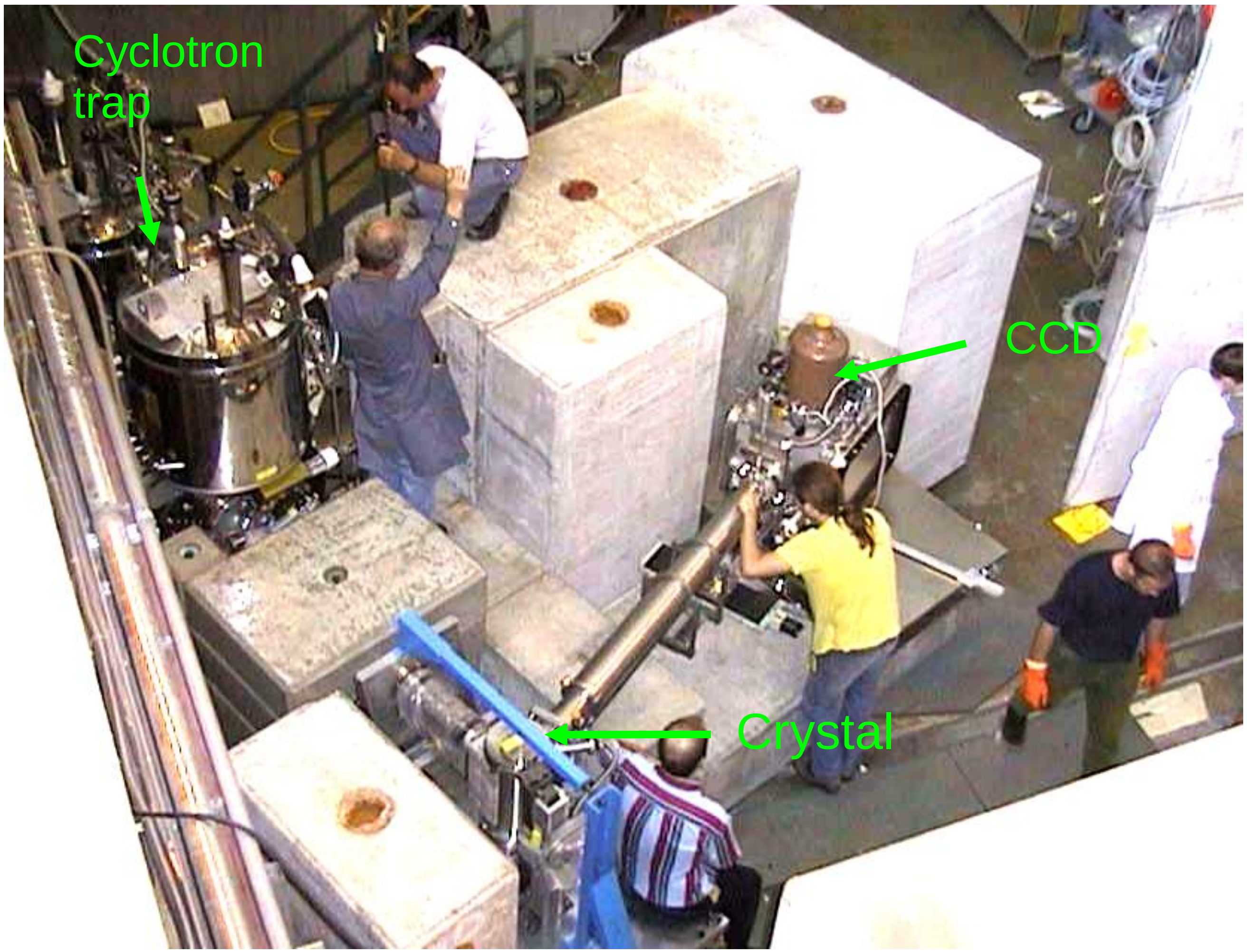
data processing 2.4 s

operates at – 100°C

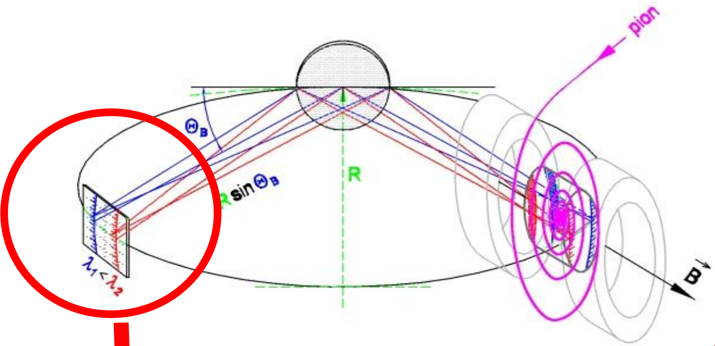
$\Delta E \approx$ 150 eV @ 4 keV

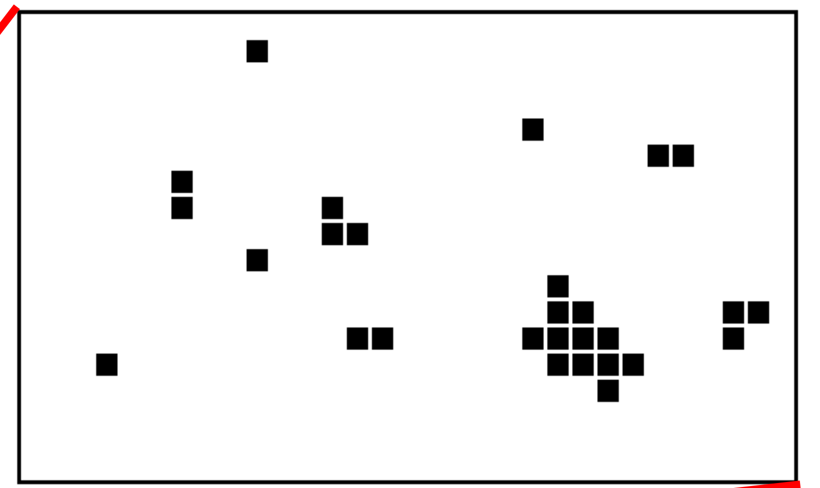
Efficiency ≈ 90%

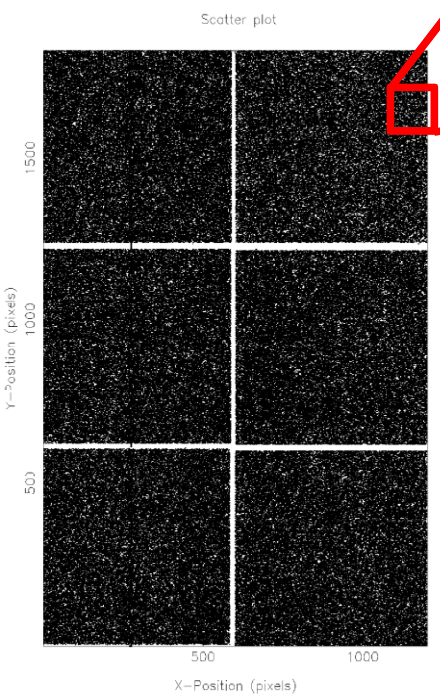
Johann-type Bragg spectrometer setup



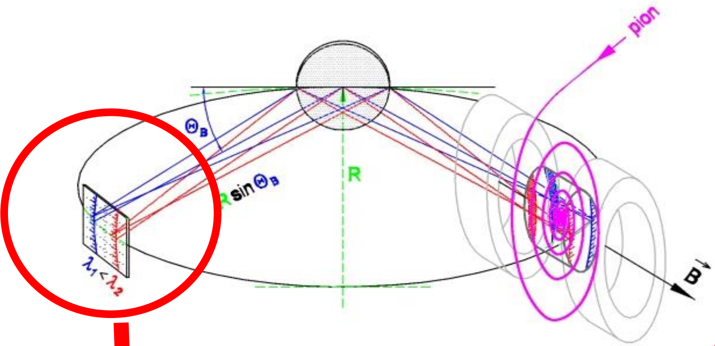
Detection (1)

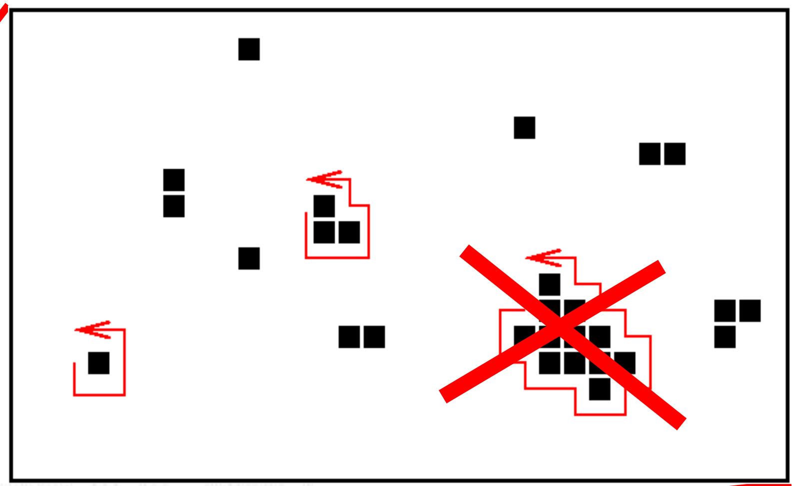

pion
ΘB
R sinΘB
R
λ1<λ2
B



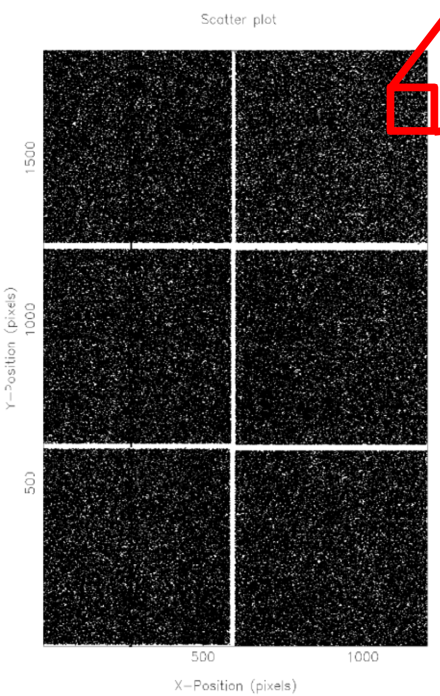

Scatter plot
1500
1000
500
Y−Position (pixels)
500
1000
X−Position (pixels)

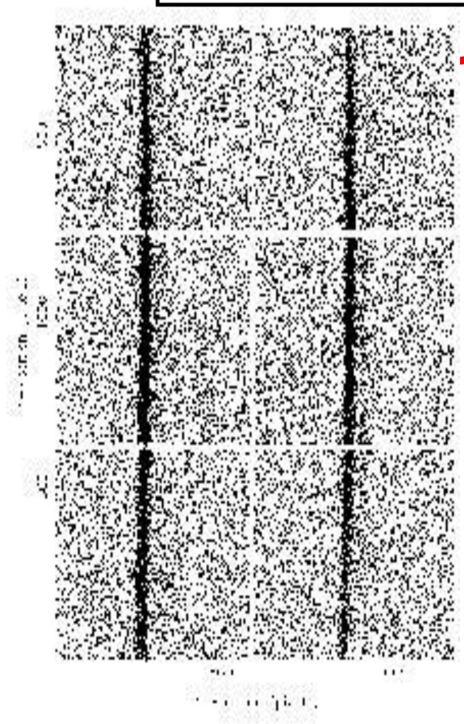
Detection (1)





