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JÜLICH FORSCHUNGSZENTRUM

Exotic Atoms

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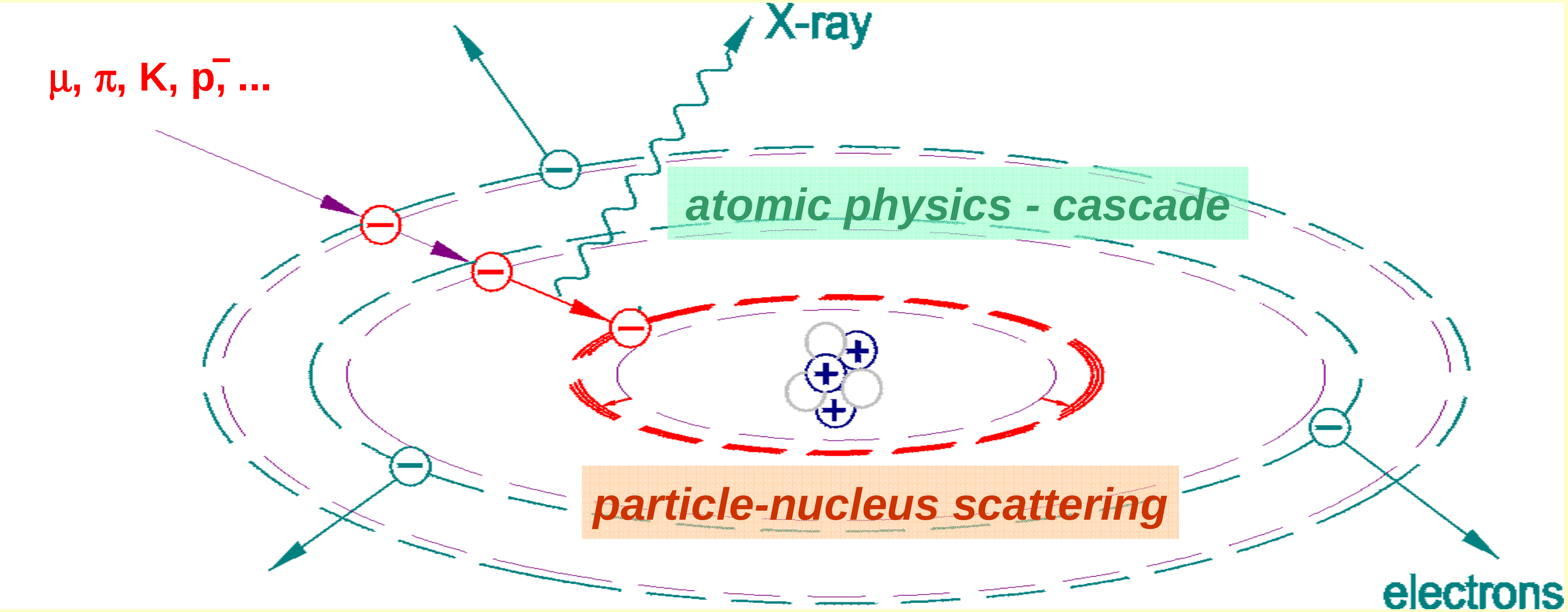
CGSWHP'10, Tbilisi, Georgia

May 4, 2010

EXOTIC ATOM



PARTICLE DECAY

CAPTURE → DE-EXCITATION CASCADE → STRONG PARTICLE-NUCLEUS INTERACTION

ELECTRO-WEAK PARTICLE-NUCLEUS INTERACTION

ORDERS OF MAGNITUDE

$$V_{Coulomb} = -Ze^2 / r$$

binding energies $B_n = -m_{red}\, c^2 \alpha^2 \cdot Z^2 / 2n^2$

radii $a_n = (hc / m_{red} c^2 \alpha) \cdot (n^2/Z)$

		m / MeV/c	$B_{n=1}$ / keV	"Bohr" radius / fm
atomic	ep	0.511	0.0136	$0.5 \cdot 10^5$
↓	μp	105	2.5	279
	πp	140	3.2	216
	$\bar{p}p$	938	12.5	58
"nuclear" dimension	$< r_p >$			0.8

capture

↓ atomic cascade

hadronic interaction

particle-nucleus scattering at "rest"

elastic and inelastic

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 ↓

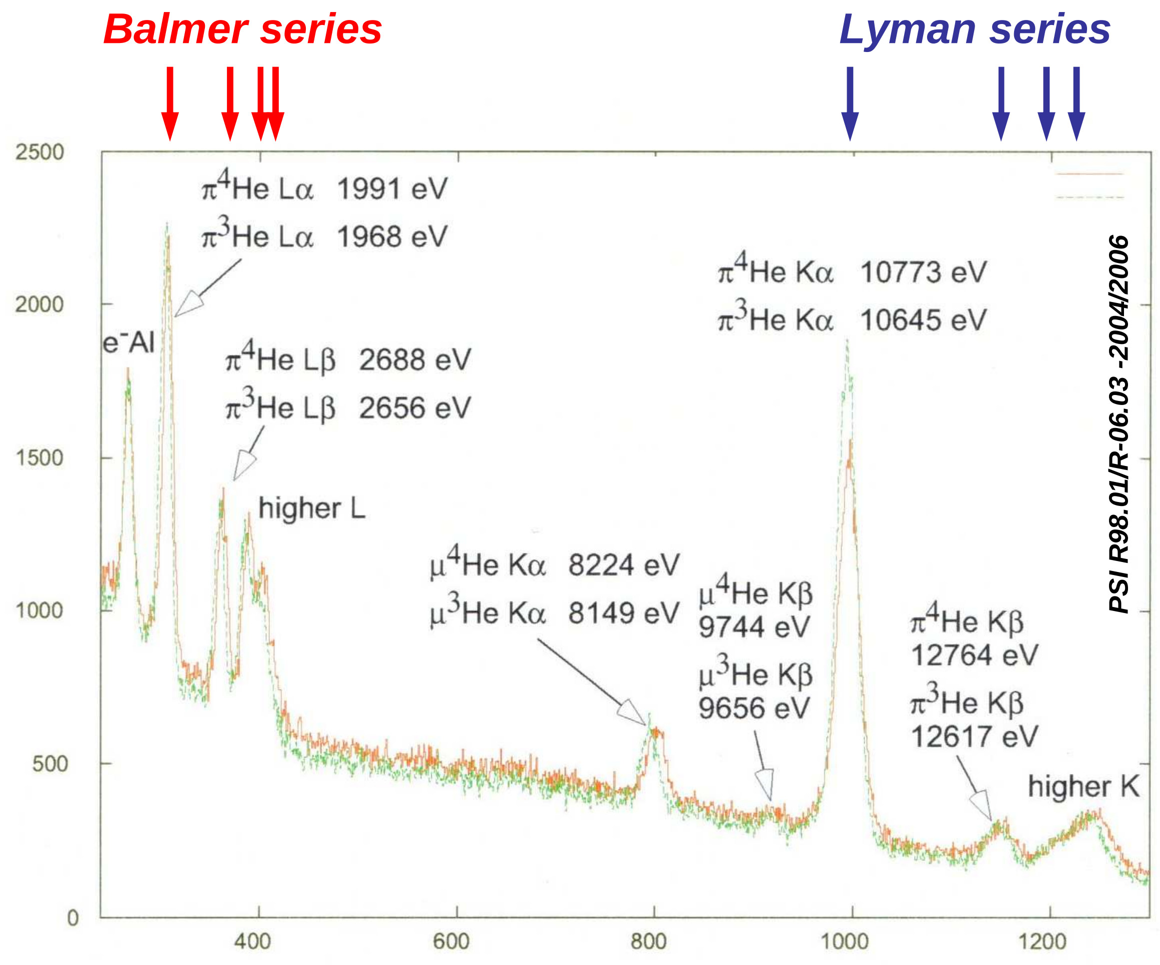
study of

– molecules	
– atoms	*depletion of electron shells*
– nuclei	*proton charge radius*
– properties of elementary particles	*pion mass*
– particle-nucleus interaction	*pion-nucleon*
	antinucleon-nucleon

WHAT DO WE EXPECT ?

WHAT CAN BE MEASURED ?

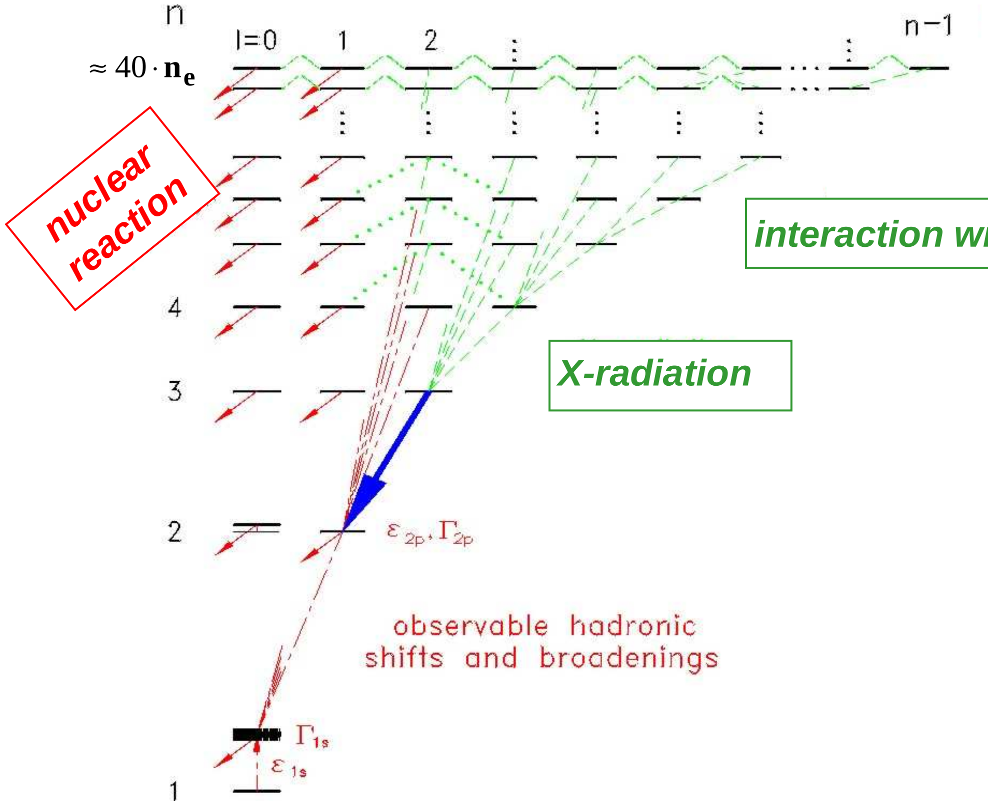
PIONIC HELIUM semiconductor detector (pnCCD PSI 2006)



π^4He

π^3He

particle capture when slowed down to a few eV kinetic energy



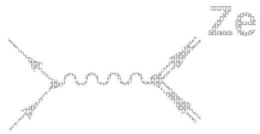
interaction with the remaining electrons - Auger emission

OBSERVABLES

- X-ray energies
- line intensities
- line width

ATOMIC BINDING ENERGY

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



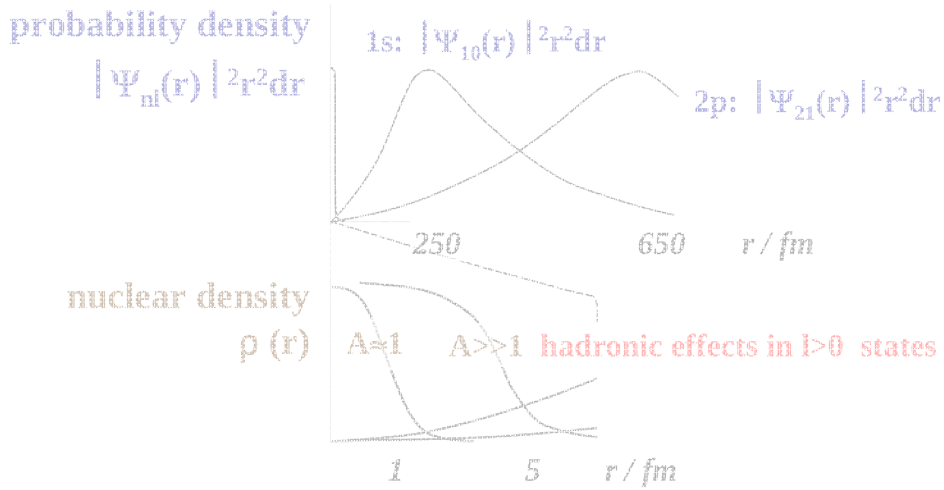
$+ \Delta E_{QED}$

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

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

$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



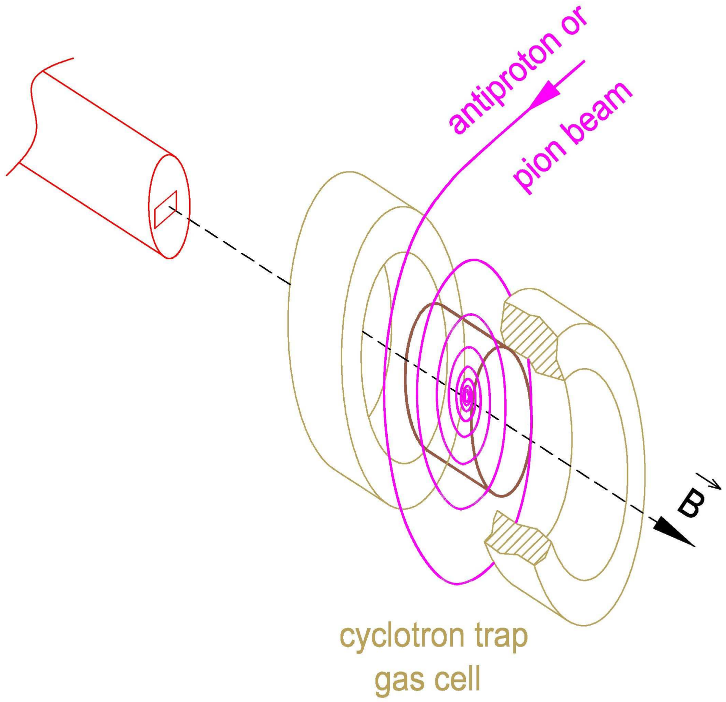
EXPERIMENT I

How to produce a suitable <u>X-ray source</u>?

