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JÜLICH FORSCHUNGSZENTRUM

Exotic Atoms

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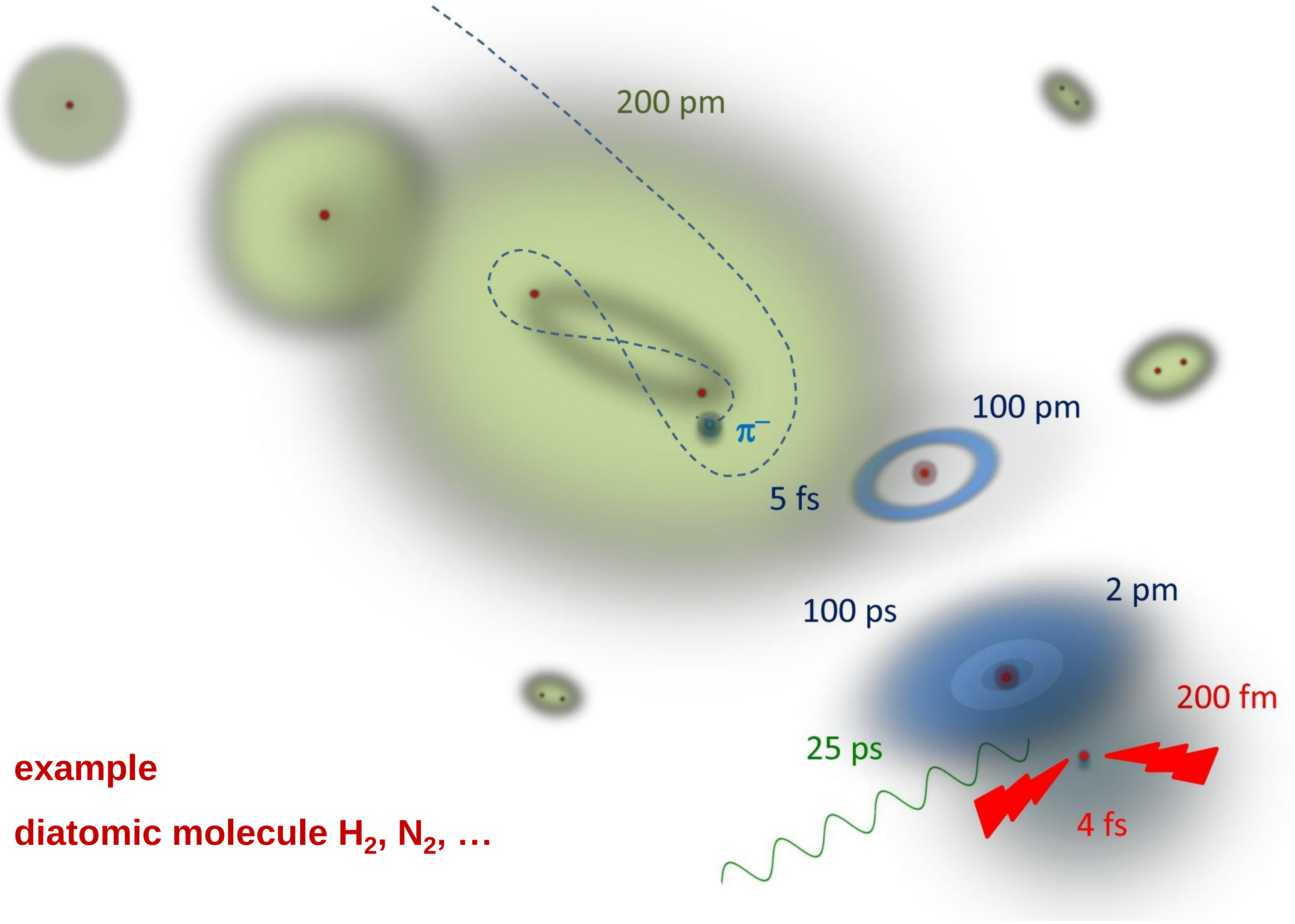
- **EXOTIC ATOM**
- **HISTORY**
- **EXPERIMENT** ***3 items***
- **PHYSICS POTENTIAL** ***5 examples***

EXOTIC ATOM

Replace electrons by heavier negatively charged particles



example

diatomic molecule H_2, N_2, …

HISTORY

- **Prediction**

1947	$\tau_{capture} << \tau_{meson}$	*Fermi &Teller*

- **First X-ray experiment**

1952	*pion*	π^- C	NaI
1953	*muon*	..., μ^- Pb *fine structure splitting ,...*	NaI
1965	*kaon*	K^- He	prop. counter
1969/70	*sigma*	Σ^- S, Σ^- K	Ge(Li)
1970	*antiproton*	$\bar{p}$Tl	Ge(Li)

- **FACILITIES**

1974 ...	*pions, muons*	Paul-Scherrer-Institut (*PSI*), *TRIUMF,LAMPF*
1983-1996	*antiprotons*	Low-Energy-Antiproton-Ring *LEAR*, *AD*
---	*kaons*	*no dedicated KAON facility yet* *@KEK, DAΦNE*

(X-ray) spectroscopy

		$\Delta E/E$
– NaI(Tl)	*1952*	*30%*
– dedicated semiconductor detectors	*1985 ...*	*2%*
– crystal spectrometers	*1985 π, 1994 $\bar{p}$...*	10^{-4}
– laser excitation	*1996 ...*	10^{-6}

energy resolution ↓

WARM UP:

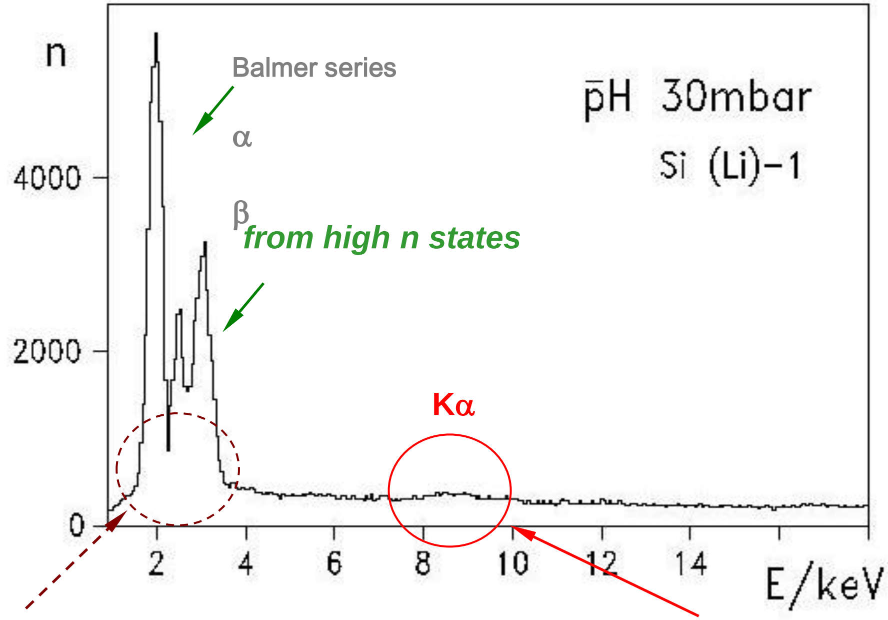
any X-RAY SPECTRUM

ANTIPROTONIC HYDROGEN *Lyman and Balmer series*

crystal spectrometer

direct measurement

two different ranges



Γ ≈ 30-500 meV
Y_X ≈ 50%

Γ ≈ 1 keV
Y_X ≈ 1%

PS175: K. Heitlinger et al., Z. Phys. A 342 (1992) 359

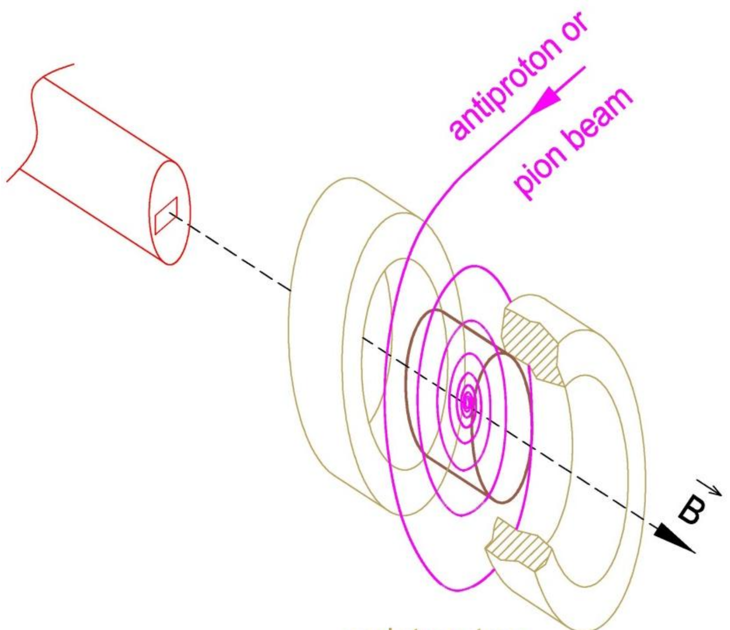
EXPERIMENT I

How to produce a suitable amount of exotic atoms?

CYCLOTRON TRAP concentrates particles

super-conducting split coil magnet

X-ray detector



"wind up" range curve

in (weakly) focusing magnetic field

increase in <u>stop density</u>

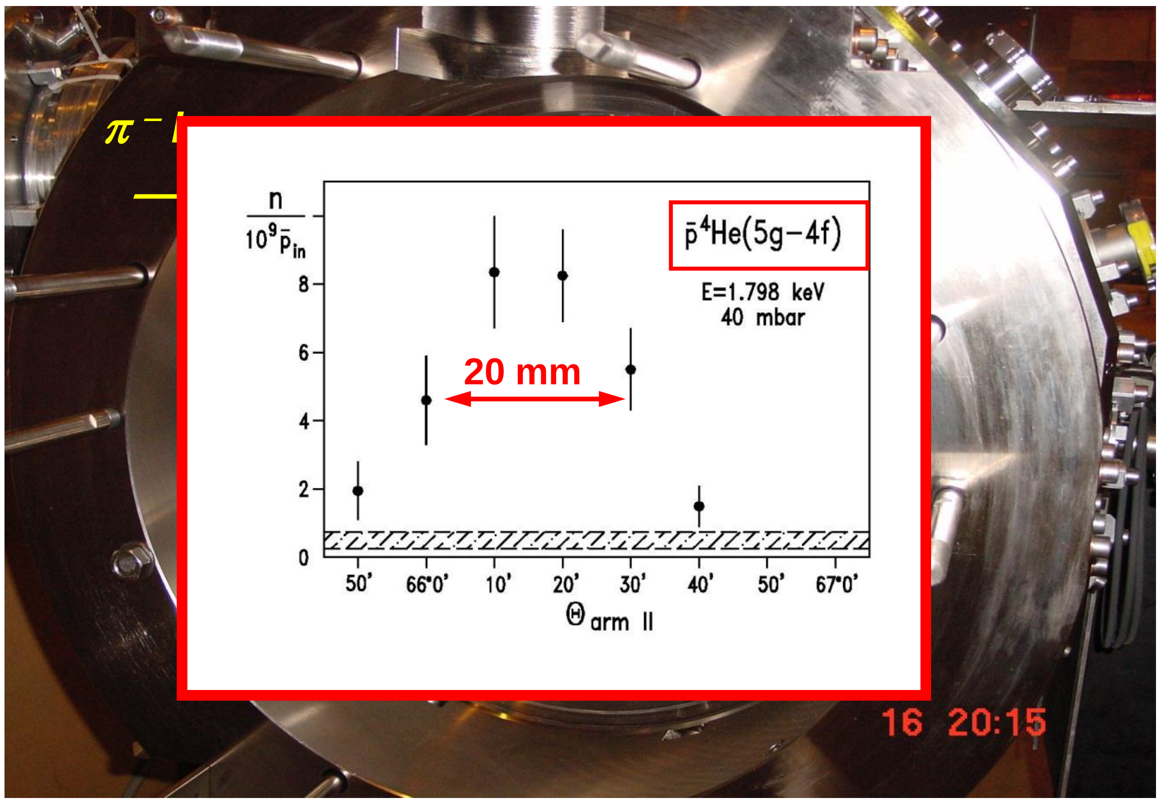
pions (PSI)	**x 200**
antiprotons (LEAR)	**x 1.000.000**

⇒ **high X - ray line yields**

⇒ **bright X - ray source**

DEGRADERS and CRYOGENIC TARGET
inside
CYCLOTRON TRAP II

super-conducting split coil magnet



EXPERIMENT II

How to achieve ultimate energy determination and resolution?