Cluster analysis





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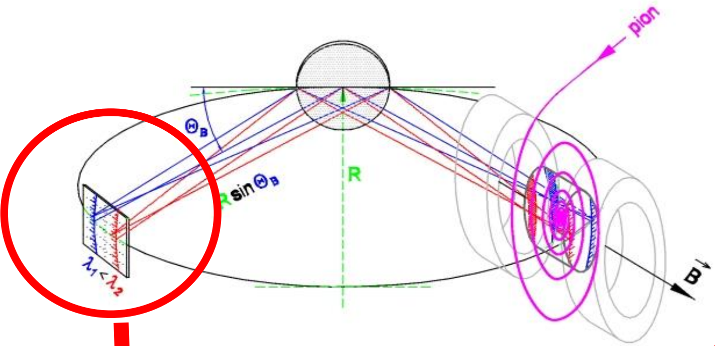
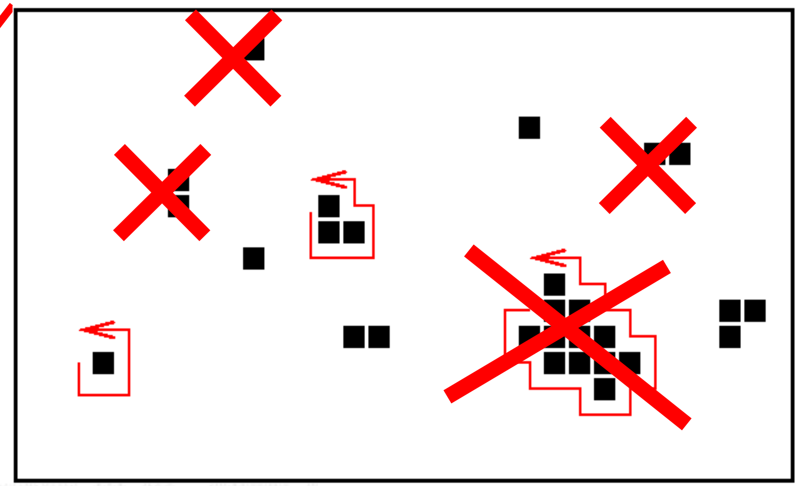
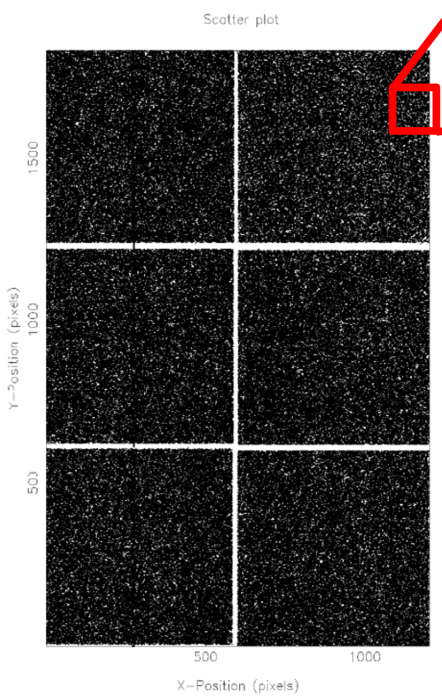
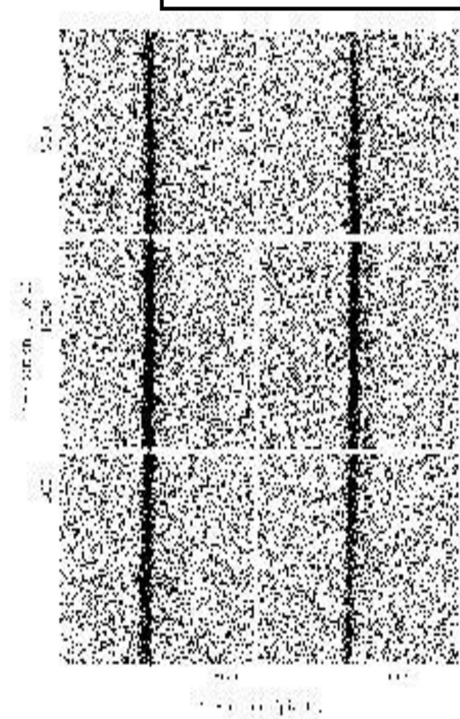


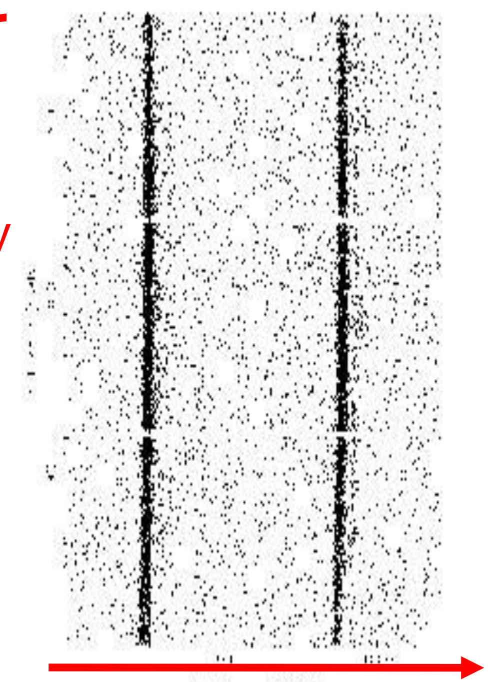




Cluster analysis

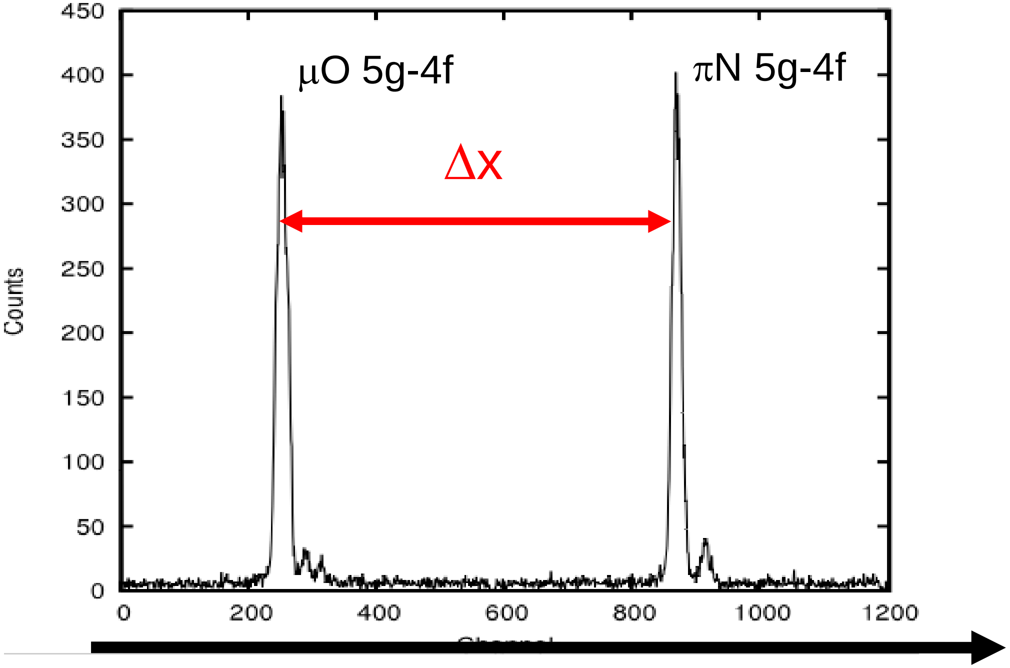


Cluster analysis and energy cuts

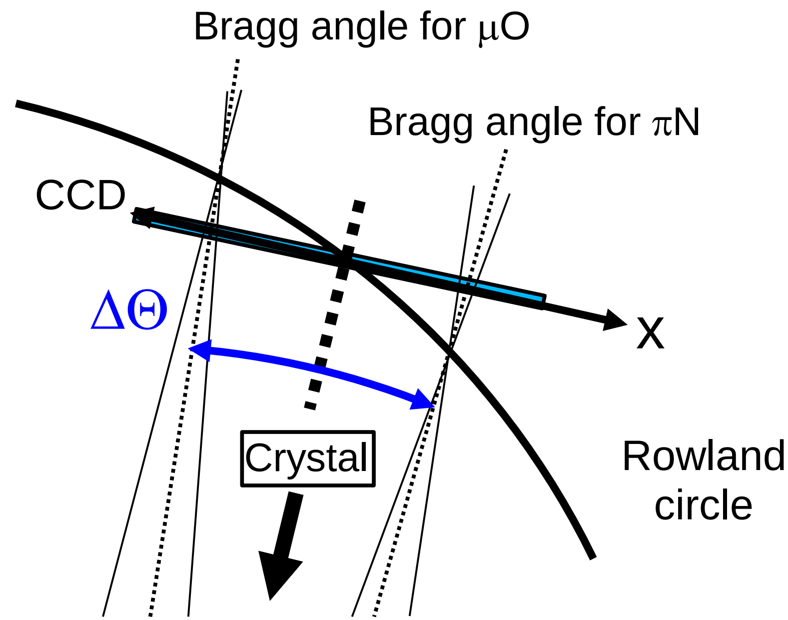


Energy (x-axis)

Detection (2)



Axe x on the CCD

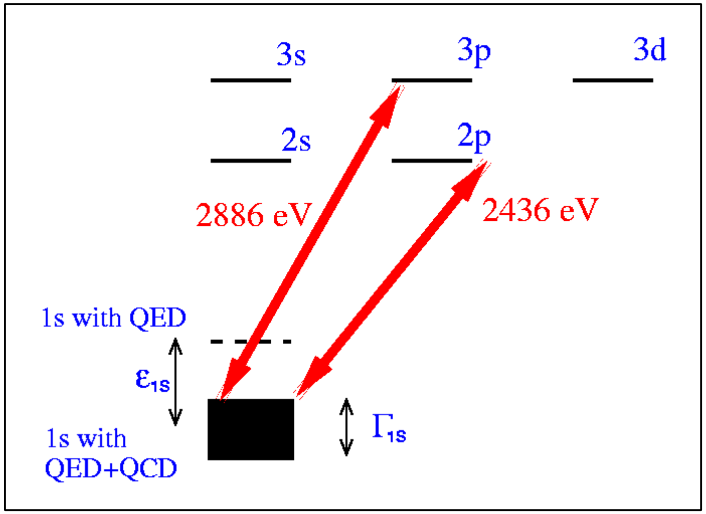


Bragg law $$\frac{h\,c}{E} = 2d\sin\Theta_B$$

Δx measurement -> ΔΘ measurement -> **measure of ΔE**

- Spectrometer resolution = 0.4 eV
- □E measurement precision < 0.005 eV

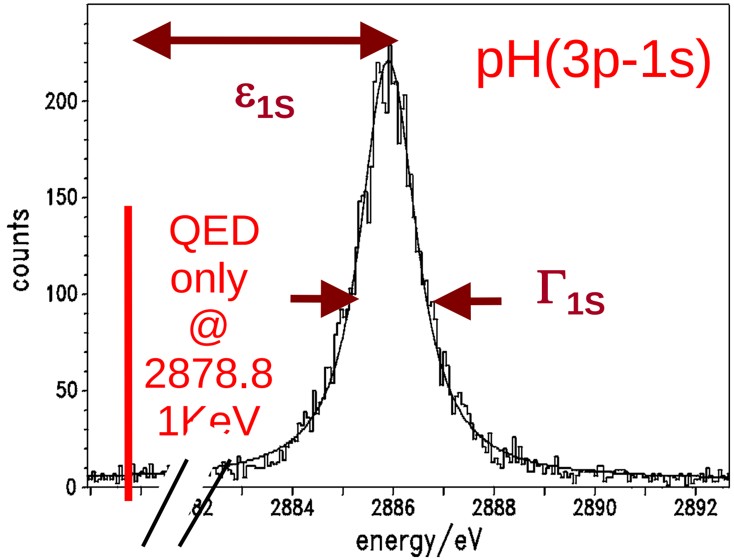
Pionic hydrogen measurements



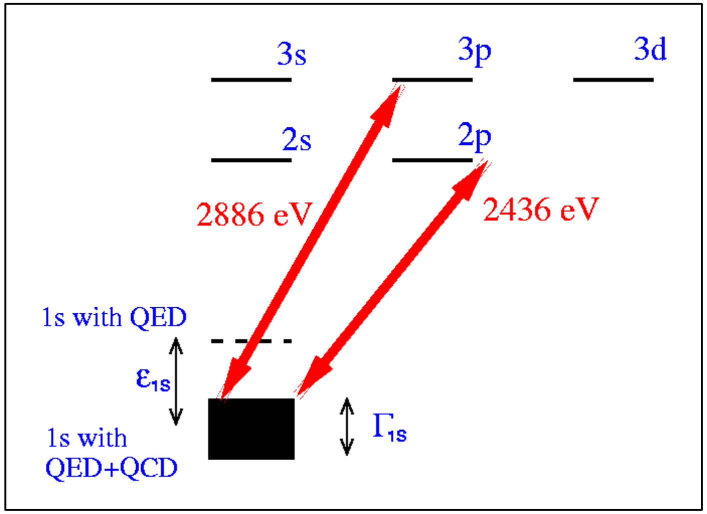
Strong interaction effect in 1s state

- Pion-proton attraction
-> shift in the 1s energy

- Pion absorption from the nucleus
-> 1s level instable and characterized by a broadening



Pionic hydrogen measurements



Strong interaction effect in 1s state

- Pion-proton attraction
-> shift in the 1s energy

- Pion absorption from the nucleus
-> 1s level instable and characterized by a broadening

Shift => proton pion elastic scattering

$$\frac{\varepsilon_{1s}}{E_{1s}} = -4\frac{1}{r_B} a^h_{\pi^- p \to \pi^- p}(1+\delta_\varepsilon)$$

Width => proton pion reaction

$$\frac{\Gamma_{1s}}{E_{1s}} = 8\frac{Q_0}{r_B}\left(1+\frac{1}{P}\right)\left(a^h_{\pi^- p \to \pi^0 n}(1+\delta_\Gamma)\right)^2$$

Deser's formulas

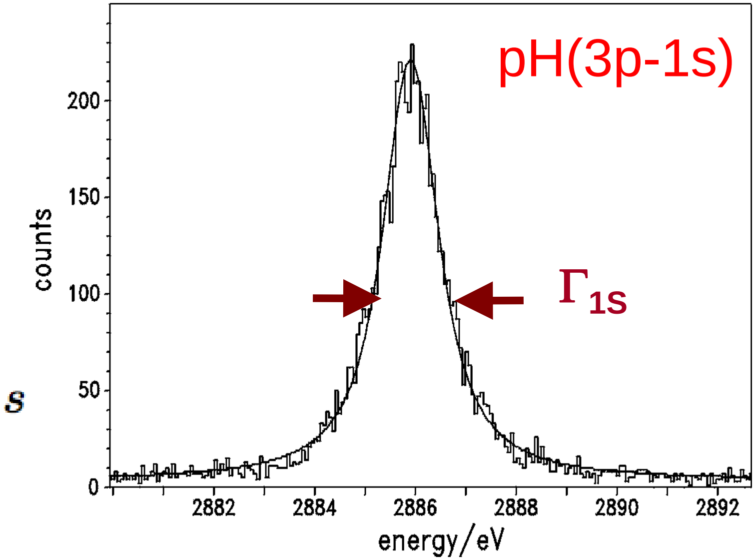
δ_ε, δ_Γ=e.m. corretions P=Panofsky ratio,
r_B Bohr radius, Q_0=kinematic factor