CYCLOTRON TRAP concentrates particles

super-conducting split coil magnet

X-ray detector



"wind up" range curve

in (weakly) focusing magnetic field

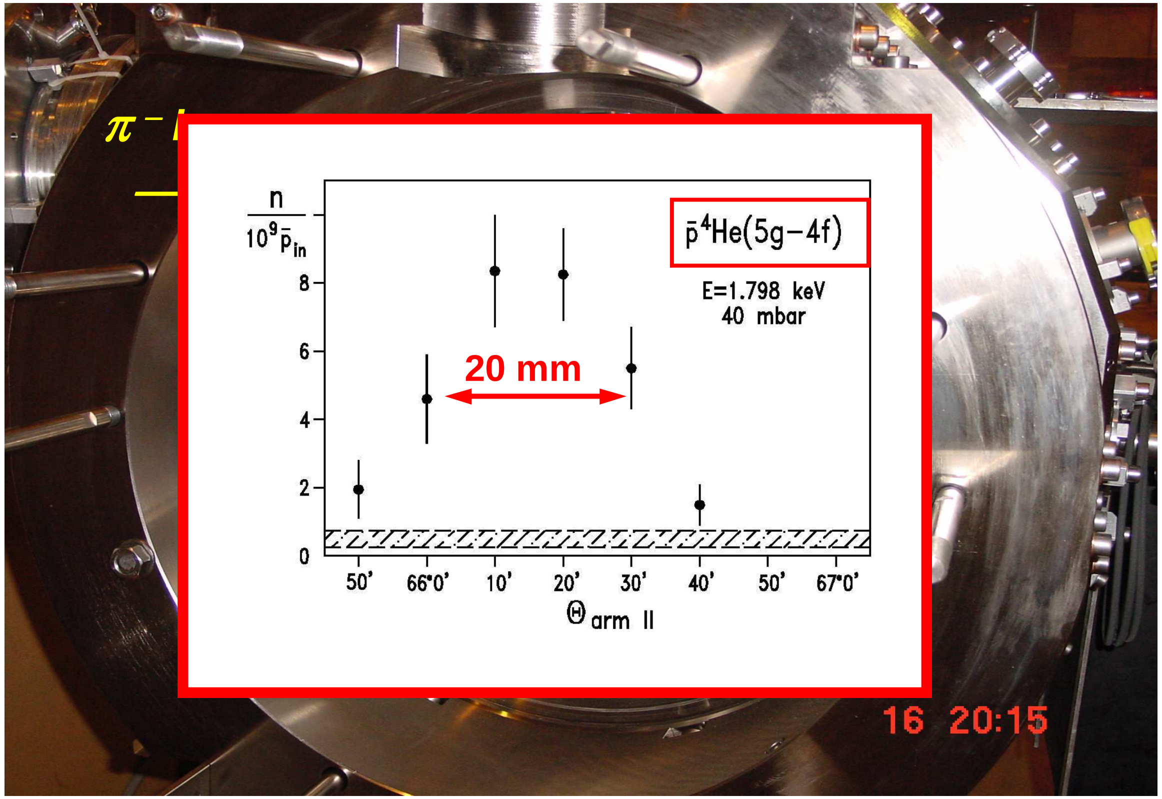
increase in stop density

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



CAPTURE

and

DE-EXCITATION CASCADE

ATOMIC BINDING ENERGY

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

Ze

$+ \Delta E_{QED}$

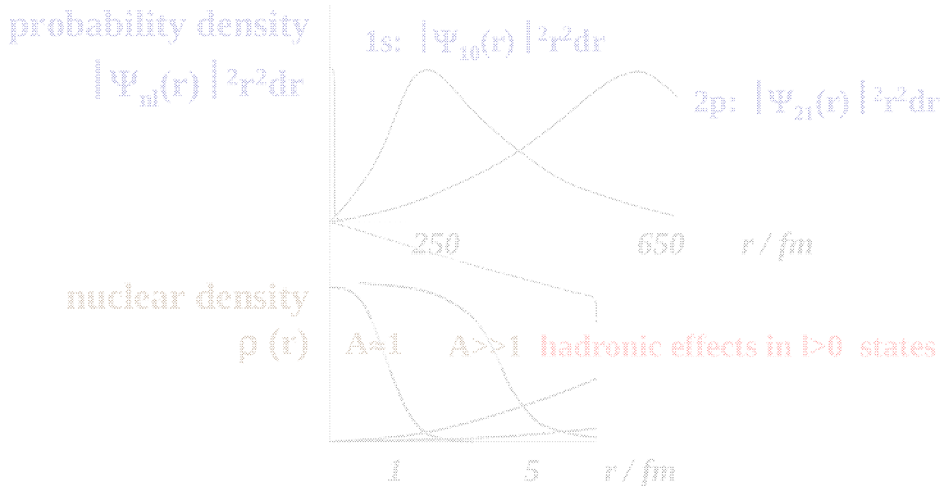
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

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

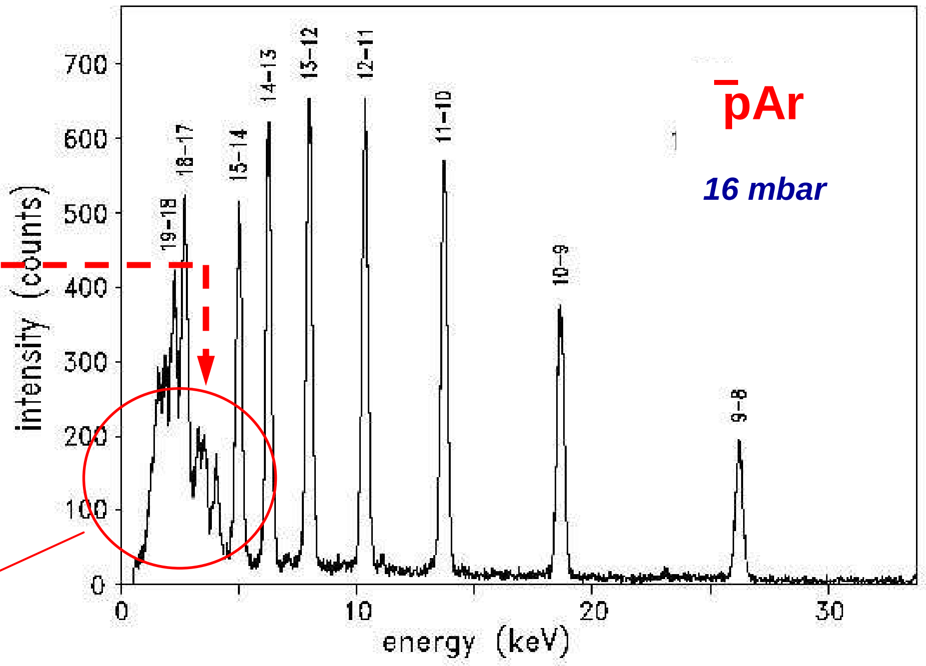
$+ \Delta E_{finite\ size}$

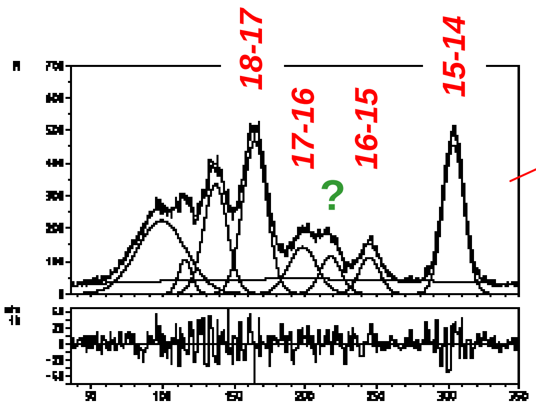
$+ \Delta E_{strong\ interaction}$



ANTIPROTONIC X-RAYS - ARGON

- many Δn=1 transitions
- starts at high n
- hole ?



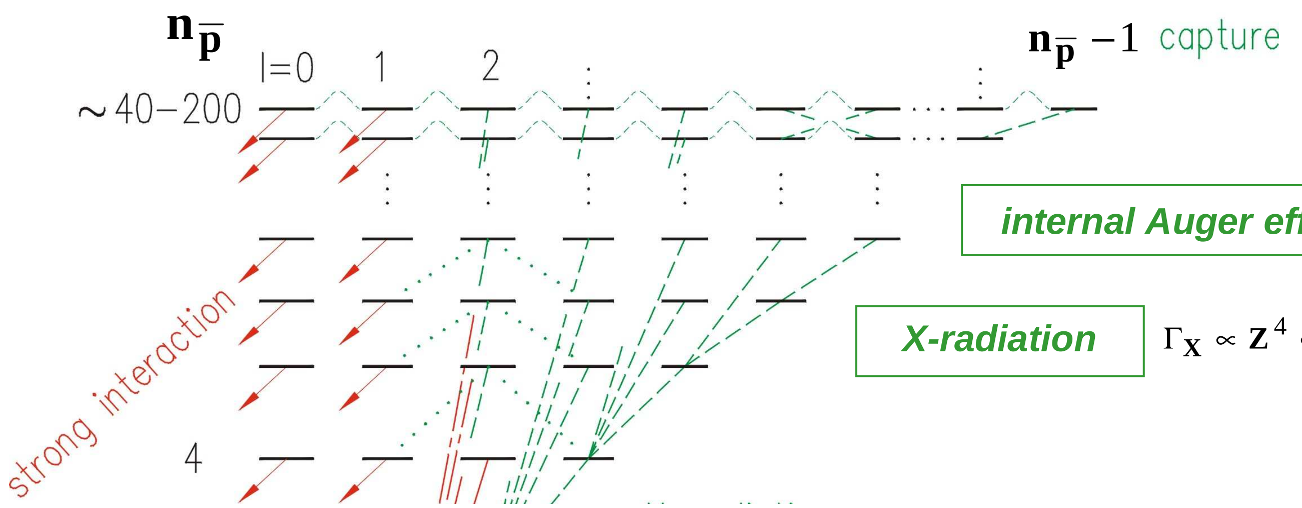


data: PS175 Ar, Kr, Xe

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

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

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



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

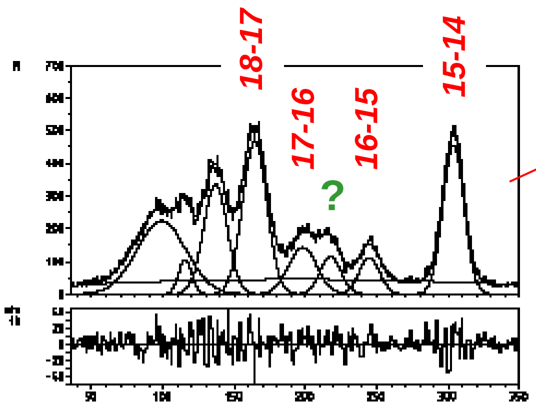
X-radiation $\Gamma_{\mathbf{X}} \propto \mathbf{Z}^4 \propto (\Delta\mathbf{E})^3$

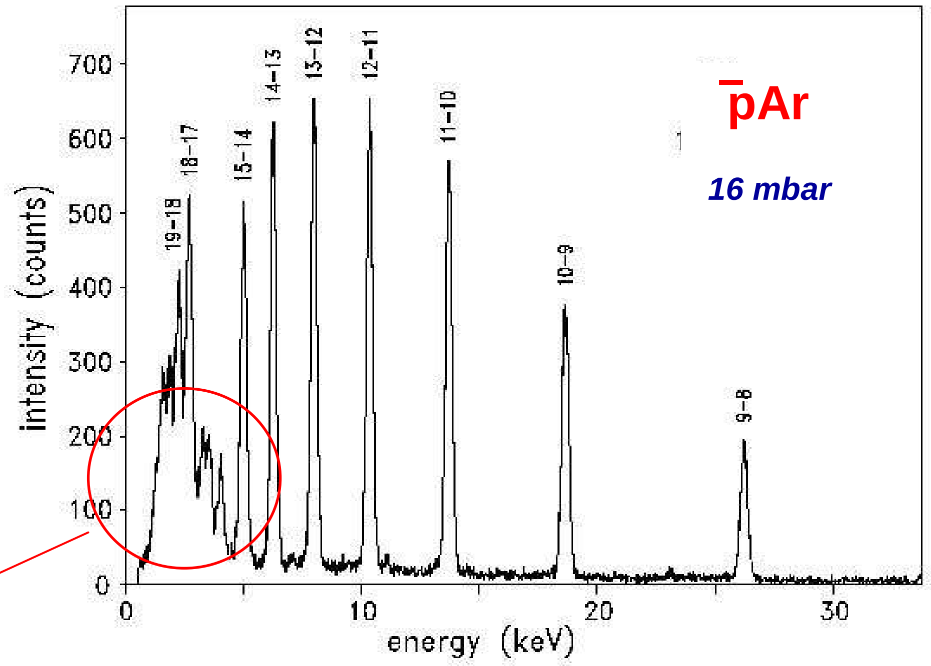
competition between AUGER and RADIATIVE DE-EXCITATION

electrons are peeled off like onion shells

ANTIPROTONIC X-RAYS - ARGON

Auger
vs.
radiative
de-ecxcitation





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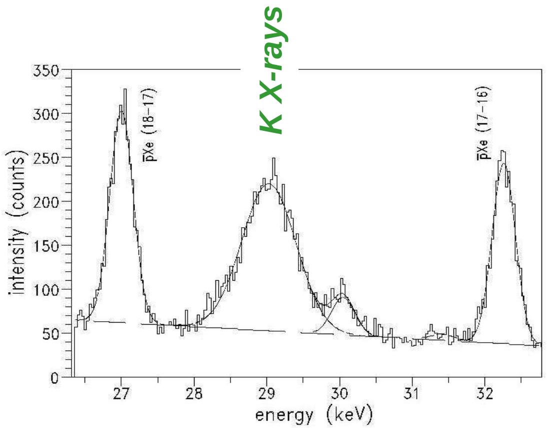
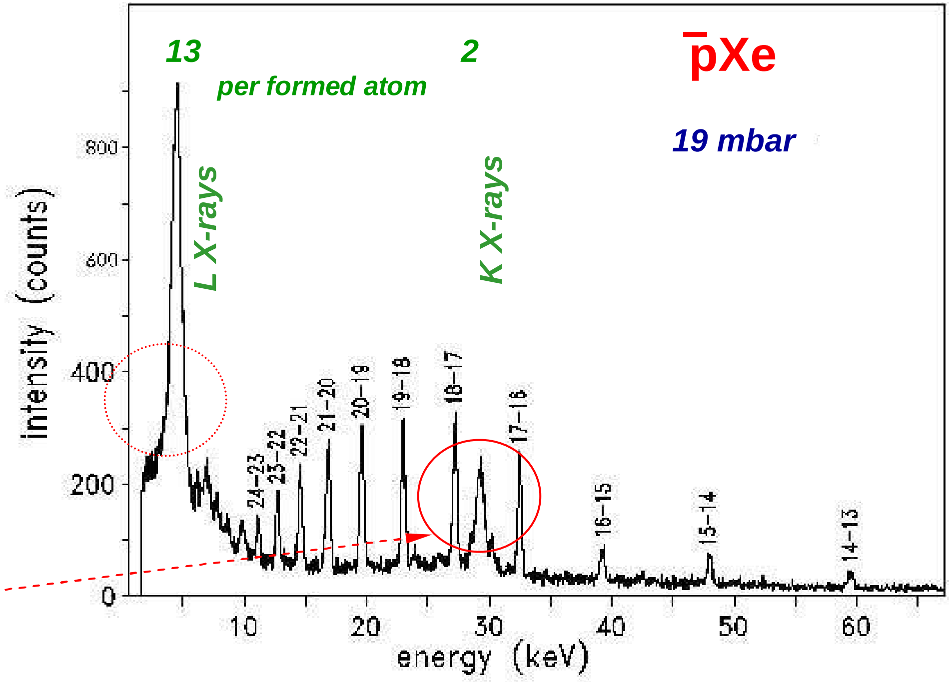
ELECTRONIC & ANTIPROTONIC X-RAYS - XENON

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

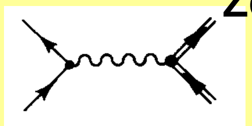
PROTON CHARGE RADIUS

muonic atoms - no strong interaction

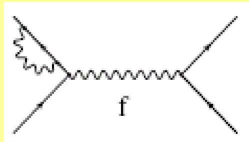
cyclotron trap as muon source

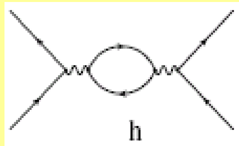
ATOMIC BINDING ENERGY

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



$+ \Delta E_{QED}$



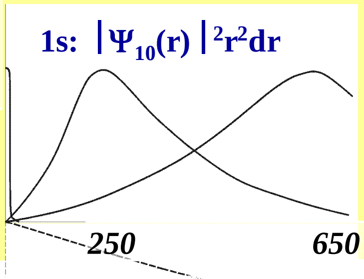


self energy + *vakuum polarisation* + *higher orders*

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

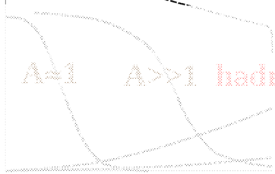
$+ \Delta E_{finite\ size}$

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



$+ \Delta E_{strong\ interaction}$

nuclear density
ρ (r)



