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Strong-interaction effects in light antiprotonic atoms

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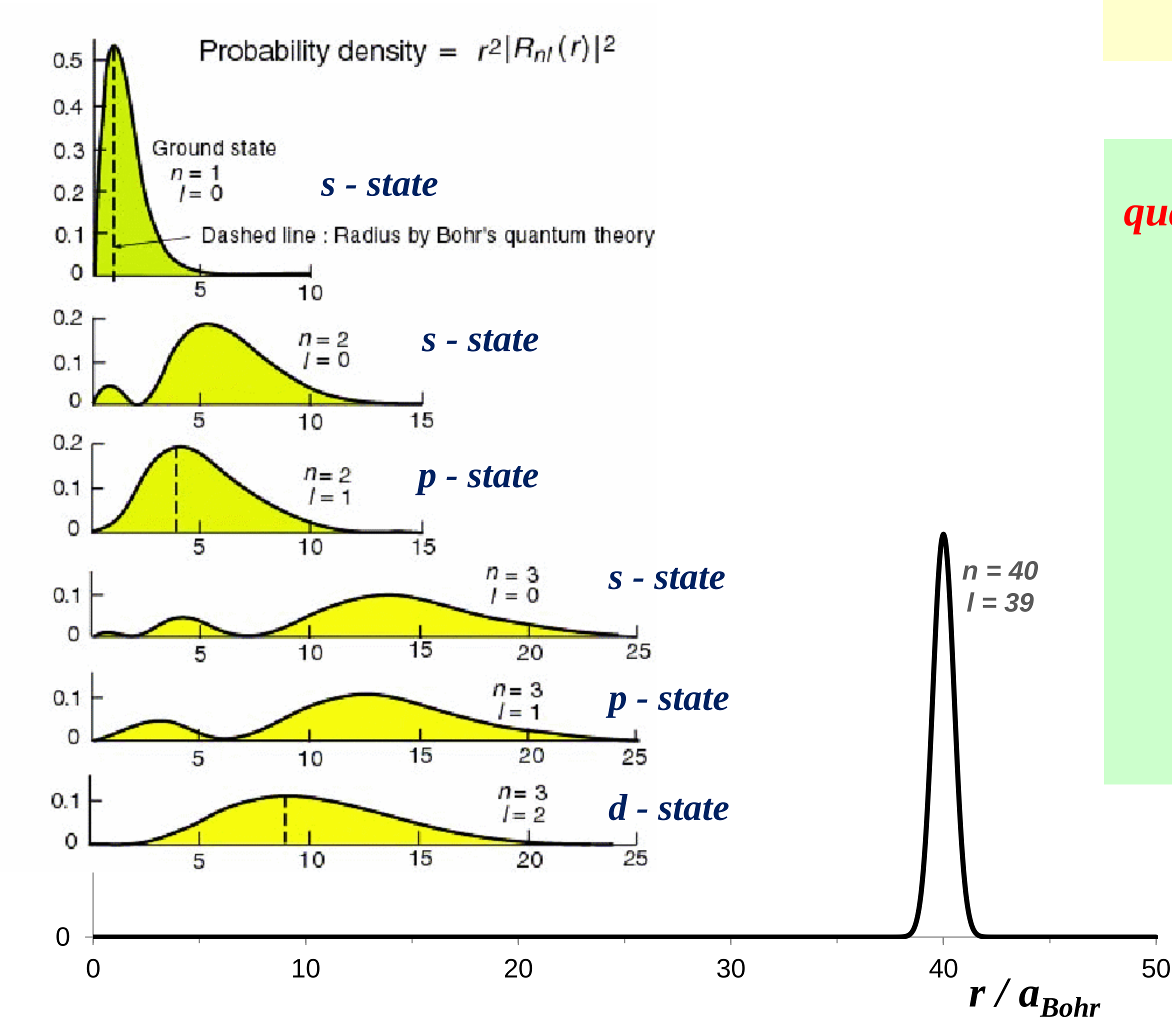
Antiproton-nucleus interactions and related phenomena, ECT Trento, 21.6.2019

- **EXOTIC ATOMS**
- **STRONG INTERACTION**
- **EXPERIMENT**
- **RESULTS**
- **RECENT DEVELOPMENTS**
- **OUTLOOK & SUMMARY**

EXOTIC ATOMS

ATOM



$$V_{Coulomb} = -\frac{Ze^2}{r}$$

quantisation of action: $E \cdot t = 2\pi\hbar$

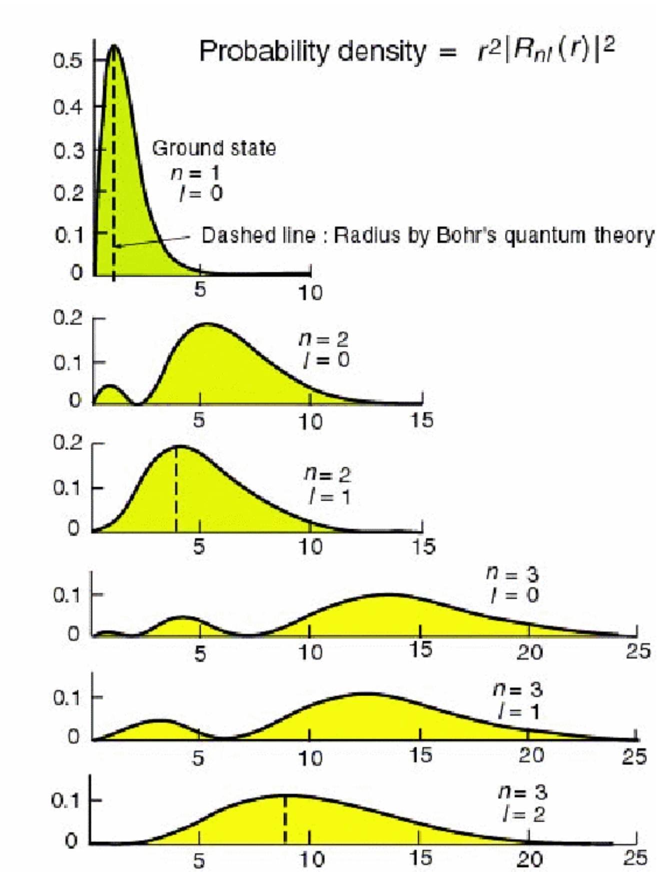
$$a_n = \frac{\hbar c}{m_{red}\, c^2 \alpha} \cdot \frac{n^2}{Z^2}$$

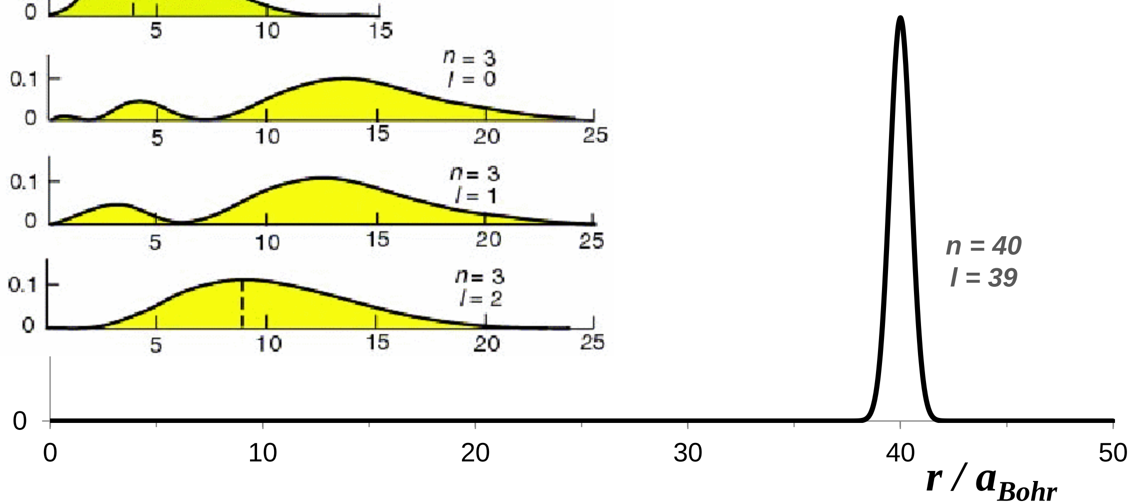
$$a_{Bohr} = \frac{\hbar c}{m_{red}\, c^2 \alpha}$$

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

EXOTIC ATOM

replace electrons by heavier negatively charged particles





		m / MeV/c²	B_1 / keV	"Bohr" radius a_0 / fm
atomic	e^-p	0.511	0.0136	$0.5 \cdot 10^5$
	μ^-p	105	2.6	279
	π^-p	140	3.2	216
	$\bar{p}\ p$	938	12.5	58
"nuclear" dimensions	$< r_p >$			0.8

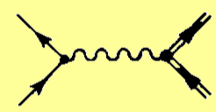
$$a_{16}(\pi^-) \approx a_1(e^-)$$

$$a_{40}(\bar{p}) \approx a_1(e^-)$$

ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$

$\propto m_{red}$



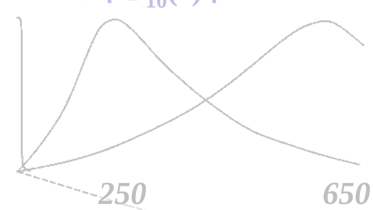
$+ \Delta E_{QED}$

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

$+ \Delta E_{screening}$

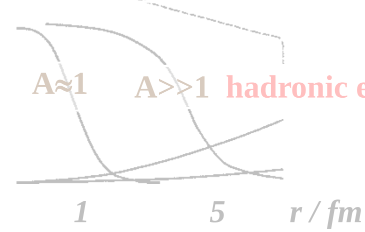
capture $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + \text{few } e^-$

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



$+ \Delta E_{finite\ size}$

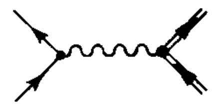
nuclear density $\rho(r)$



$+ \Delta E_{strong\ interaction}$

ATOMIC BINDING ENERGY

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



$+ \Delta E_{QED}$

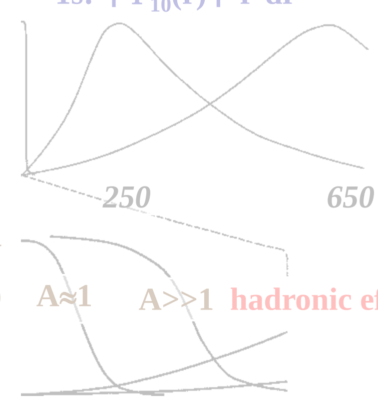
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

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

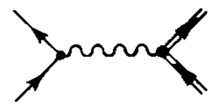
$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



ATOMIC BINDING ENERGY

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



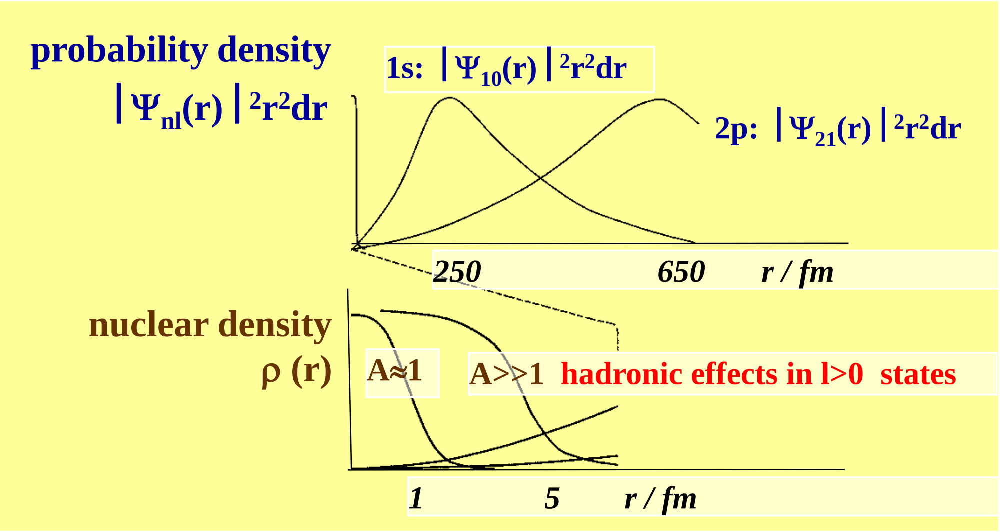
$+ \Delta E_{QED}$

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

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

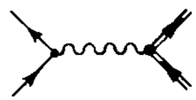
$+ \Delta E_{finite\ size}$

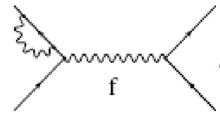
$+ \Delta E_{strong\ interaction}$



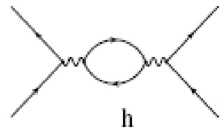
including STRONG INTERACTION

$$V_{Coulomb} = -\frac{Ze^2}{r} + \Delta EQED + U_{strong\ interaction}$$





self energy



vakuum polarisation

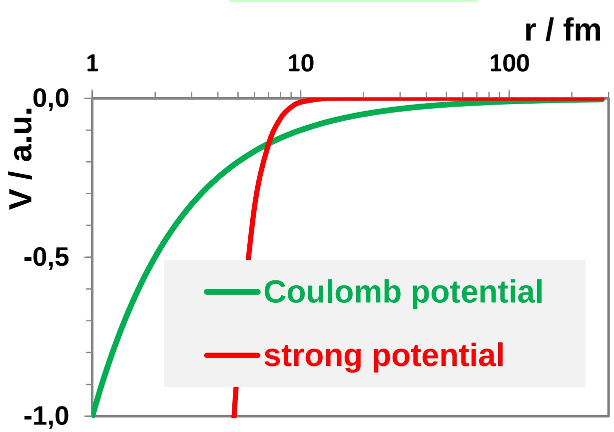
+ higher orders

Yukawa potential

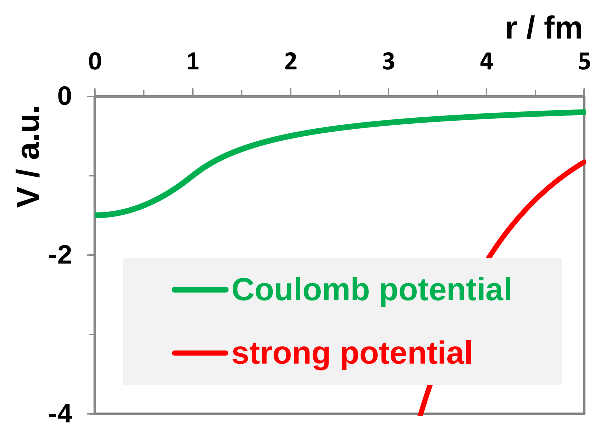
$$U_{strong} = g^2 \cdot \frac{e^{-\mu r}}{r}$$