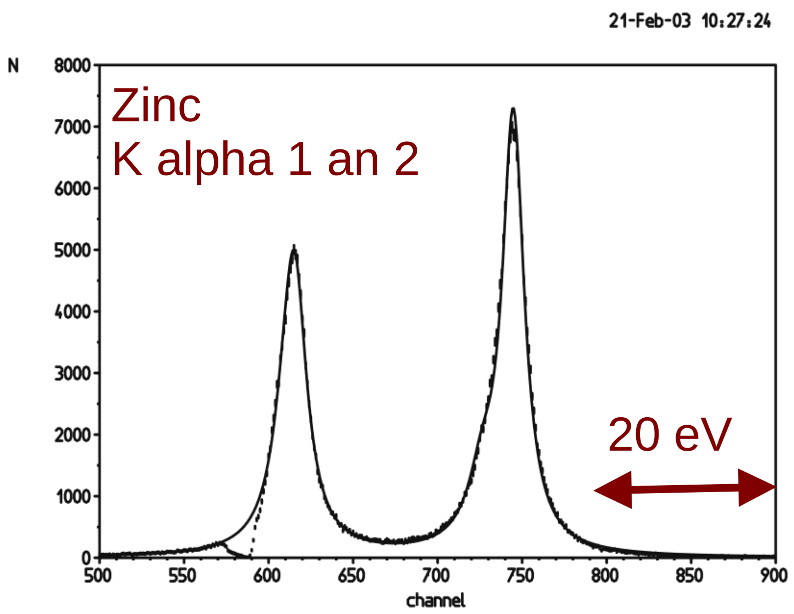
3p-1s width in pionic hydrogen

Pionic Hydrogen fundamental level width

- Γ_{1s} not measurable directly
- Broadening due to the pionic atoms kinetic energy
- Broadening due to the spectrometer resolution

$$\Gamma_{\text{exp}} = \Gamma_{\text{Spectrometer}} \otimes \Gamma_{\text{Doppler}} \otimes \Gamma_{1s}$$





Problem: it necessary to know the response function of the spectrometer

Solution: X-ray transitions from H- and He-like ions (natural width << meV)

Strong interaction shift and width: preliminary results

ε_{1S}= +7.120 ± 0.017 eV [1]

Previous experiment ε_{1S}= +7.108 ± 0.047 eV [2]

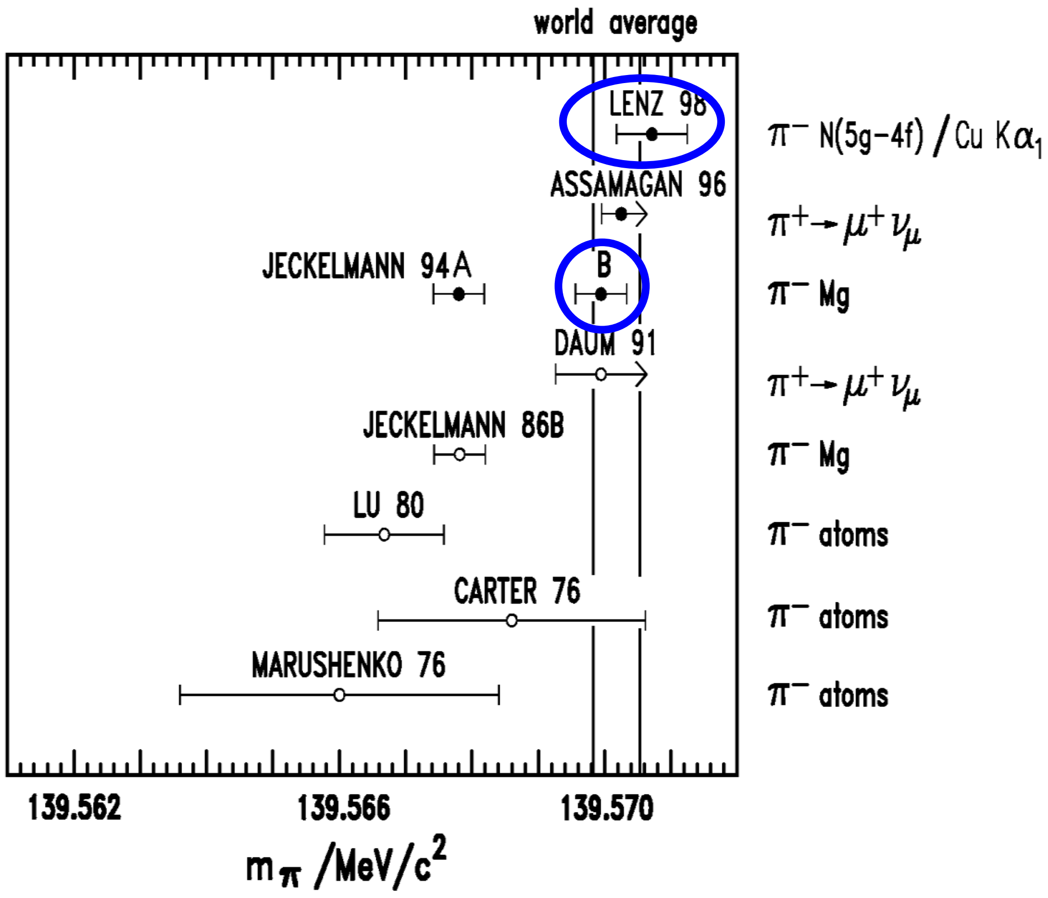
Γ_{1S} =800± 30 meV [1]

Previous experiment Γ_{1S} =865± 69 meV [2]

[2] H.C.Schroder et al., EUR. Phys. J. C 21, 473 (2001)

Measurement of the charged pion mass

Present precision: 2.5 ppm (average between 2 measurements: Lenz 1998 and solution B of Jeckelmann 1994 [1])



[1] Particle Data Book, Phys. Lett. B 592, 1+ (2004)

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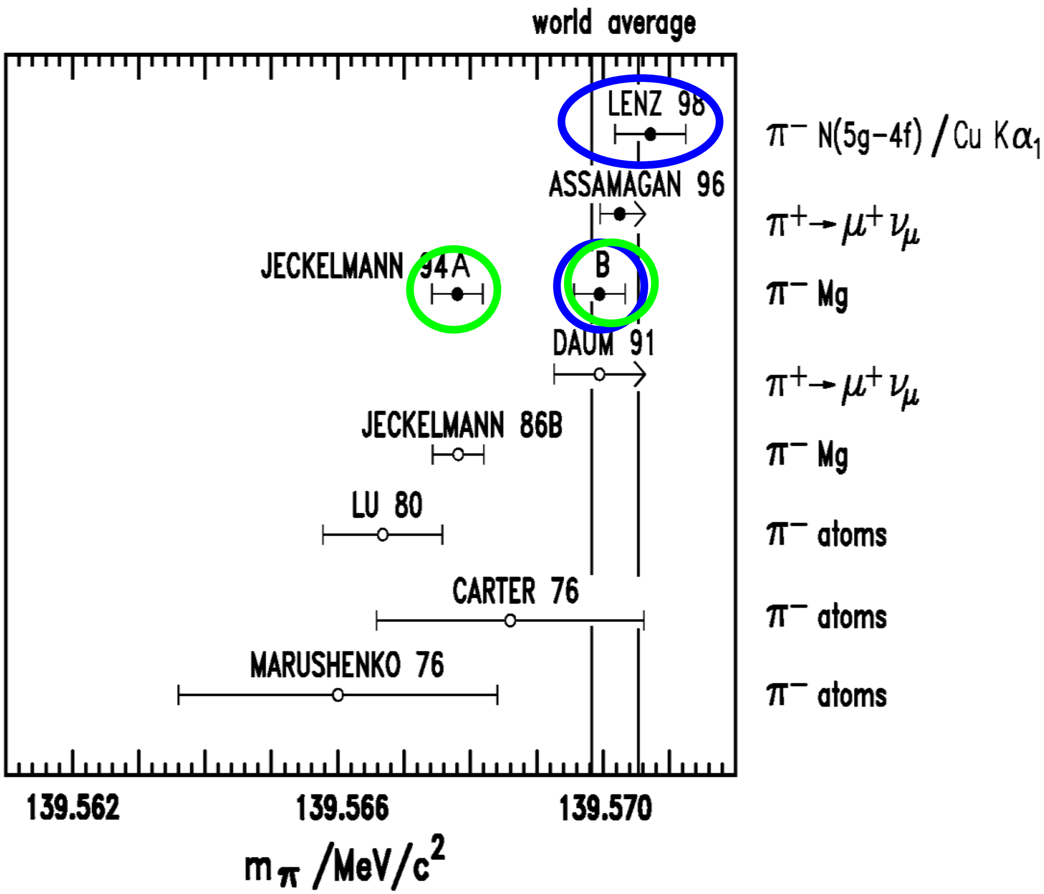

Ambiguity of the measurement due to the electronic recapture in the solid target

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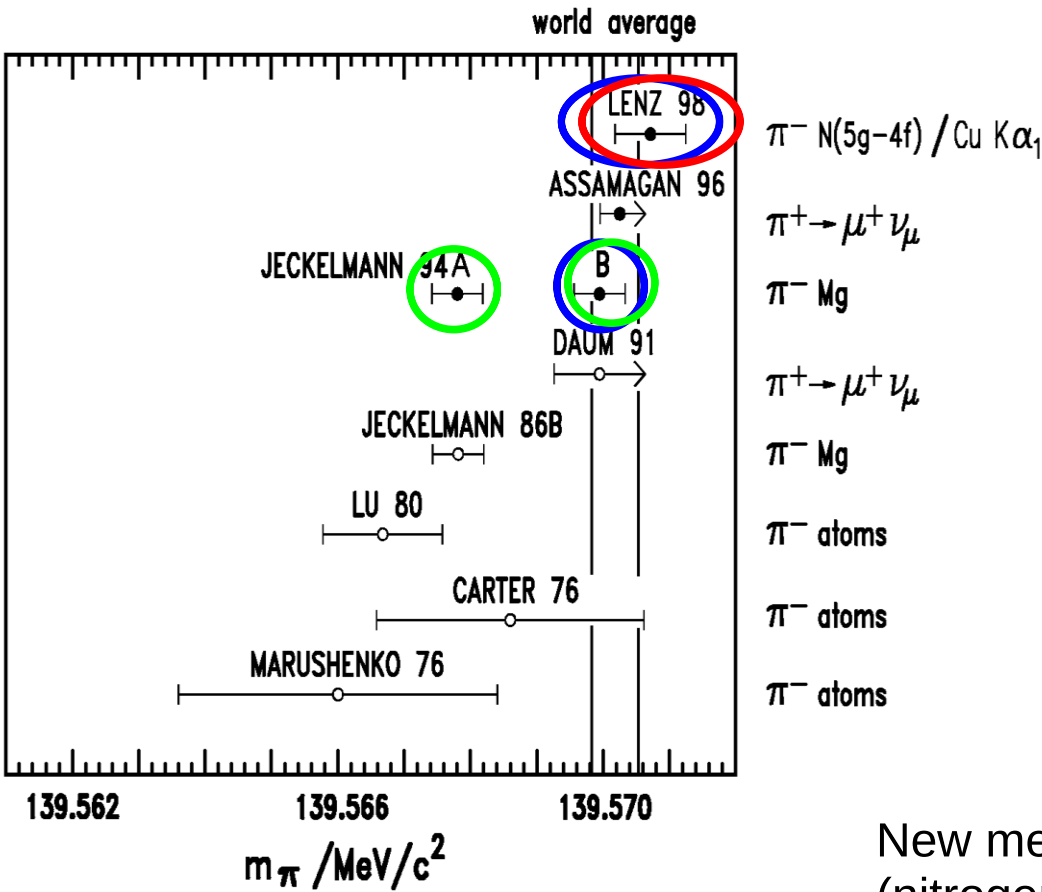