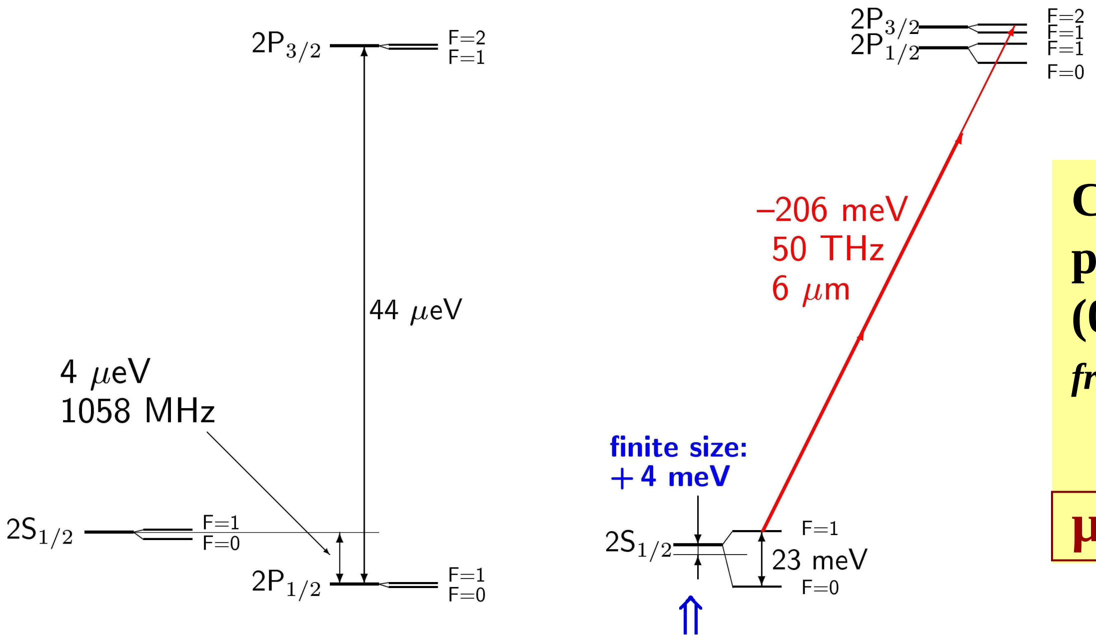
MUONIC HYDROGEN LAMB SHIFT

e⁻p

large! ***$2{\cdot}10^5$ fm***

μ⁻p

small! ***$1{\cdot}10^3$ fm***



CODATA
proton rms charge radius
$(0.8768 \pm 0.0069){\cdot}10^{-15}$ m
from electron scattering

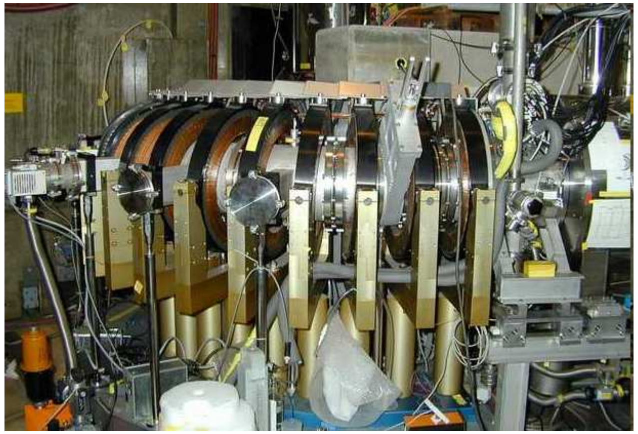
μp: *error* → ≈ error / 10 !

very sensitive to proton charge radius

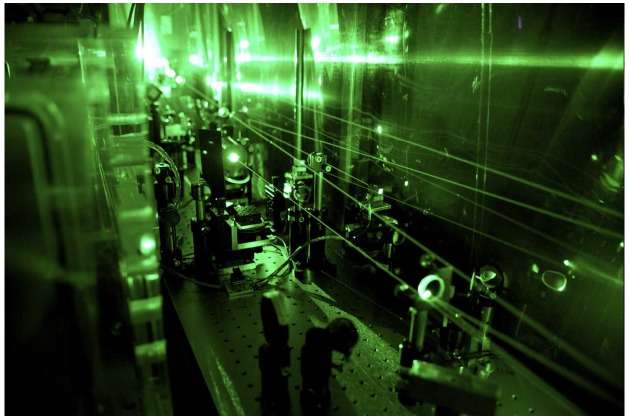
μH collaboration: see e.g. R. Pohl et al., Hyperf. Int. 193 (2009) 115.

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

EXPERIMENT II

How to achieve ultimate energy determination and resolution?

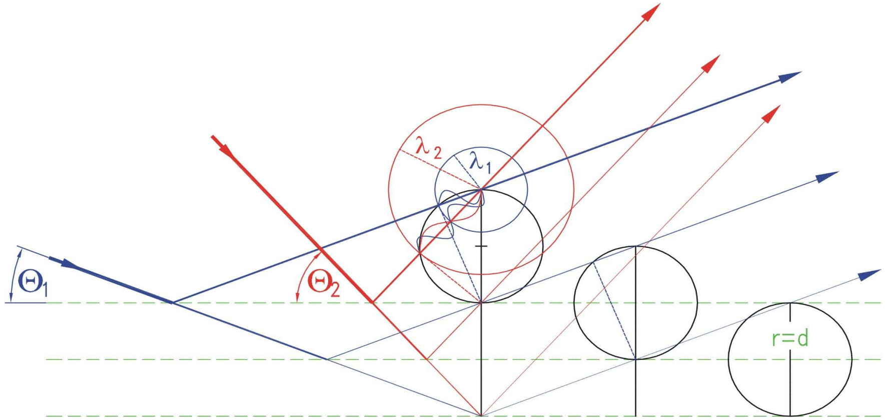
together with

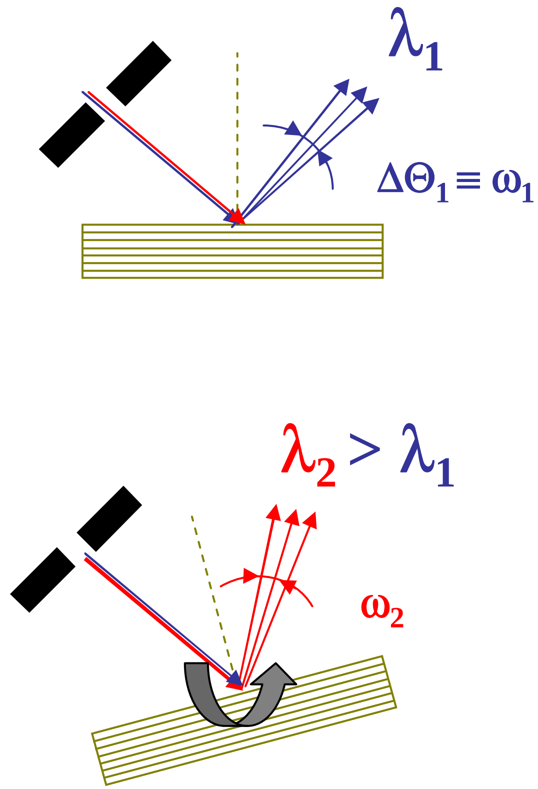
sufficient count rate?

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

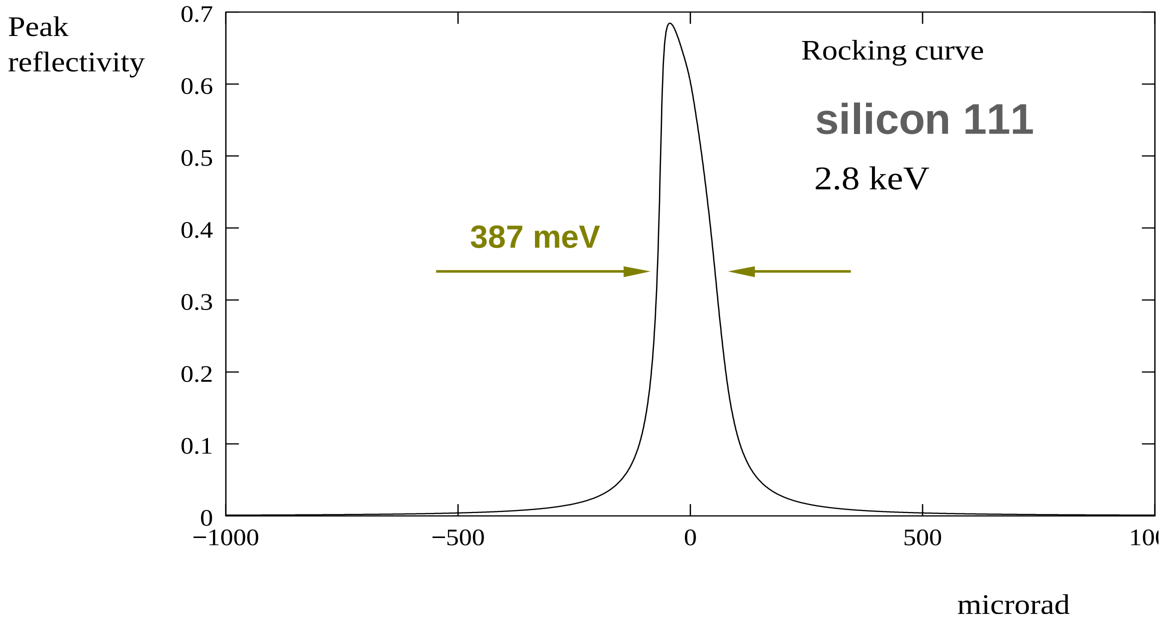




τ_e	extinction length	*coherent reflection*
τ_a	absorption length	*incoherent*

usually $\tau_e \ll \tau_a$

calculated CRYSTAL RESPONSE



diffraction theory

XOP2 code
plane crystal

for real crystal mounting?

no ***narrow*** *few keV γ lines*

BASIC RELATIONS derived from Bragg's law

$$n\lambda = 2d \cdot \sin\theta_B$$

conversion

$$\lambda = 2\pi \frac{\hbar c}{E}$$

$$= 2\pi \frac{197.326968\,(17)\ MeV \cdot fm}{E} \qquad (85\ ppb)$$

$$= \frac{12.39841857\,(48)\ \overset{o}{A}}{E/keV} \approx \frac{4\pi\ \overset{o}{A}}{E/keV}$$

derivatives

angular dispersion

$$\frac{\Delta E}{\Delta\Theta} = -\frac{E}{\tan\Theta}$$

energy resolution ⇔ Bragg angle

$$\frac{\Delta E}{E} = -\cot\Theta_B \cdot \Delta\Theta_B$$

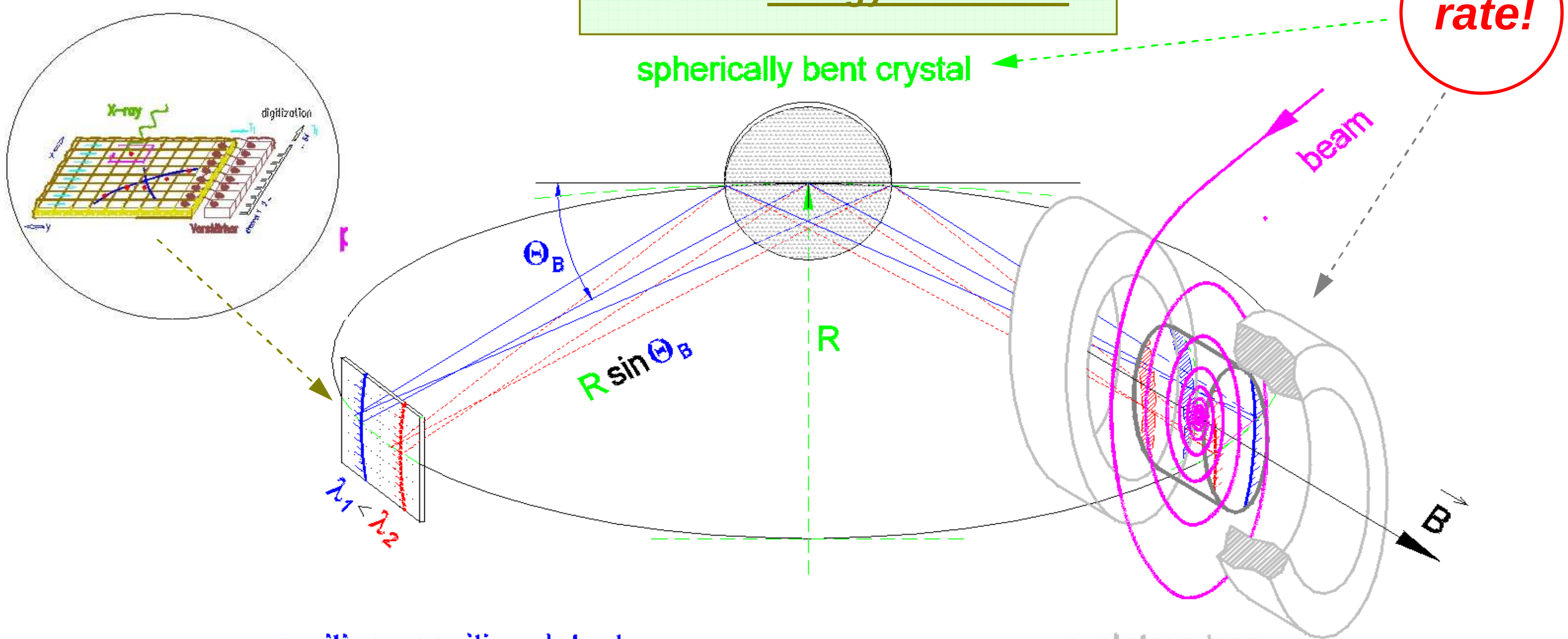
energy resolution ⇔ energy

$$\frac{\Delta E}{E} \propto \frac{E}{n}$$

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}}$$ *ionisation detectors*

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

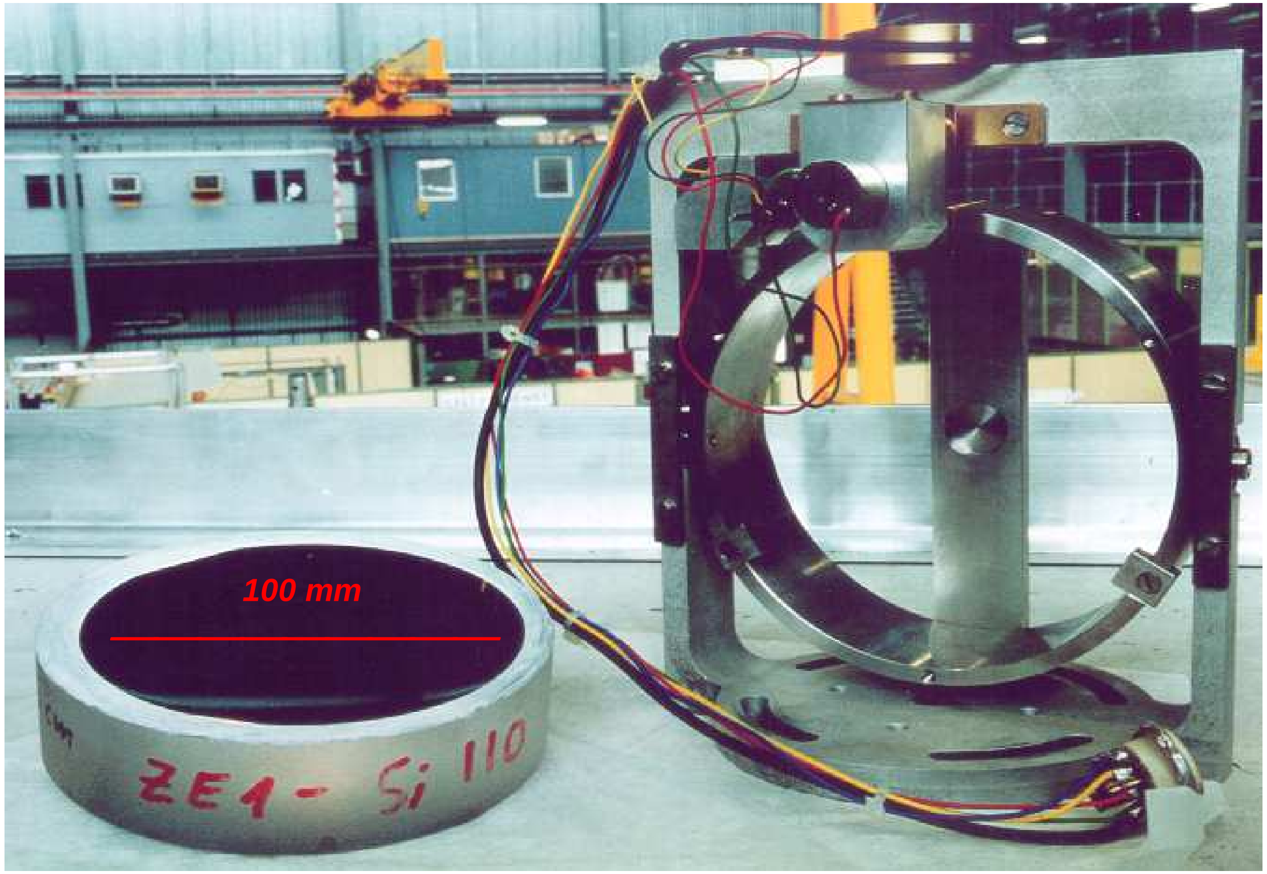
SPHERICALLY BENT BRAGG CRYSTALS

radius of curvature
2985.4 mm

energy range
quartz, Si
E = 1.7 – 15 keV

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

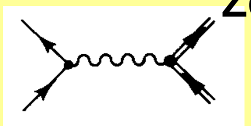
energy resolution
$\Delta E/E \cong 10^{-4}$