$$\mu = \frac{\hbar c}{m_\pi c^2}$$

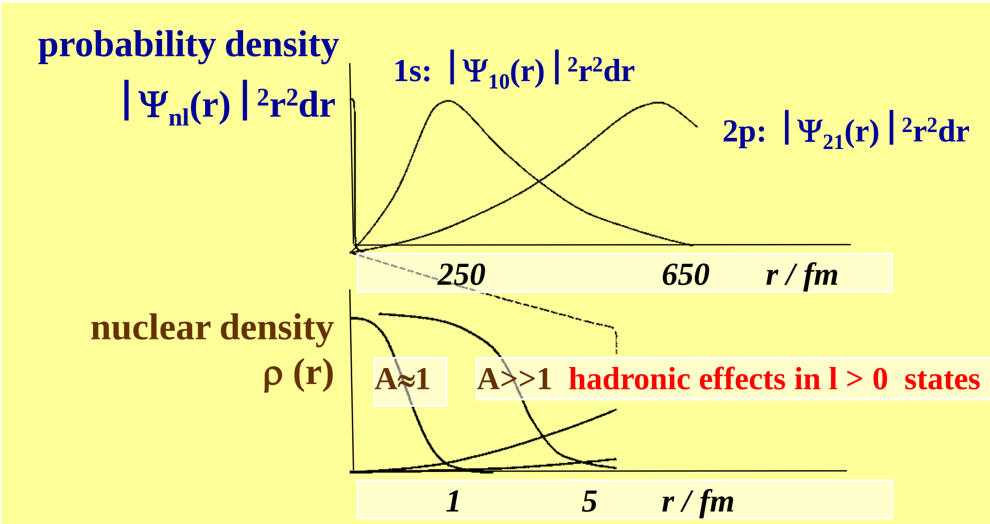
long range



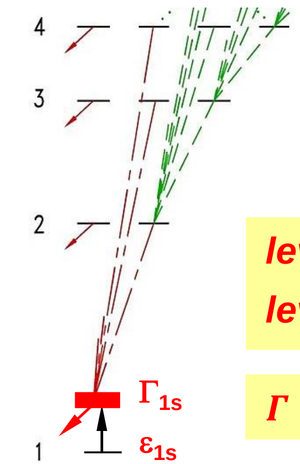
short range



HADRONIC ATOM



strong - interaction effect



level shift ε

level broadening Γ

$\Gamma \cdot t = 2\pi\hbar$

$$\Delta E_{strong} = \epsilon - i\frac{\Gamma}{2} = \int \Psi^{\dagger}_{nl} U_{strong} \Psi_{nl}\, \mathrm{d}V \propto a_l \in \mathbb{C}$$

ΔE_{strong} ***reduces to*** ***complex numbers***

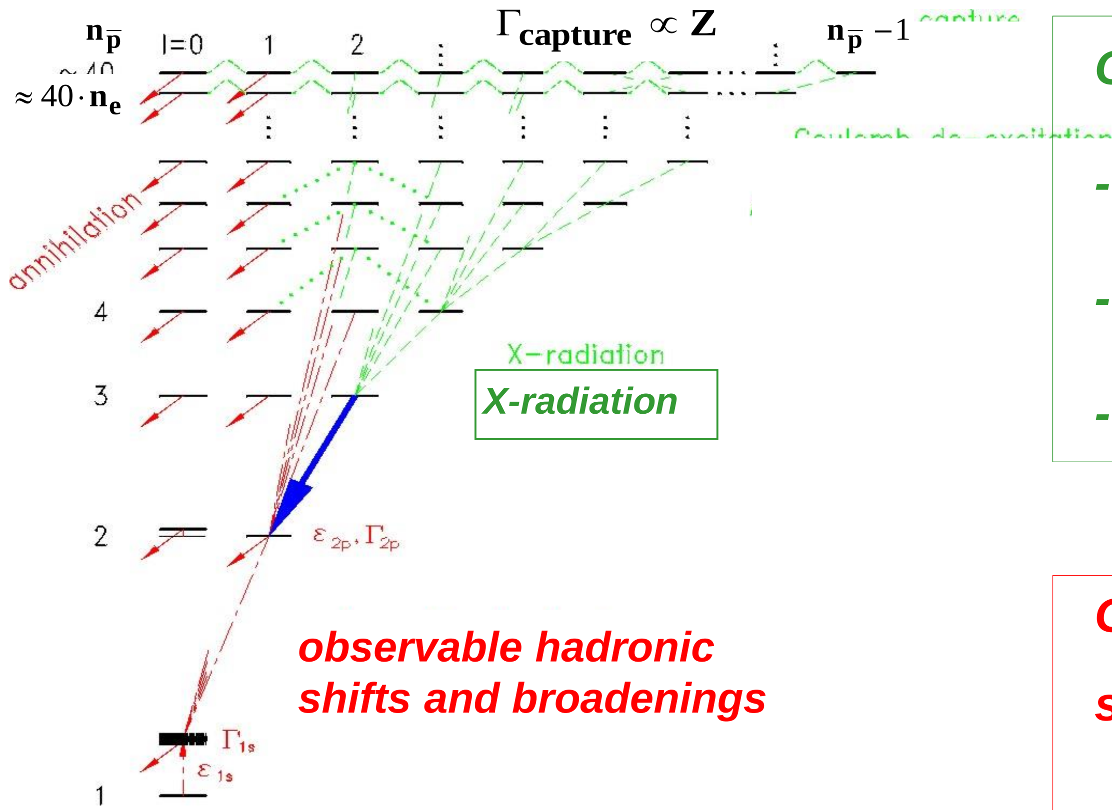
- scattering length a_S *for s-waves*

- scattering volume a_p *for p-waves*

scattering experiment at threshold = relative energy ≈ 0

ATOMIC CASCADE

capture



X-radiation

observable hadronic shifts and broadenings

OBSERVABLES

- ***X-ray energies***
- ***line intensities***
- ***line width***

GOAL

scattering length

$$a \propto \varepsilon - i\,\Gamma / 2$$

$\Gamma \cdot \Delta t \cong \hbar$

$\varepsilon > 0$ (<0) $\equiv$ ***attractive (repulsive) interaction***

Prediction 1947 ***Fermi & Teller***

First X-rays from pionic and antiprotonic atoms

Rochester 1952

X-Rays from Mesic Atoms*

M. CAMAC, A. D. MCGUIRE, J. B. PLATT, AND H. J. SCHULTE
University of Rochester, Rochester, New York
(Received August 18, 1952)

NaI(Tl) *inorganic scintillator*

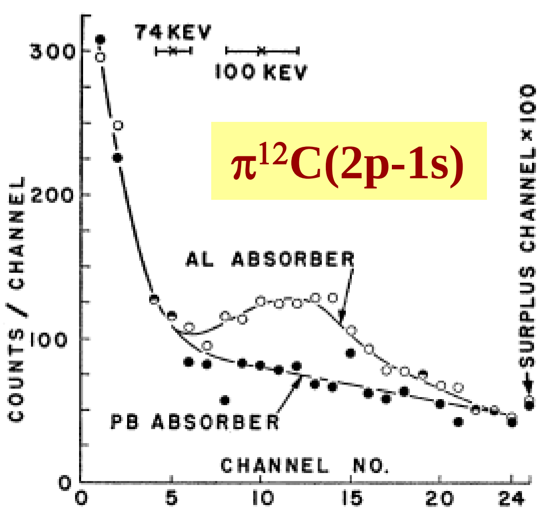


FIG. 1. Pulse-height spectrum from carbon.

CERN 1970

OBSERVATION OF ANTIPROTONIC ATOMS

A. BAMBERGER, U. LYNEN, H. PIEKARZ *, J. PIEKARZ **, B. POVH and H. G. RITTER
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
and CERN, Geneva, Switzerland
and
G. BACKENSTOSS, T. BUNACIU, J. EGGER ***, W. D. HAMILTON ‡ and H. KOCH
Institut für Experimentelle Kernphysik der Universität und des Kernforschungszentrums, Karlsruhe, Germany
and CERN, Geneva, Switzerland

Received 28 August 1970

Ge(Li) *semiconductor detector*

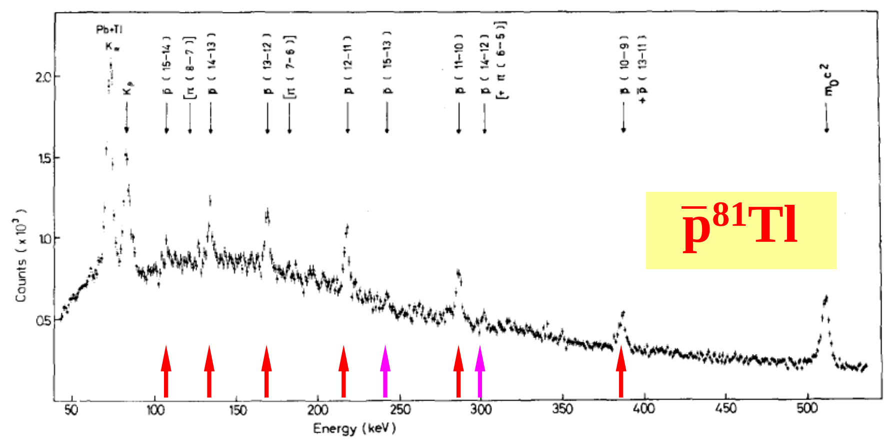
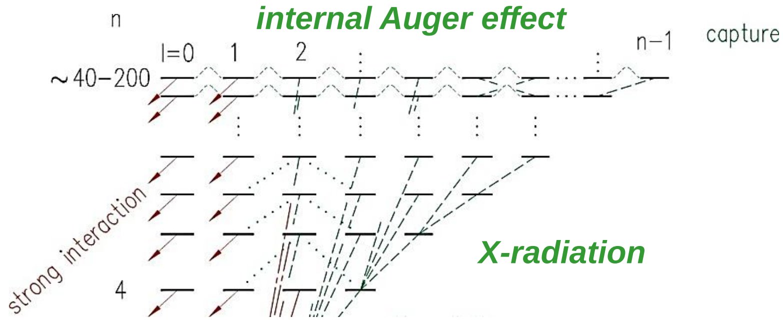


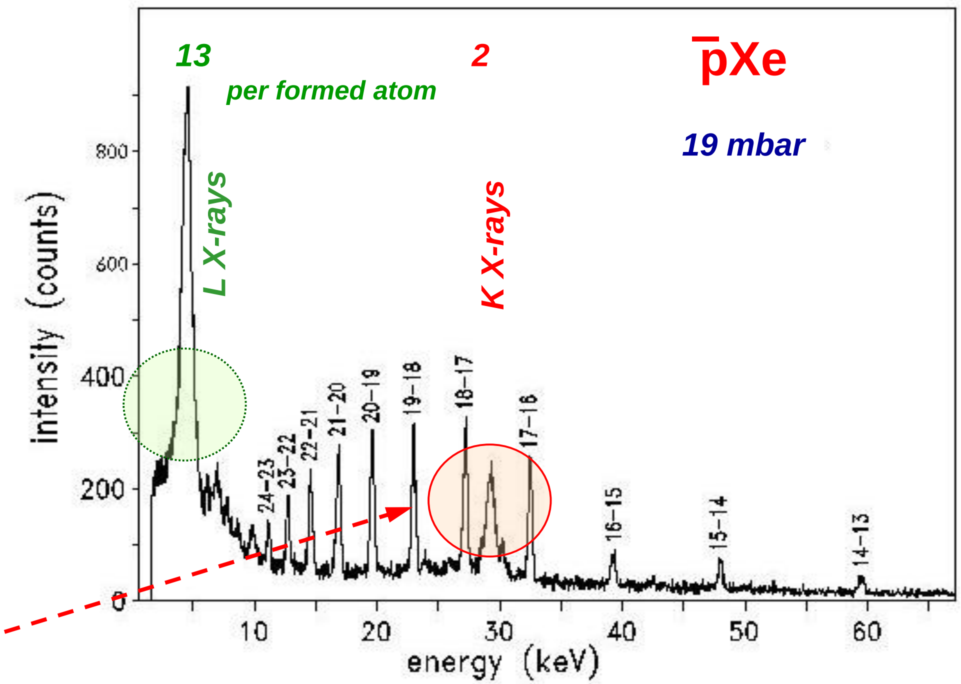
Fig. 2. Antiprotonic X-ray spectrum of $_{81}$Tl obtained from 14 × 10^6 stopped antiprotons measured with a 10 cm^3 Ge(Li)-detector.