Ambiguity of the measurement due to the electronic recapture in the solid target

Gaseous target -> drastic reduction of the electron recapture

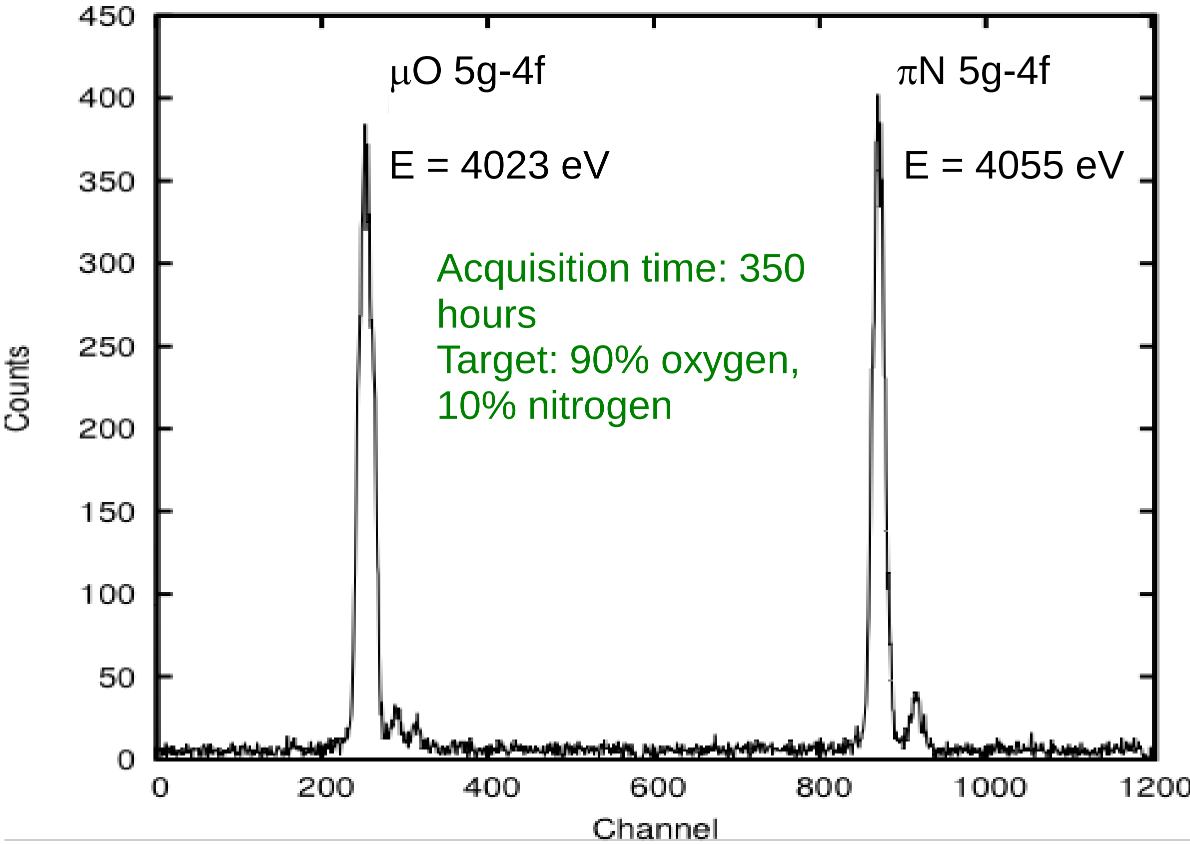
New measurement with gaseous target (nitrogen) and muonic oxygen transitions as calibration line

[1] Particle Data Book, Phys. Lett. B 592, 1+ (2004)

New measurement of the pion mass

- Measurement of the relative energy between 5-4 transitions in pionic nitrogen and muonic oxygen
- Muon mass accuracy = 0.05 ppm

-> pion mass measured with a precision of 1.7 ppm



$$\frac{m_\pi}{m_\mu} = F(\Delta E, \alpha, m_O, m_N) + \mathcal{O}\left[\left(\frac{m_\pi}{m_N}\right)^3\right] + \mathcal{O}\left[\left(\frac{m_\mu}{m_O}\right)^3\right]$$

Determination of F -> Theoretical predictions!!

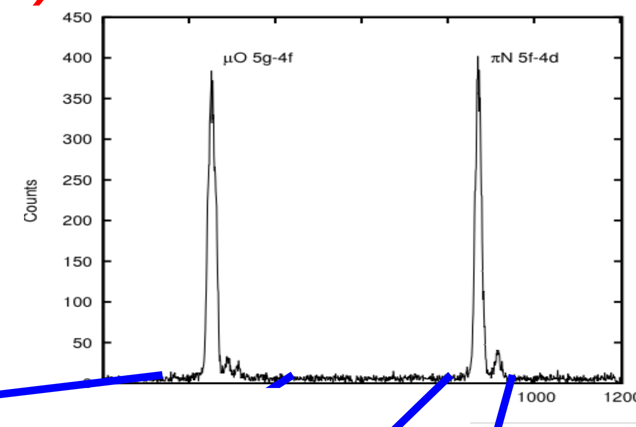
Transition energy calculations for pionic atoms

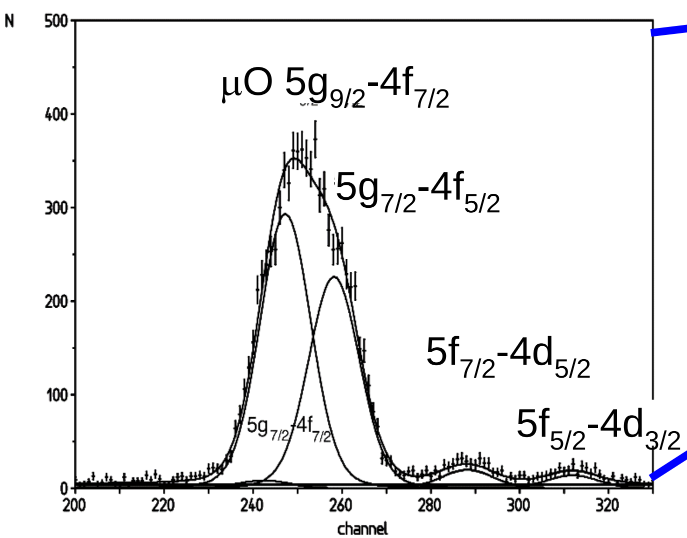
- Klein-Gordon equation -> for spin-0 particles
- QED corrections: self-energy, vacuum polarization, ...
- Recoil correction
- Shift due to the hyperfine structure (HFS)

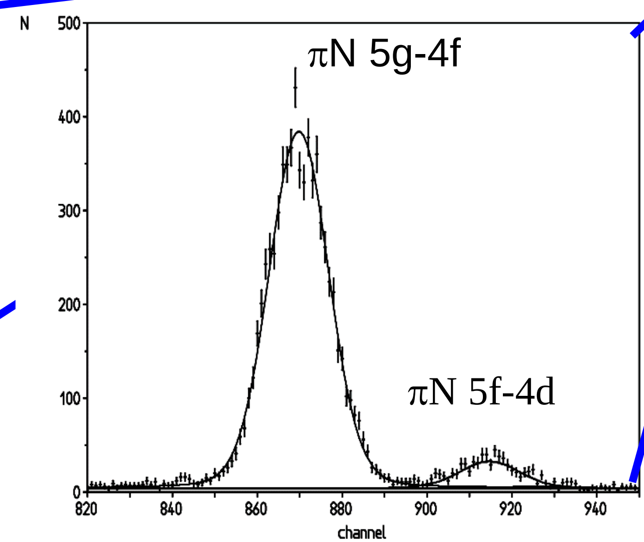
	5g-4f	5f-4d
Coulomb	4054.1180	4054.7189
Self Energy	-0.0001	-0.0003
Vac. Pol. (Uehling)	1.2485	2.9470
Vac. Pol. Wichman-Kroll	-0.0007	-0.0010
Vac. Pol. Two-loop Uehling	0.0008	0.0038
Vac. Pol. Källén-Sabry	0.0116	0.0225
Relativistic Recoil	0.0028	0.0028
HFS Shift	-0.0008	-0.0022
Total	4055.380	4057.691

Pion mass results (1)

- Line fit using the response function of the spectrometer
- Adapted profile for each group of line
- Different lines structure due to the particle spin difference







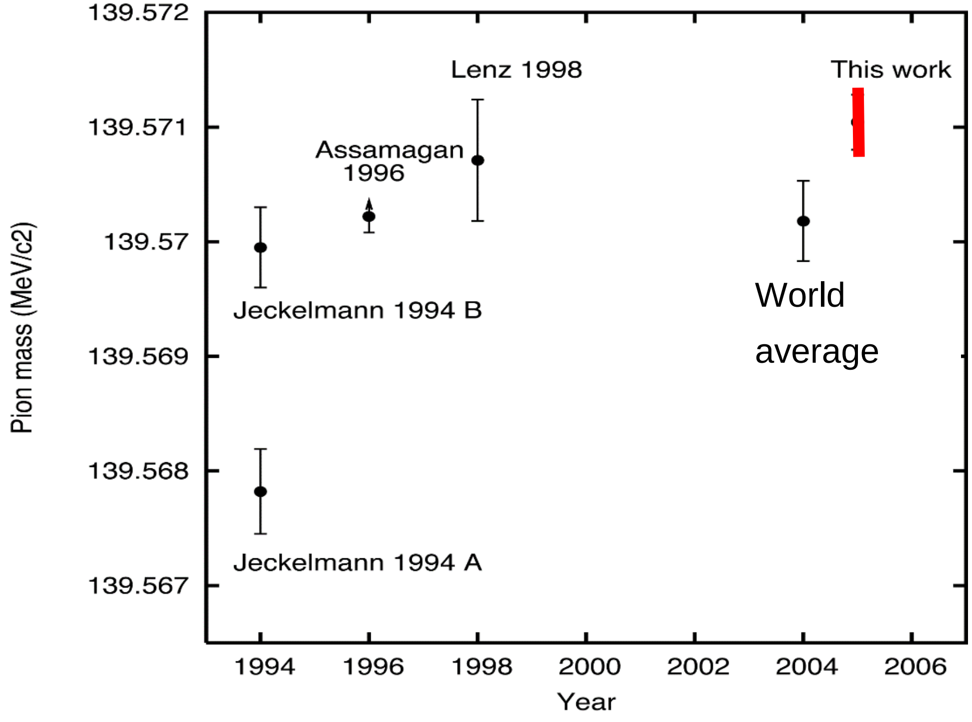
- Total acquisition time: 350 hours
- Precision of the peak distance measurement: ~ 0.11 pixels -> 6 meV -> 1.5 ppm in the pion mass value (statistic error)
- Systematic errors....

Pion mass results (2)

	Correction	Errors		Errors	
	µO-piN arcsec	error + arcsec	error - arcsec	error + ppm	error - ppm
Bending correction	0.214	0.004	0.004	0.015	0.015
Penetration depth correction	-0.004	0.001	0.001	0.004	0.004
Strong interaction 45 µeV	-0.003	0.003	0.003	0.011	0.011
1 K electron <0.16%		0.000	0.050	0.000	0.184
Curvature correction		0.040	0.040	0.147	0.147
Off-line CCD height reduction		0.061	0.061	0.225	0.225
Fit region		0.004	0.004	0.015	0.015
Model for the line fit		0.070	0.070	0.258	0.258
Detector-Crystal distance		0.153	0.153	0.564	0.564
Orientation detector + tubes ≤ 0.14°		0.000	0.008	0.000	0.030
Height CCD (out of plane) ≤ 20 mm		0.000	0.009	0.000	0.032
Target shape		0.027	0.027	0.099	0.099
CCD alignment ("gap")		0.090	0.090	0.332	0.332
Pixel distance		0.033	0.033	0.122	0.122
πN, µO energies		0.093	0.093	0.343	0.343
Temperature renormalisation of Det-Cry dist.	-0.003	0.005	0.005	0.018	0.018
Corr: sum /Errors: quadratic sum	0.207	0.209	0.215	0.769	0.792

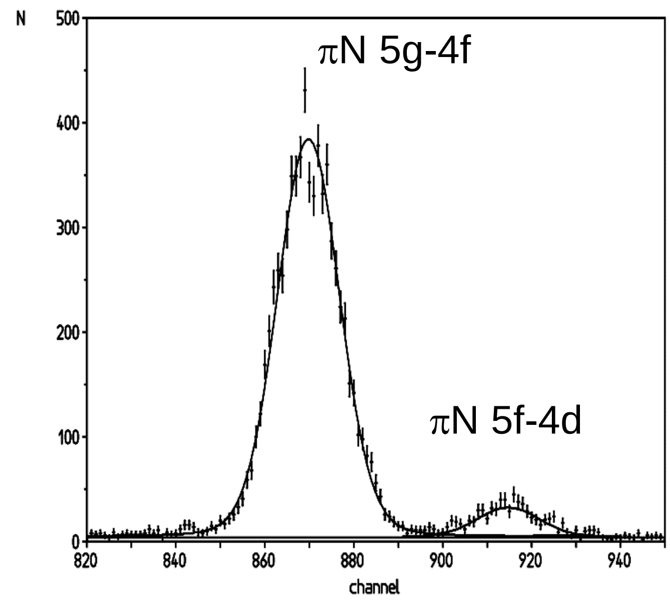
Error on the pion mass : $[(0.8)^2_{(systematic)} + (1.5)^2_{(statistic)}]^{1/2}$ =1.7 ppm

Pion mass results (3)

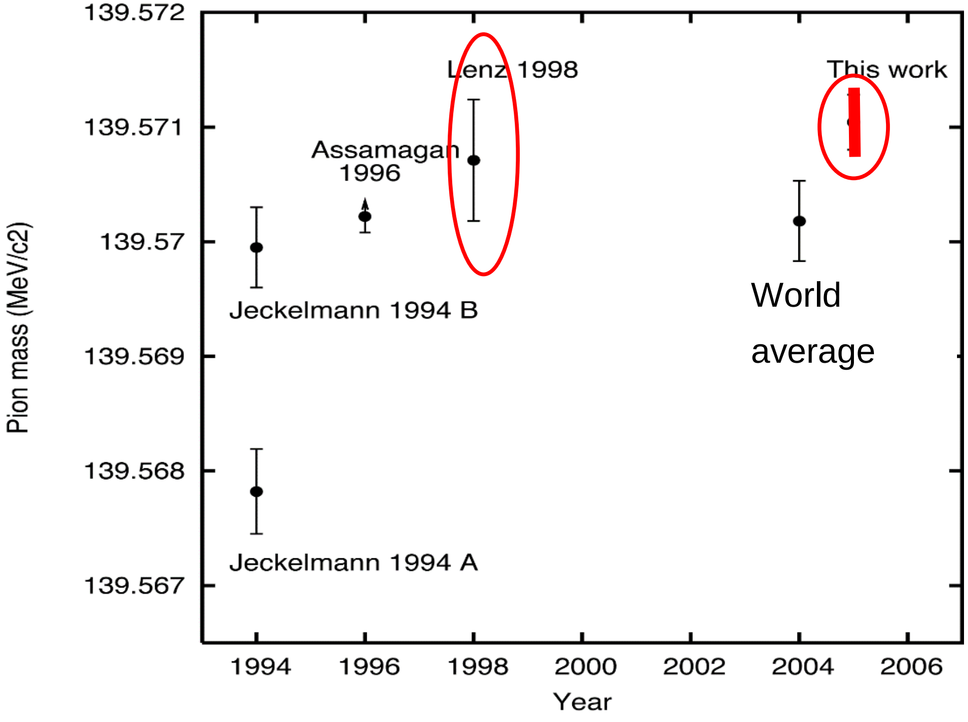


$m_{\pi} = (139.571\ 04 \pm 0.000\ 23)$ MeV

- 30% more precise than the world average
(2 times more precise than Lenz 1998)
- Increasing of the X-ray standard precision
- New evaluation of the muonic neutrino mass