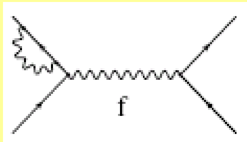
CHARGED PION MASS

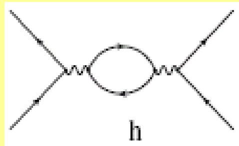
ATOMIC BINDING ENERGY

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



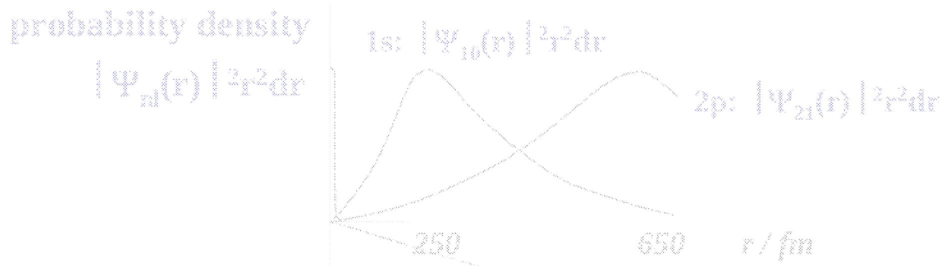
$+ \Delta E_{QED}$





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

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

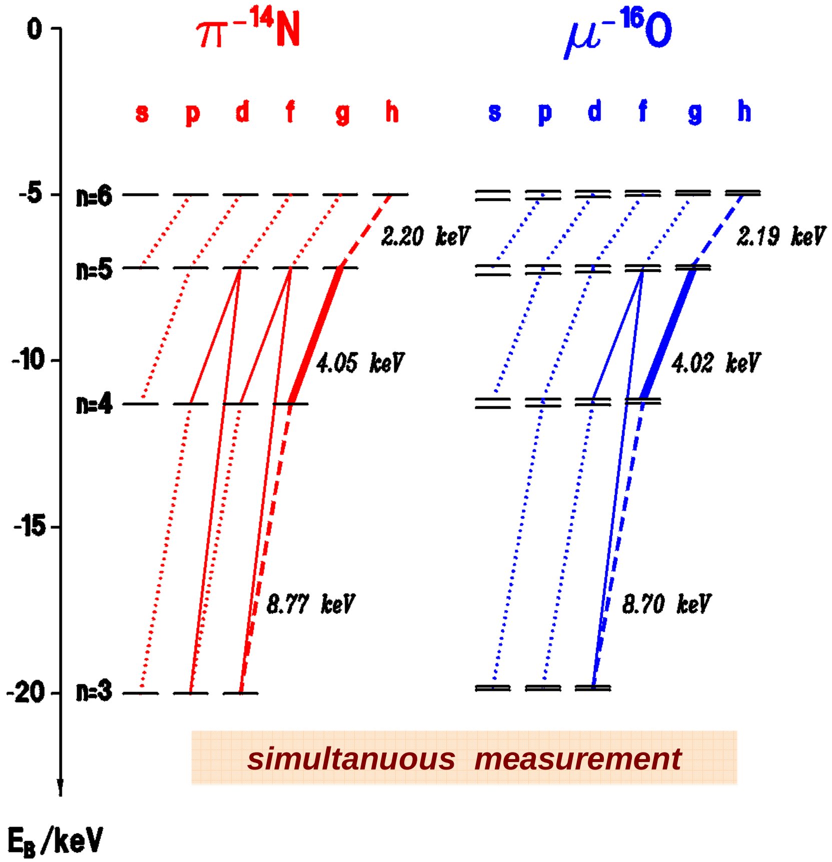


$+ \Delta E_{finite\ size}$

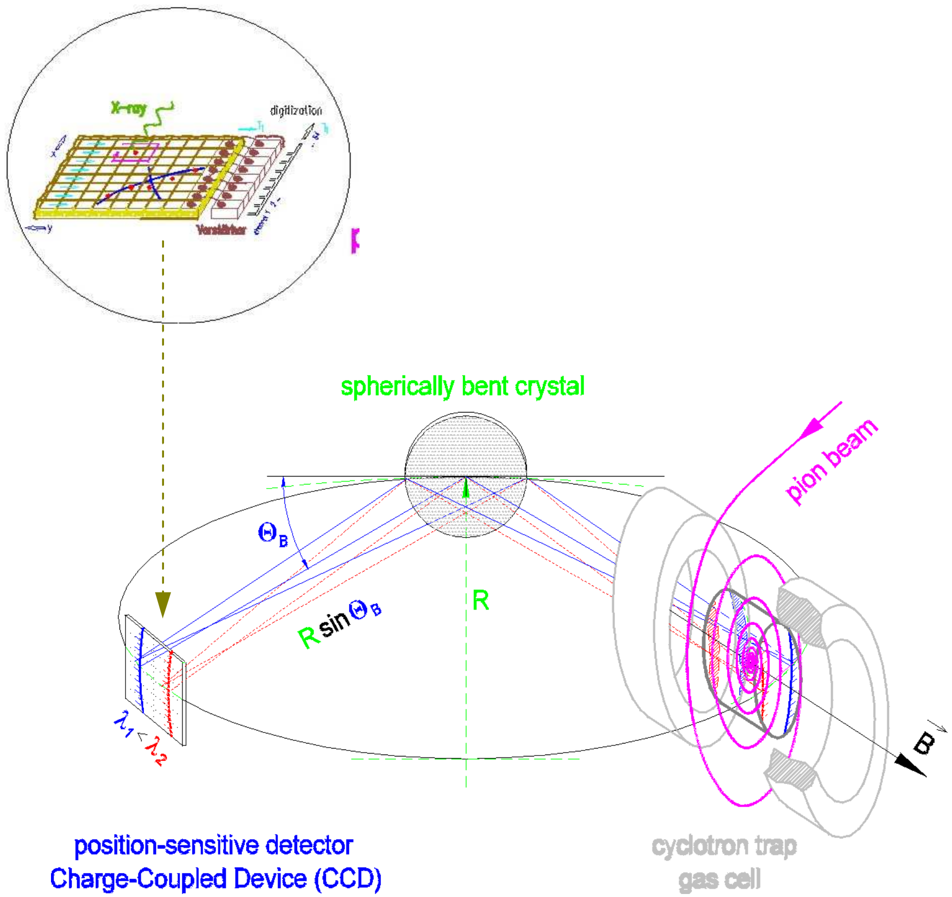
$+ \Delta E_{strong\ interactic}$

measurement *calibration*

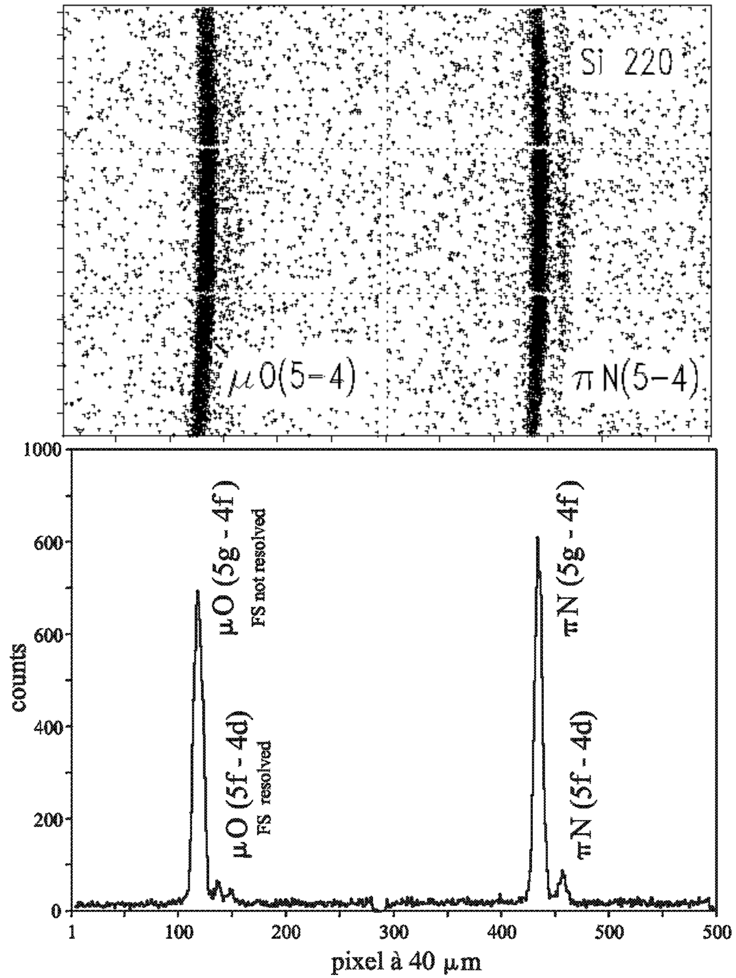
πN(5g-4f) μO(5g-4f)



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



← *pion mass* →



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

EXPERIMENT III

What about background?

DETECTOR *crystal spectrometer* *Large - Area Focal Plane Detector*

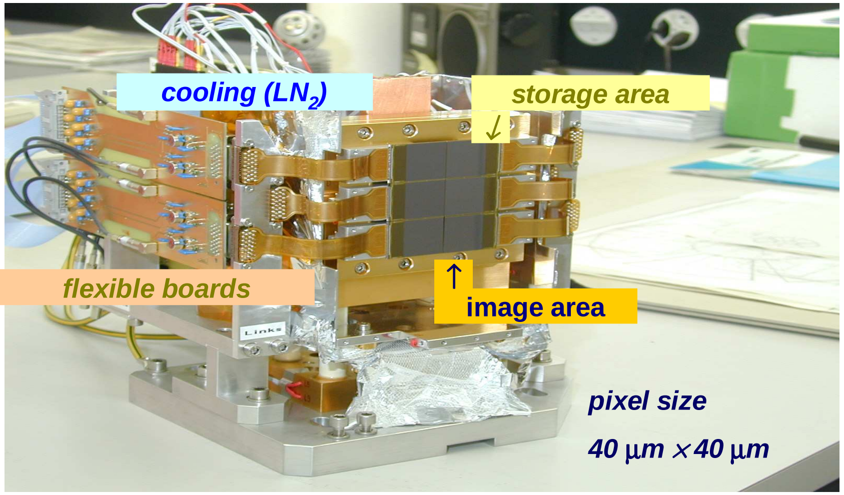
CCD: charge-coupled device

pixel distance

manufacturer
@ 20°C 40.0 µm ± 0.17 nm
@ -100°C 39.9775 µm ± 0.6 nm

P. Indelicato et al., Rev. Sc. Instr. 77 (2006) 043107

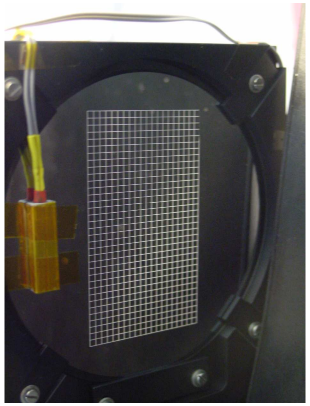
2 × 3 array of 24 mm × 24 mm devices



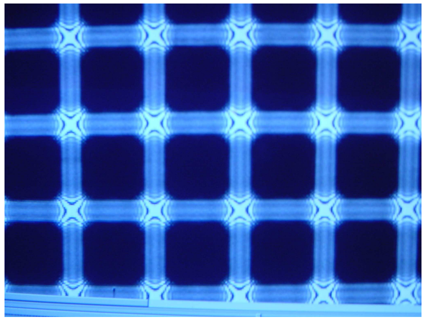
N. Nelms et al., Nucl. Instr. Meth 484 (2002) 419

***1. try* wire eroded mask**
- gap ▤
- pixel size ?

***2. try* nano mask** *(C. David LNS/PSI)*

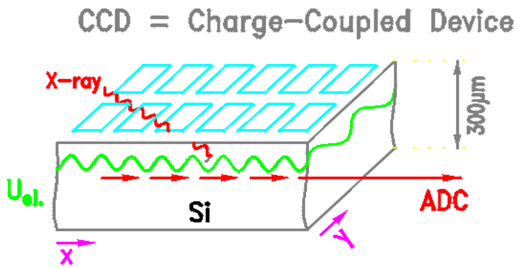


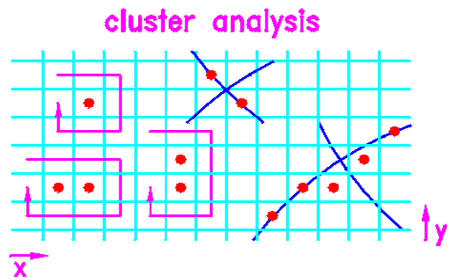
illuminated
by light source
at 6 m distance
T = 20°C



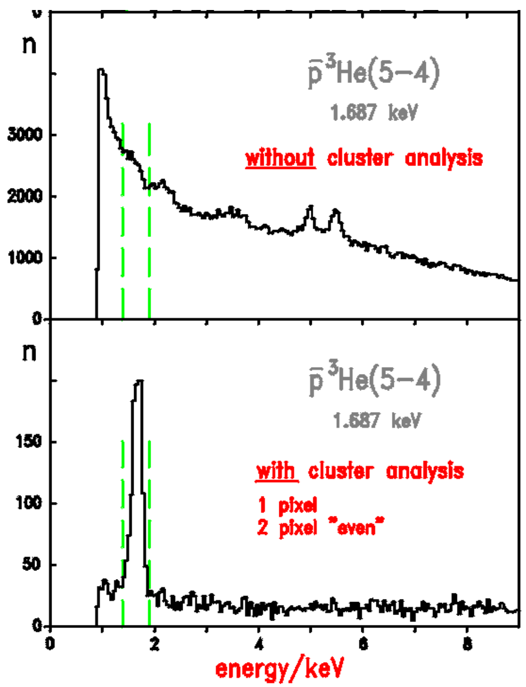
@ -100°C HOR 39.9802 ±0.0026 µm
VER 39.9794±0.0022 µm