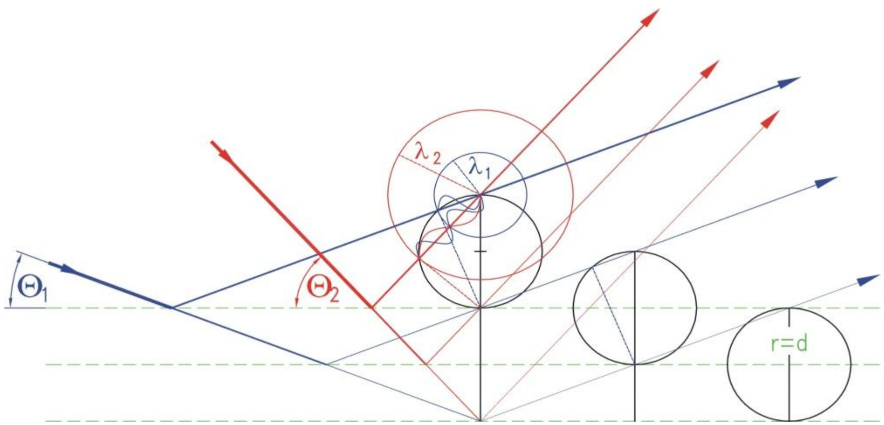
together with

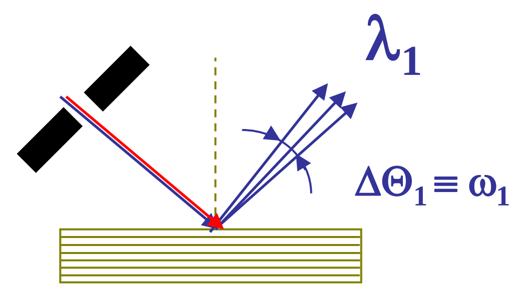
sufficient count rate?

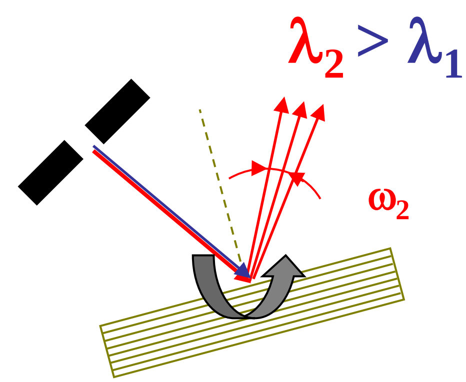
BRAGG'S LAW $n\lambda = 2d \cdot \sin\theta_B$

n	**order of diffraction**
λ	**wave length**
d	**spacing of diffracting planes**
θ_B	**Bragg angle**

ω	**angular spread of reflection**



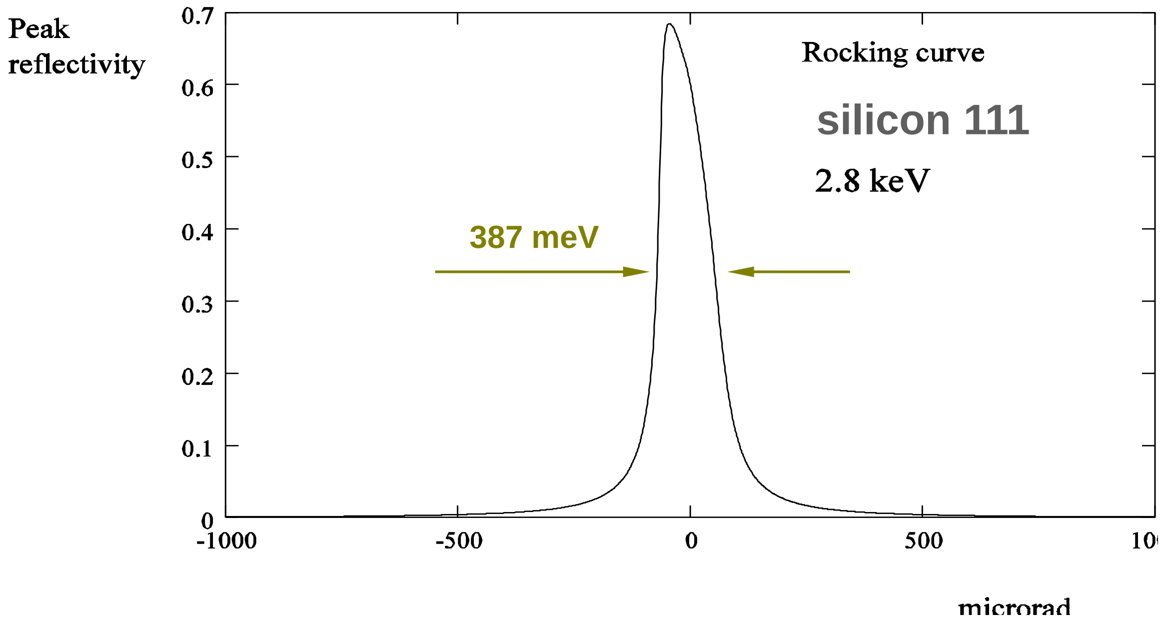




τ_e	**extinction length**	***coherent reflection***
τ_a	**absorption length**	***incoherent***

usually $\tau_e << \tau_a$

calculated CRYSTAL RESPONSE



diffraction theory

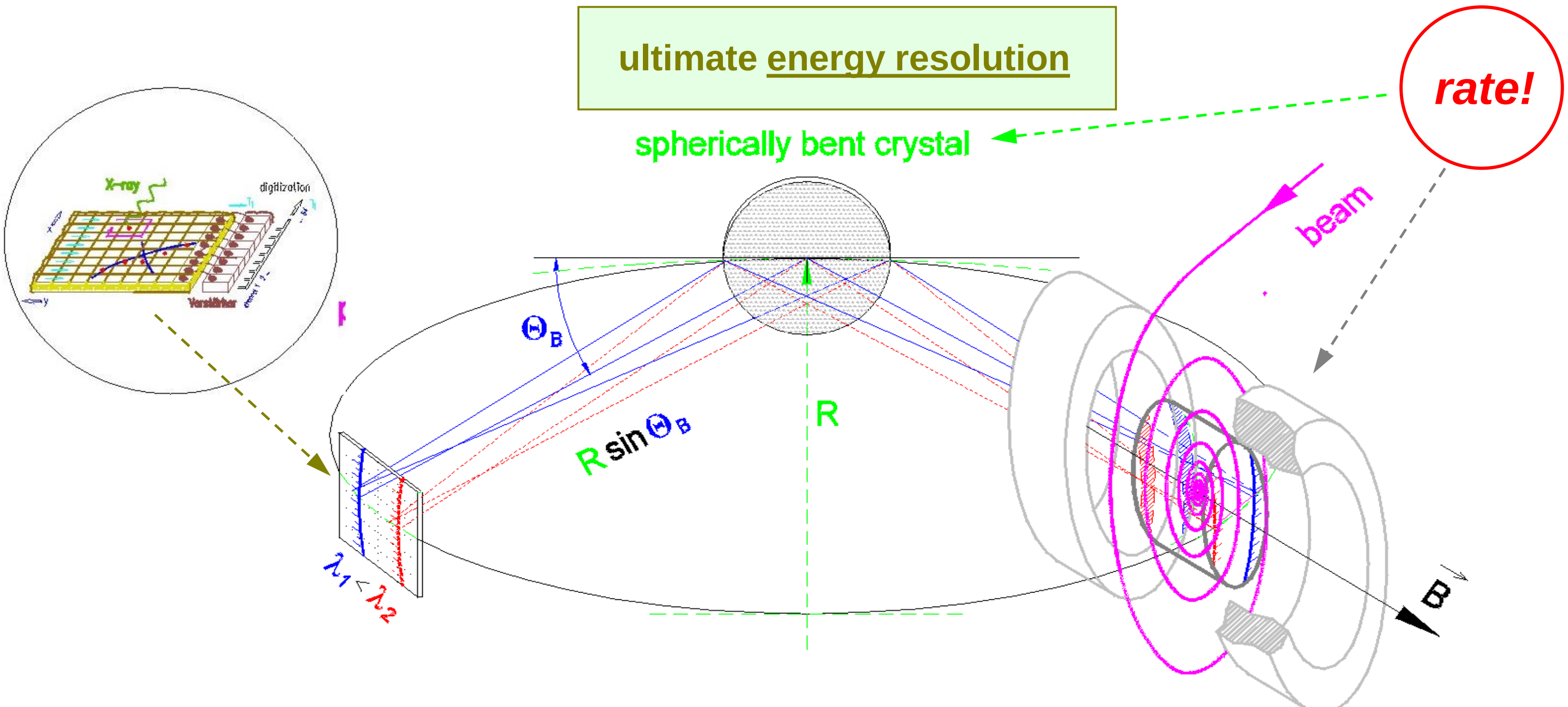
XOP2 code
plane crystal

for real crystal mounting?

no <u>narrow</u> few keV γ lines

Johann-type SET-UP

ultimate energy resolution



position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

position & energy resolution

⇒ **background reduction**

by analysis of hit pattern

high stop density

⇒ **high X - ray line yields**

⇒ **bright X - ray source**

L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253

PIONIC HYDROGEN collaboration - SET-UP at PSI

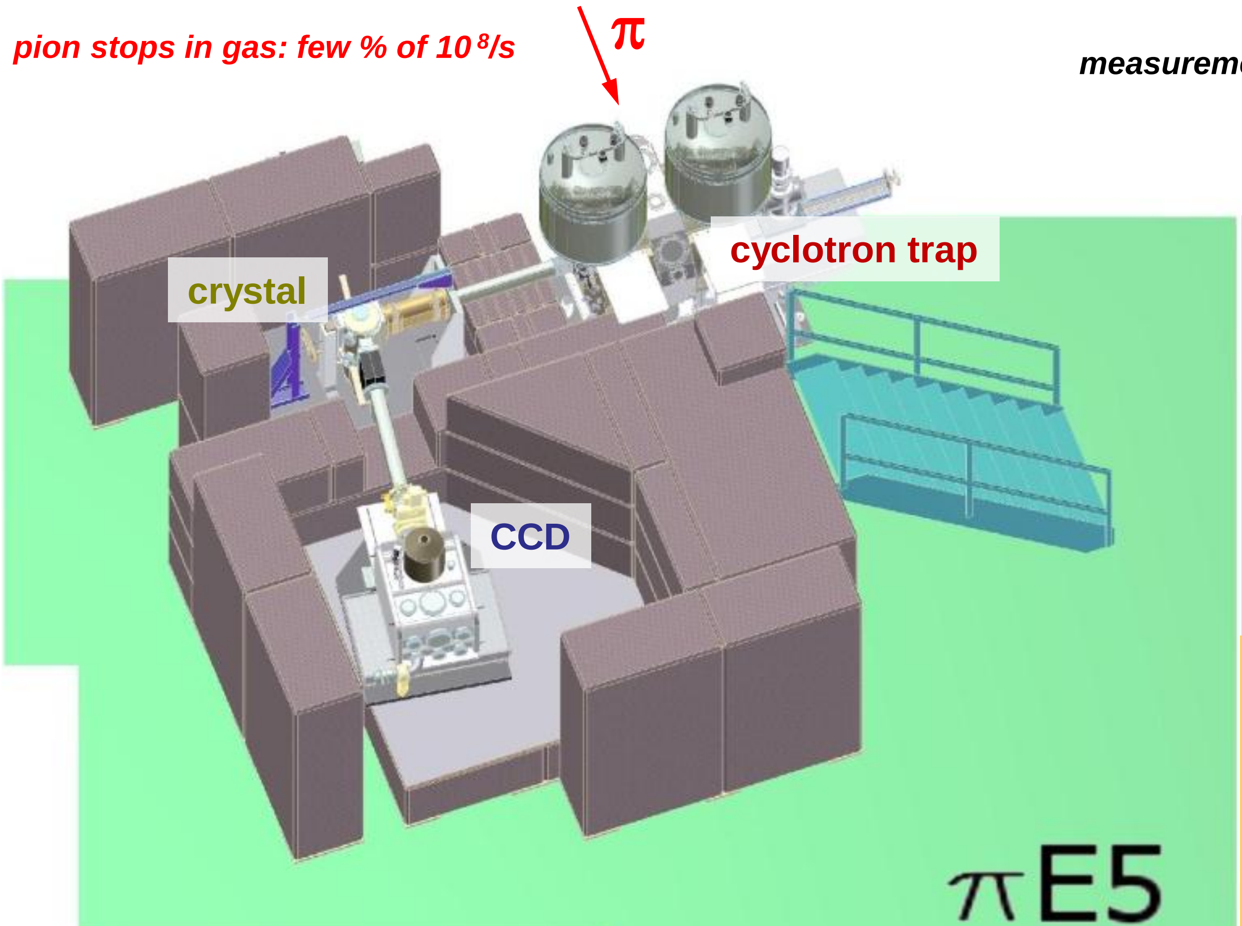
PSI experiments ***R-98.01 and R-06.03***

measurements ***πH(2-1), πH(3-1), πH(4-1)***

πD(3-1)