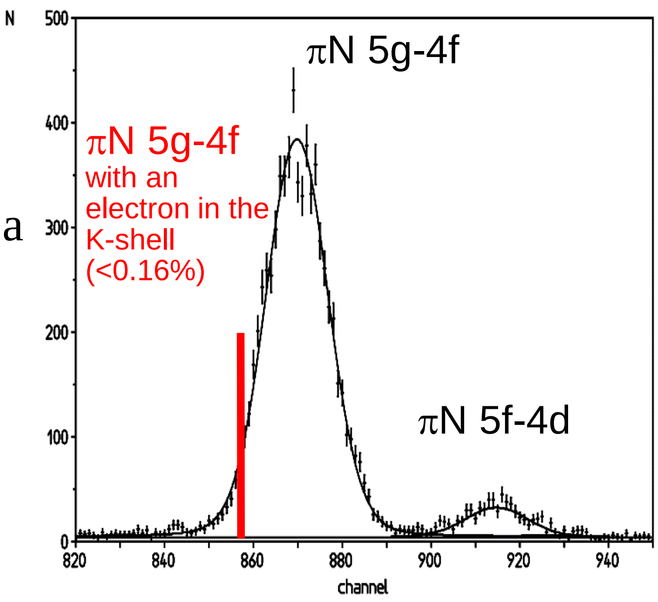
Pion mass results (3)



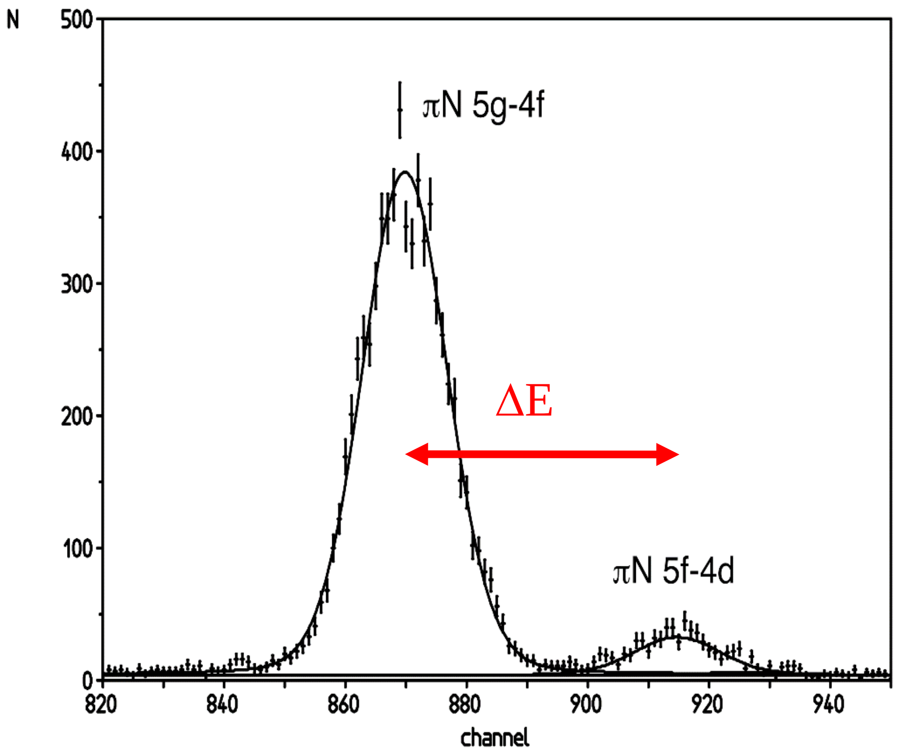
m_π = (139.571 04 ± 0.000 23) MeV

- 30% more precise than the world average
(2 times more precise than Lenz 1998)
- Increasing of the X-ray standard precision
- New evaluation of the muonic neutrino mass

- Agreement with the previous measurement with a gaseous target
- Any ambiguity due to the electronic recapture



Test of the Klein-Gordon equation



- Pionic atoms spectroscopy
  -> QED test for spin-0 particles

- Fine structure of the 5-4 transition in pionic nitrogen

- Previous test:
  pionic titanium, precision = 2%

- Theoretical value
  (QED + strong interaction): $\Delta E = 2.321$ eV

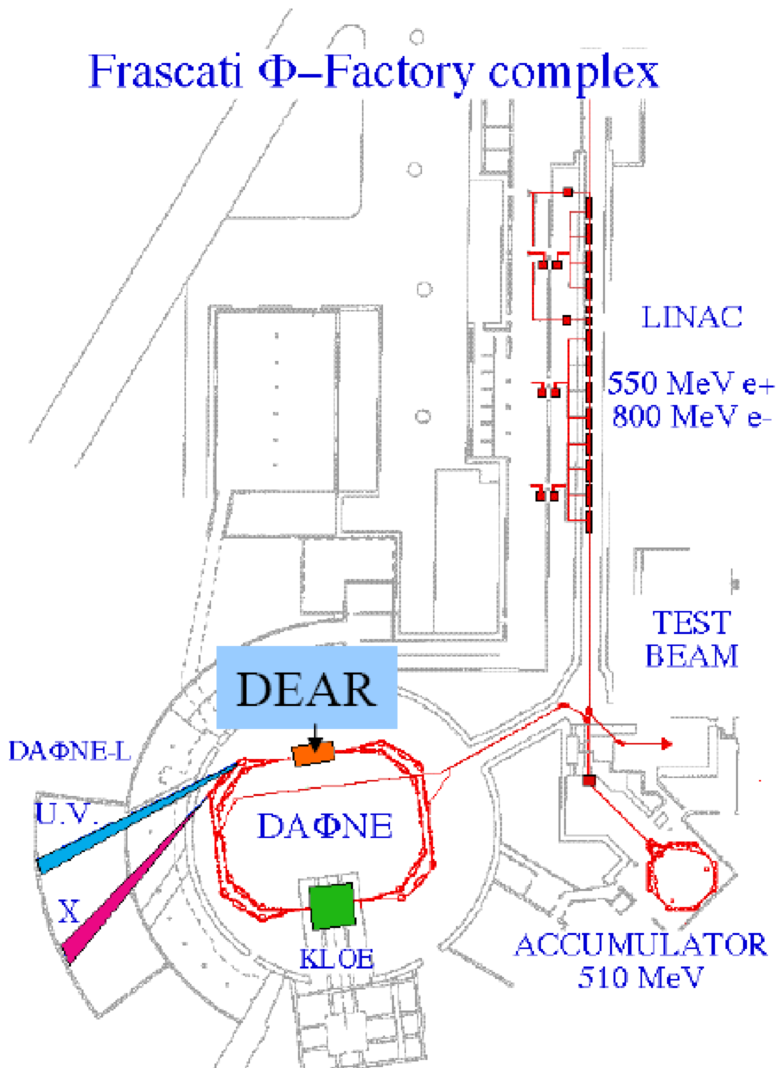
- New measurement: $\Delta E = 2.300^{+0.014}_{-0.007}$ eV
  (relative error = 0.6%)

- Limitation: prediction of the contribution due to a remaining electron in the K-shell

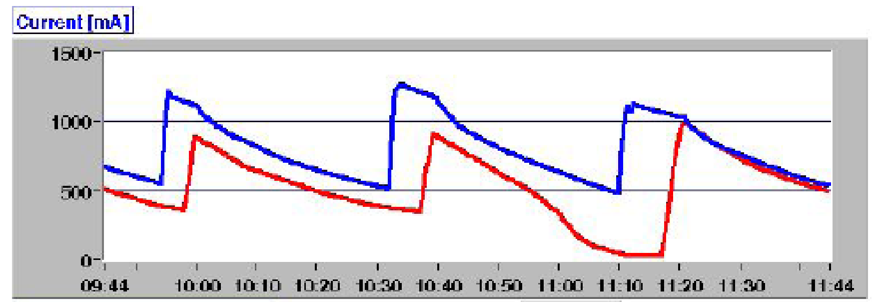
Other exotic atoms

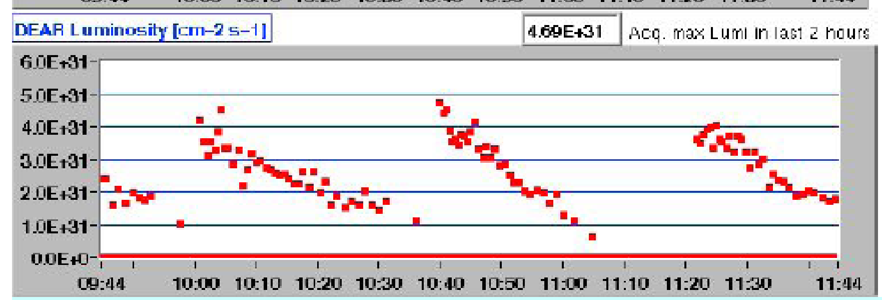
Kaonic Nitrogen at DAΦNE

DAΦNE (LN Frascati)



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





Φ production cross section ~ 3000nb (corrected for radiative losses)

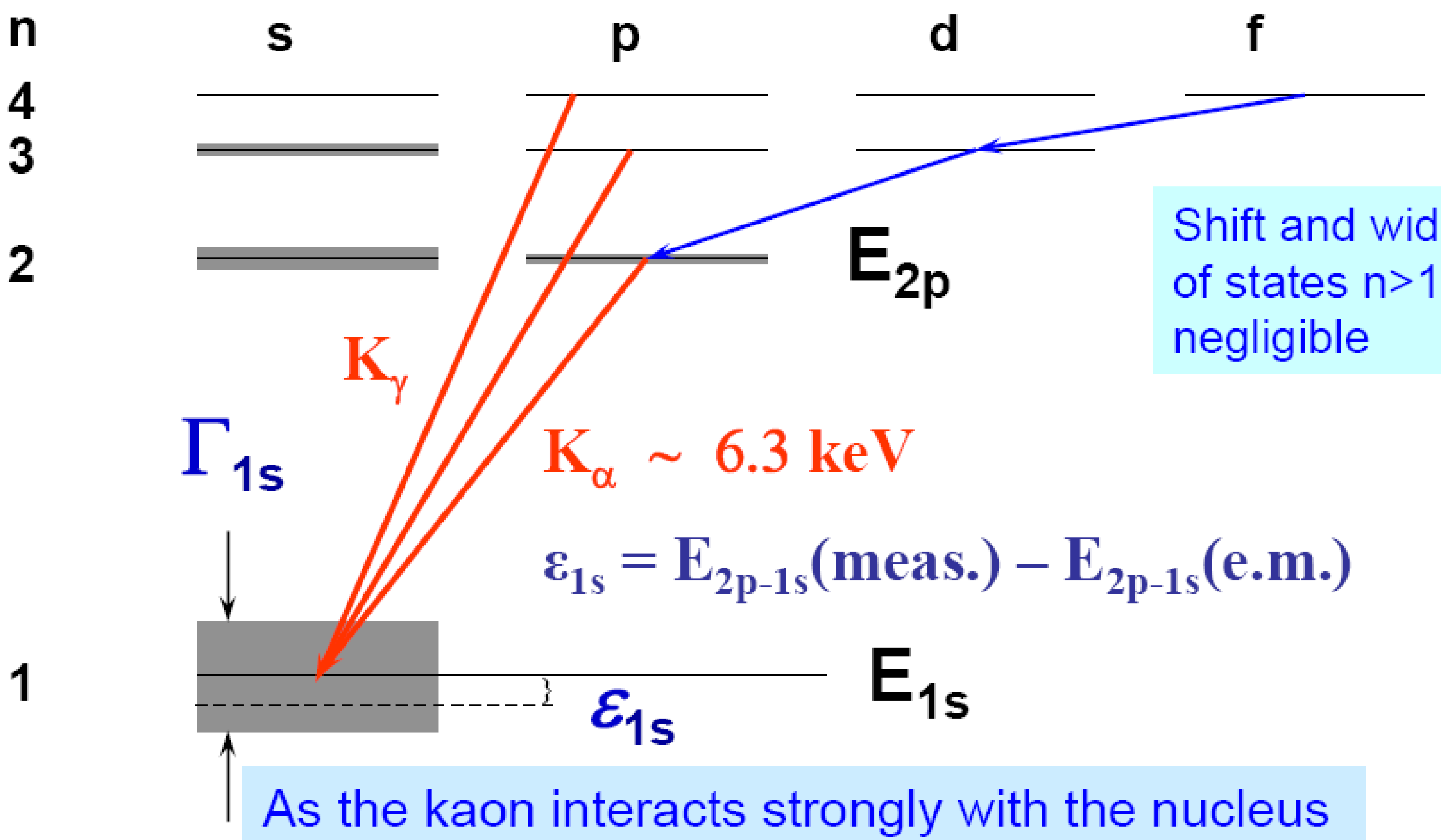
Integrated luminosity ~ 2 pb^{-1} per day