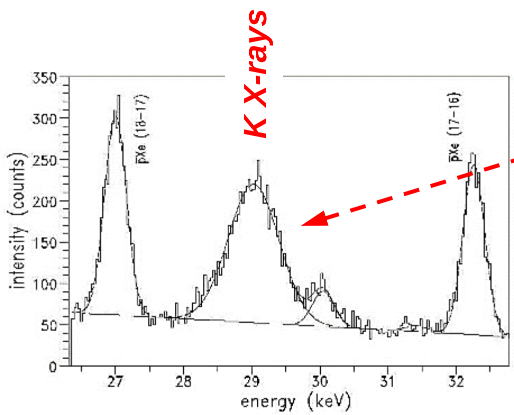
ELECTRONIC & ANTIPROTONIC X-RAYS - XENON

What happens when an antiproton meets 54 electrons ?

many remaining electrons







many unresolved lines ?

data: PS175 Ar, Kr, Xe

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

- **high resolution spectroscopy with crystal spectrometer**
- **coincidence experiments X-rays / Auger electrons**

HISTORY

strong-interaction effects in $Z \leq 8$

pre - LEAR experiments *1974 - 1980*

		targets
	Si(Li), Ge	^{4}*He* *Li* *N* *O*

LEAR experiments *1983 - 1996*

Years	Experiment	Detectors	Targets
1983 - 1988	**PS176**	*Si(Li), Ge*	^{4}*He* *Li* *N* *O* ...
	PS171	*XDC*	H_2
	PS174	*Si(Li), GSPC*	H_2 D_2 ^{4}*He*
	PS175	*cyclotron trap* *Si(Li), Ge, XDC*	H_2 D_2 ^{3}*He* ^{4}*He*
1984 - 1996	**PS207**	*cyclotron trap* *crystal spectrometer* *CCDs*	H_2 D_2

STRONG INTERACTION

THEORETICAL DESCRIPTION

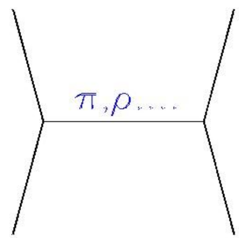
$$V_{Coulomb} + U_{hadronic}$$

$U_{hadronic}$ = meson exchange + annihilation

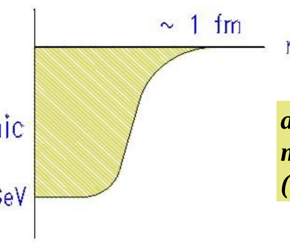
scattering: $\bar{p}p \leftrightarrow \bar{p}p$, $\bar{p}p \leftrightarrow \bar{n}n$ — $\bar{p}p \rightarrow$ mesons

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

Re $U_{hadronic}$



Im $U_{hadronic}$



at present no satisfactory microscopic description (i.e. at the quark level)

+ phenomenological short range

ε,Γ <--> medium + long-range part of $\bar{N}N$ interaction

spin-spin "deuteron"
spin-orbit effects

no microscopic theory

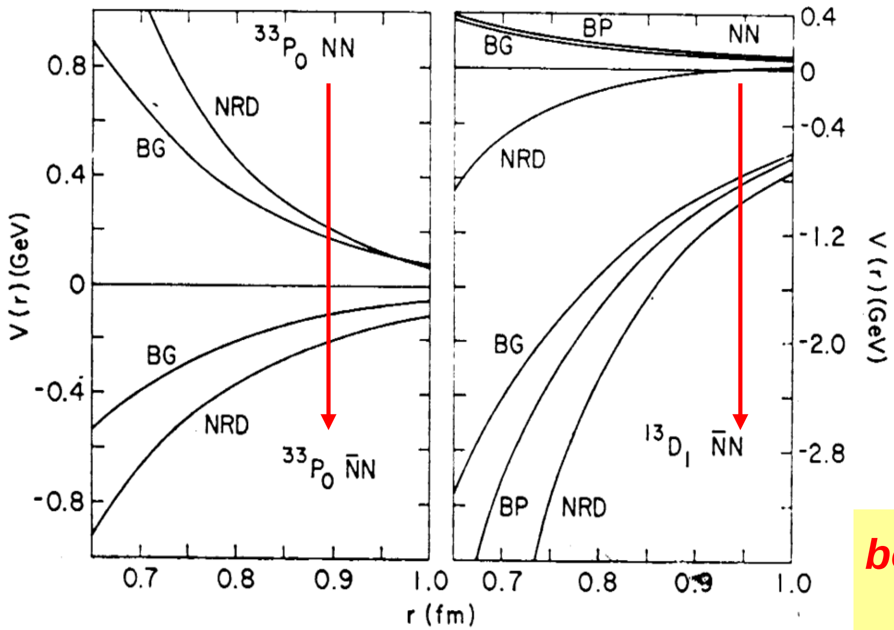
☞ ***check spin dependence !***

Buck, Dover, Richard, Ann. Phys. (NY) 121 (1979) 47
Klempt, Bradamante, Martin, Richard, Phys. Rep. 368 (2002) 119 - review

$\bar{N}N$ POTENTIAL – real part

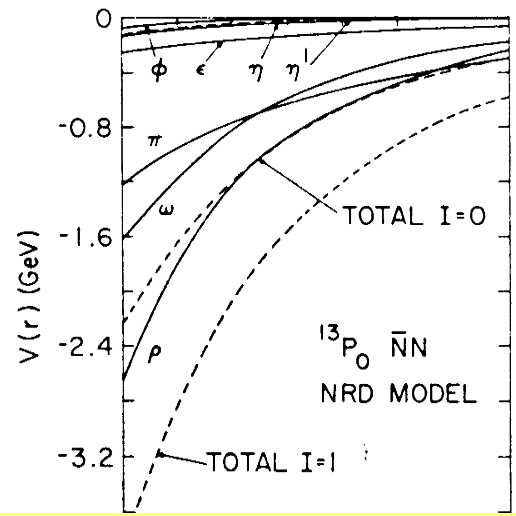
G-parity for fermion-antifermion systems $\eta_G = (-1)^{L+S+I+1}$

quantum numbers



spectroscopic notation: $^{2I+1,\,2S+1}L_j$

meson contribution



bound states?

would lead to anomalous behavior of shift and width

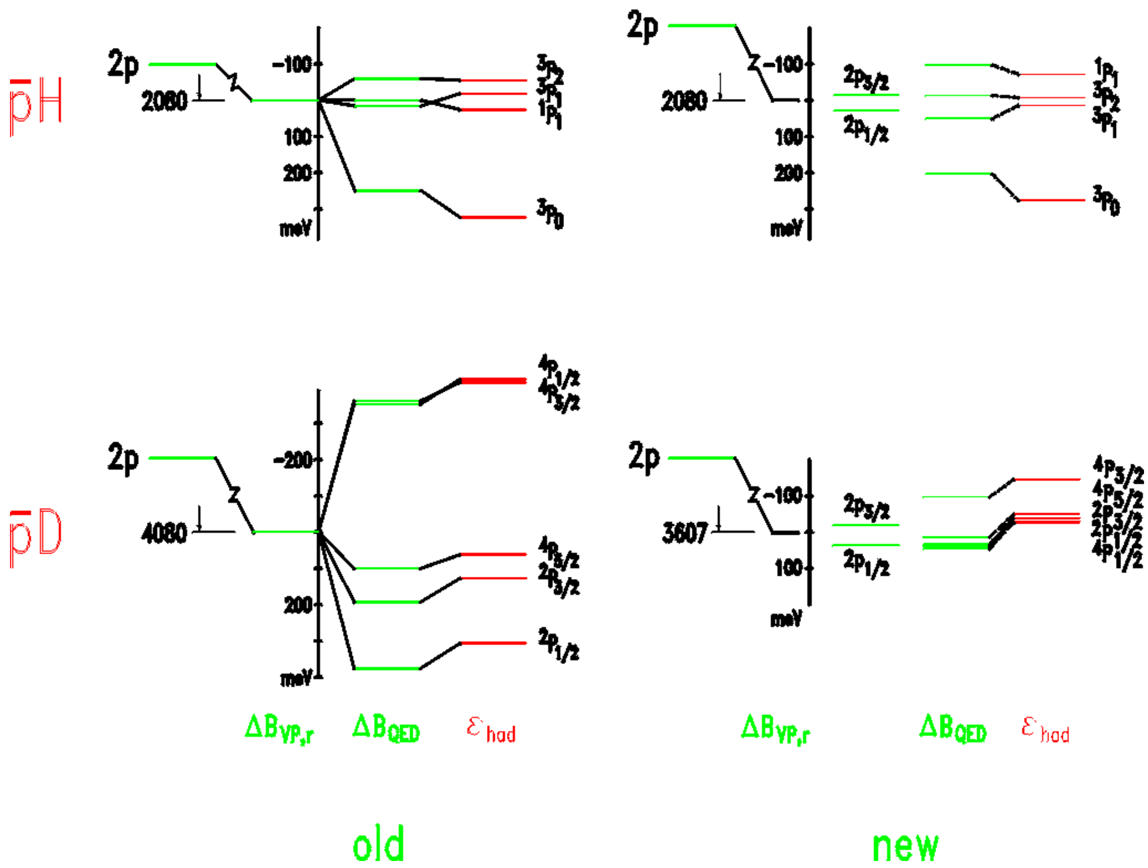
but: annihilation - many bound states disappear

Lacombe, Loiseau, Moussallam, Vinh Mau, Phys. Rev C 29 (1984) 1800,

...

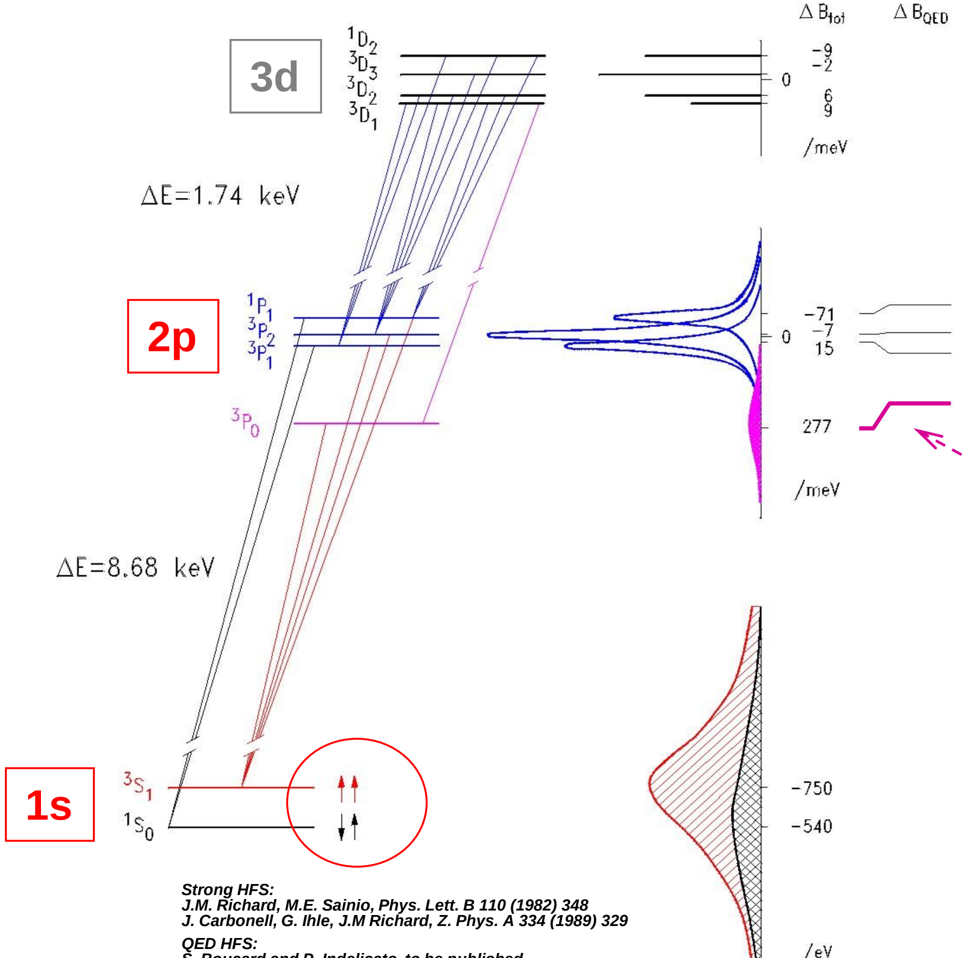
Antiprotonic Hydrogen and Deuterium

2p hyperfine splitting



bound-state QED + strong interaction

PROTONIUM - hyperfine transitions



Strong HFS:
J.M. Richard, M.E. Sainio, Phys. Lett. B 110 (1982) 348
J. Carbonell, G. Ihle, J.M Richard, Z. Phys. A 334 (1989) 329