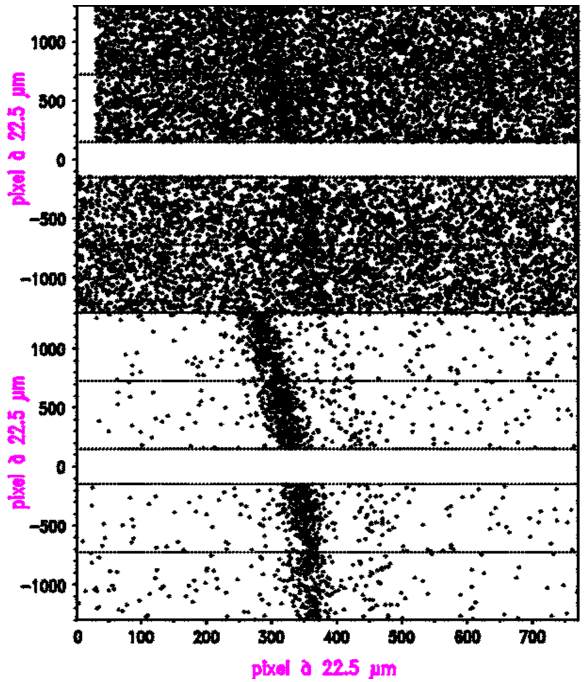
BACKGROUND SUPPRESSION WITH CCDs





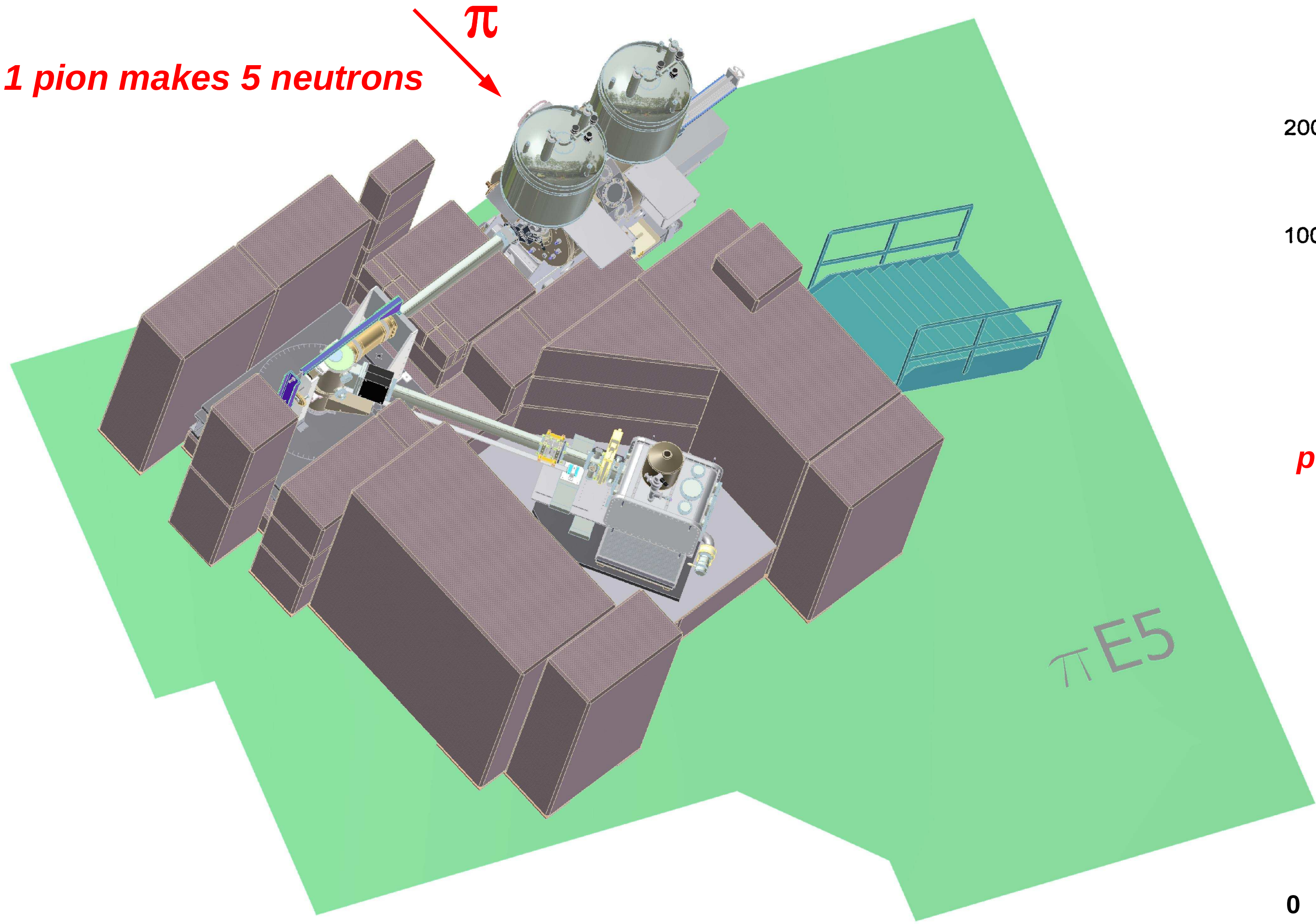
X-ray ≡ 1-2 pixel



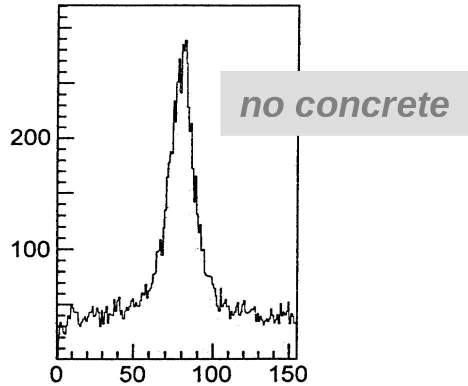


charge deposit ∝ X-ray energy

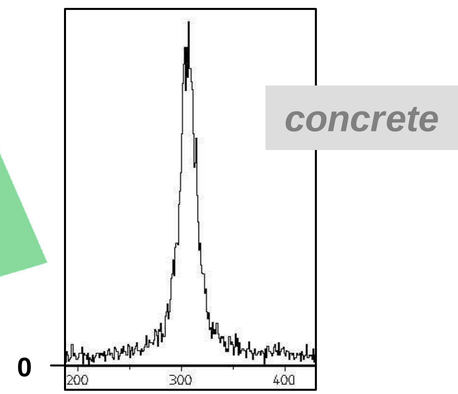
TYPICAL SET-UP at PSI



pionic hydrogen



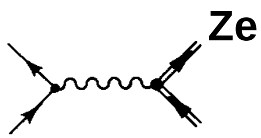
peak/background x 10



STRONG INTERACTION

ATOMIC BINDING ENERGY

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



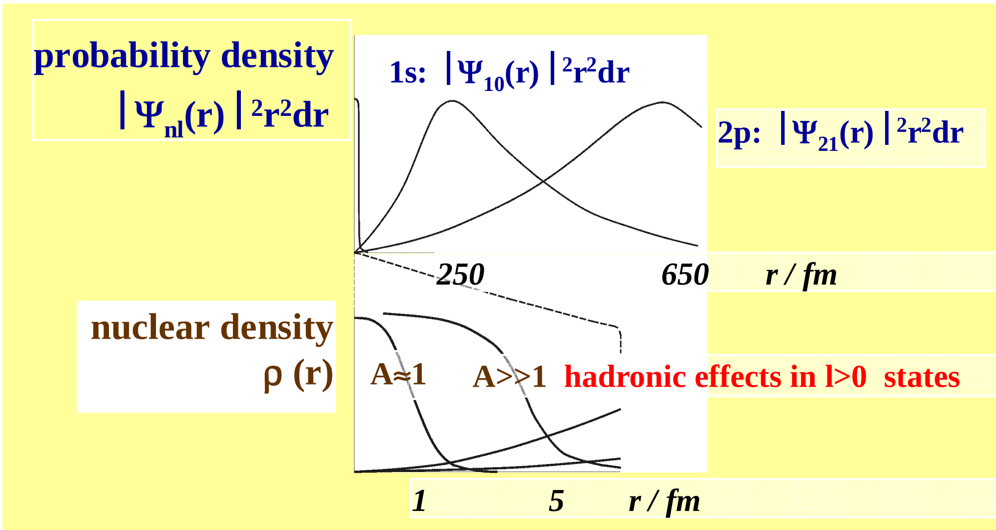
$+ \Delta E_{QED}$

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

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

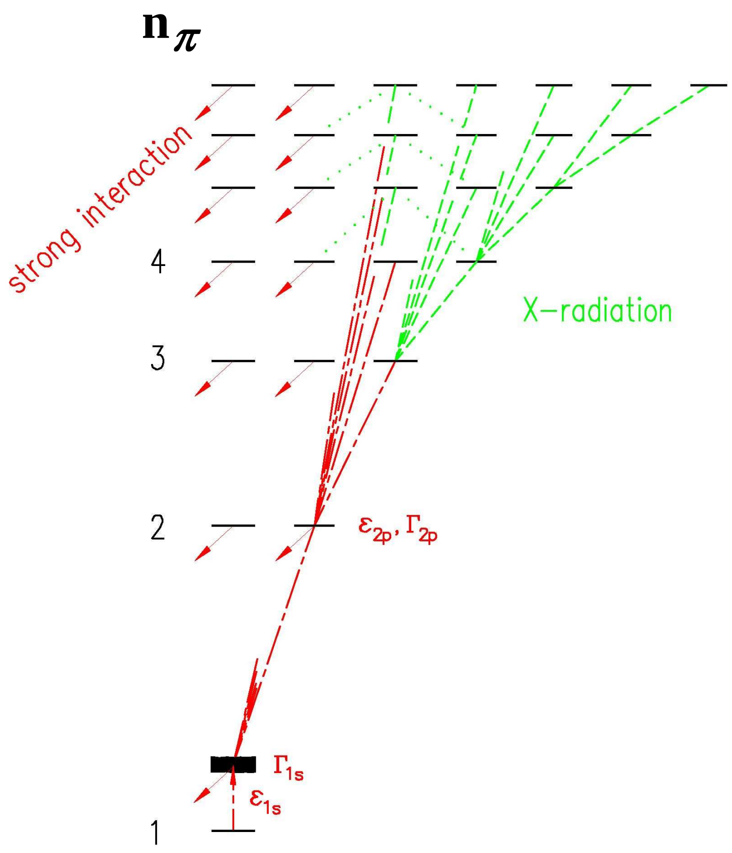
$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



LOWER PART of the ATOMIC CASCADE ***pionic deuterium***

equivalent to scattering experiment at threshold



scattering amplitude reduces to

- ***scattering length a*** ***s-wave***
- ***scattering volume b*** ***p-wave***
- ***...***

measure shift ε of X-ray energy relative to QED value

$\varepsilon \propto a +$ higher orders

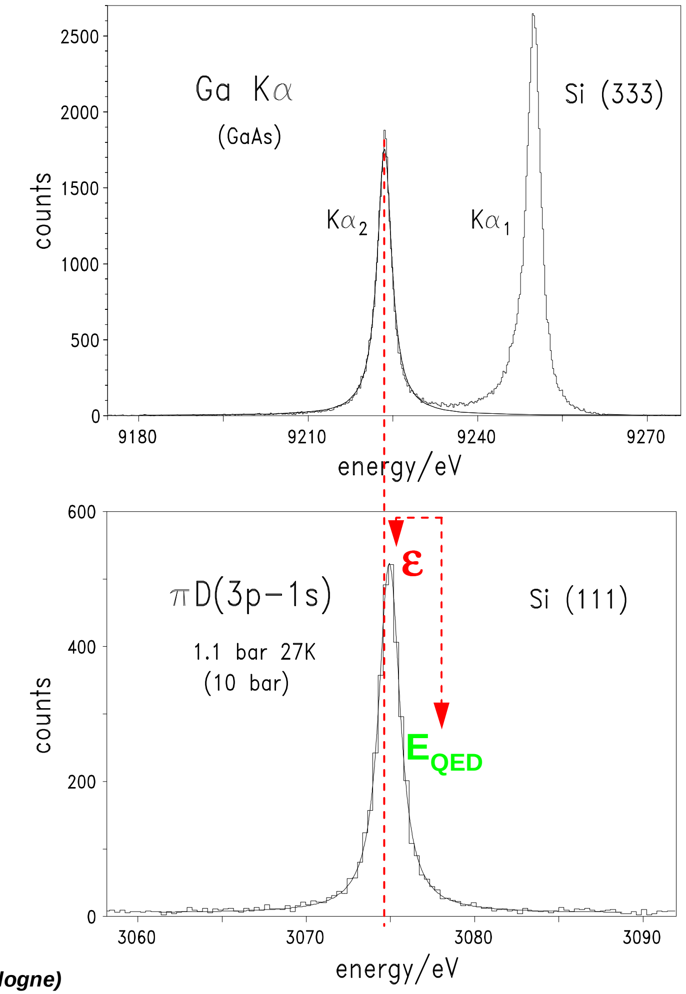
PIONIC DEUTERIUM

energy calibration

Ga Kα

strong interaction

πD(3p-1s)



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

ε = -2 eV

target material: GaAs

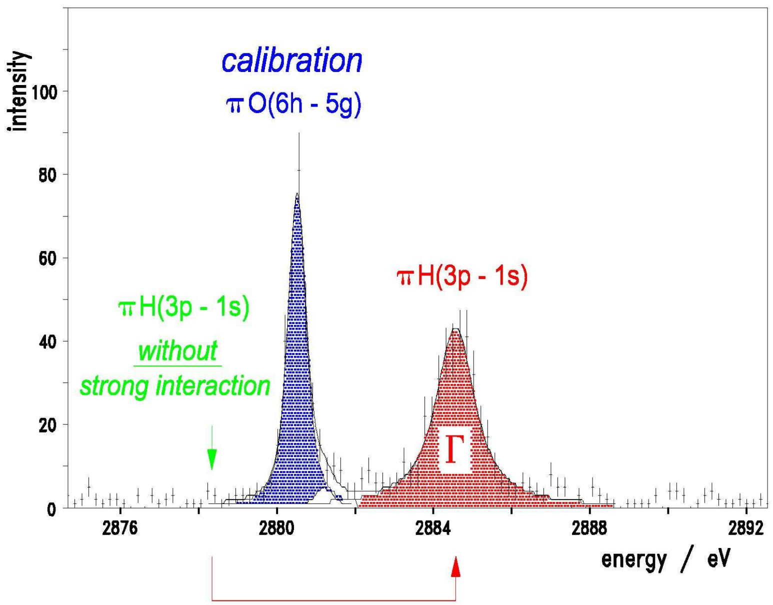
by chance: tabulated energy
<u>also</u>
from GaAs