~ 3×10^6 K^- per day

From M. Cargnelli talk at PSAS 2006

Kaonic hydrogen

Negative kaons stopped in H_2 → initial atomic capture →
→ electromagnetic cascade → X-ray transitions



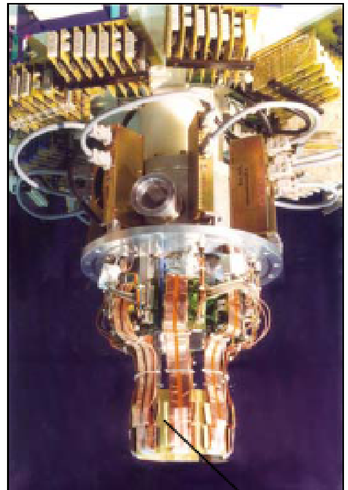
Shift and width of states n>1 negligible

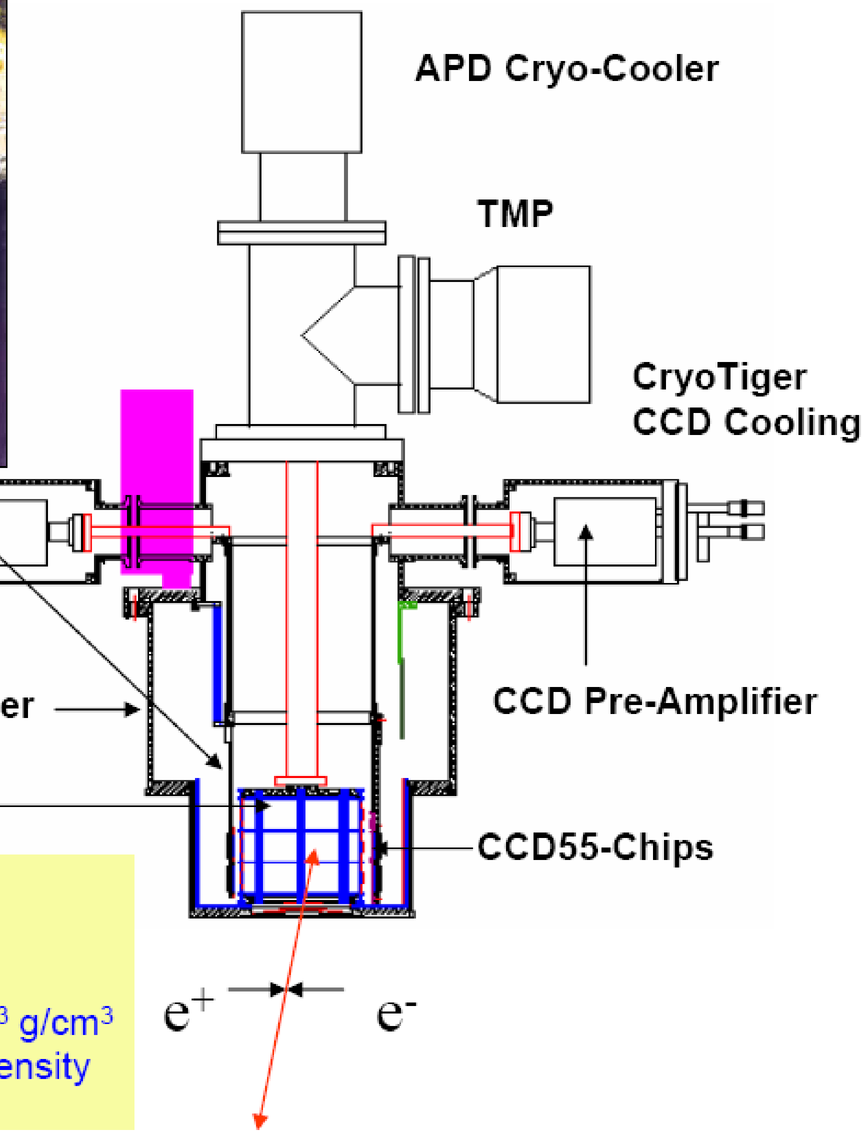
As the kaon interacts strongly with the nucleus the 1s energy level is shifted and broadened

DEAR Experimental Set-up

Energy measurement of kaonic K lines with an array of 16 CCD X-ray detectors

- pixel size 22.5x22.5 μm
- total area per chip 7.24 cm^2
- depletion depth ~30 μm
- read-out time per CCD 2 min.
- energy resolution ~140 eV @ 5.9keV

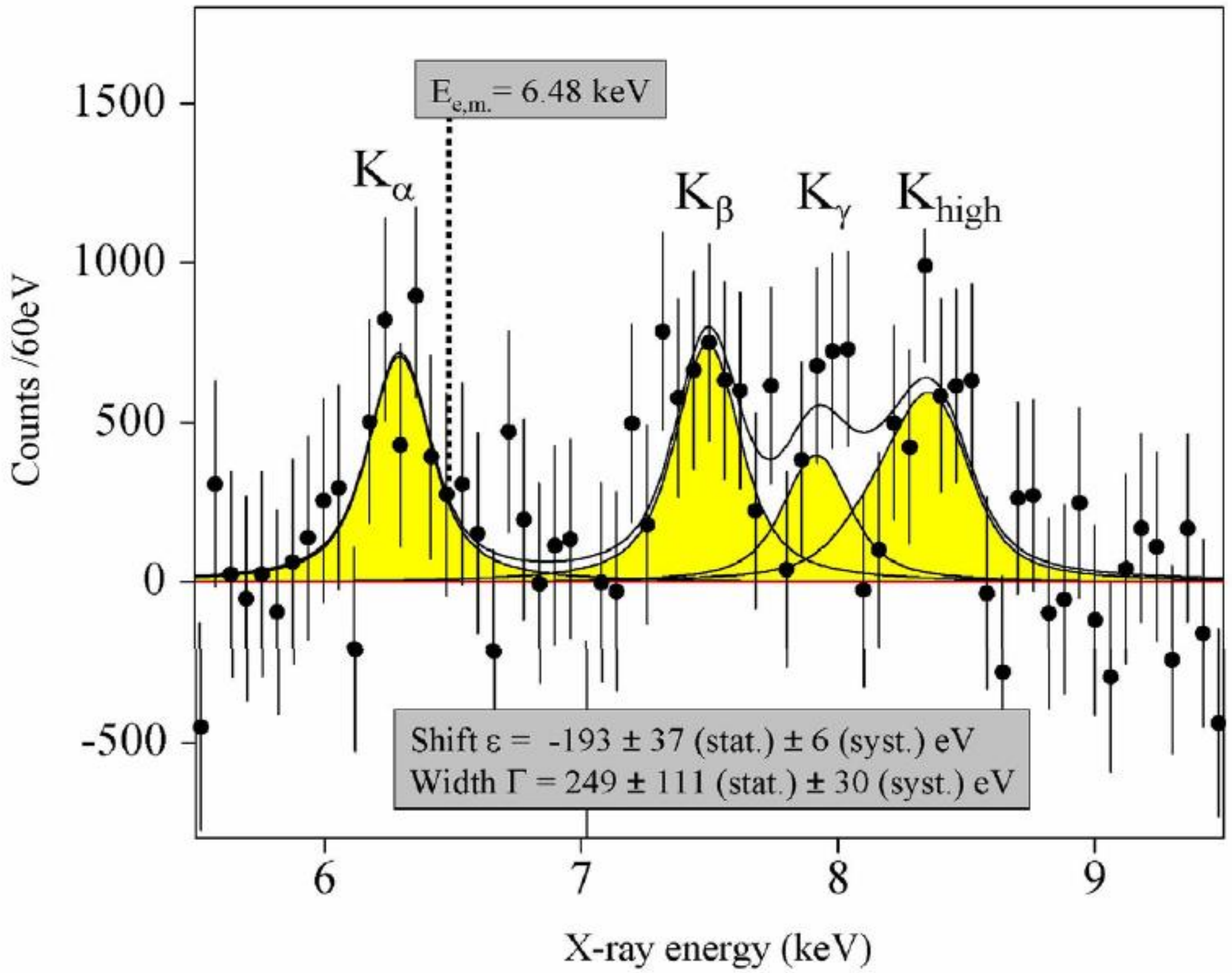




volume: 1150 cm^3 cryogenic H_2 gas
side: 75 μm Kapton
entrance: 125 μm Kapton
grid structure: glass fiber reinforced epoxy

Gas properties:
Pressure = 2 bar,
Temp = 25 K
Density = 2.070×10^{-3} g/cm^3
= 0.029 × liq. hydr. density
= 23 × STP density

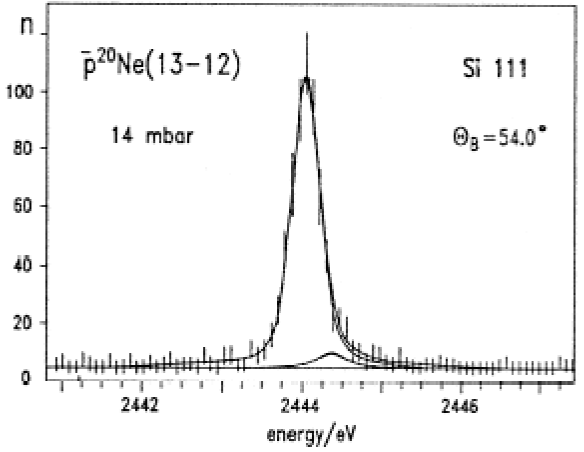
Kaonic hydrogen results from DEAR



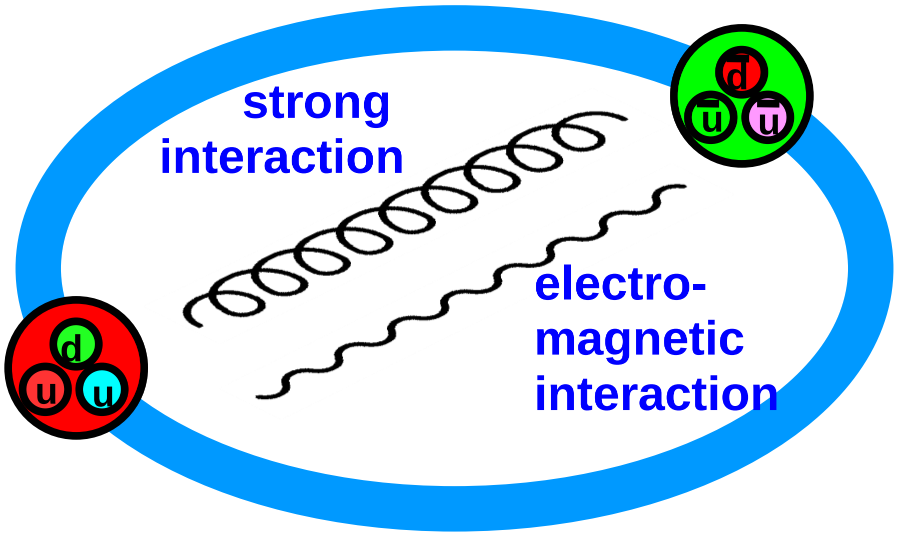
Antiprotonic atoms at LEAR

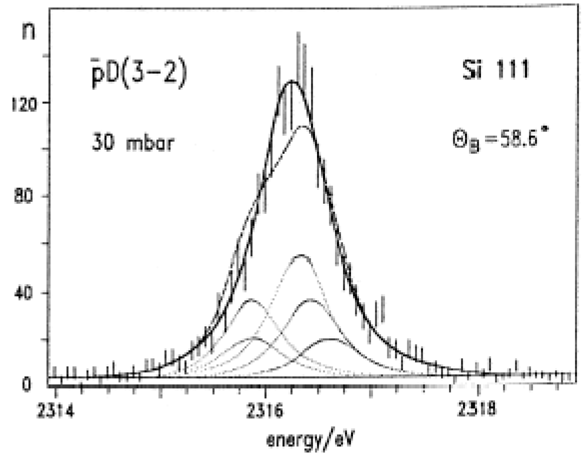
- EM and **strong interaction**
- Nucleon-antiproton interaction (Z=1,2,..)
  -> nucleon-nucleon interaction
- Nuclear probe (high Z)
- Recoil and QED corrections

- Soon available in **high quantities at FAIR**



Obtained at LEAR (Gotta 1999)





Z ↓

Muonic hydrogen (-2.5 keV)

Lamb shift:	**-1.9 eV**
Self energy	0.4%
Vacuum Polarization	97.9%
Nuclear size	1.6%

H-like silicon (-2.6 keV)

Lamb shift:	**0.48 eV**
Self energy	93.6%
Vacuum Polarization	5.9%
Nuclear size	0.5%

Muonic nitrogen (-136 keV)