QED HFS:
S. Boucard and P. Indelicato, to be published
Veitia, Pachucki, Phys. Rev A 69 (2004) 042501

strong-interaction effects in s- and p-states

d state

strong interaction negligible

p state

spin-orbit interaction

meson exchange:
strongly attractive
isoscalar tensor interaction

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

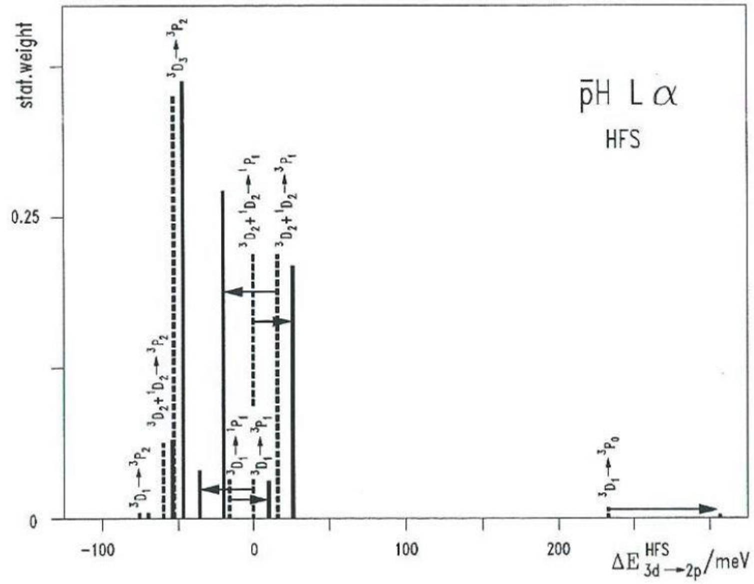
s state

spin-spin interaction

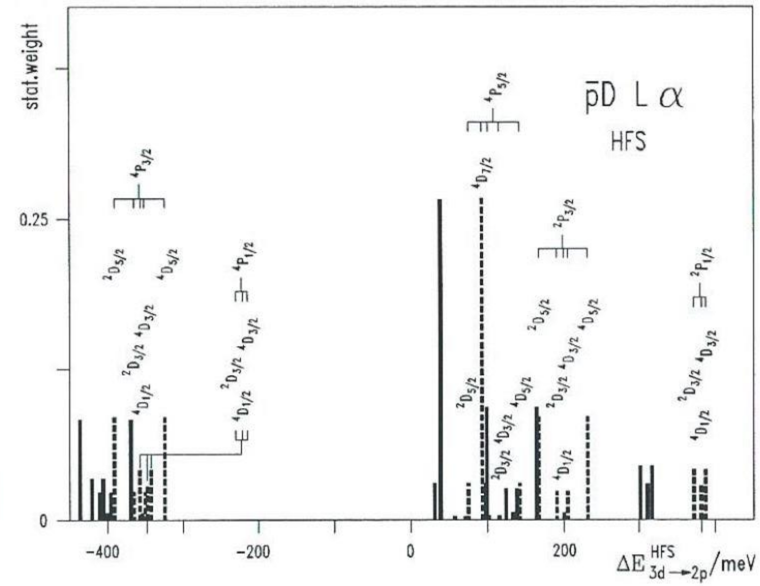
ε > 0 (<0) ≡ attractive (repulsive) interaction

3d – 2p HYPERFINE TRANSITIONS

$\bar{p}p$



$\bar{p}d$



HFS QED old

A ≤ 4 nuclei

hadronic effects in s, p, and d waves

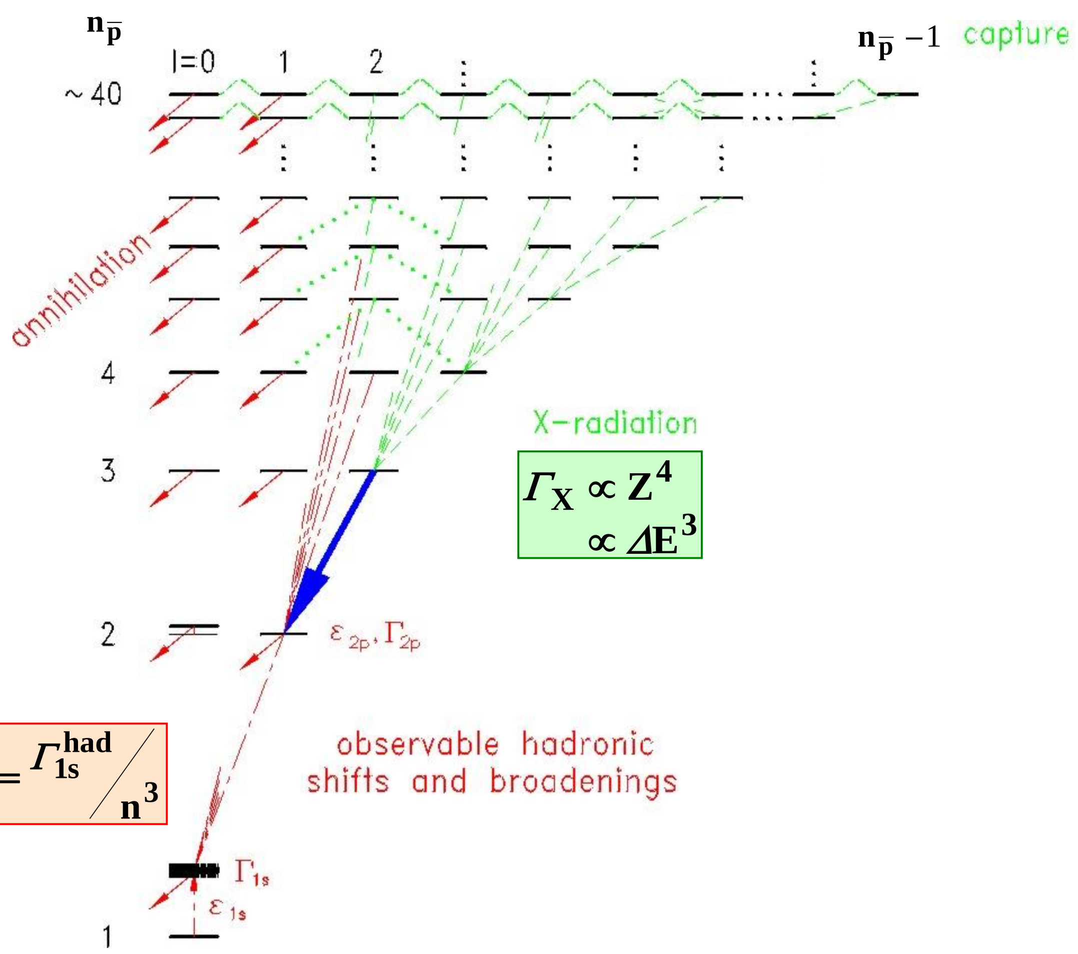
$\bar{p}p$	*s-wave*	*spin-spin interaction* $^1S_0$ / $^3S_1$
$\bar{p}d$	$\bar{p}n$	*isospin*
$\bar{p}p$, $\bar{p}d$	*p-wave*	*spin-orbit interaction* *nuclear bound states*
$\bar{p}A(N,Z)$		*annihilation strength* *baryon-antibaryon asymmetry*
X-ray energies		*bound-state QED*

EXPERIMENT I

general considerations for stopped antiprotons $Z \leq 2$

ATOMIC CASCADE — *isolated hydrogen atom*

$$n_{\bar{p}} \approx n_e \cdot \sqrt{m_{\bar{p}} / m_e}$$



$$\Gamma_X \propto Z^4$$
$$\propto \Delta E^3$$

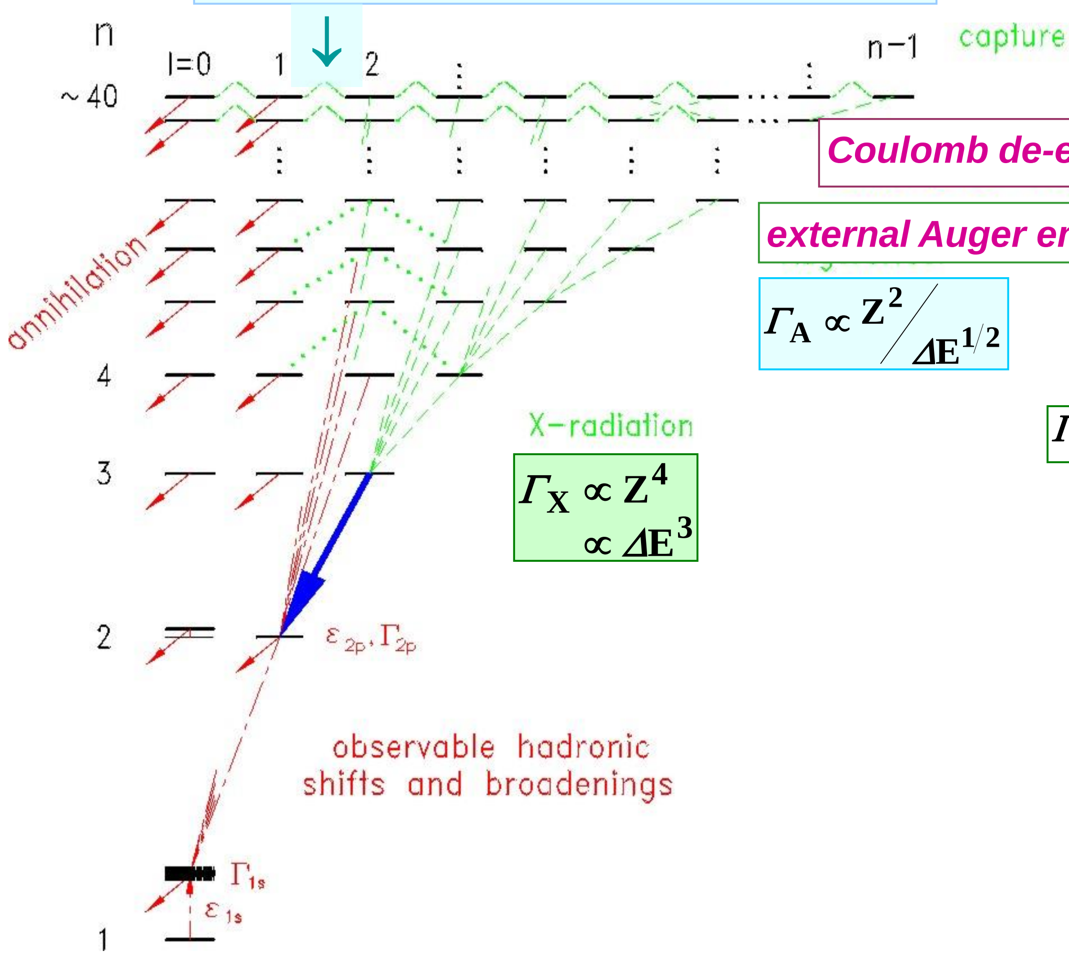
$$\Gamma_{ns}^{had} = \Gamma_{1s}^{had} / n^3$$

ATOMIC CASCADE

exotic hydrogen is <u>not</u> an isolated system

collisions with H_2

Stark mixing $\langle n,l|E1|n,l\pm1\rangle \propto n\sqrt{n^2-l^2}$



Coulomb de-excitation

external Auger emission

$\Gamma_A \propto Z^2 / \Delta E^{1/2}$

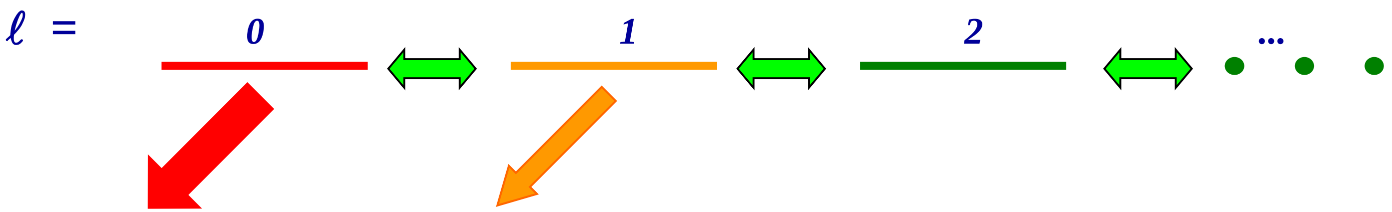
$\Gamma_X \propto Z^4$
$\propto \Delta E^3$