µH(3-1)

pion stops in gas: few % of 10^8/s



crystal spectrometer setup

πH(4-1) and πD(3-1) ***$\Theta_{Bragg} \approx 40°$***

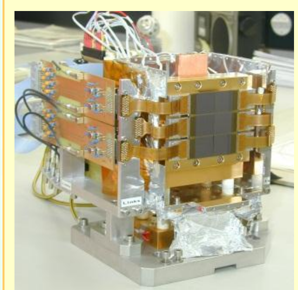
BRAGG CRYSTAL ***Si 111***

spherically bent

R = 3 m
Φ = 10 cm

FOCAL PLANE DETECTOR

3×2 CCD array



pixel size

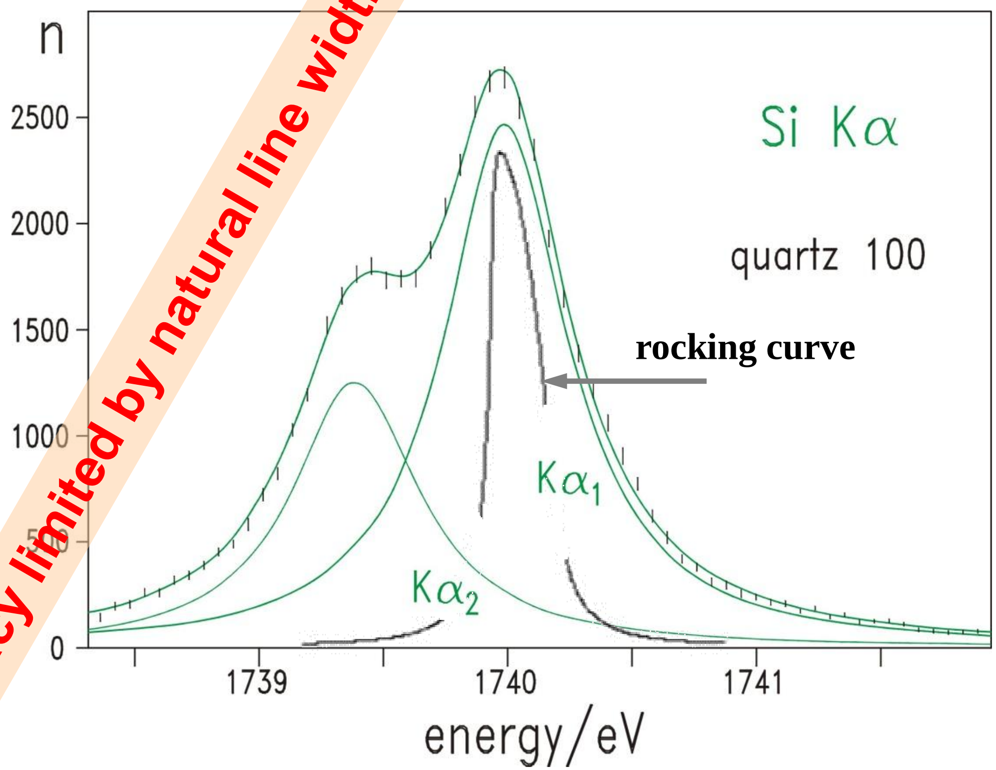
40 µm × 40 µm

see talk by
M. Jabua
Fr 14:30

EXPERIMENT III

How to measure the resolution of the crystal spectrometer ?

CALIBRATION *by fluorescence X-rays*



accuracy limited by natural line width !

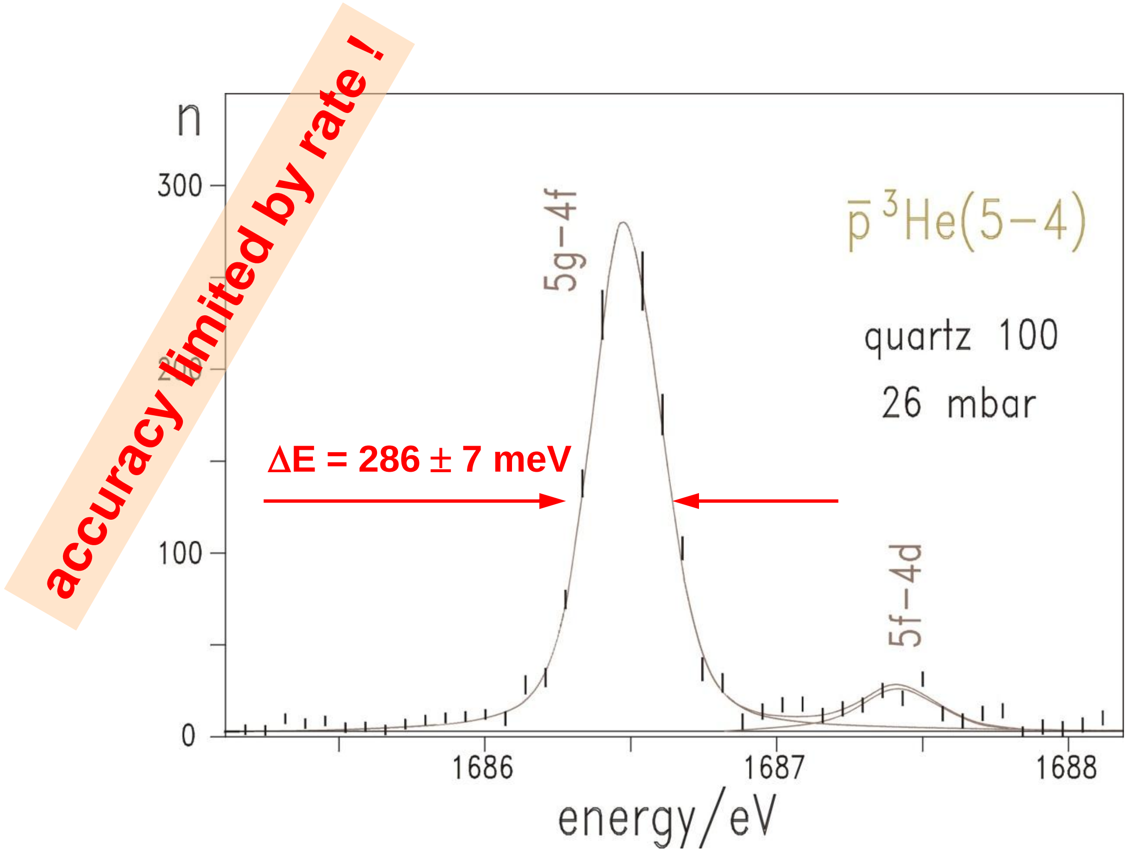
closest to energy of $\bar{p}$H(3d-2p)

excitation of Si X-rays by means of X-ray tube

high rate

large line width and satellites - resolution hardly measurable

RESPONSE FUNCTION *from exotic atoms*



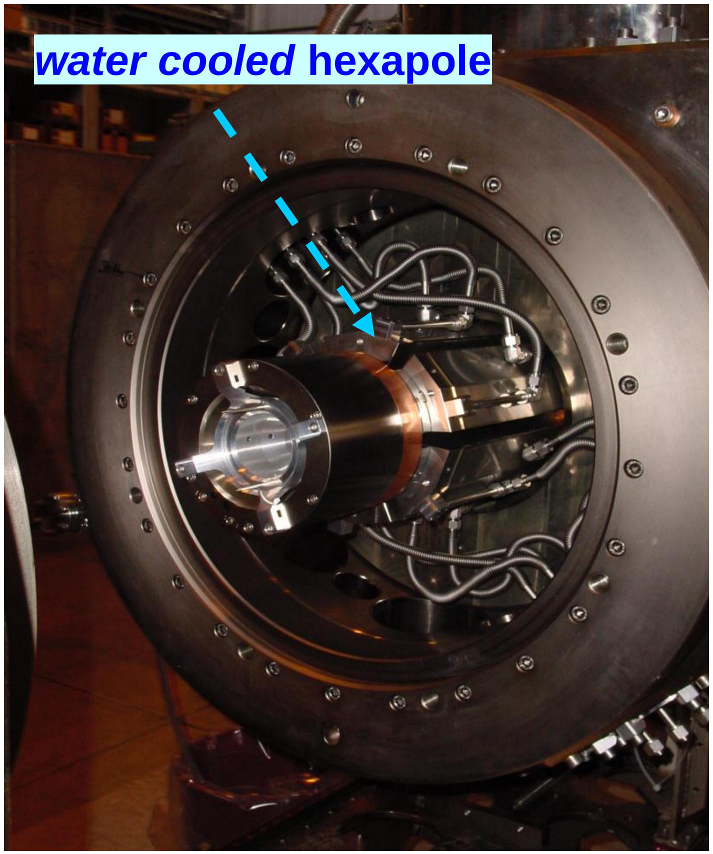
closest to energy of $\bar{p}$H(3d-2p)

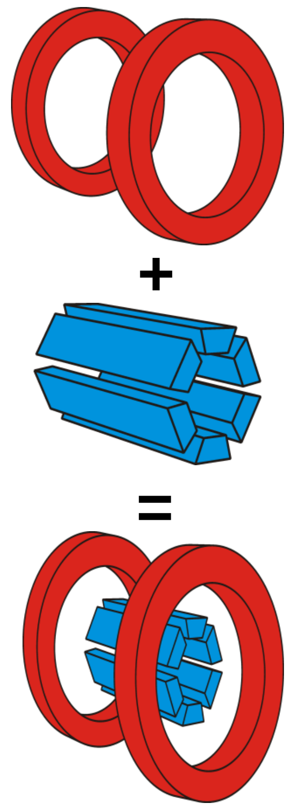
920 events

3 days

SPECTROMETER RESPONSE *new approach (PSI) ECRIT*

ECRIT = Electron Cyclotron Resonance Ion Trap





Superconducting coils

- *cyclotron trap*

permanent hexapole

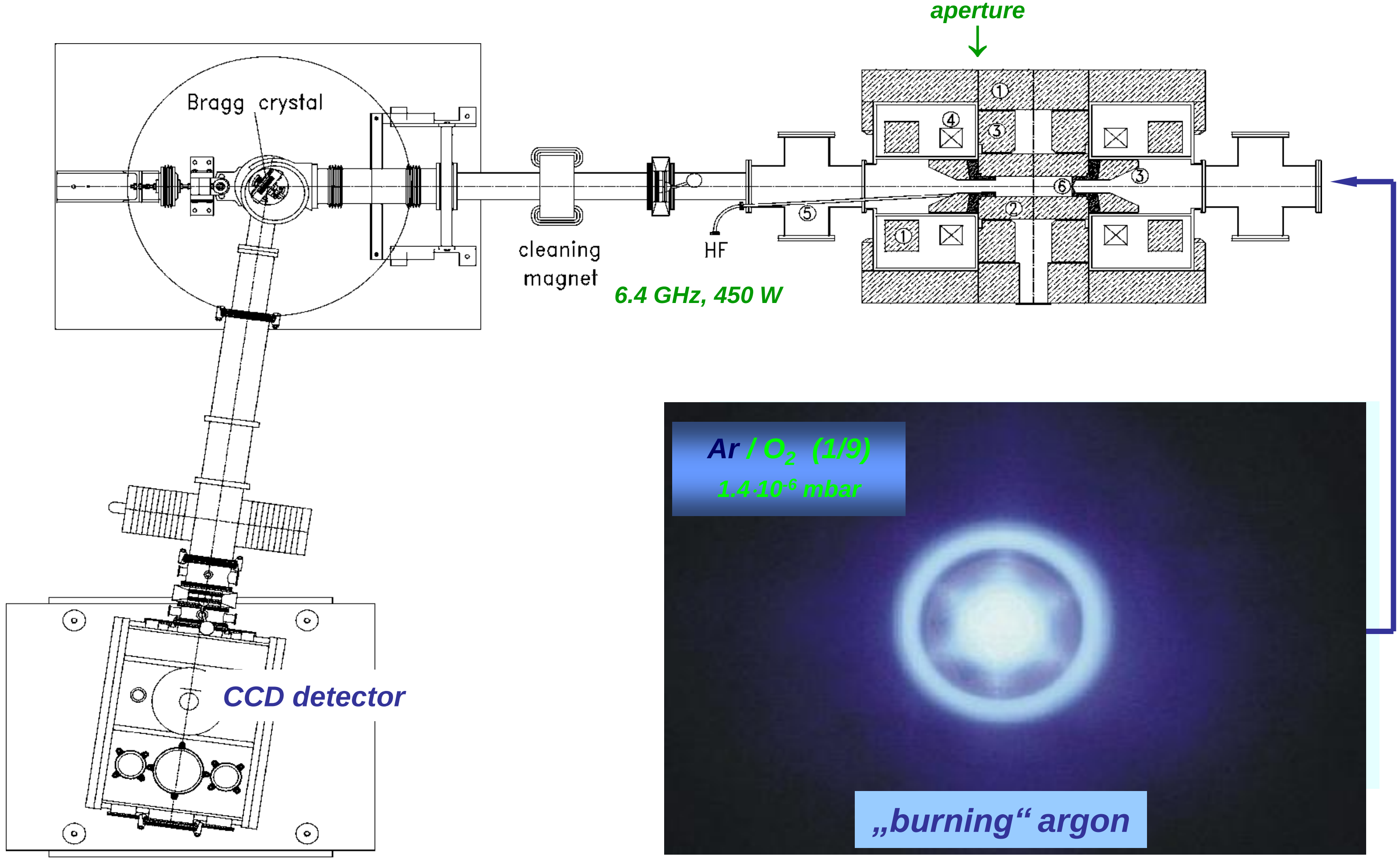
- *AECR-U type*
- *1 Tesla at the hexapole wall*
- *open structure*

large mirror ratio = 4.3
B_{max} / B_{min} *!*

S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116
K. Stiebing, Frankfurt – design assistance

CRYSTAL SPECTROMETER and PSI ECRIT

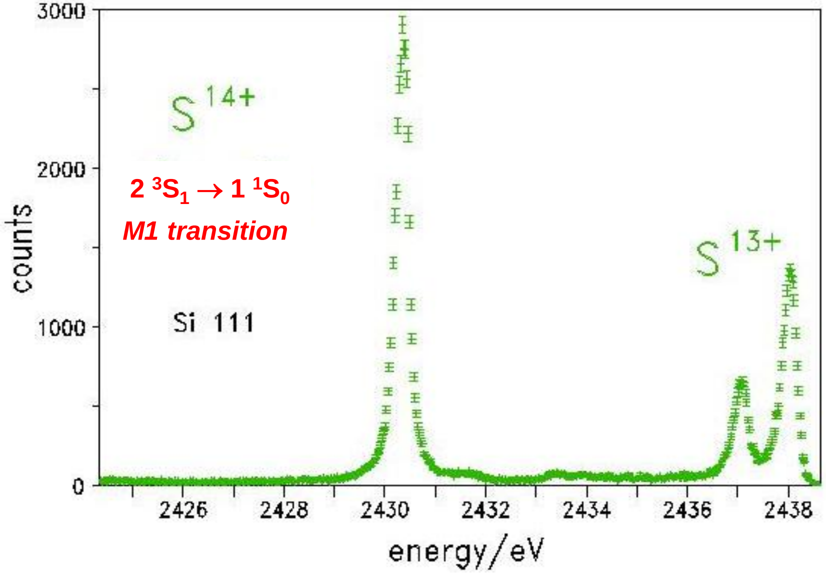
Electron Cyclotron Resonance Ion Trap
=
cyclotron trap (4) + hexapole magnet (2)