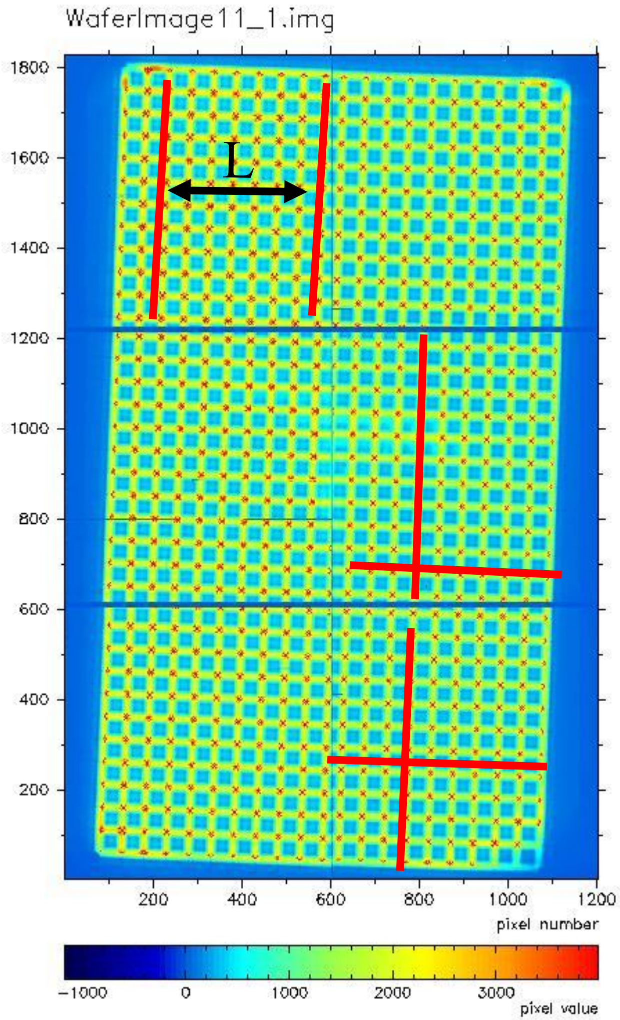
Lamb shift:	**199 eV**
Self energy	0.7%
Vacuum Polarization	42.8%
Nuclear size	56.5%

H-like uranium (-132 keV)

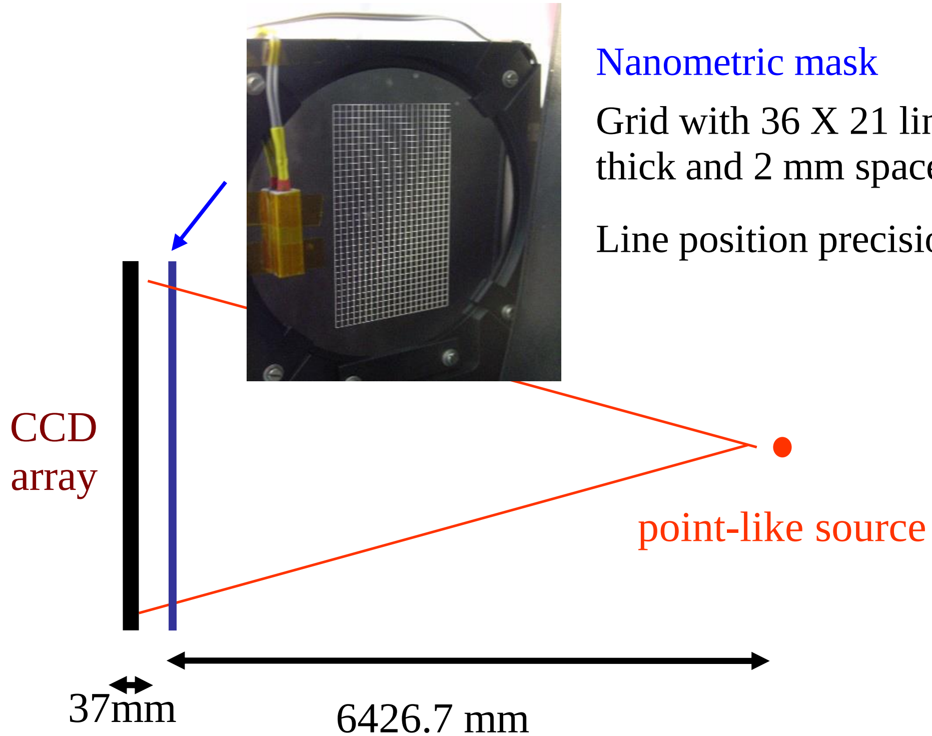
Lamb shift:	**462 eV**
Self energy	54.3%
Vacuum Polarization	13.8%
Nuclear size	30.4%

Complementary systems!!

Distance between pixels and CCDs position on the detector



Measurement on September 2003...



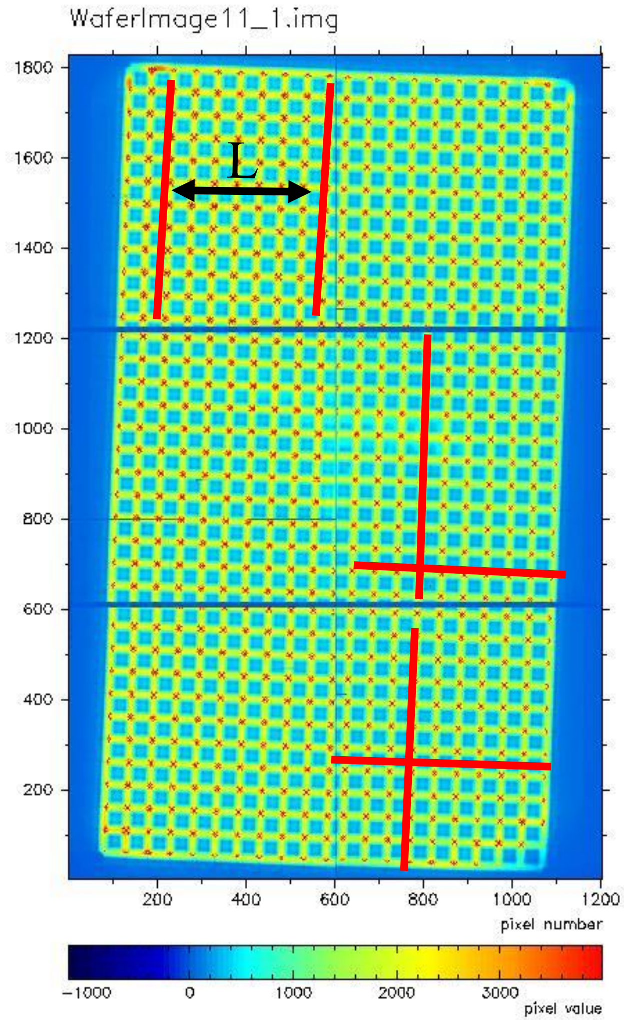
Nanometric mask

Grid with 36 X 21 lines 50 μm thick and 2 mm spaced

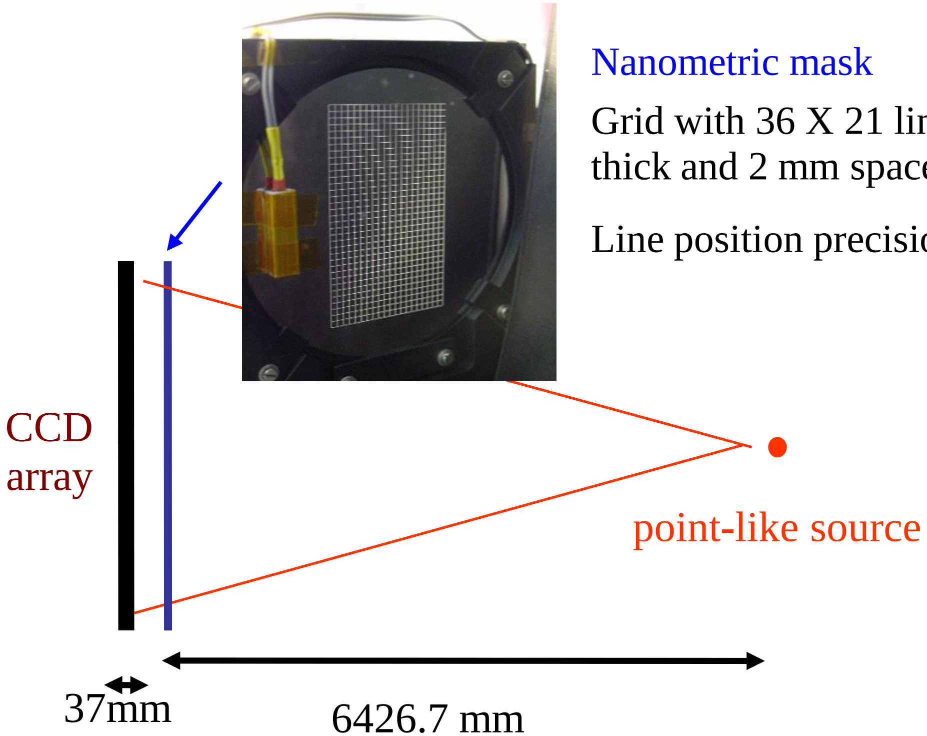
Line position precision: 0.05 μm

... after 8 months of analysis...

Distance between pixels and CCDs position on the detector



Measurement on September 2003...



Nanometric mask

Grid with 36 X 21 lines 50 µm thick and 2 mm spaced

Line position precision: 0.05 µm

... after 8 months of analysis...

- Distance between pixels = 39.9775 ± 0.0006 µm ->0.1 ppm
- Error on the CCDs position : 0.05 mrad (orientation)

  0.02 pixels (displacement) ->0.3 ppm

M. T., et al., Review of Scientific Instruments 77, 043107 (2006).

X-Ray Spectroscopy Experiments Based on Micro-Calorimeters

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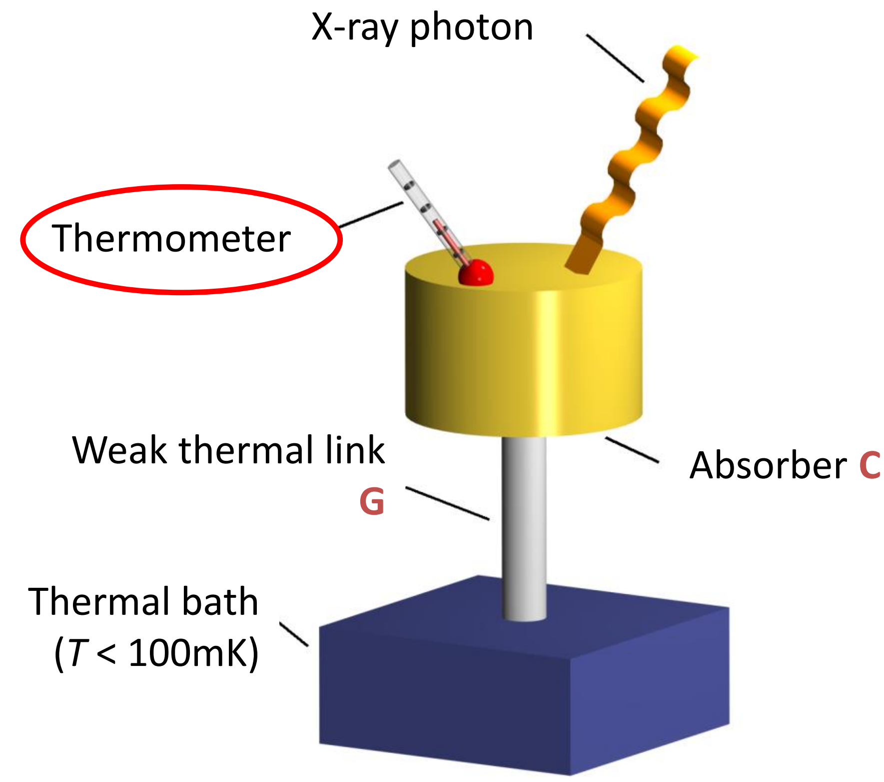
Karl-Heinz Blumenhagen
Tobias Gassner
Renate Märtin
Günter Weber
Thomas Stöhlker
GSI
IOQ, Friedrich-Schiller-Universität Jena
Helmholtz-Institut Jena

Robert Lötzsch
Ingo Uschmann
Eckhart Förster
IOQ, Friedrich-Schiller-Universität Jena

And the SPARC **collaboration**

Structure of a Microcalorimeter



- Thermistor (S. Kraft-Bermuth)
- Transition Edge Sensor (TES)
- Metallic Magnetic (A. Fleischmann)

Main observable: temperature change

$$\delta T = \frac{E_\gamma}{C}$$

- E_γ: given: E_γ = 60 keV ≙ 10^{-15} cal (tiny)
- δT: should be large
- C: As small as possible; hence ***Micro***calorimeter