$\Gamma_X \propto \Gamma_A$ at $n_{\bar{p}} \approx 9$

LINE YIELDS *strong density dependence*

collisions → *electric field* → *Stark - mixing* *z = 1 (Z=2)*

$\Gamma_{n,l \to n, l \pm 1} \neq 0$

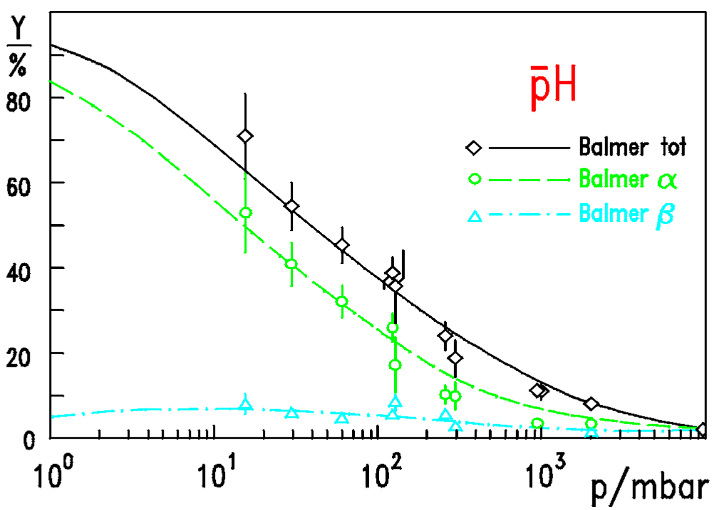


nuclear reactions

⇒ *large beam-induced background*

2 GeV/c² per annihilation $\bar{p}p \to n\,\pi^{+} + n\,\pi^{-} + m\,\pi^{0}$

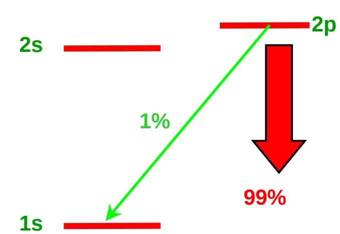
↘ 2 γ



PS171
PS174
PS175

Lyman α X-ray yield Y_X < 1%

$\Gamma_{annihilation} \approx 100 \times \Gamma_{X\text{-ray}}$ ***for p states***



ANTIPROTONIC HYDROGEN

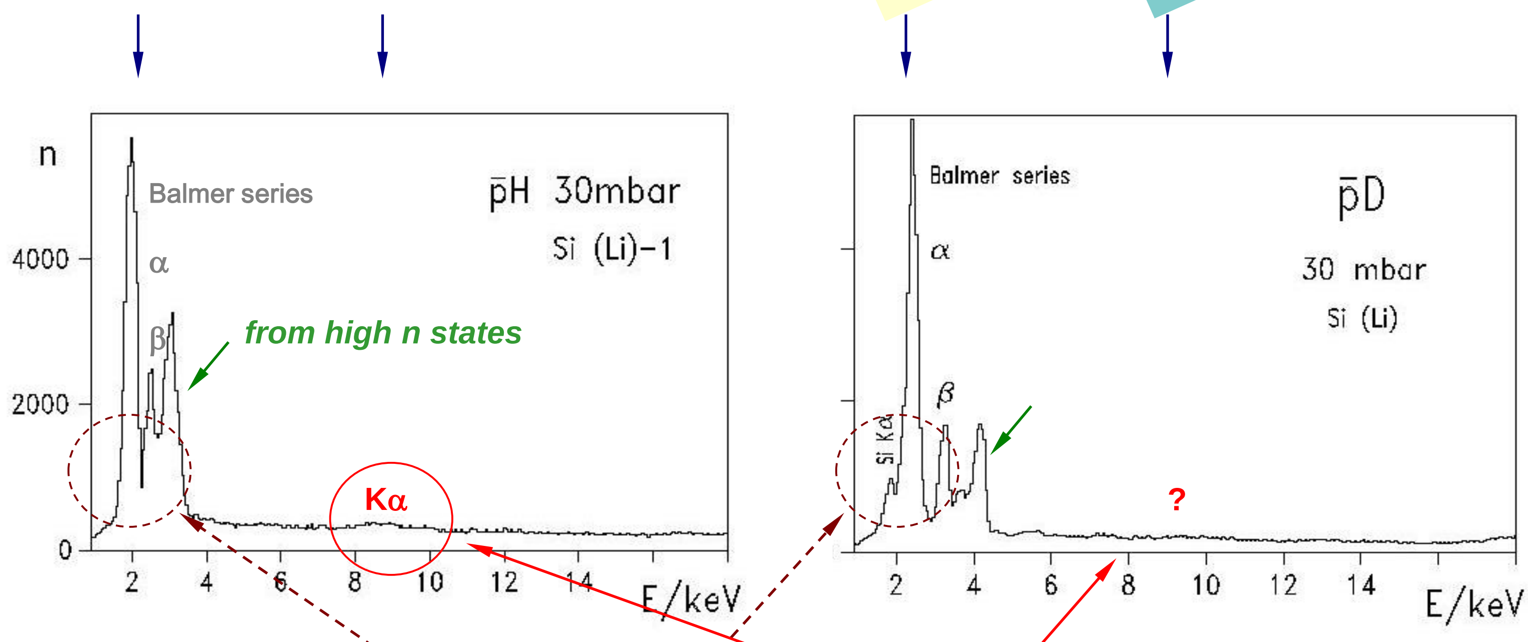
Lyman and Balmer series

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

two different energy ranges

crystal spectrometer

direct measurement



$\Gamma \approx$ **30-500 meV**
$Y_X \approx$ **50%**

$\Gamma \approx$ **1 keV**
$Y_X \approx$ **1%**

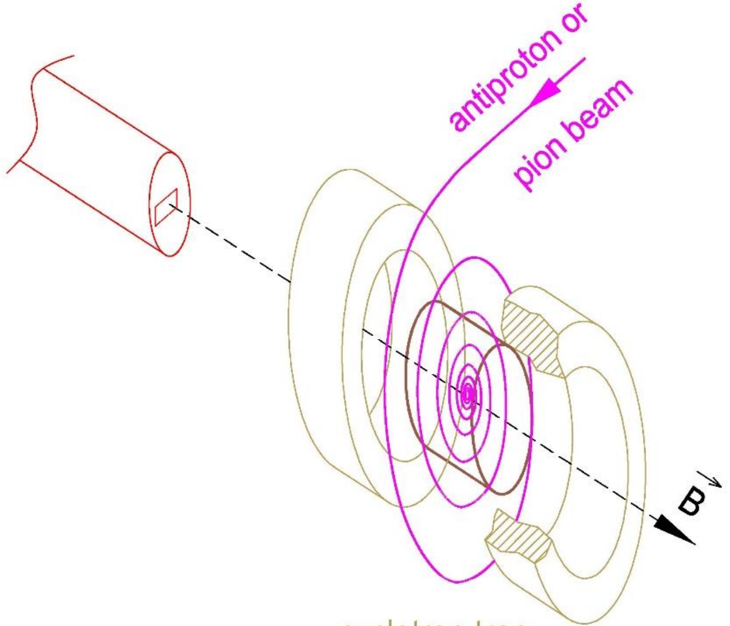
EXPERIMENT II

PS 175 + PS 207 *- X-ray source + X-ray detector*

PS 207 *- X-ray source + crystal spectrometer + X-ray detector*

CYCLOTRON TRAP concentrates particles

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**

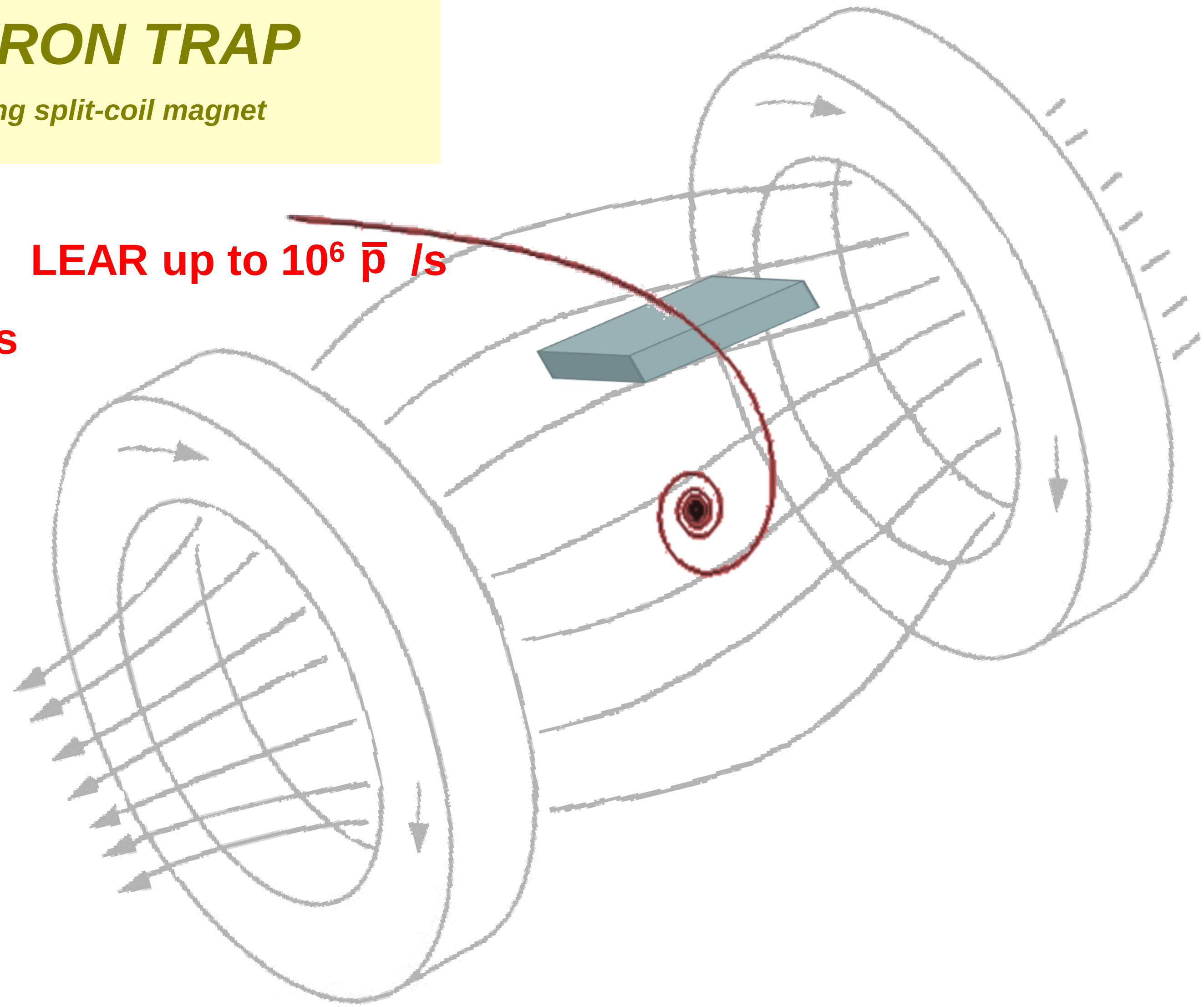
⇒ **bright X - ray source**

CYCLOTRON TRAP

superconducting split-coil magnet

high stop density LEAR up to 10^6 $\bar{p}$ /s

in gaseous targets



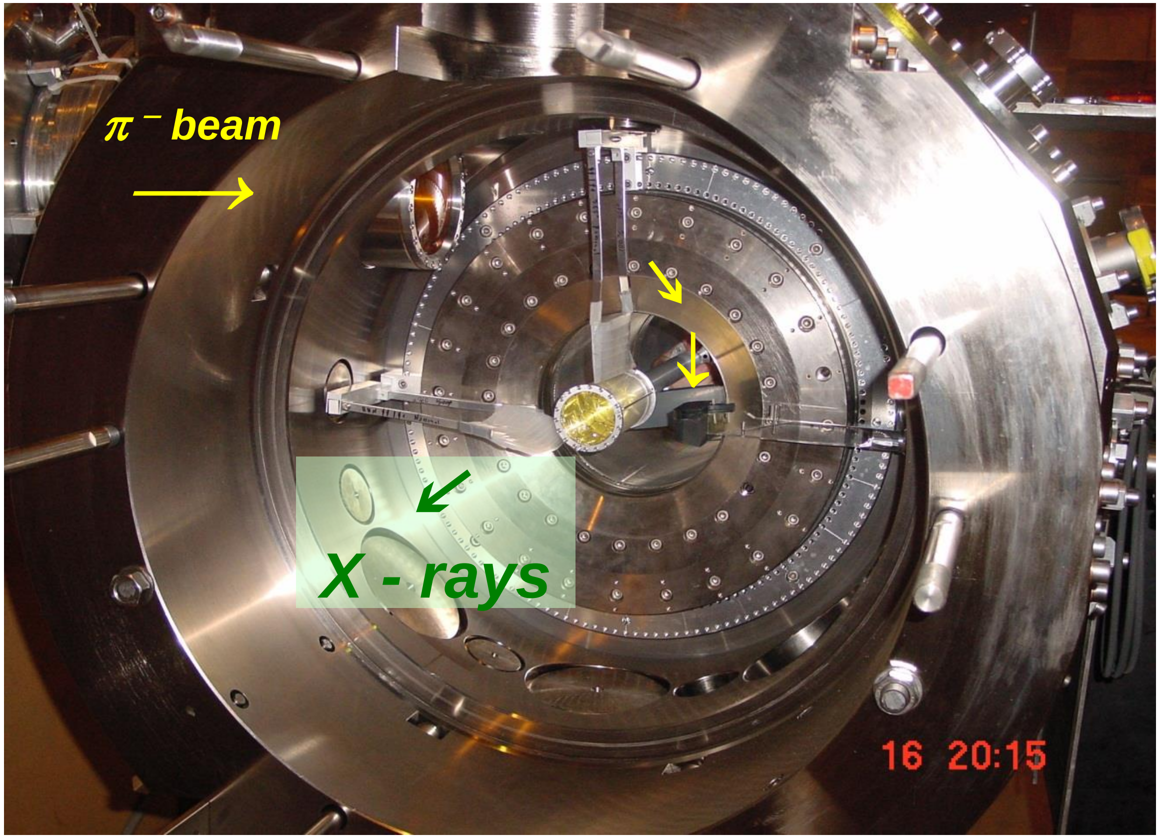
gain ≈ 10^6 compared with linear stop arrangement

stop efficiency ≈ 80% @ 30 mbar

cyclotron trap: L.M. Simons, Phys. Scripta T22 (1988) 90, Hyperfine Int. 81 (1993) 253