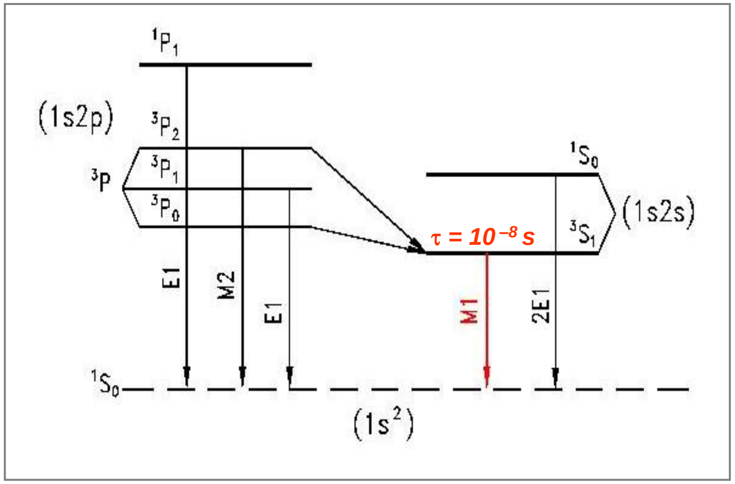


SPECTROMETER RESPONSE at πH Lyman ENERGIES

M1 transitions **in He - like**

S	$\leftrightarrow$	**πH(2p-1s)**
Cl	$\leftrightarrow$	**πH(3p-1s)**
Ar	$\leftrightarrow$	**πH(4p-1s)**





30000 events in line (3 h) $\leftrightarrow$ ***tails can be fixed with sufficient accuracy***

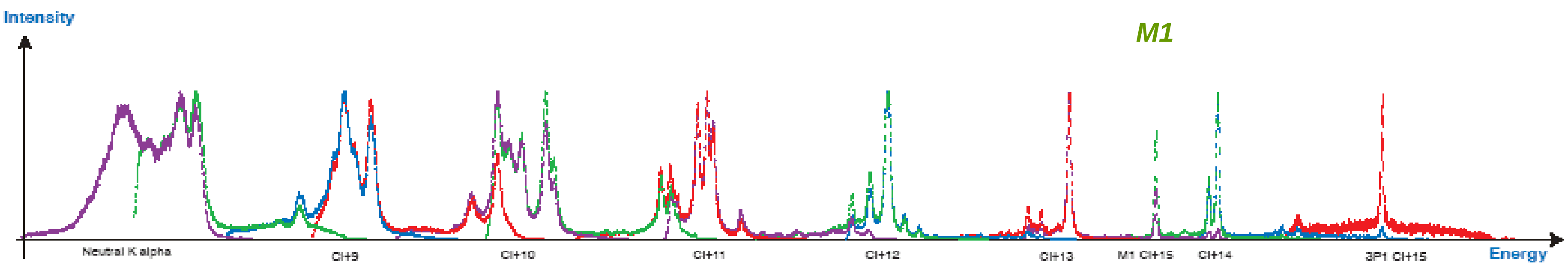
to be compared with Monte-Carlo ray tracing folded with plane crystal response

D.F.Anagnostopoulos et al., Nucl. Instr. Meth. B 205 (2003) 9
D.F.Anagnostopoulos et al., Nucl. Instr. Meth. A 545 (2005) 217

CHLORINE SKY LINE

Cl^{15+}

M1



↑

RESPONSE FUNCTION

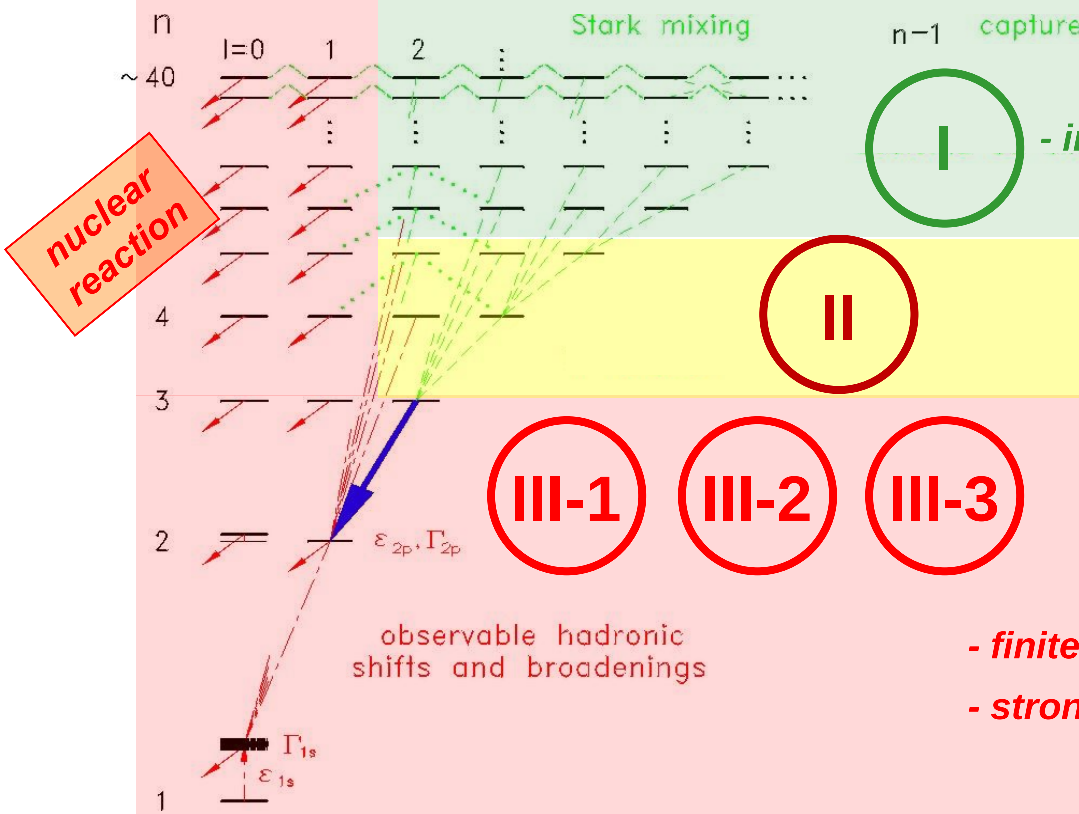
2757 ev

PHYSICS POTENTIAL

LEAR experiments	*PS 175*	*cyclotron trap*
		L. Simons et al.
	PS 207	*antiprotonic hydrogen*
PSI experiments	*R-97.02*	*pion mass*
	R-98.01	*pionic hydrogen*
	R-06.03	*pionic deuterium*
	R-98.02	*muonic hydrogen Lamb shift*
		A. Antognioni, F. Kottman, R. Pohl et al.

LEVEL SCHEME and CASCADE

particle capture when slowed down to a few eV kinetic energy into high-lying atomic levels



upper part

- interaction with the remaining electrons

- Auger emission

intermediate part

X-radiation from hydrogen-like atoms

under suitable conditions

lower part

- finite size effects

- strong interaction

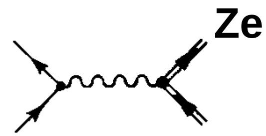
I

CAPTURE and DE-EXCITATION

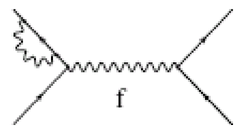
multi-particle systems

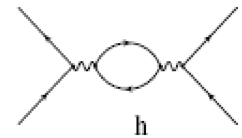
ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$ $-\frac{Ze}{r}$



$+ \Delta E_{QED}$





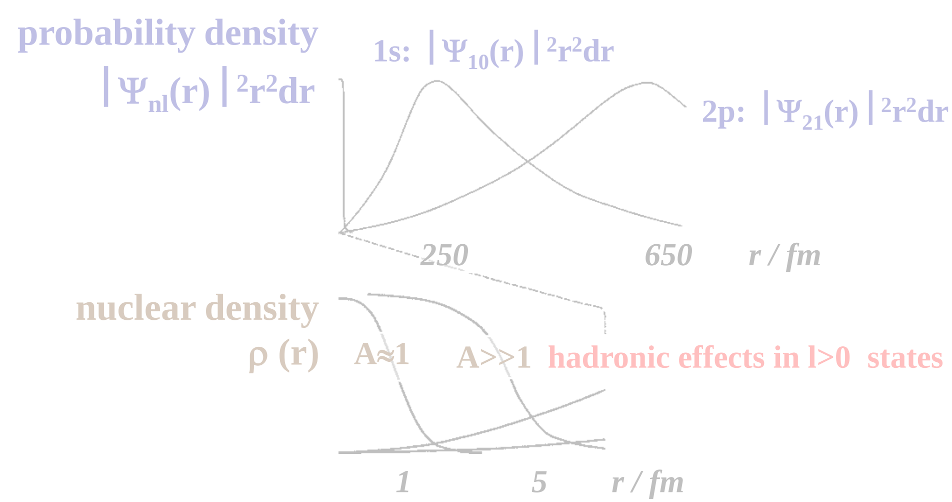
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

capture $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + \text{few } e^-$

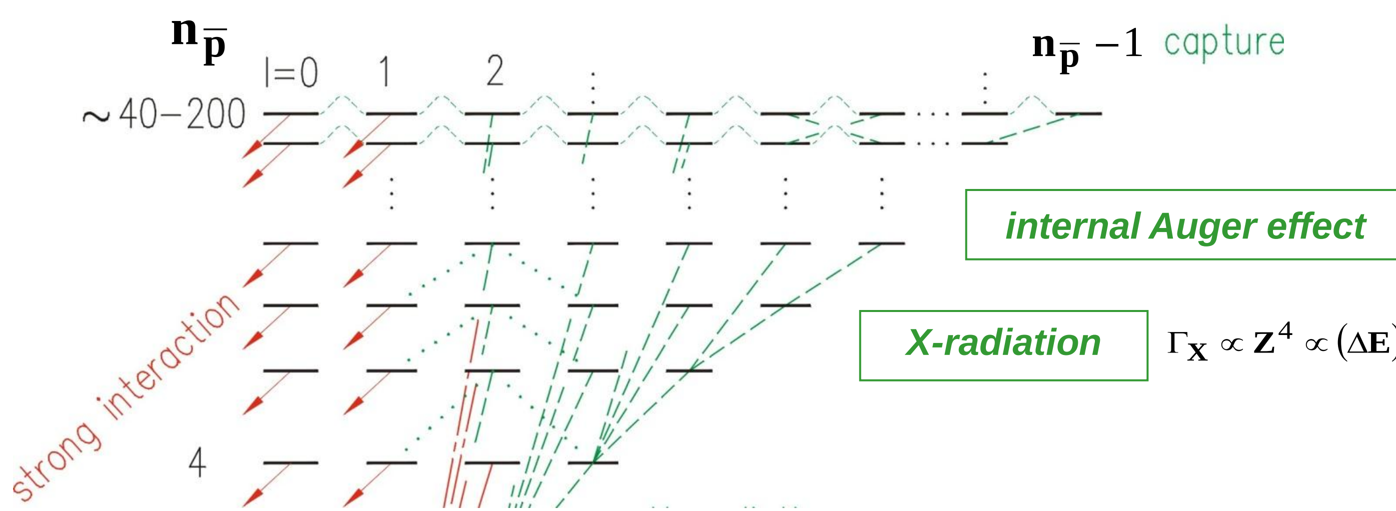
$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



CAPTURE and UPPER PART of the ATOMIC CASCADE ***antiprotonic atom***

where?	$\mathbf{n}_{\bar{\mathbf{p}}} \approx 40 \cdot \mathbf{n_e}$
probability?	$\Gamma_{\mathbf{capture}} \propto \mathbf{Z}$
how?	$\mathbf{Pop(n,\ell)} \propto (2\ell+1) \cdot \mathbf{e}^{-\alpha\ell}$