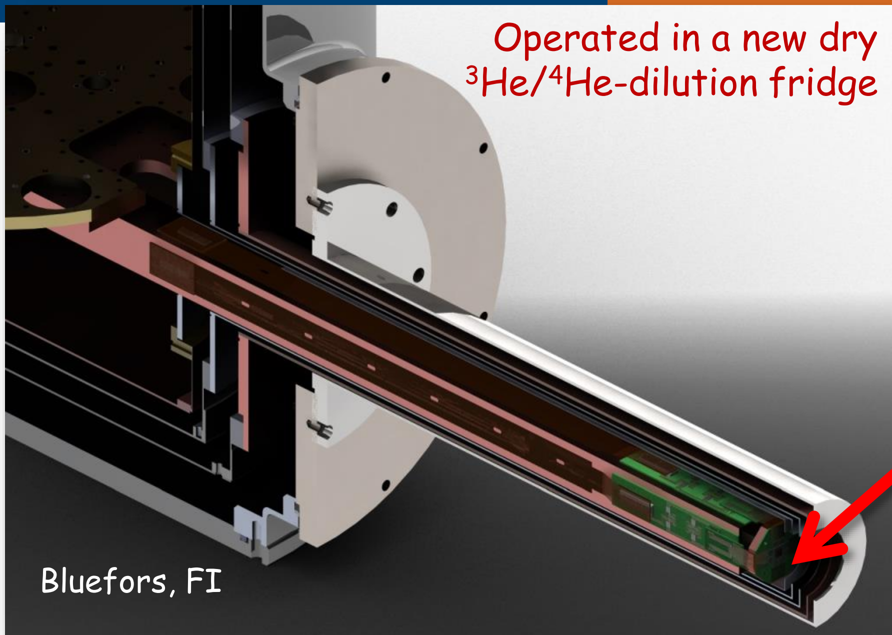
Heat capacity of a conductor:

$$C = V(\gamma T + \beta T^3)$$

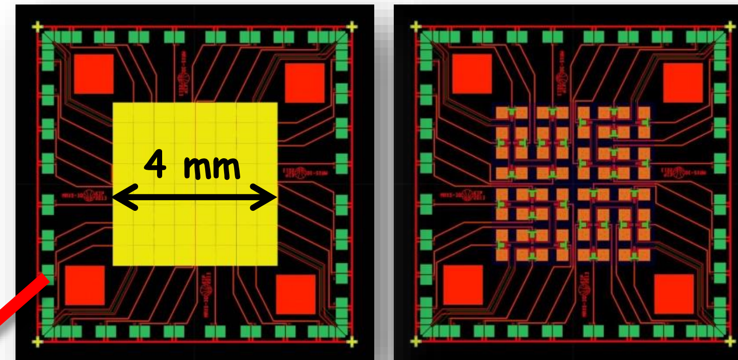
=> small volume at low temperatures

maXs: micro-calorimeter arrays for hi-res x-ray spectroscopy

Operated in a new dry $^3He/^4He$-dilution fridge



maXs-30: first of 4 arrays for different energies

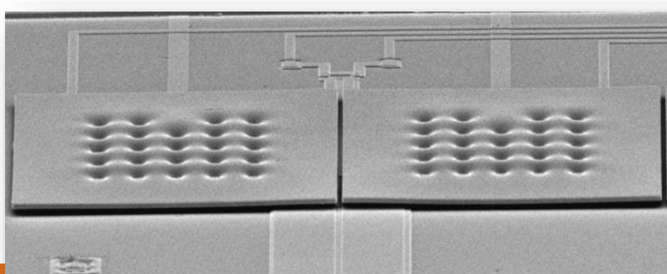


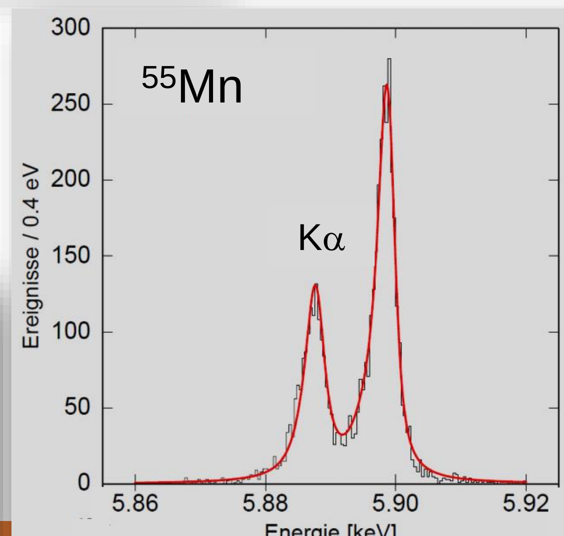
- 8 x 8 pixels 30 μm thick gold
- 75% Q.E. at 30 keV
- **ΔE_{FWHM} < 6eV**

C. Enss, A. Fleischmann (Uni. Heidelberg)

During system integration:

two maXs-20 pixels
in this cryostat at T = 20 mK



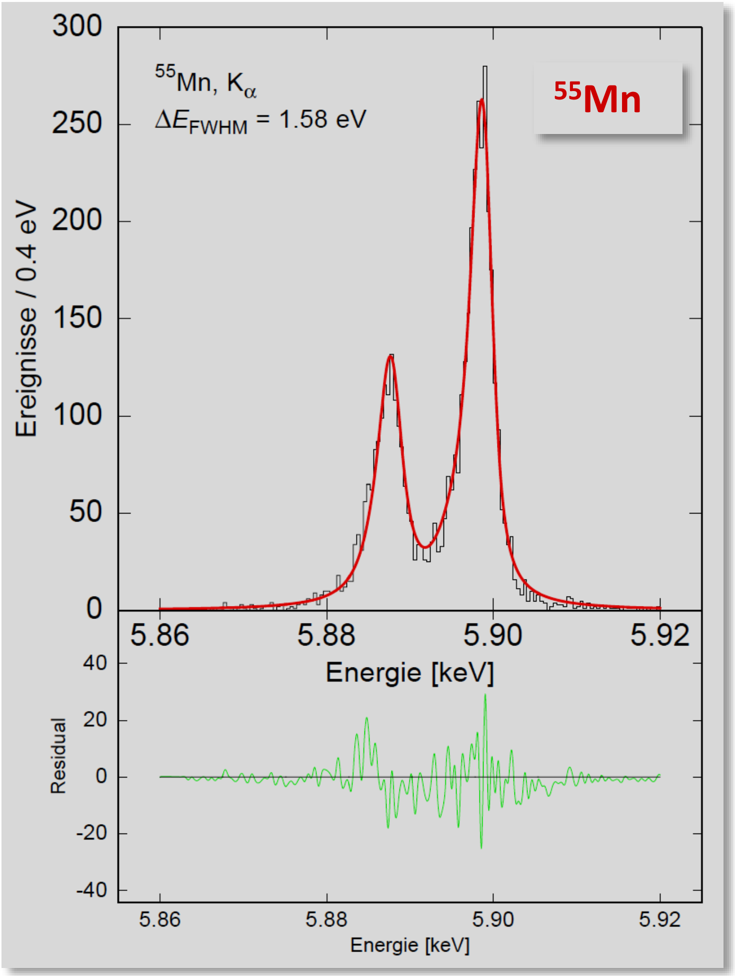


ΔE_{FWHM} = 1.6 eV @ 0…6 keV

World record !

together with
TES-sensors of NASA-GSFC

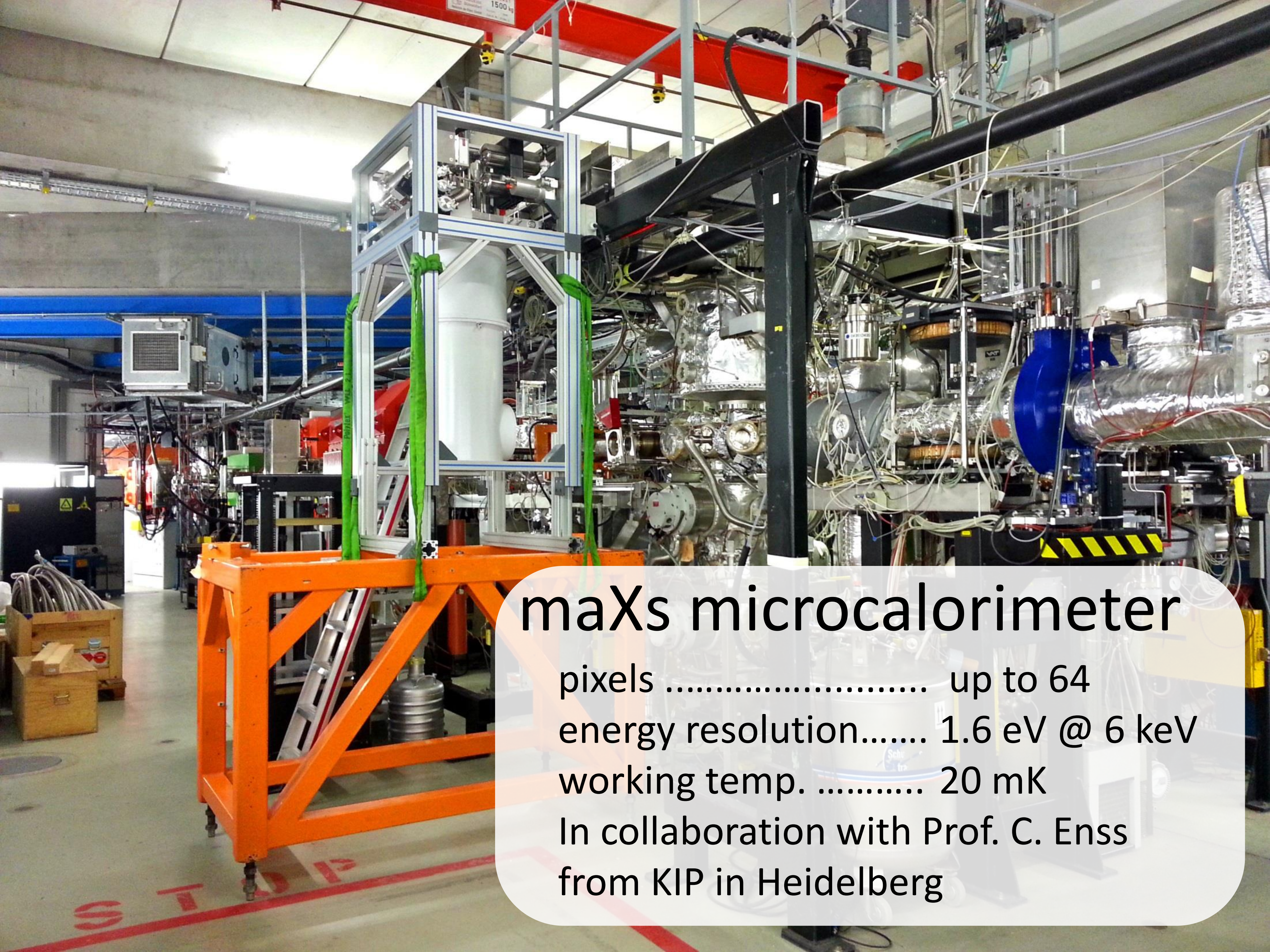
maXs-20 Prototyp Spectrum



ΔE_{FWHM} = 1.6 eV @ 6 keV

World record together with TES-sensors of NASA-GSFC!

HI Jena
Helmholtz Institute Jena

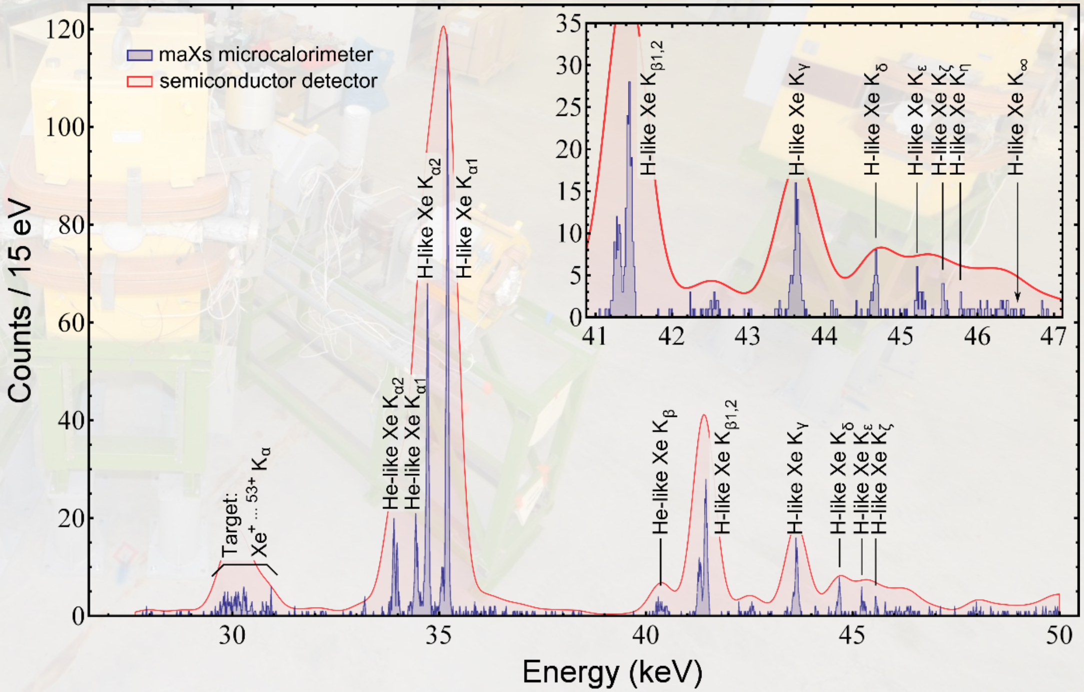


maXs microcalorimeter

pixels .... up to 64
energy resolution……. 1.6 eV @ 6 keV
working temp. ………. 20 mK
In collaboration with Prof. C. Enss
from KIP in Heidelberg

CRYRING

- first beam (expected)........... 2016
- circumference .... 54 m
- min ion velocity .... 7 ‰ c_0
- swedish in-kind contribution



T. Gassner *et al.*, GSI Scientific Report 2014 (2015)