DEGRADERS and CRYOGENIC TARGET
inside
CYCLOTRON TRAP II

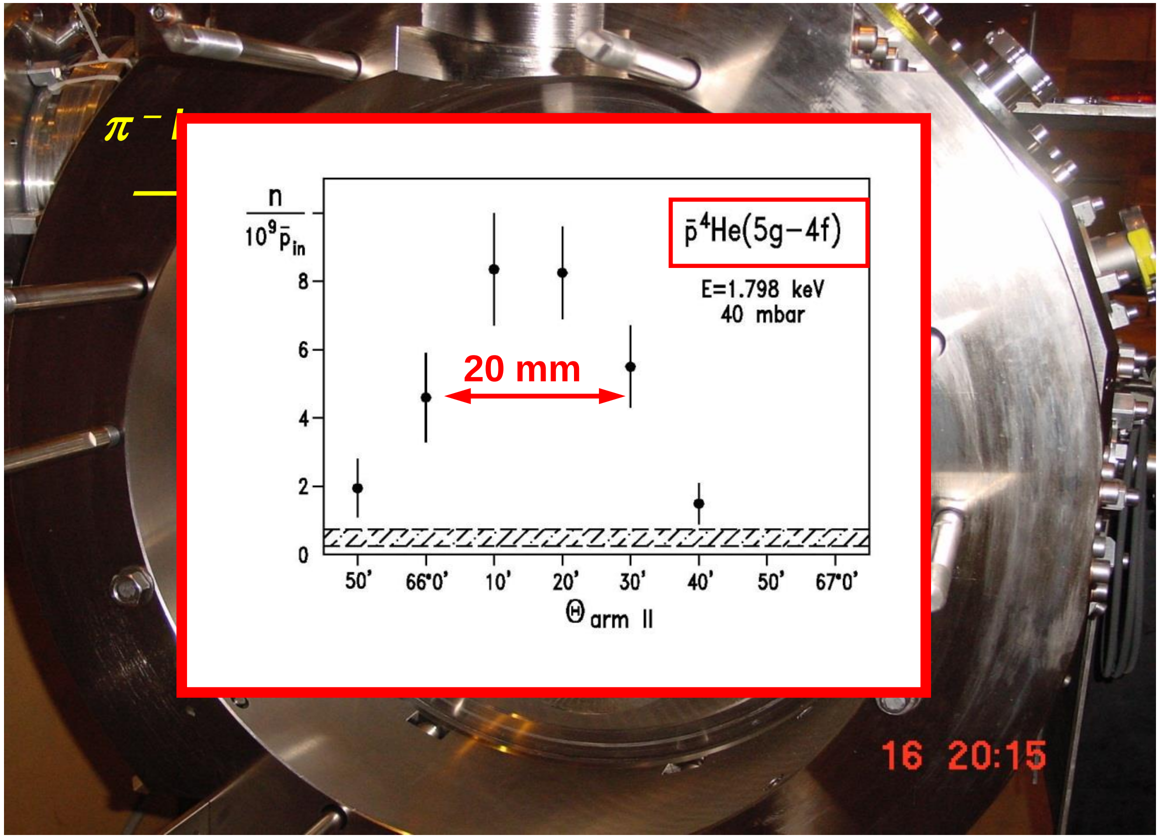
super-conducting split coil magnet



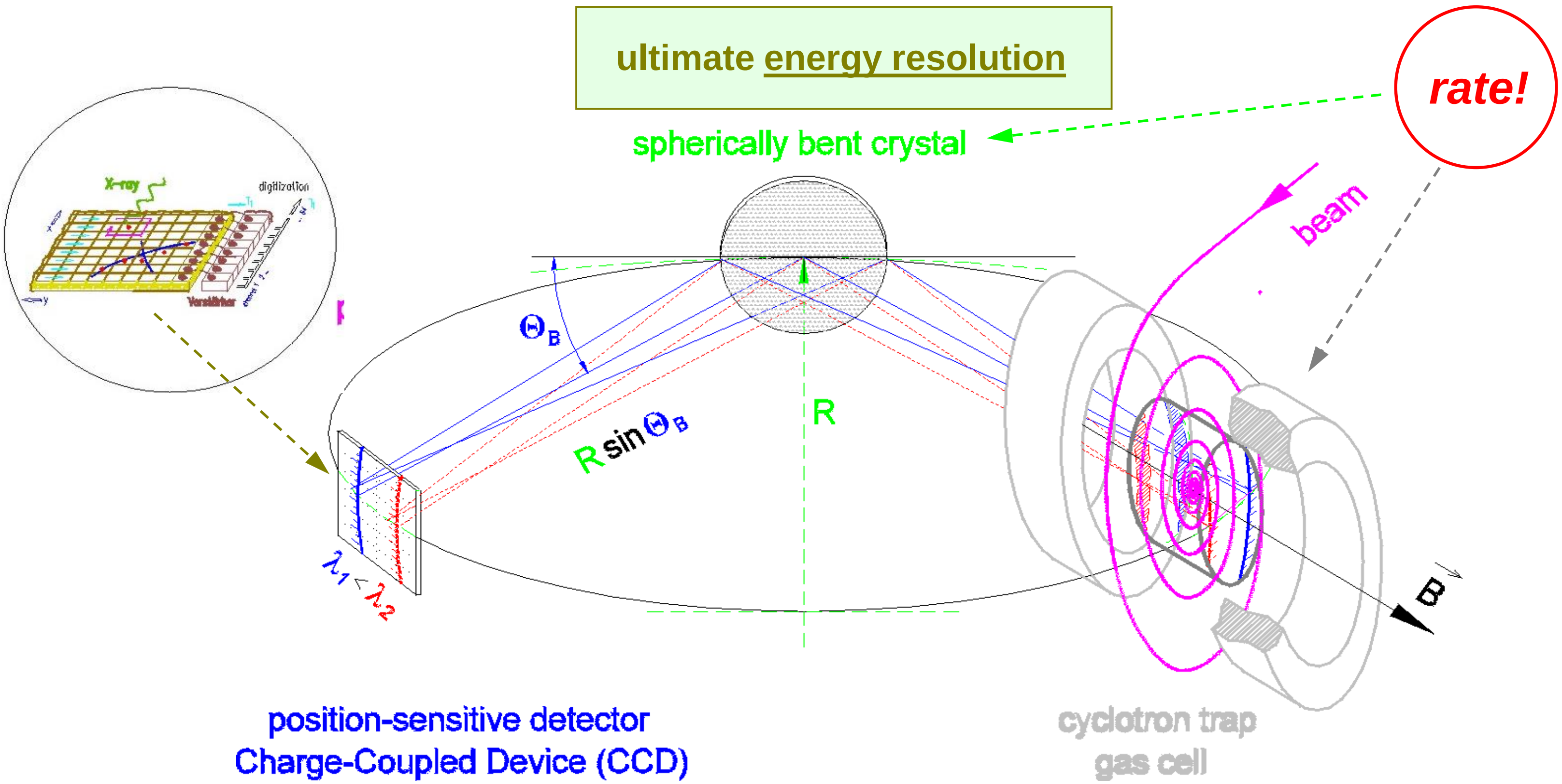
DEGRADERS and CRYOGENIC TARGET
inside
CYCLOTRON TRAP II

super-conducting split coil magnet

stop efficiency 80% @ 30 mbar



PRINCIPLE of SET-UP



position & energy resolution

⇒ **background reduction**
by analysis of hit pattern

high stop density

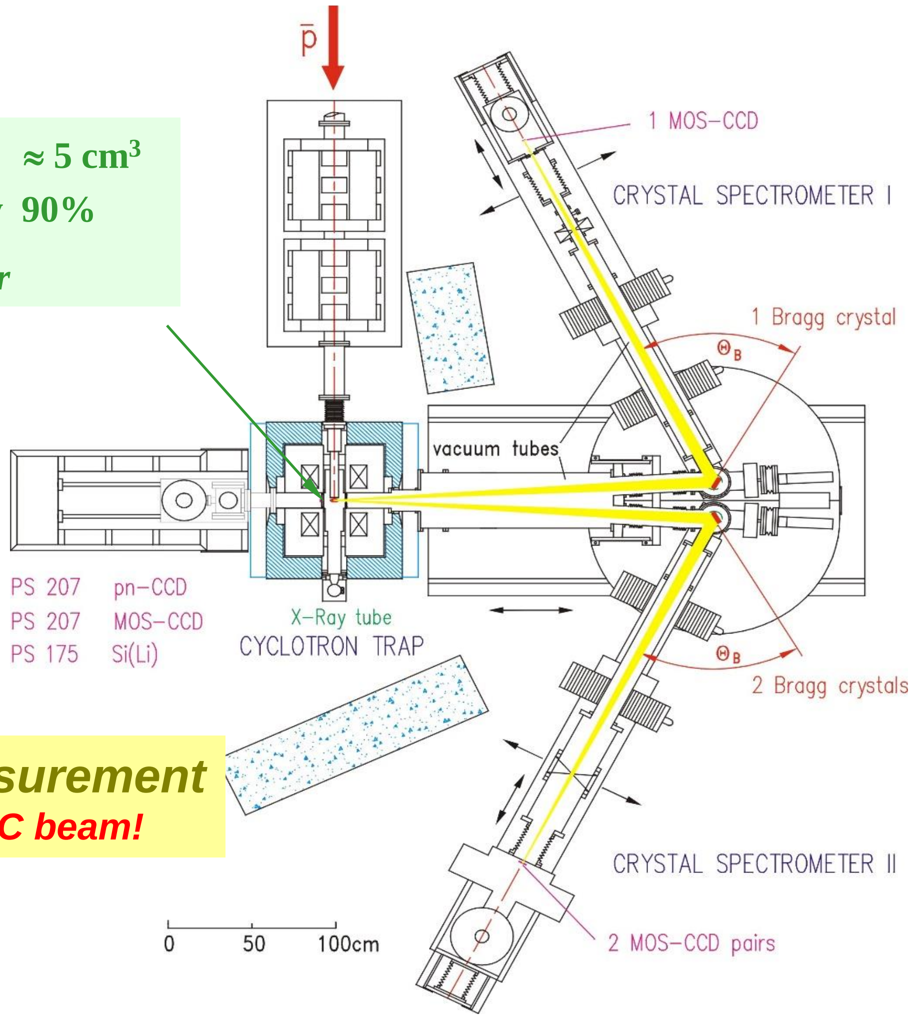
⇒ **high X - ray line yields**
⇒ **bright X - ray source**

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

PS207 - LEAR

105 MeV/c
10^6 / s

stop volume ≈ 5 cm^3
stop efficiency 90%
at p = 16 mbar



energy determination	*energy resolution*
few 10^{-6}	*few 10^{-4}*

direct measurement
requires DC beam!