$\Gamma_{\mathbf{A}} \propto \mathbf{Z}^2 \propto (\Delta\mathbf{E})^{-1/2}$

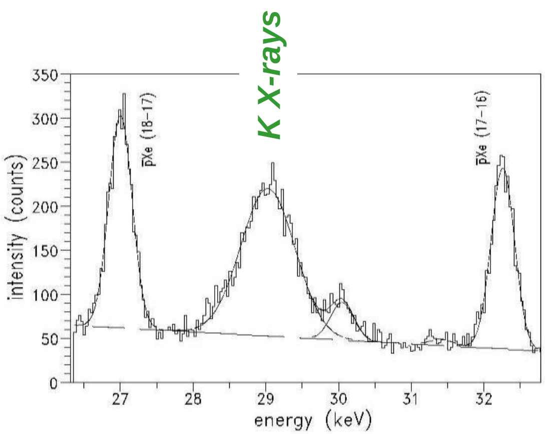
$\Gamma_{\mathbf{X}} \propto \mathbf{Z}^4 \propto (\Delta\mathbf{E})^3$

competition between AUGER and RADIATIVE DE-EXCITATION

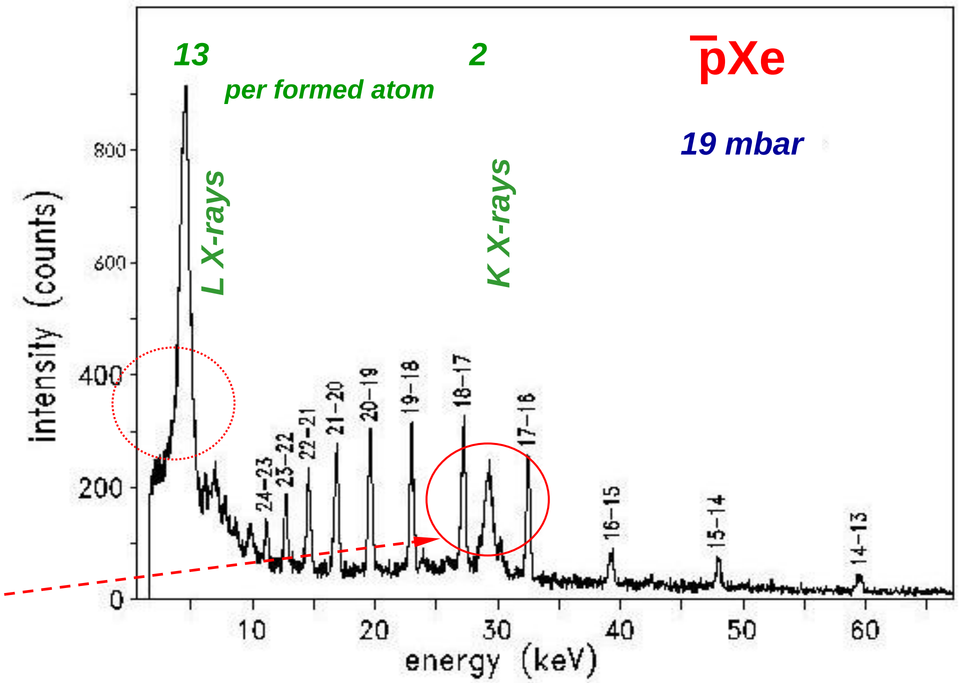
electrons are peeled off like onion shells

ELECTRONIC & ANTIPROTONIC X-RAYS - XENON

many remaining electrons



many unresolved lines ?



data: PS175 Ar, Kr, Xe

Reanalysis: D.G., K.Rashid, B. Fricke, P. Indelicato, L.M. Simons, Eur. Phys. D 47 (2008) 11

OUTLOOK - high resolution spectroscopy
- coincidence experiments X-rays / Auger electrons

II

CHARGED PION MASS

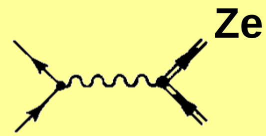
How to measure the mass of a short-lived particle?

life time $\tau_{\pi^\pm} = 26 \cdot 10^{-9}$ ***s***

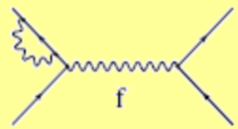
$\Rightarrow$ ***use a hydrogen-like systems***

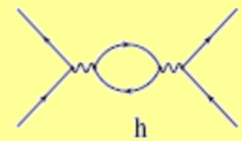
ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$ $\propto M_\pi$



$+ \Delta E_{QED}$





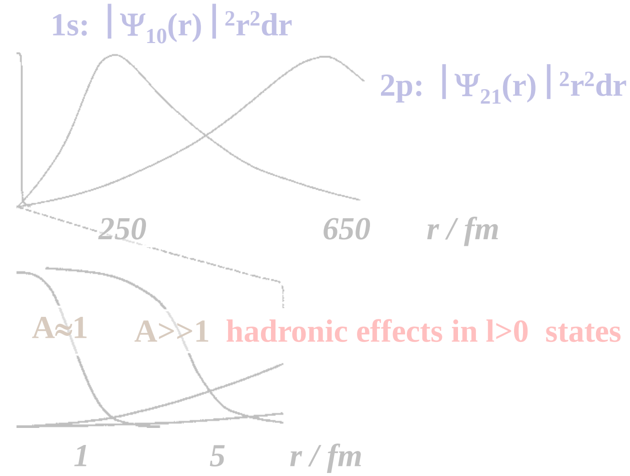
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

capture $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + few\ e^-$

probability density

$|\Psi_{nl}(r)|^2 r^2 dr$



nuclear density

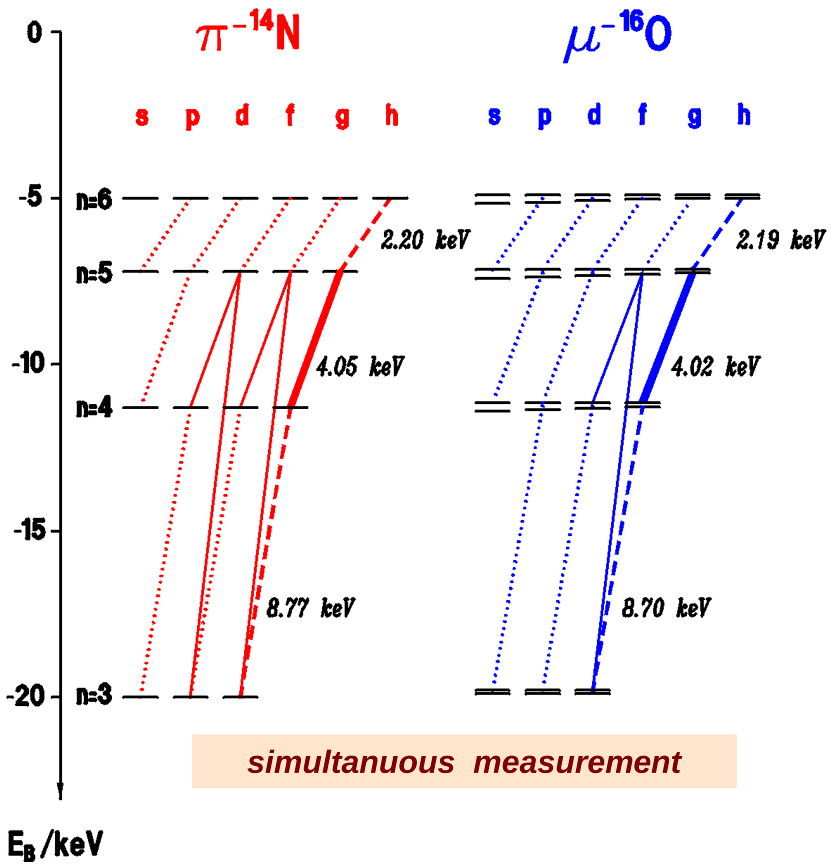
ρ (r)

$+ \Delta E_{finite\ size}$

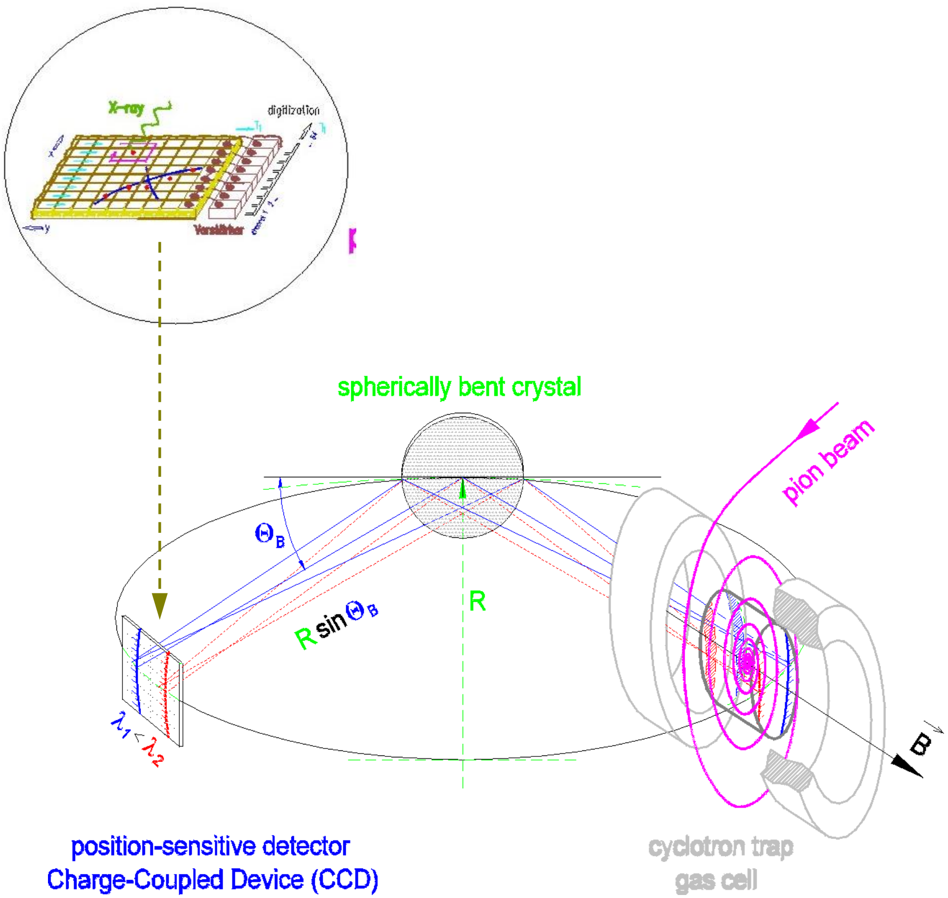
$+ \Delta E_{strong\ interaction}$

measurement *calibration*

πN(5g-4f) μO(5g-4f)

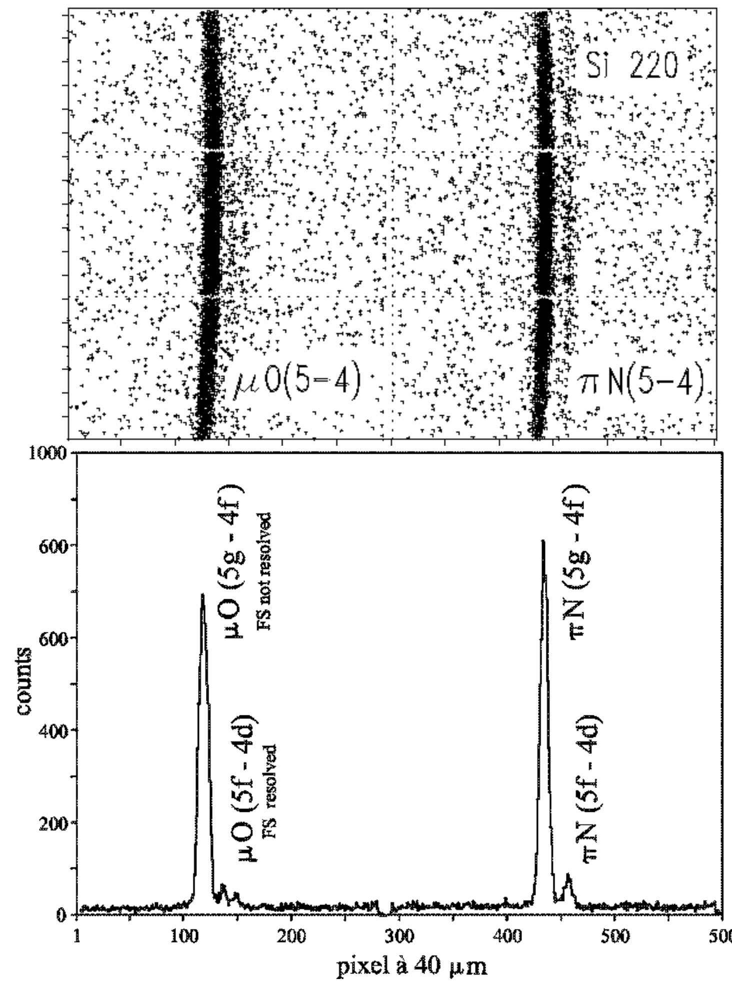


- point like Coulomb potential
- no electron screening
- $E_{\mu O(5g-4f)} / E_{\pi N(5g-4f)} = m_\mu / m_\pi$