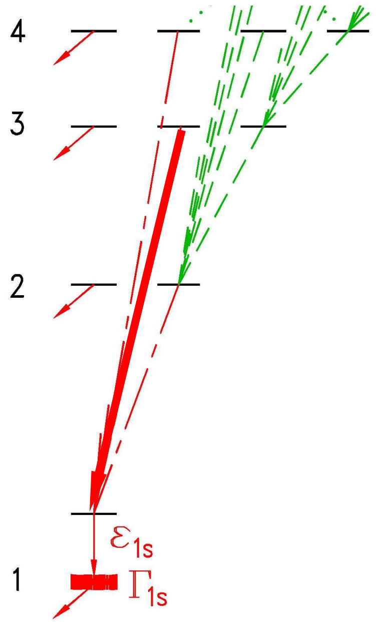
identical Bragg angle

3 bar
10 bar
22 bar

to identify molecule formation

PIONIC HYDROGEN



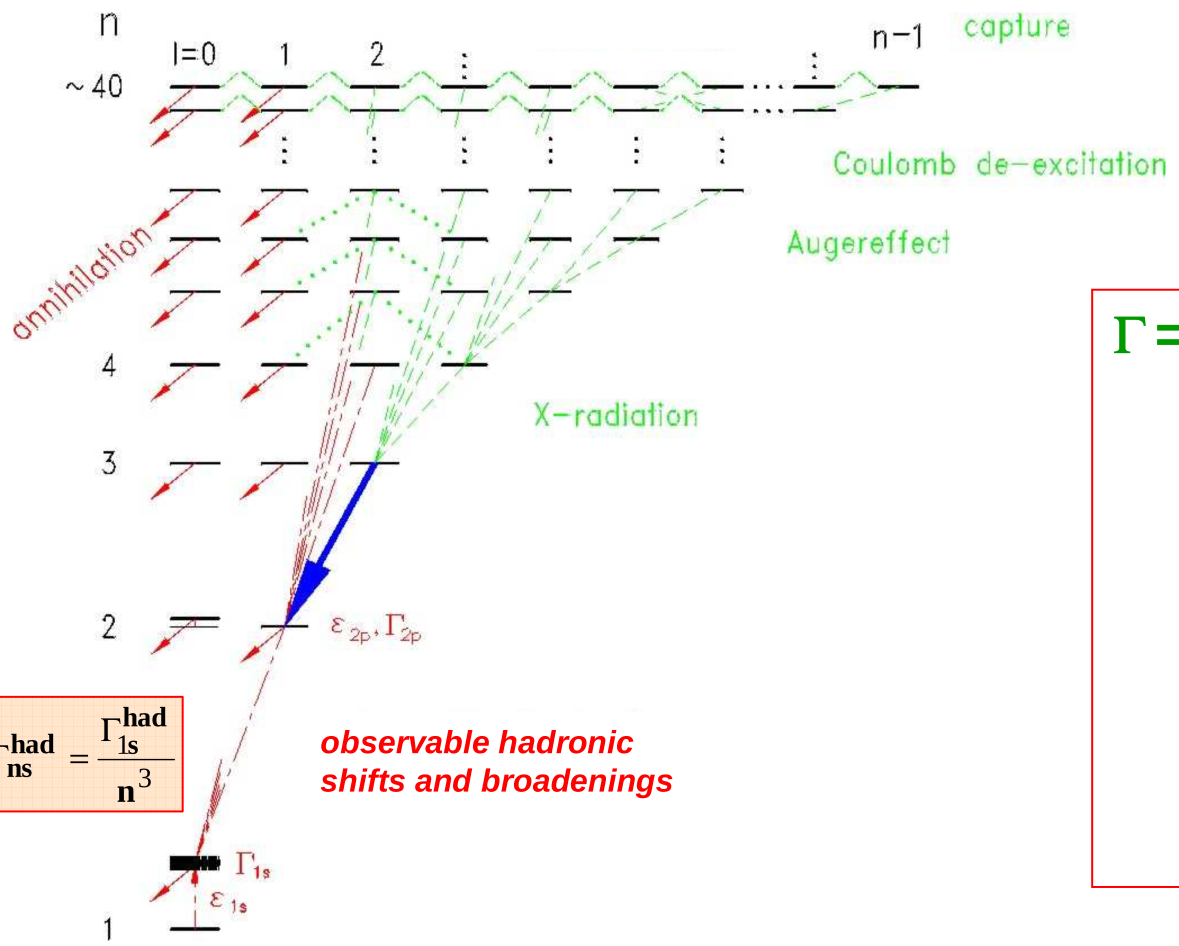


ε = +7 eV

first conclusions	***πp***	***attractive***
	πd	***repulsive***
	strength (π^-p) ≈ - strength (π^-n)	

ATOMIC LEVEL WIDTH Γ

life time equivalent to energy uncertainty = width *(uncertainty relation $\Gamma \cdot \Delta t \cong \hbar$)*



$$\Gamma_{ns}^{had} = \frac{\Gamma_{1s}^{had}}{n^3}$$

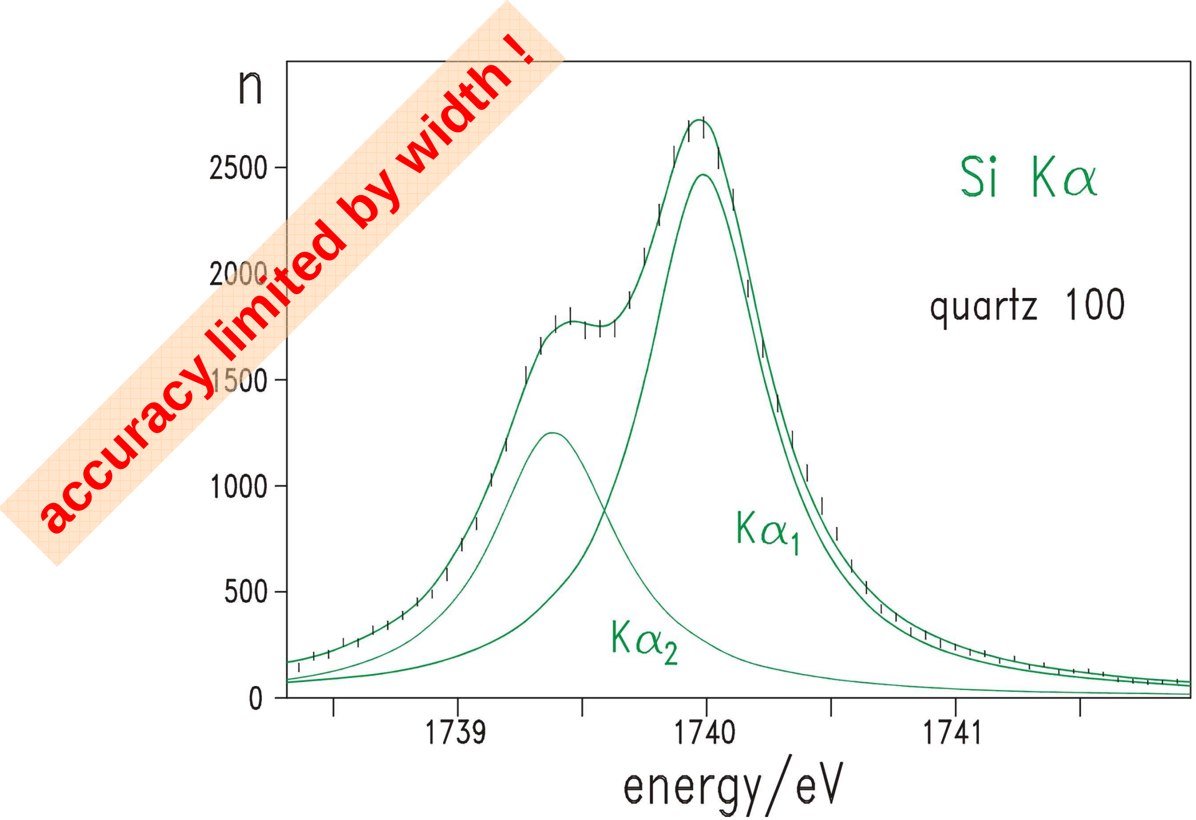
observable hadronic shifts and broadenings

$$\Gamma = \Gamma_{X\text{-ray}} + \Gamma_{Auger} + \ldots + \ldots + \Gamma_{strong\ interaction}$$

EXPERIMENT IV

How to measure the resolution of the crystal spectrometer ?

ENERGY CALIBRATION *for Balmer α transition*



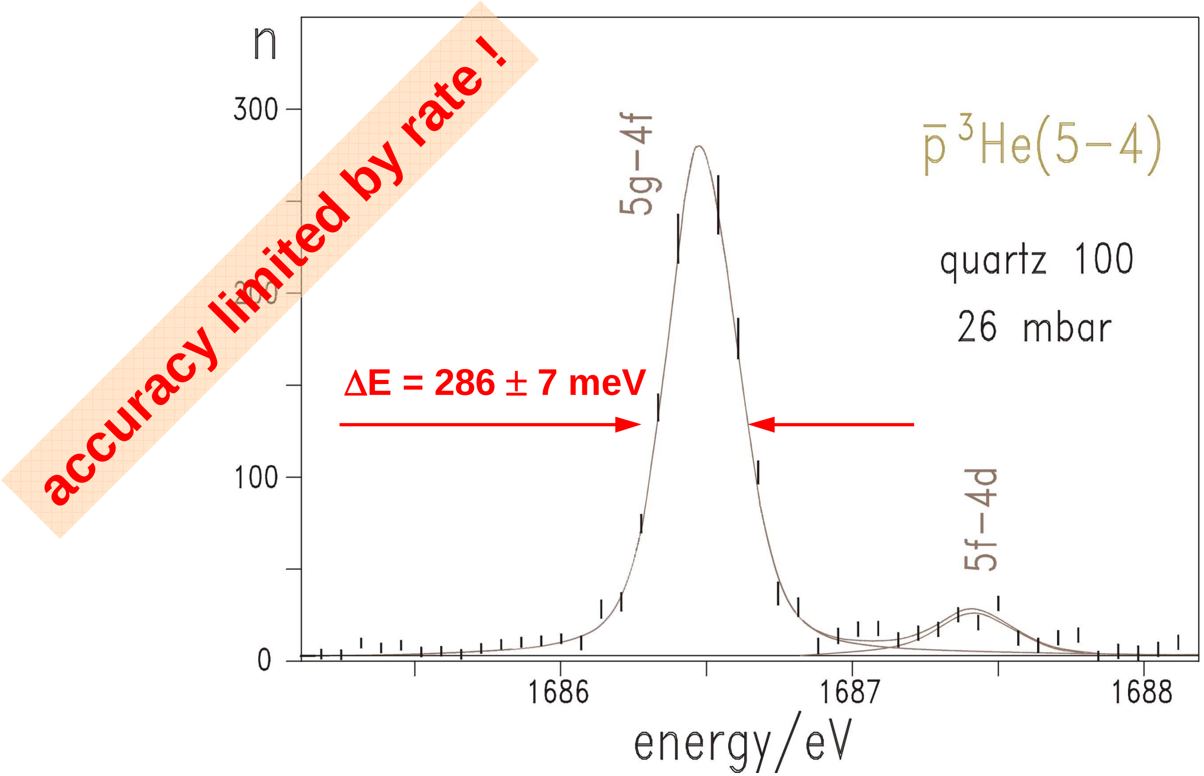
closest to energy of $\bar{p}$H(3d-2p)

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

high rate

large line width and satellites - resolution hardly measurable

RESPONSE FUNCTION *for Balmer α transition*



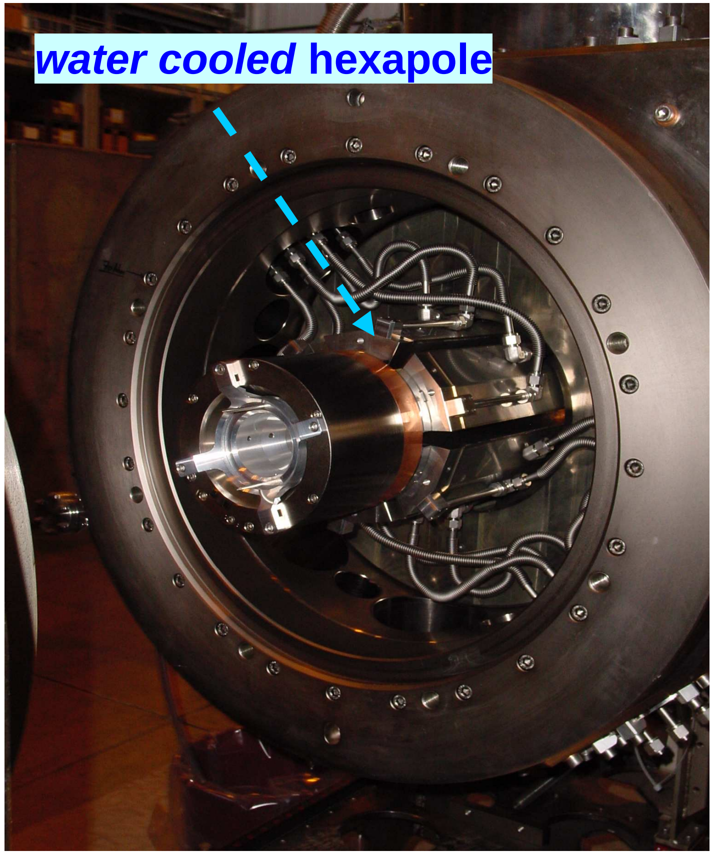
closest to energy of $\bar{p}H(3d\text{-}2p)$

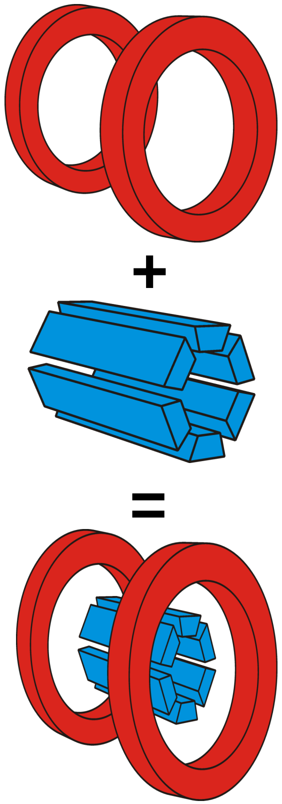
920 events

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*

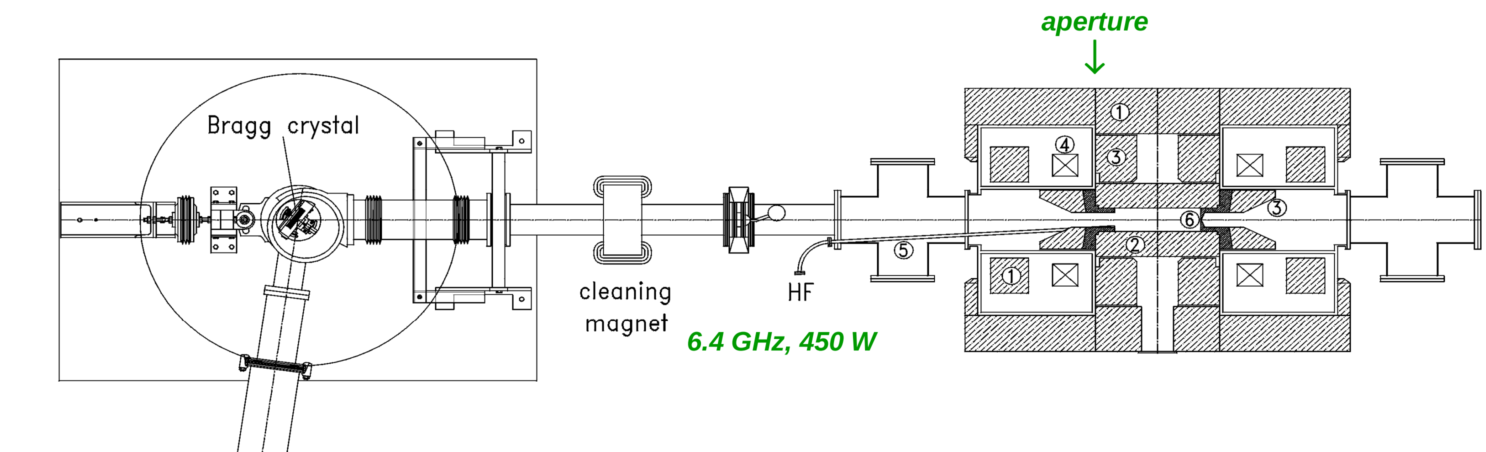
large mirror ratio = 4.3

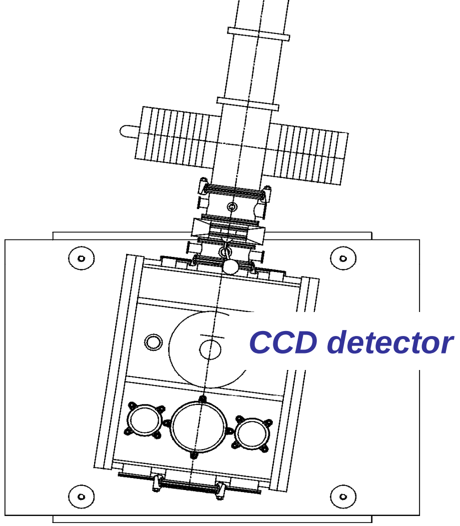
B_{max} / B_{min} !