crystal spectrometer

BRAGG CRYSTAL

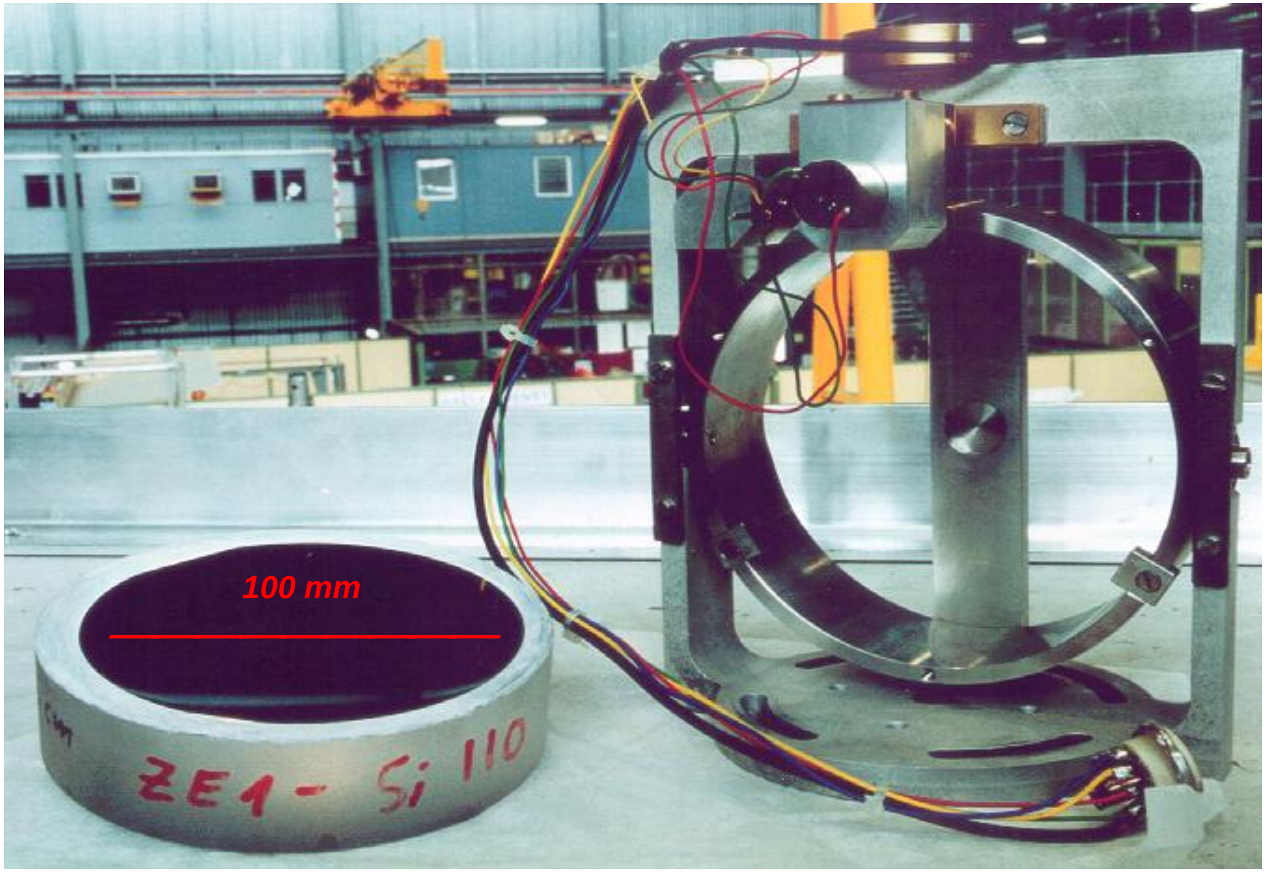
spherically bent

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



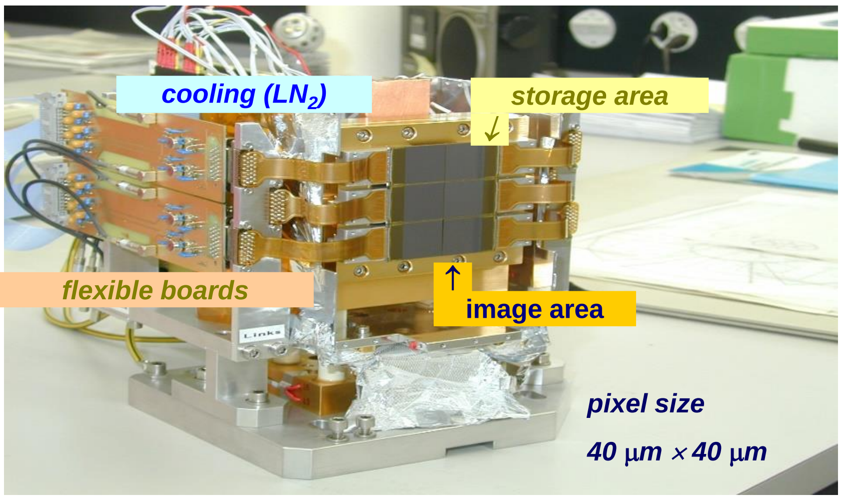
DETECTOR *crystal spectrometer* *Large - Area Focal Plane Detector*

CCD: charge-coupled device

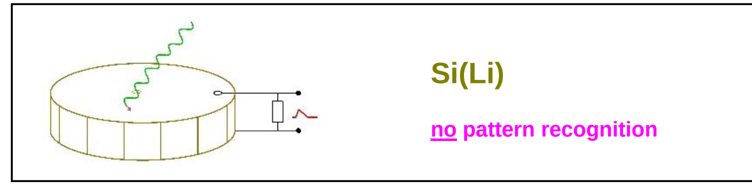
allows background suppression

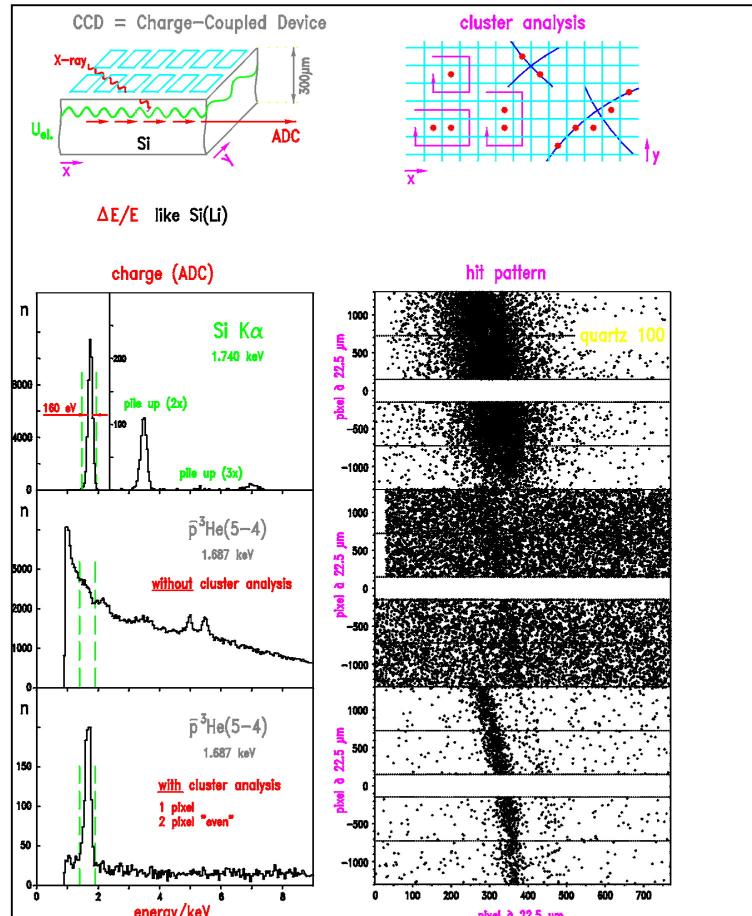
$\Delta E \approx$ *150 eV @ 4 keV*
$\varepsilon_X \approx$ *90%*

2 × 3 array of 24 mm × 24 mm devices



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





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

RESULTS from LEAR

- PS 175

- PS 176

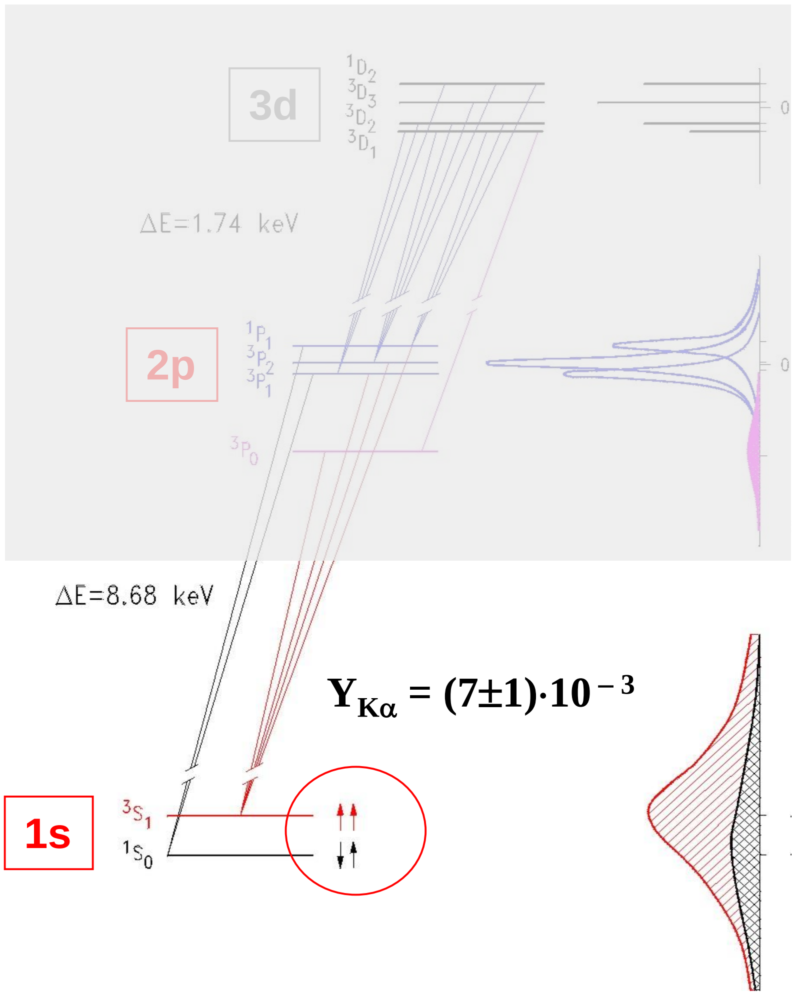
- PS 207

NUCLEON-ANTINUCLEON

SPIN-SPIN and SPIN-ORBIT INTERACTION

EXPERIMENT - PROTONIUM 1s state

cyclotron trap + MOS CCD

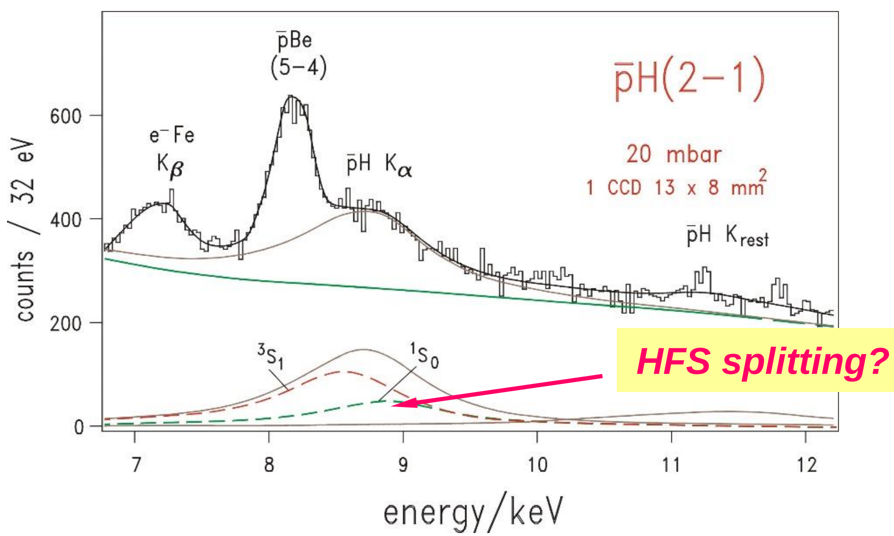


$$Y_{K\alpha} = (7\pm1)\cdot10^{-3}$$

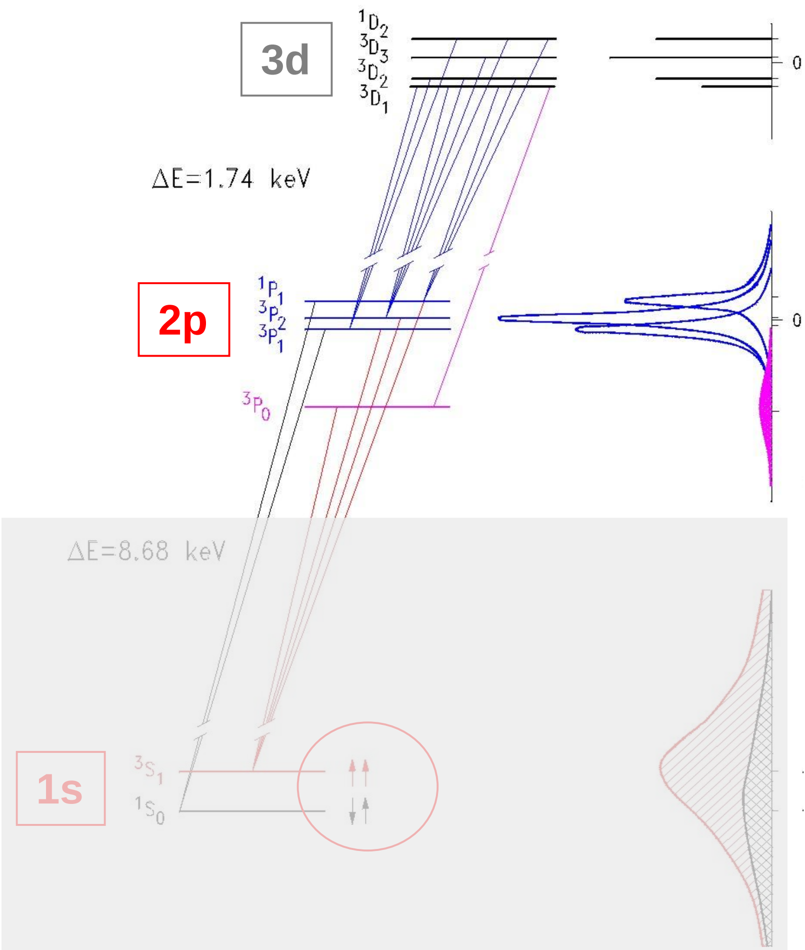
LEAR PS207: M. Augsburger et al., Nucl. Phys. A 658 (1999) 149

	ε / eV	Γ / eV
spin average	- 714 ± 14	1097 ± 42
$^1S_0$	- 440 ± 75	1200 ± 250 *
$^3S_1$	- 785 ± 35	940 ± 80 *