$\Delta E/E \geq 1\text{-}2 \cdot 10^{-6}$

← *pion mass* →



III-1

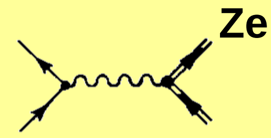
PROTON CHARGE RADIUS

muonic hydrogen Lamb shift

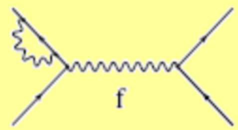
ATOMIC BINDING ENERGY

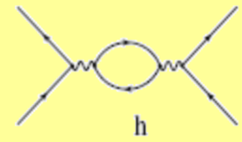
$E_B = E_{Coulomb}$

$r \propto \frac{1}{M}$



$+ \Delta E_{QED}$



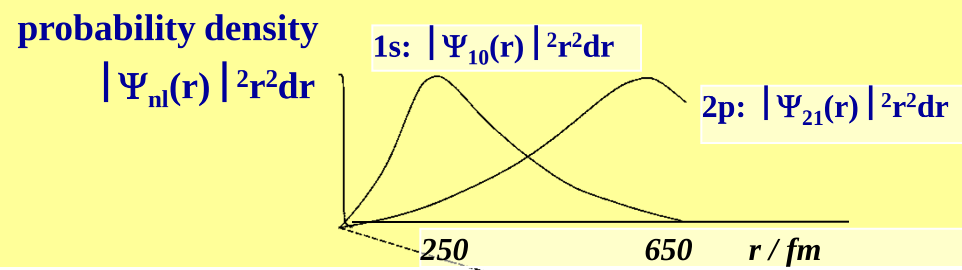


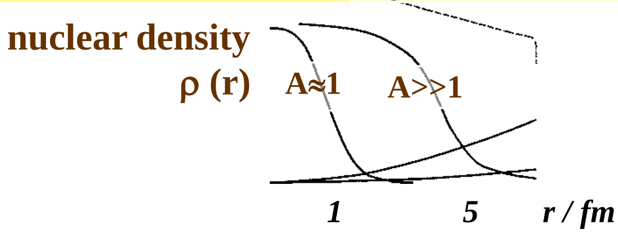
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

capture $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + few\ e^-$

$+ \Delta E_{finite\ size}$





$+ \Delta E_{strong\ interaction}$

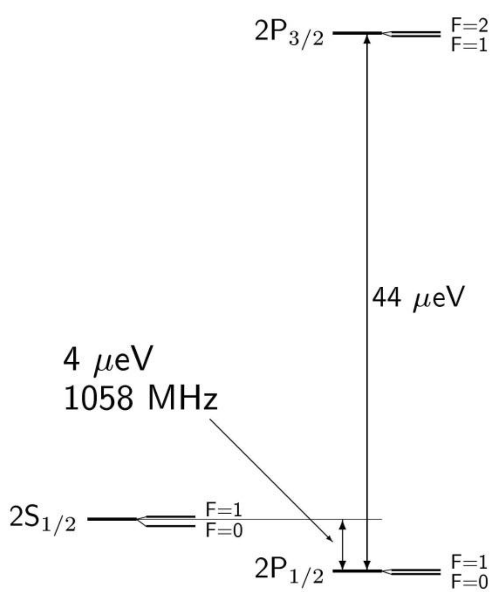
MUONIC HYDROGEN LAMB SHIFT

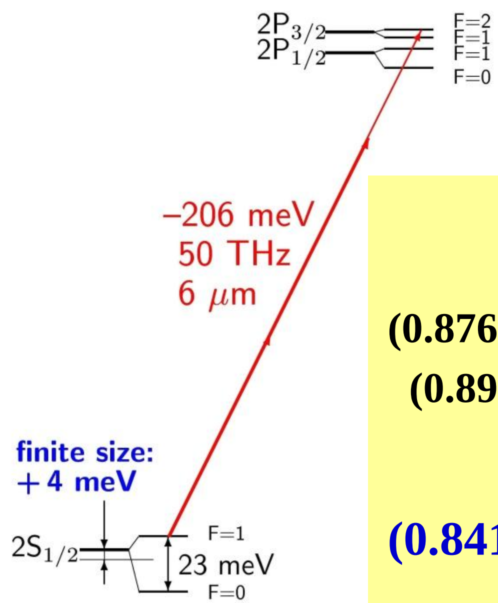
e^-p

large! $2 \cdot 10^5$ fm

μ^-p

small! $1 \cdot 10^3$ fm





proton charge radius

$(0.8768 \pm 0.0069) \cdot 10^{-15}$ m   *H spectroscopy*

$(0.897 \pm 0.018) \cdot 10^{-15}$ m   *electron scattering*

$(0.84184 \pm 0.00067) \cdot 10^{-15}$ m   ***μH***

error → ≈ error / 10 !

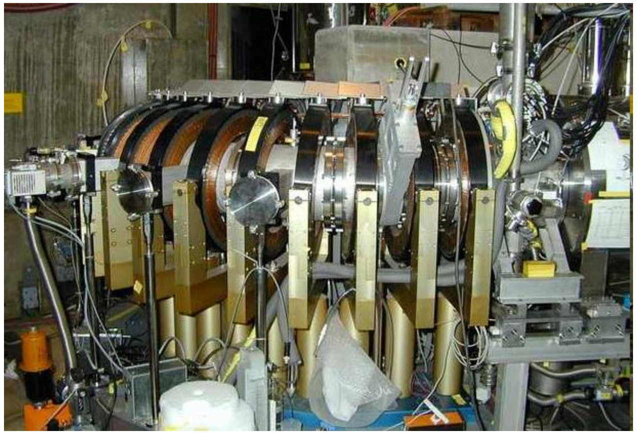
⇑

very sensitive to proton charge radius

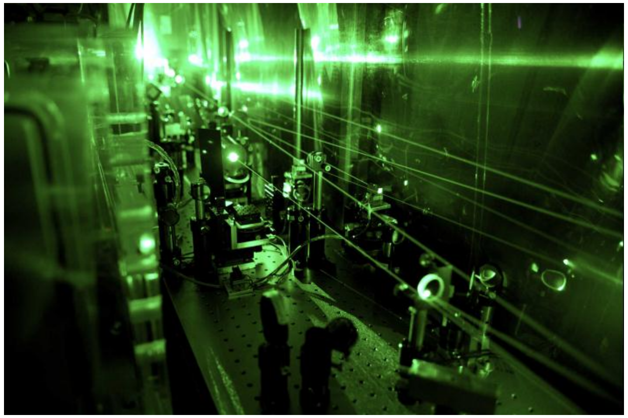
μH collaboration: see e.g. R. Pohl et al., Hyperf. Int. 193 (2009) 115;Nature, vol. 466, issue 7303, pp. 213-216 (2010)

MUONIC HYDROGEN LAMB SHIFT - EXPERIMENT

extraction channel



part of LASER system



1. Stop pions in cyclotron trap
2. extract decay muons to extraction channel
3. Form µH in dilute hydrogen
4. Pump 2s-2p resonance with laser
5. Identify 2s-2p energy difference by resonance condition

III-2

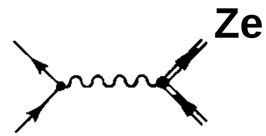
STRONG INTERACTION

PION-NUCLEON SCATTERING LENGTHS

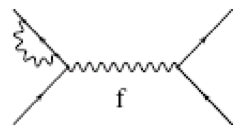
„QCD Lamb shift“

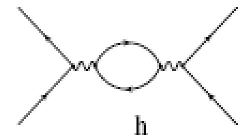
ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$ $\quad -\frac{Ze}{r}$



$+ \Delta E_{QED}$



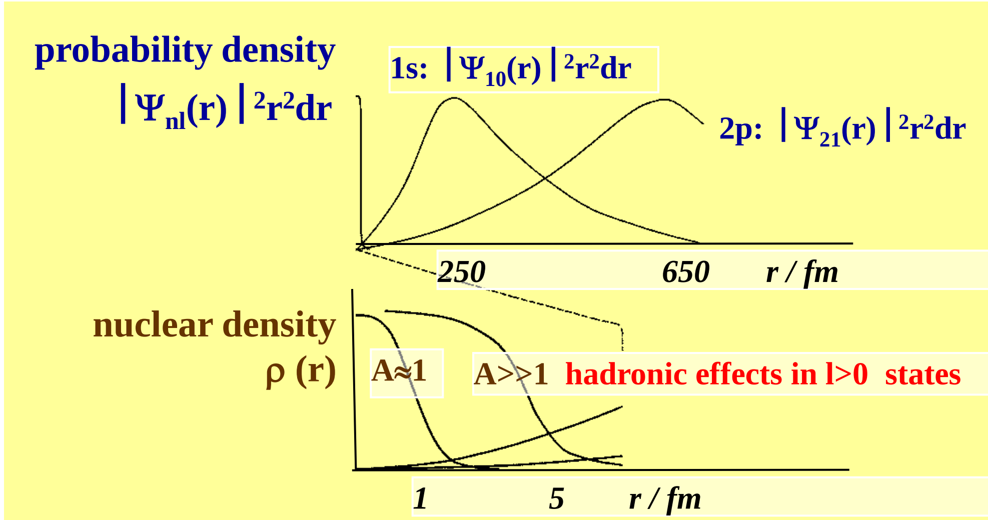


self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$ *capture* $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + \text{few } e^-$

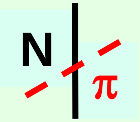
$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



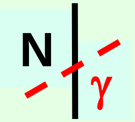
HYDROGEN & DEUTERIUM - ORIGIN OF Γ_{1s}

CEX scattering



πH *scattering* $\pi^- p \to \pi^0 n + n\gamma$

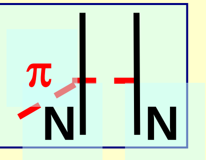
radiative capture



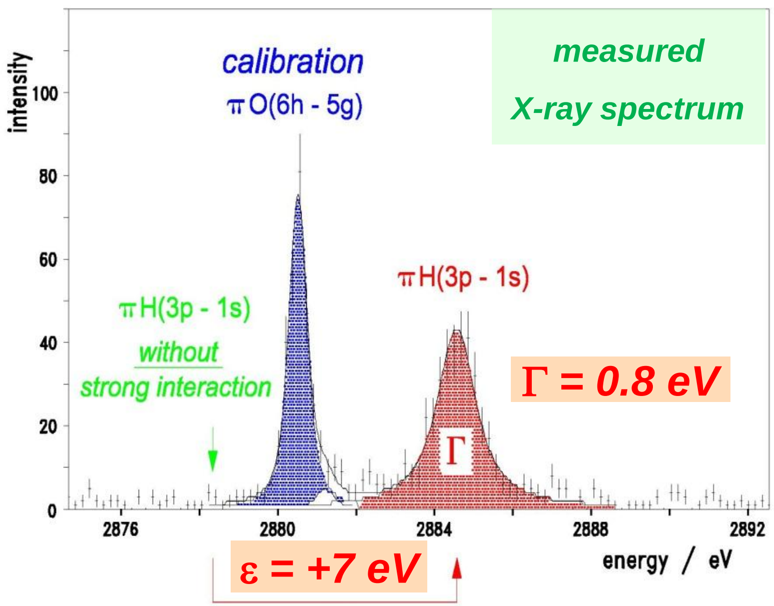
BR are well known from experiment

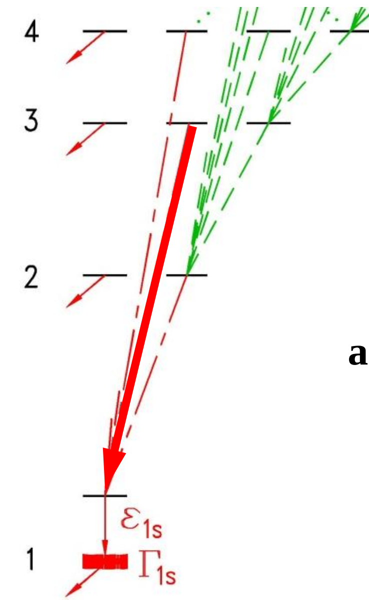
πD *absorption* $\pi^- d \to nn + nn\gamma$

„true“ absorption



PIONIC HYDROGEN 3p-1s transition





$$E_B^{\pi H} = -3238\,\text{eV}$$

$$a_{Bohr}^{\pi H} = 140\,\text{fm}$$

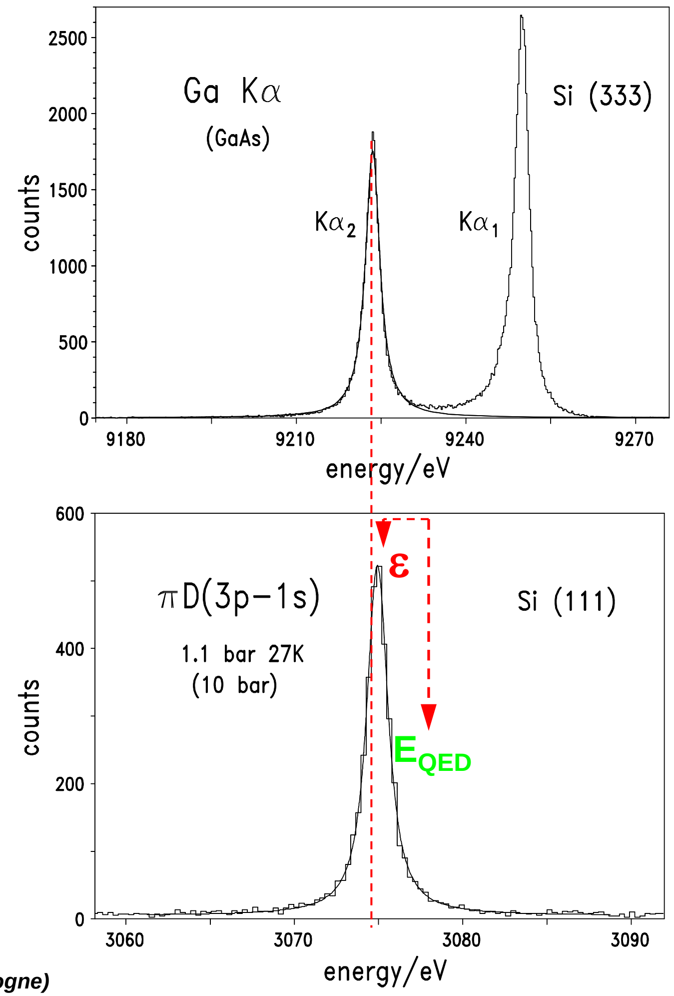
	scattering lengths	experiment	Trueman correction	χPT *
πH	$\varepsilon_{1s} \propto a_{\pi\text{-}p\to\pi\text{-}p} \propto a^+ + a^- + \ldots$	± 0.2%	… ≈ 1%	+ (–9.0 ± 3.5)%
	$\Gamma_{1s} \propto (a_{\pi\text{-}p\to\pi^0 n})^2 \propto (a^-)^2 + \ldots$	± 2.5%	… ≈ 1%	+ (+0.5 ± 1.0)%
πD	$\varepsilon_{1s} \propto a_{\pi\text{-}d\to\pi\text{-}d} \propto 2\cdot a^+ + \ldots$	± 1.3%	… ≈ 1%	+ ± 4%

** J. Gasser et al., Phys. Rep. 456 (2008) 167*
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru et al., Phys. Lett. B 694 (2011) 473

PIONIC DEUTERIUM SHIFT

energy calibration

Ga Kα



target material: GaAs

by chance: tabulated energy
<u>also</u>
from GaAs

strong interaction

πD(3p-1s)

identical Bragg angle

3 bar
10 bar
22 bar

to identify molecule formation

T.Strauch, PhD thesis: (FZJ, Univ. Cologne)

ε = -2 eV

which scattering length?