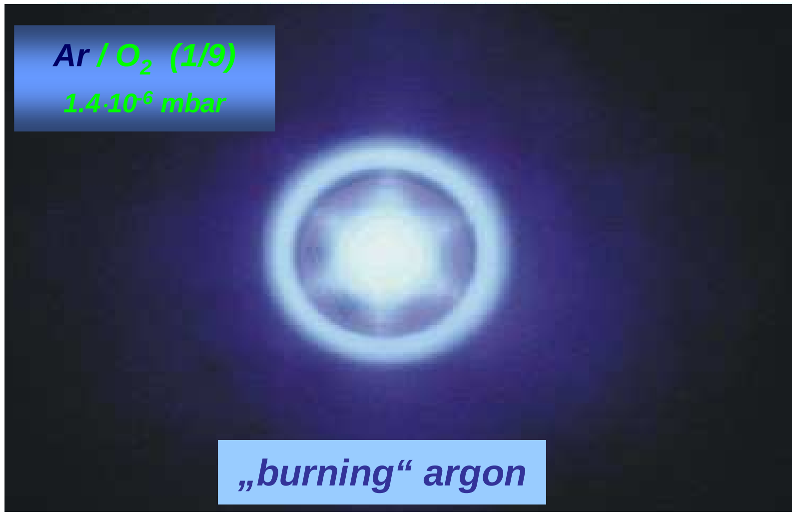
S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116
K. Stiebing, Frankfurt – design assistance

CRYSTAL SPECTROMETER and PSI ECRIT

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



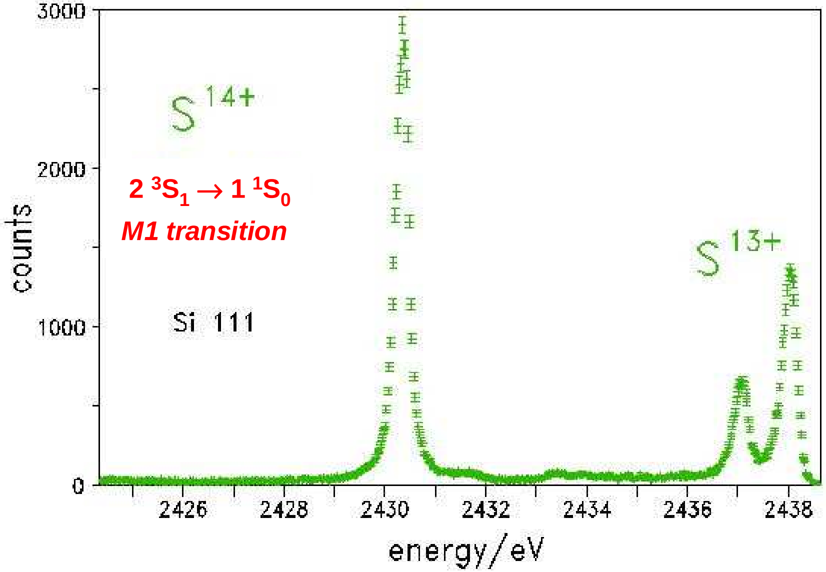


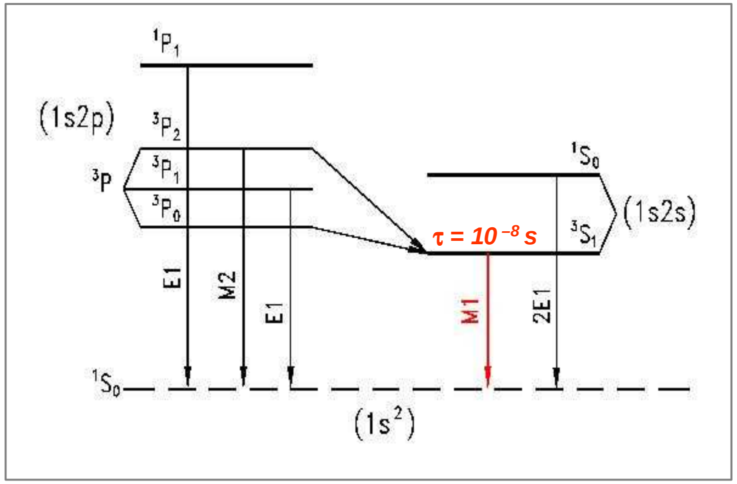


SPECTROMETER RESPONSE at πH Lyman ENERGIES

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***

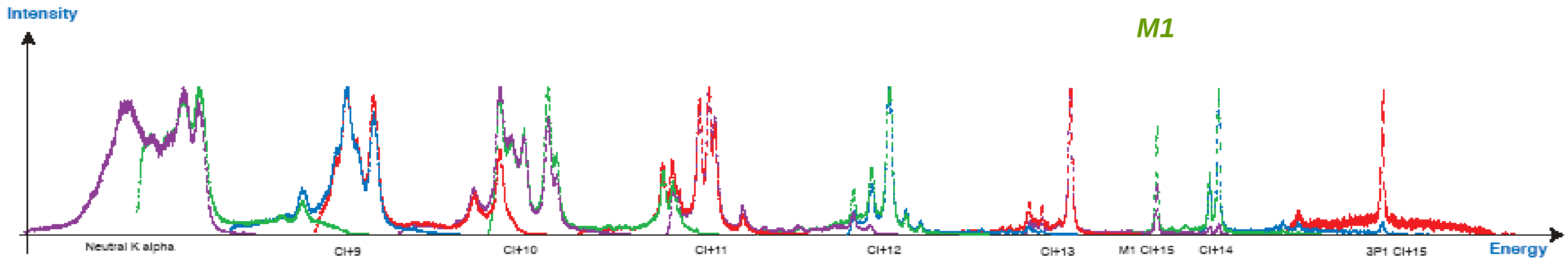
to be compared with Monte-Carlo ray tracing folded with plane crystal response

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



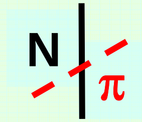
RESPONSE FUNCTION
2757 ev

PION-NUCLEON

SCATTERING LENGTHS

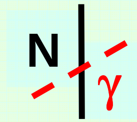
HYDROGEN & DEUTERIUM - ORIGIN OF Γ_{1s}

CEX scattering



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

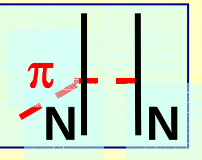
radiative capture



BR are well known from experiment

πD absorption $\pi^- d \rightarrow nn + nn\gamma$

„true“ absorption



which scattering length?

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

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

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

two independent scattering length - all others linked by isospin

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

PION PRODUCTION / ABSORPTION

$$NN \Leftrightarrow \pi NN$$

πNN threshold parameter α

charge symmetry *detailed balance*

$$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$$

$NN \quad {}^3S_1(I=0) \to {}^3P_1(I=1)$

πD atom

$$\Im\, a_{\pi D} \propto \Gamma_{\pi^- d \to nn} + \Gamma_{\pi^- d \to nn\gamma}$$

$$= \frac{1}{6\pi} m_p \cdot \alpha$$

J. Hüfner, Phys. Rep. 21 (1975) 1

π production

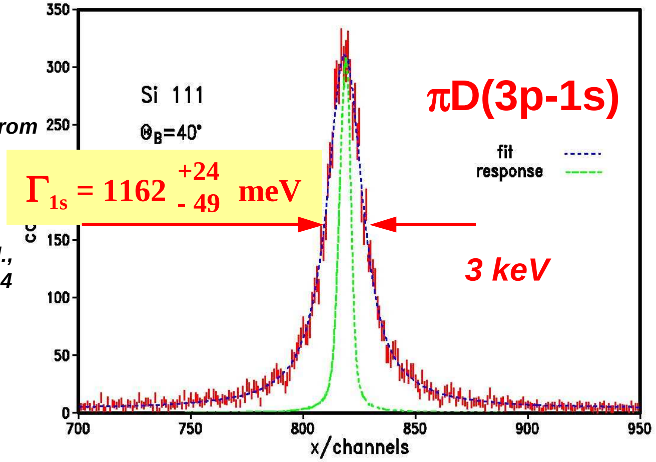
$$\sigma_{pp \to \pi^+ d} \to \alpha\, C_0^2\, \eta + \beta\, C_1^2\, \eta^3$$

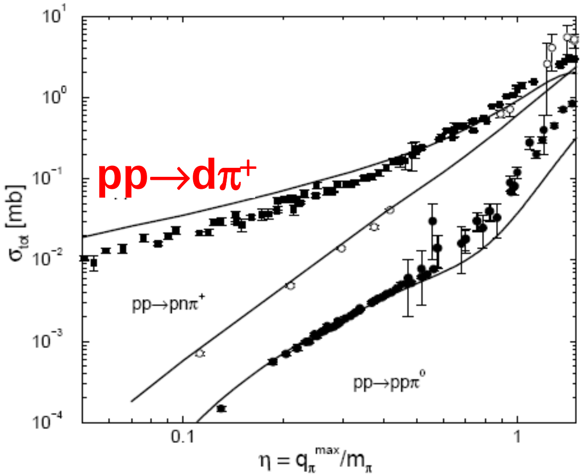
extrapolation to threshold

$$\eta = k_\pi / m_\pi$$

X-ray spectrum from

Th. Strauch, PhD thesis, Cologne 2009
Th. STrauch et al., Phys.Rev.Lett.104



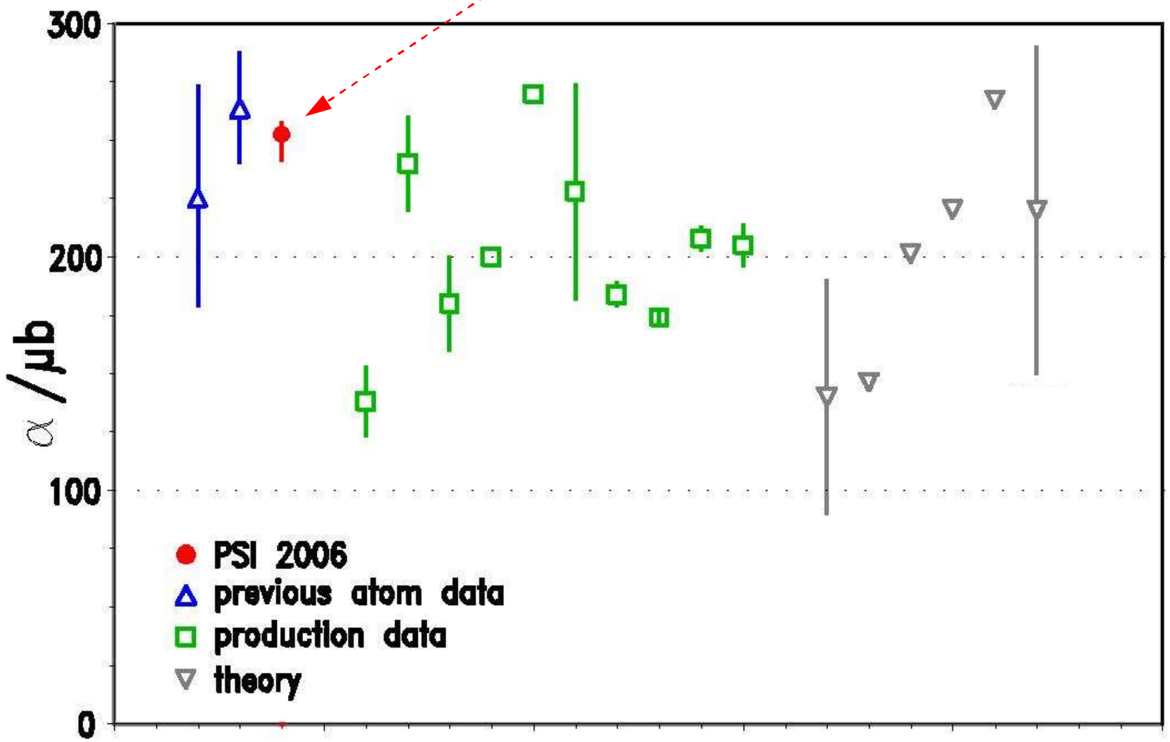


data compilation from

C. Hanhart, J.Haidenbauer, and J. Speth, Acta Pol. 29 (1998) 3047 (MESON'98)

πNN threshold parameter α - data & theory

recent exotic-atom result



Th. Strauch et al., Phys Rev. Lett. 104 (2010) 142503
Th. Strauch, PhD thesis Univ. Cologne, 2009

χPT NLO

χPT LO

χPT

at present

$\Delta\alpha / \alpha \approx 30\%$

$\rightarrow$ few %

V. Lensky et al.,
Eur. Phys. J. A 27 (2006) 37

NUCLEON-ANTINUCLEON

SPIN-SPIN and SPIN-ORBIT INTERACTION

THEORETICAL DESCRIPTION

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

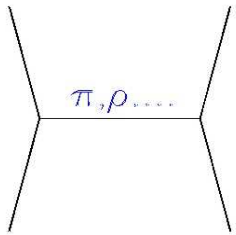
$U_{hadronic}$ = meson exchange + annihilation

scattering: $\bar{p}p \leftrightarrow \bar{p}p$ | $\bar{p}p \rightarrow$ mesons

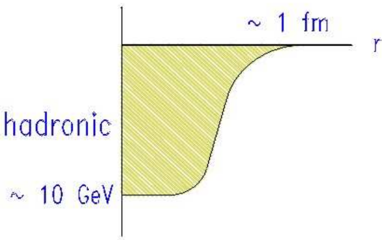
$\bar{p}p \leftrightarrow \bar{n}n$

NN --G-parity--> $\bar{N}N$ | $U \propto a\,\rho(r)$

Re $U_{hadronic}$



Im $U_{hadronic}$



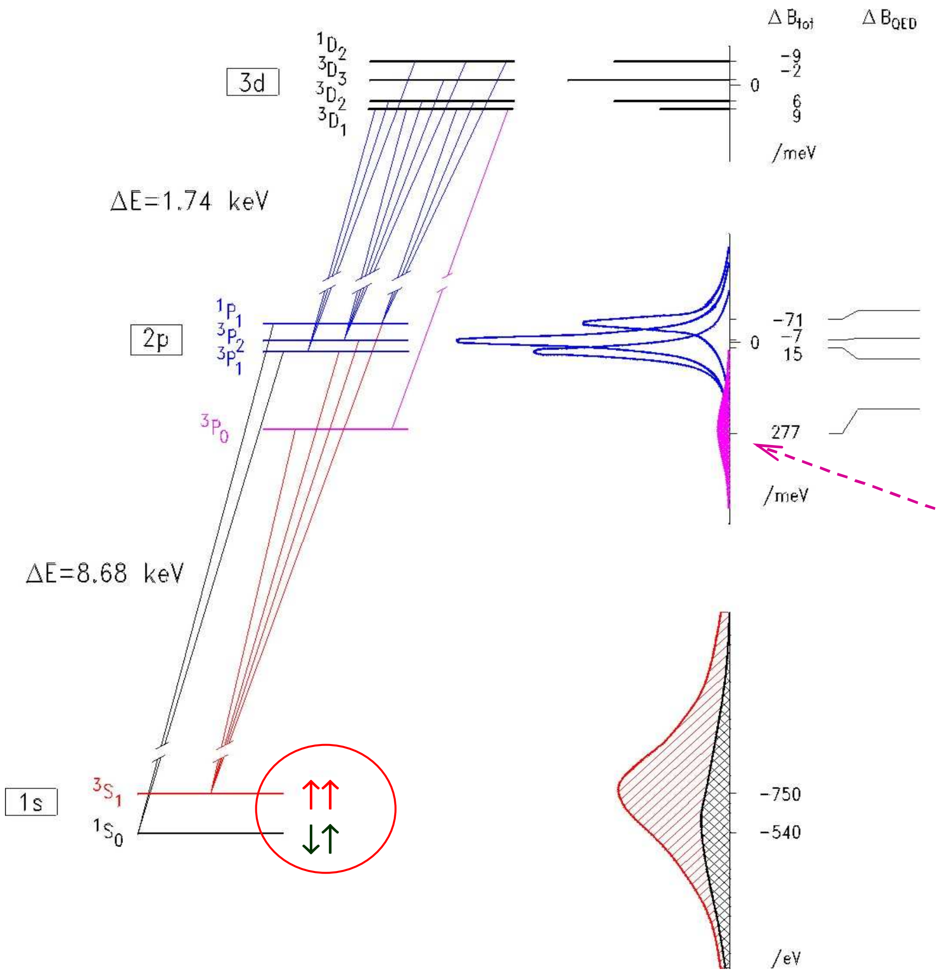
$\varepsilon, \Gamma \leftrightarrow$ medium + long-range part of $\bar{N}N$ interaction