πH(np - 1s) energy shift ε_{1s} $\Rightarrow$ $a_{\pi^- p \rightarrow \pi^- p}$

πH(np - 1s) level width Γ_{1s} $\Rightarrow$ $a_{\pi^- p \rightarrow \pi^0 n}$

πD(np - 1s) level shift ε_{1s} $\Rightarrow$ $a_{\pi^- p \rightarrow \pi^- p} + a_{\pi^- n \rightarrow \pi^- n}$

two independent scattering length - all others linked by isospin

!!! πD(np - 1s) level width Γ_{1s} $\Rightarrow$ $\Im\, a_{\pi^- d \rightarrow nn + nn\gamma}$

πN isospin scattering lengths a^+ and a^-

Δ exp $\approx$ 2 $\times$ Δ theory - no LEC f_1 in NLO

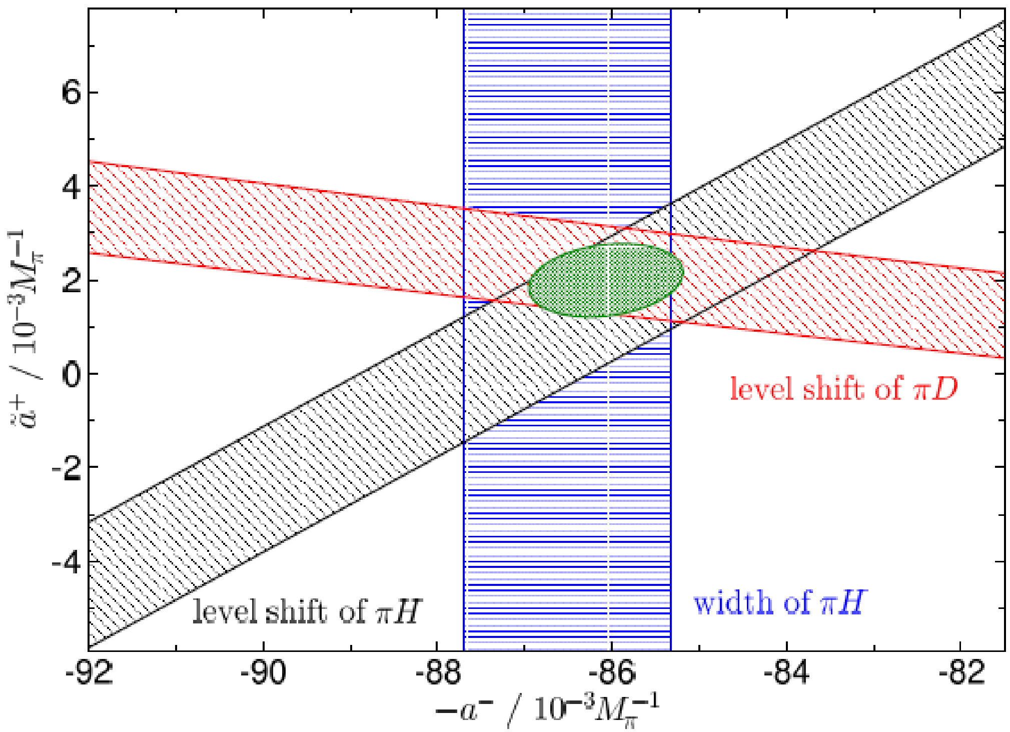


FIG. 2: Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energy shift of πH, as well as the πD energy shift.

Δ exp << Δ theory - LEC f_1

Δ exp << Δ theory - LEC f_1

- **constistency ✓**
- **$a^+ > 0$!**

χPT: V. Baru, C. Hanhart, M. Hoferichter, B. Kubis, A. Nogga, and D. R. Phillips, Phys. Lett. B 694 (2011) 473

data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (208) 165 (preliminary)

πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88 (final)

III-3

NUCLEON-ANTINUCLEON

SPIN-SPIN and SPIN-ORBIT INTERACTION

THEORETICAL DESCRIPTION

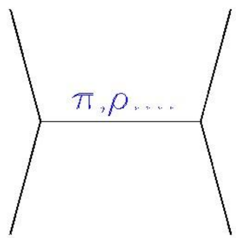
$$V_{Coulomb} + U_{hadronic}$$

$U_{hadronic}$ = meson exchange + annihilation

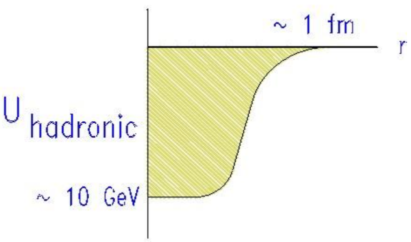
scattering: $\bar{p}p \leftrightarrow \bar{p}p$, $\bar{p}p \leftrightarrow \bar{n}n$; $\bar{p}p \rightarrow$ mesons

$NN \xrightarrow{G\text{-parity}} \bar{N}N$; $U \propto a\,\rho(r)$

Re $U_{hadronic}$



Im $U_{hadronic}$



$\varepsilon, \Gamma \longleftrightarrow$ medium + long-range part of $\bar{N}N$ interaction

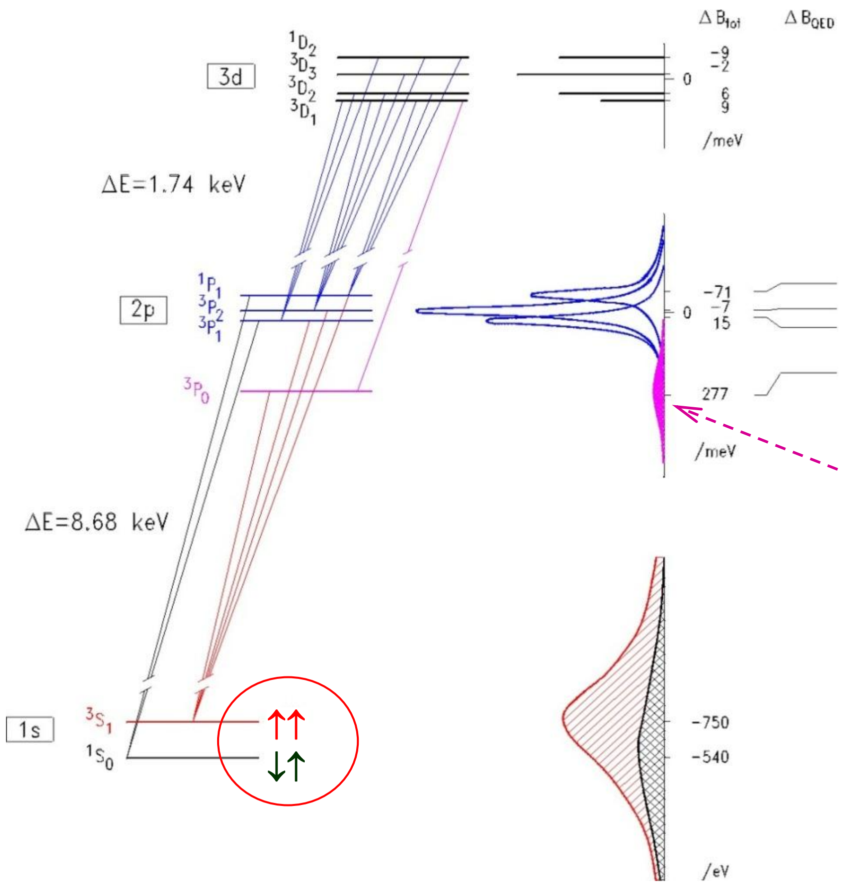
Buck, Dover, Richard, Ann. Phys. (NY) 121 (1979) 47

spin-spin "deuteron"
spin-orbit effects

no microscopic theory

☞ ***check spin dependence !***

PROTONIUM - s & p state strong-interaction effects



d state

strong interaction negligible

p state ***spin-orbit interaction***

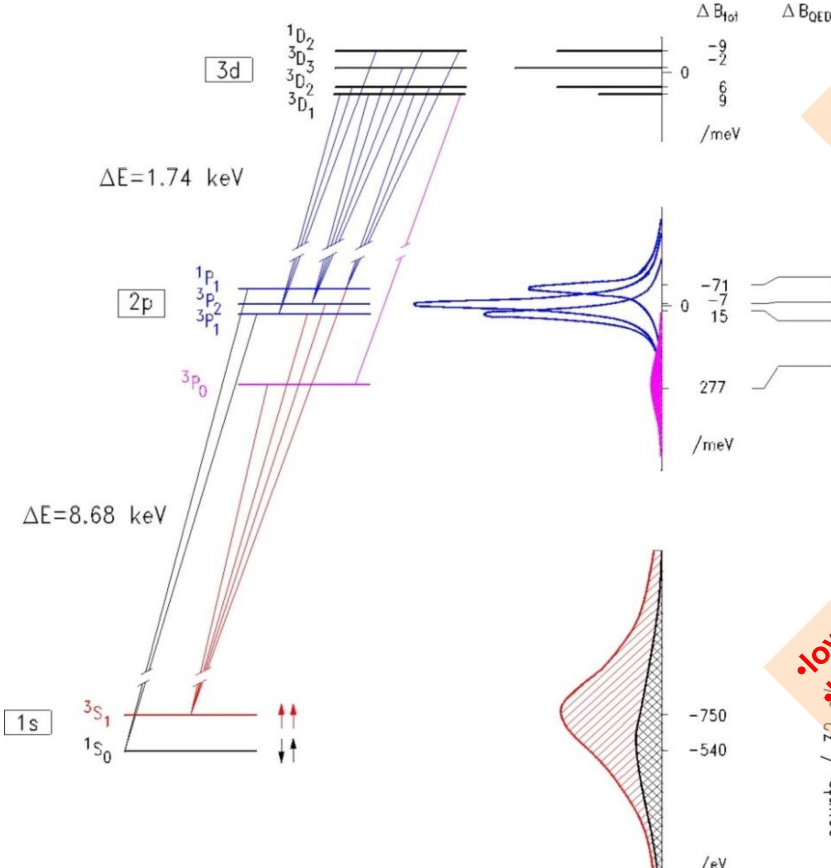
meson exchange:
strongly attractive
isoscalar tensor interaction

Richard, Sainio, Phys. Lett. B (1982)349

s state ***spin-spin interaction***

ε > 0 (<0) ≡ attractive (repulsive) interaction

PROTONIUM - EXPERIMENT

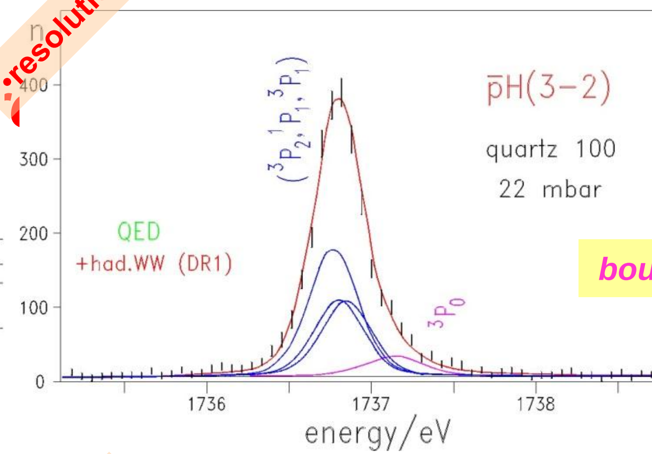


LEAR experiment PS207

M. Augsburger et al., Nucl. Phys. A 658 (1999) 149
D. Gotta et al., Nucl. Phys. A 660 (1999) 283

•resolution

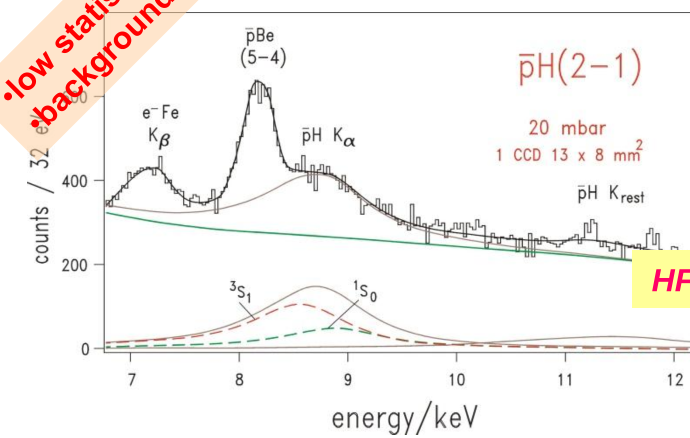
cyclotron trap + MOS CCD



bound states ?