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

spin-spin "deuteron" ***no microscopic theory***
spin-orbit effects

☞ ***check spin dependence !***

PROTONIUM - s & p state strong-interaction effects



d state

strong interaction negligible

p state

spin-orbit interaction

spin-orbit interaction

s state

spin-spin interaction

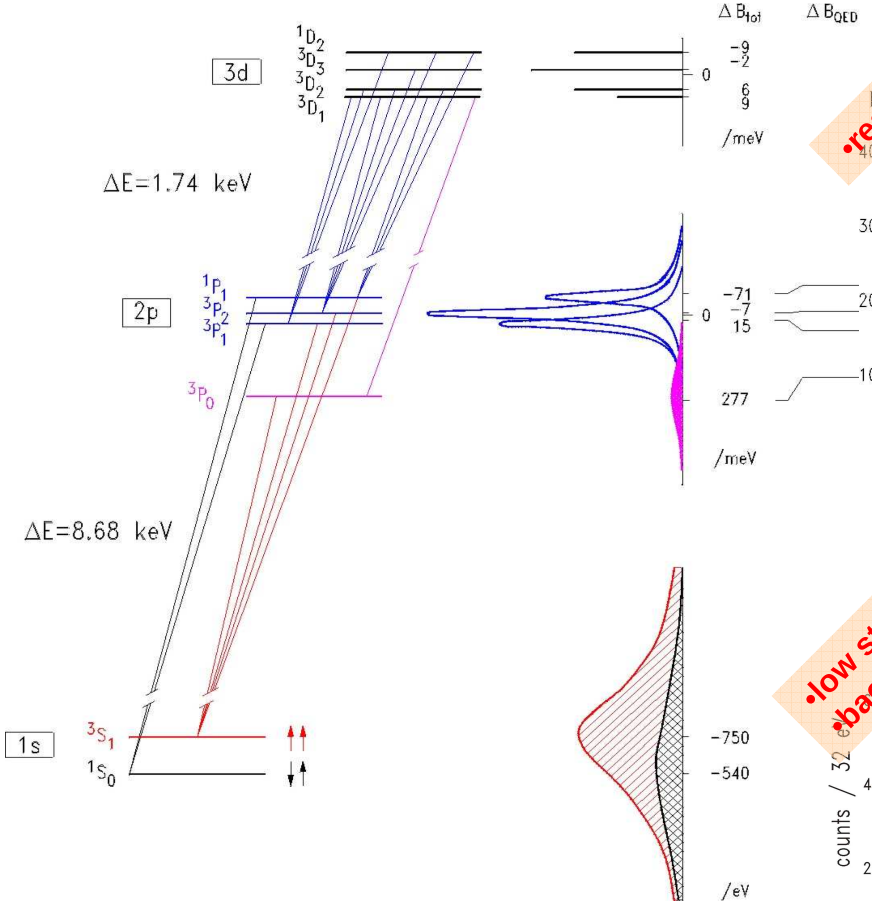
meson exchange:
strongly attractive
isoscalar tensor interaction

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

spin-spin interaction

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

PROTONIUM - EXPERIMENT

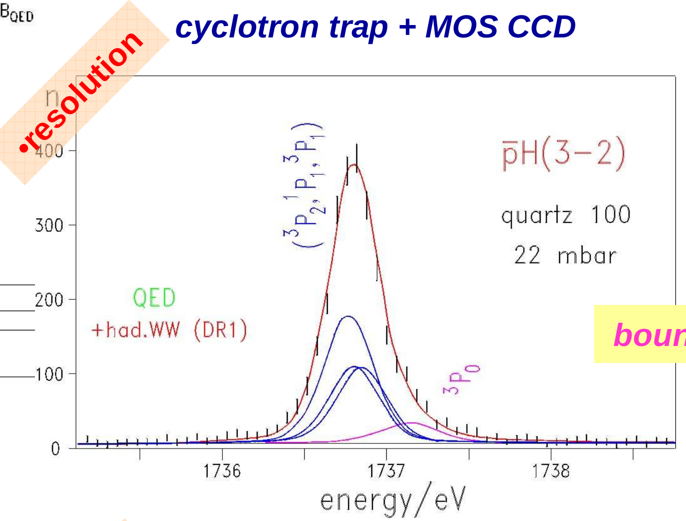


LEAR experiment PS207

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

•resolution

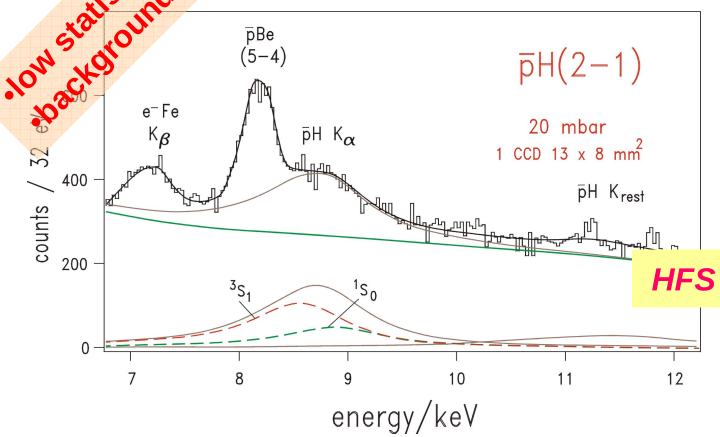
cyclotron trap + MOS CCD



bound states ?

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

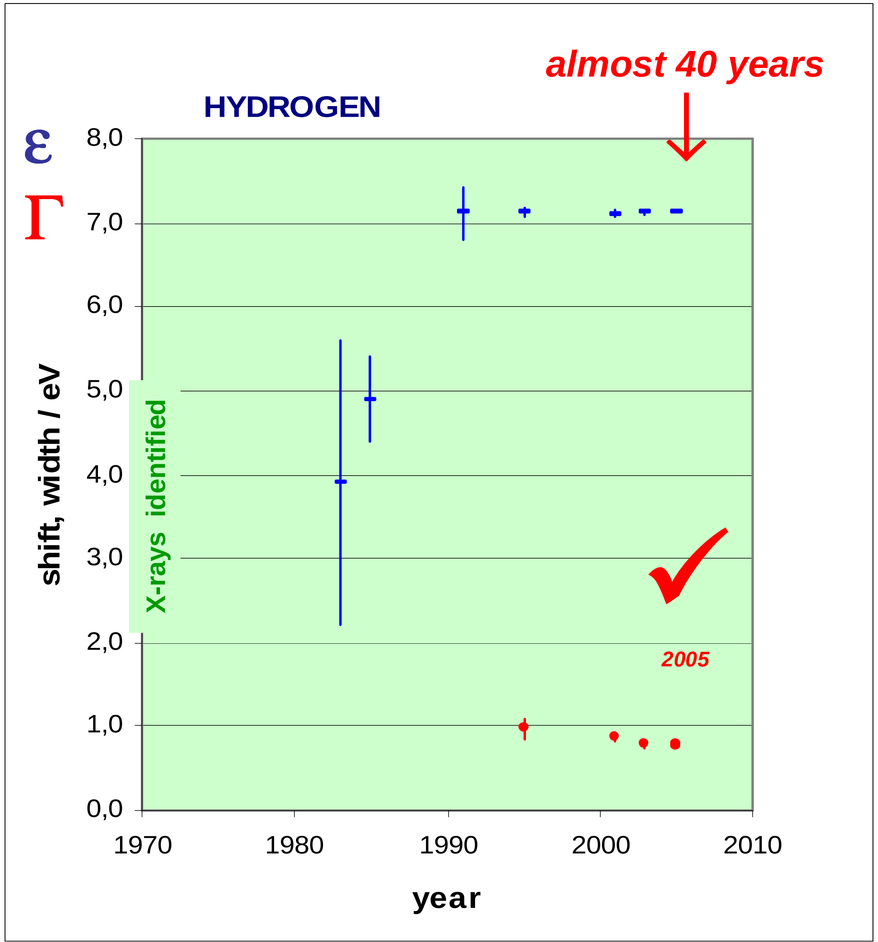
•low statistics
•background

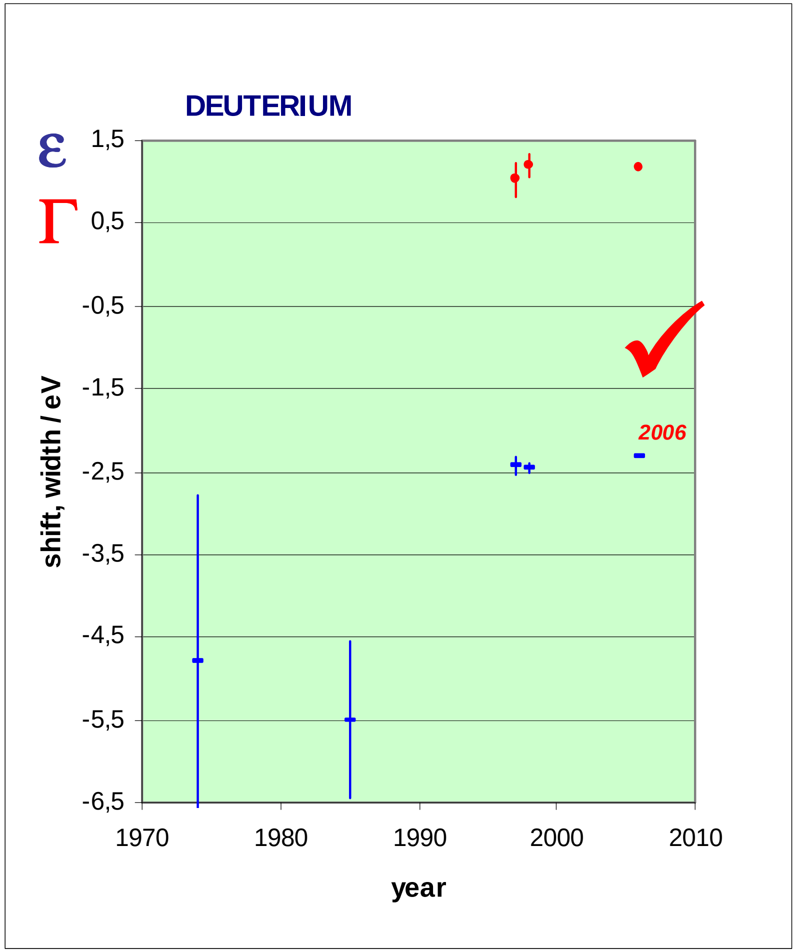


HFS splitting?

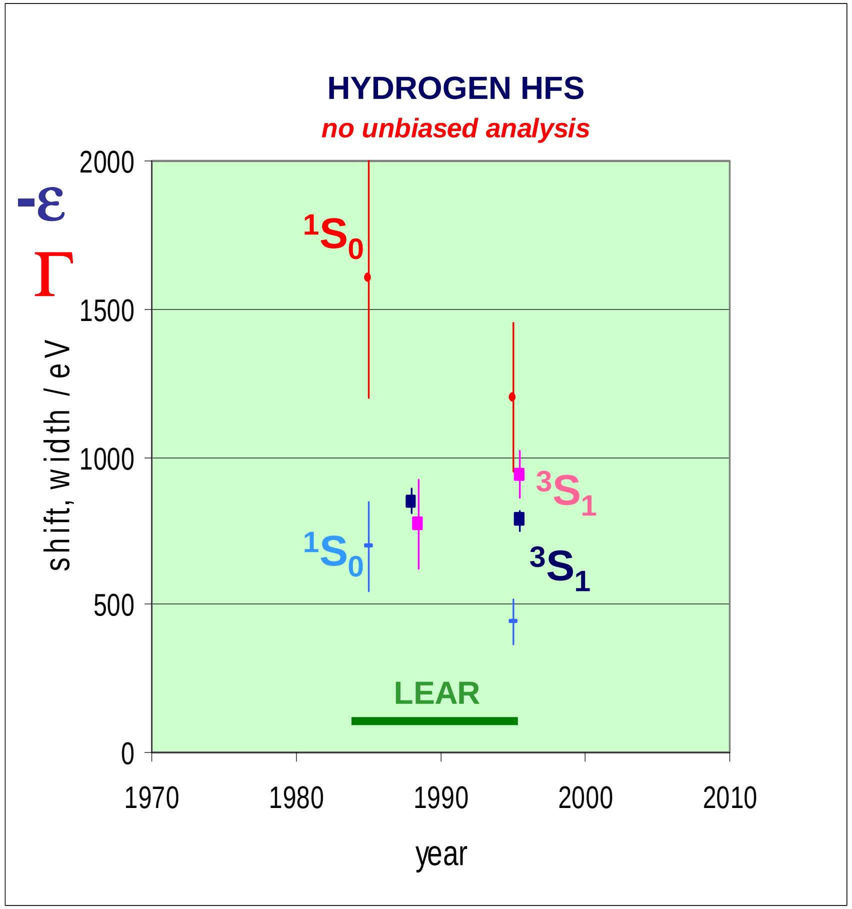
SUMMARY

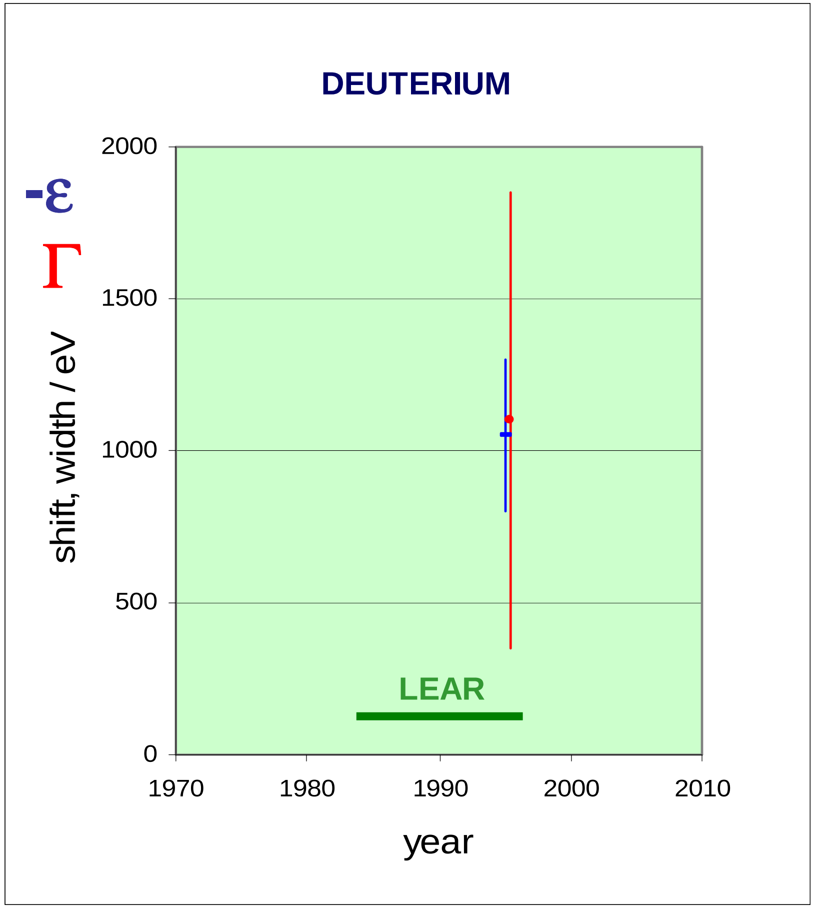
PIONIC HYDROGEN STORY





ANTIPROTONIC HYDROGEN STORY *s-wave*





still a lot to do !

THANK YOU