***most recent** theo. paper:*
J. Carbonell,
Nucl. Phys. A 692 (2001) 11

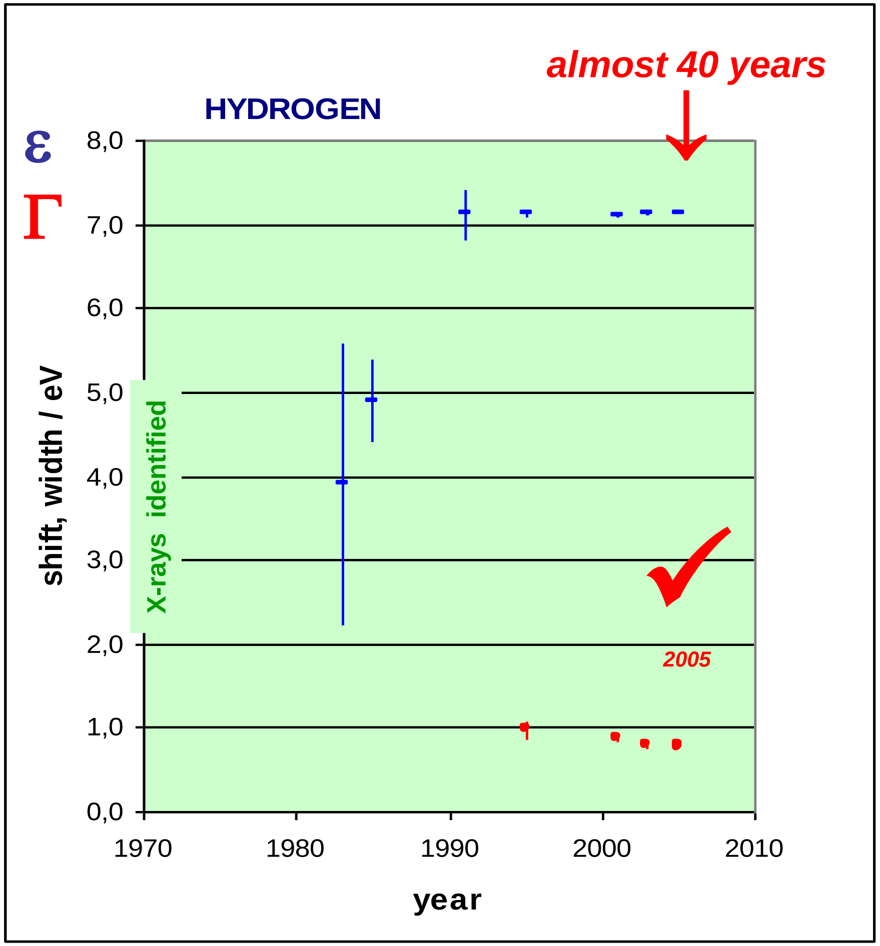
•low statistics
•background

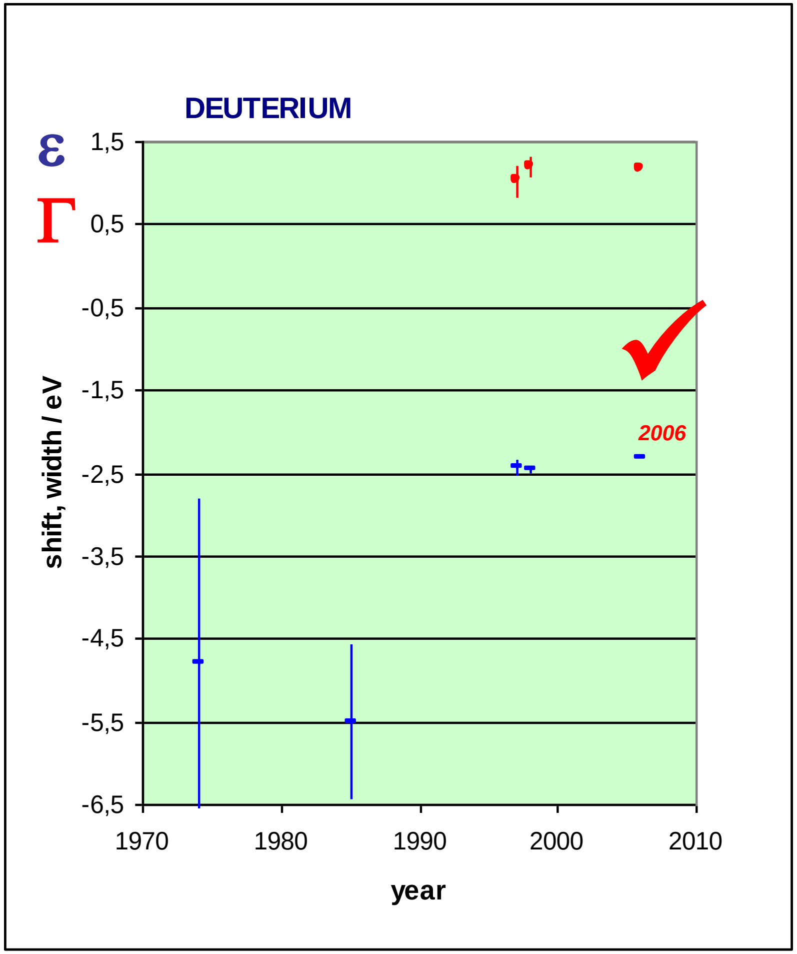


HFS splitting?

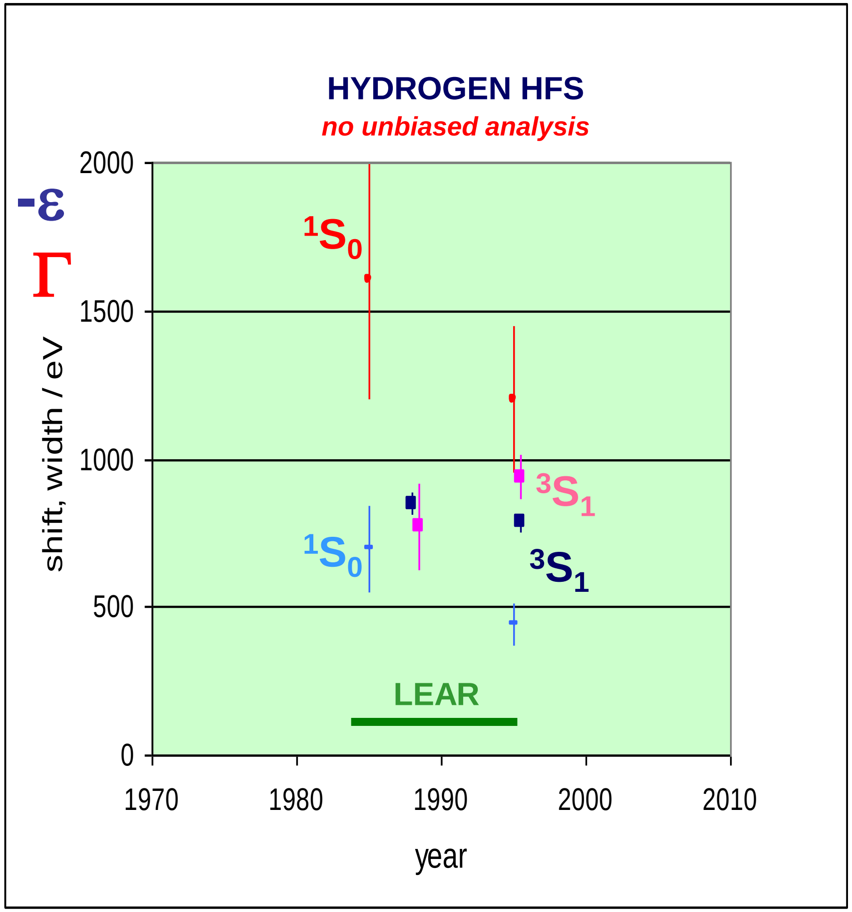
SUMMARY

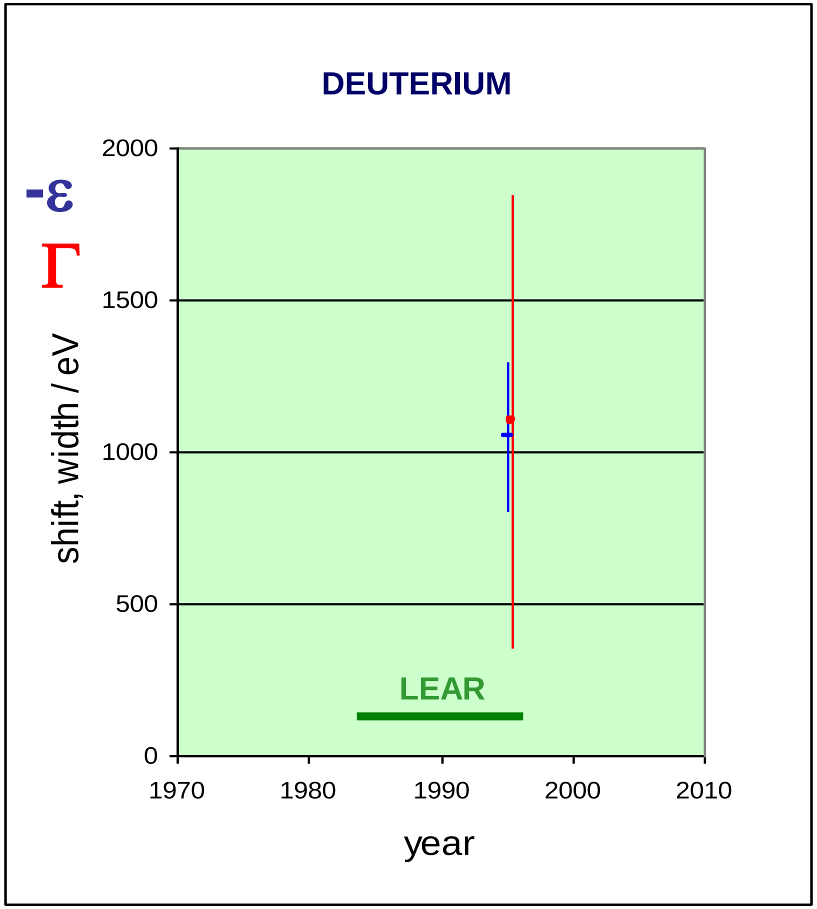
PIONIC HYDROGEN STORY



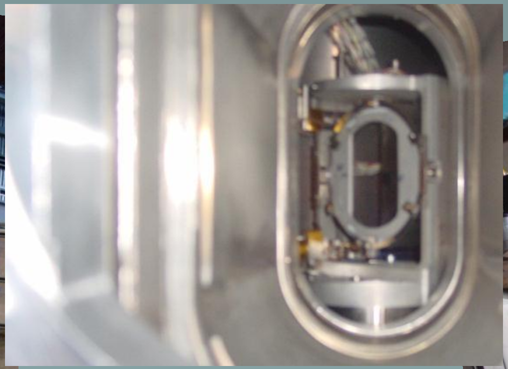


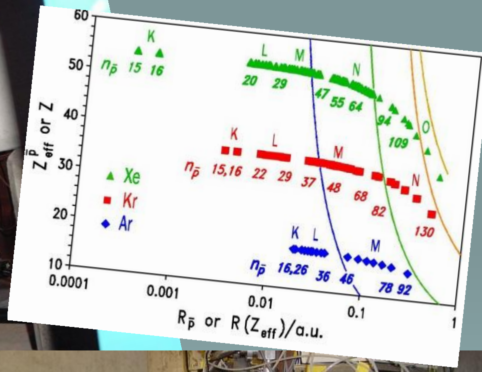
ANTIPROTONIC HYDROGEN STORY *s-wave*



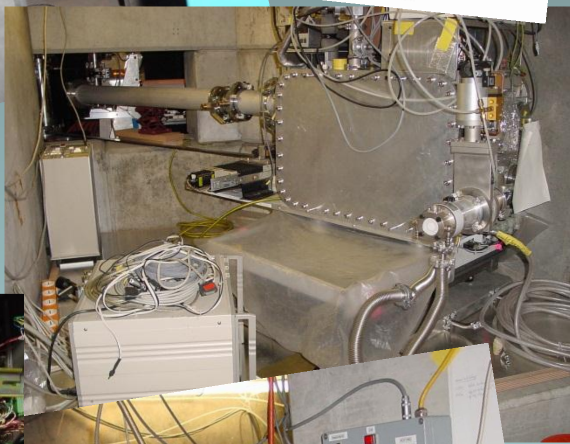


still a lot to do !





$Z_{eff}^{\bar{p}}$ or Z
$R_{\bar{p}}$ or $R(Z_{eff})$/a.u.
60
50
40
30
20
10
0.0001
0.001
0.01
0.1
1
Xe
Kr
Ar
$n_{\bar{p}}$ 15 16
K
L M
20 29
47 55 64
N
94
109
O
$n_{\bar{p}}$ 15,16 22 29 37 48 68 82 130
K L M N
$n_{\bar{p}}$ 16,26 36 46 78 92
K L M



THANK YOU