* fixed $^1S_0$ / $^3S_1$ ratio
background from pD



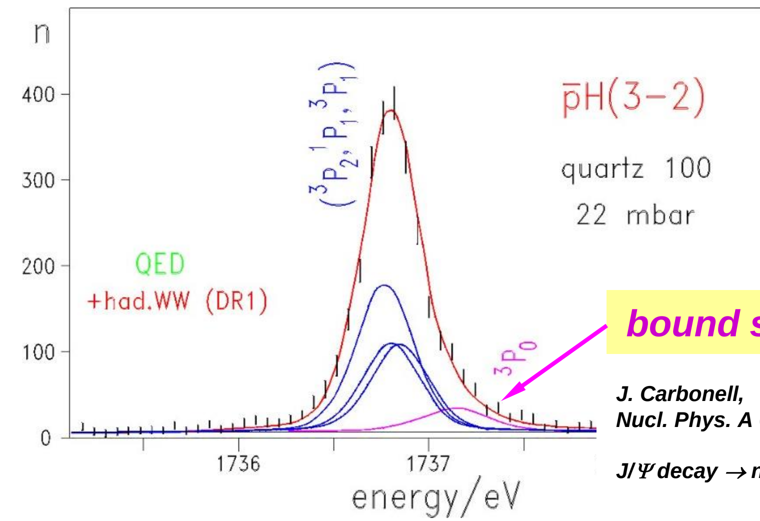
EXPERIMENT - PROTONIUM 2p state



cyclotron trap + crystal spectrometer

ΔE = 290 ± 9 meV

LEAR PS207: D.Gotta et al., NP A 660 (1999) 283



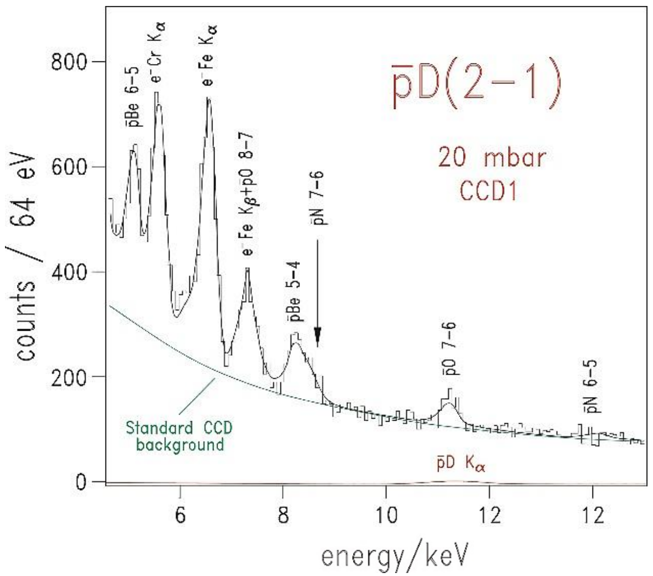
bound states ?

J. Carbonell,
Nucl. Phys. A 692 (2001) 11

J/Ψ decay → new theor. efforts

	ε / meV	***Γ / meV***
spin average	***+ 15 ± 20***	***38.0 ± 2.8***
$^3P_0$	***+ 139 ± 38***	***120 ± 25***

EXPERIMENT - ANTIPROTONIC DEUTERIUM



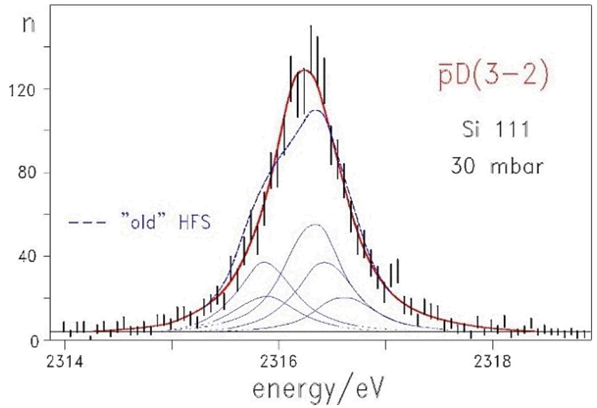
ground state transition weak signal

spin average ε_{1s} = - 1050 ± 250 eV

Γ_{1s} = 1100 ± 750 eV

LEAR PS207: M.. Augsburger et al., NP A 658 (1999) 149

$$Y_{K\alpha} = (5\pm1)\cdot10^{-4}$$



2p state **HFS not resolvable**

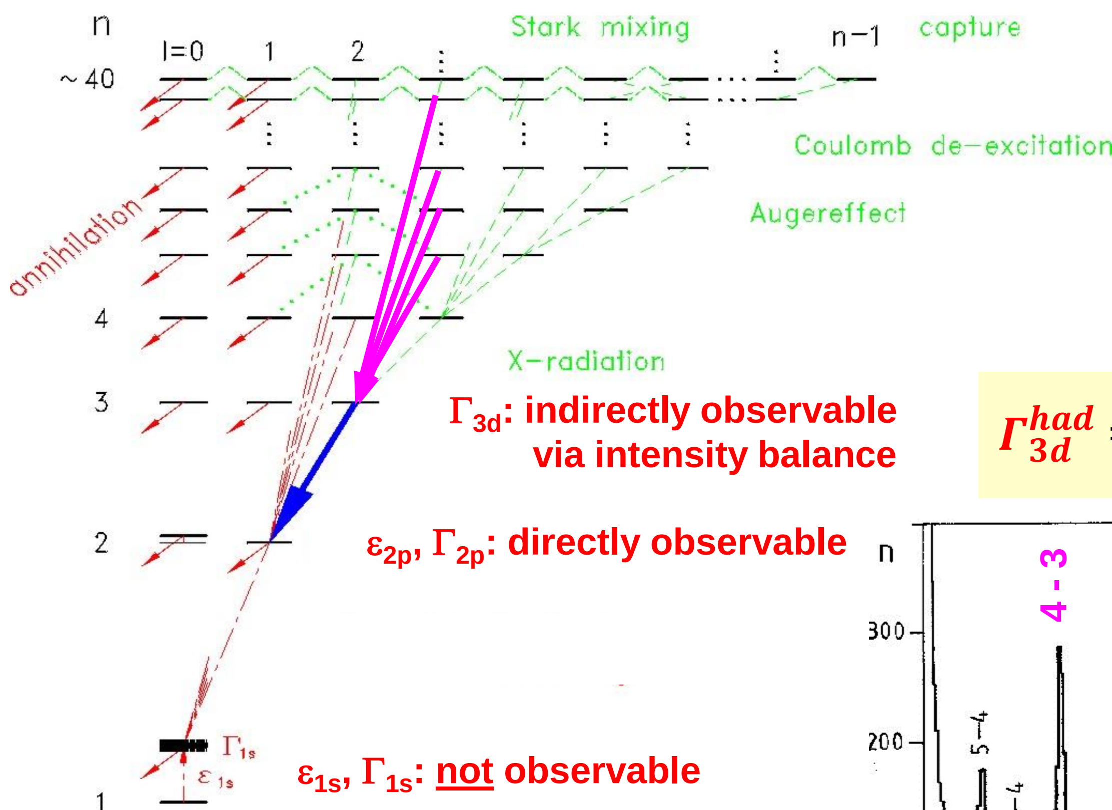
spin average ε_{2p} = − 243 ± 26 meV

Γ_{2p} = 489 ± 30 meV

LEAR PS207: D.Gotta et al., NP A 660 (1999) 283

ΔE = 333 ± 34 meV

EXPERIMENT - ANTIPROTONIC HELIUM

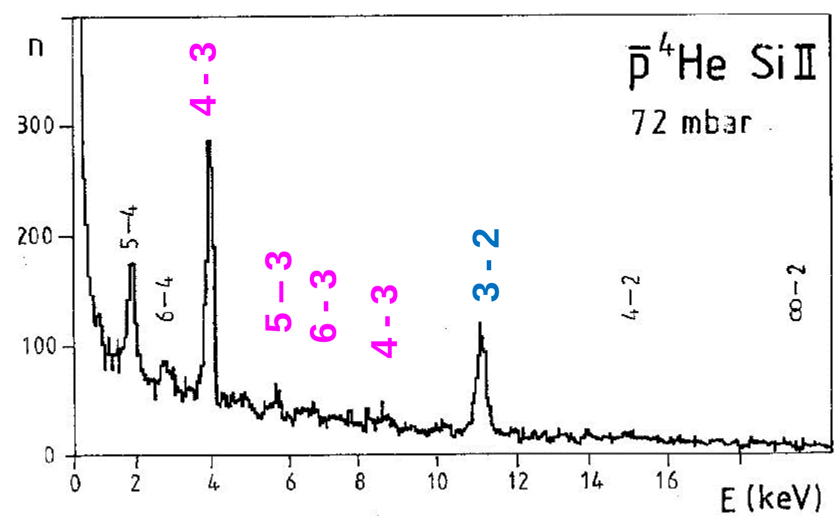


Γ_{3d}: indirectly observable via intensity balance

ε_{2p}, Γ_{2p}: directly observable

ε_{1s}, Γ_{1s}: not observable

$$\Gamma_{3d}^{had} = \Gamma_{3d}^{el.-mag} \cdot \left(\frac{Pop_{3d}}{I_{3d-2p}} - 1 \right)$$

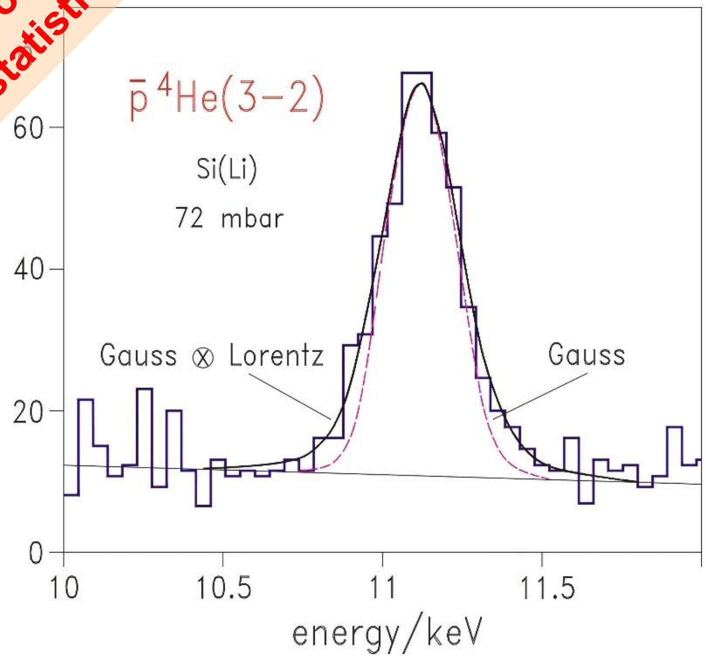


PS175 M. Schneider et al., Z. Phys. A 338 (1991) 217

EXPERIMENT - ANTIPROTONIC HELIUM results

•resolution
•statistics

PS175: M. Schneider et al., Z. Phys. A 338 (1991) 217



spin average			ε	Γ	
$\bar{p}\,^3He$	2p		-17 ± 5	25 ± 9	eV
	3d*			2.14 ± 0.18	meV
$\bar{p}\,^4He$	2p		-18 ± 2	45 ± 5	eV
	3d*			2.36 ± 0.10	meV

* from intensity balance

isotope effects ?

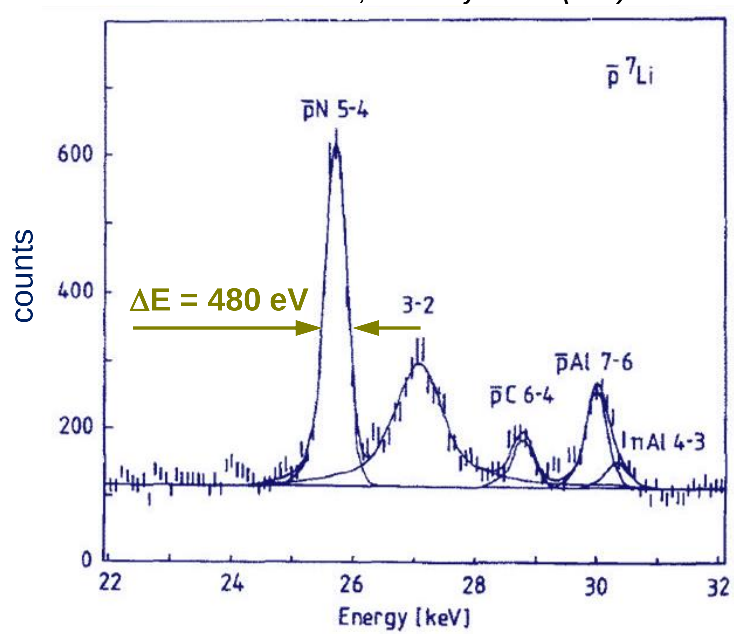
$\Delta\Gamma/\Gamma = 10\% - 50\% \quad \rightarrow \quad \leq 5\%$

- ^3He HFS up to 10 eV
- ^4He HFS 1-3 eV unresolvable
- single - nucleon annihilation ?

$$\Gamma_{A(Z,N)} \propto Z \cdot \Gamma_{\bar{p}n} + N \cdot \Gamma_{\bar{p}p}$$

EXPERIMENT - ANTIPROTONIC LITHIUM

PS176 H. Poth et al., Nucl. Phys. A 466 (1987) 667



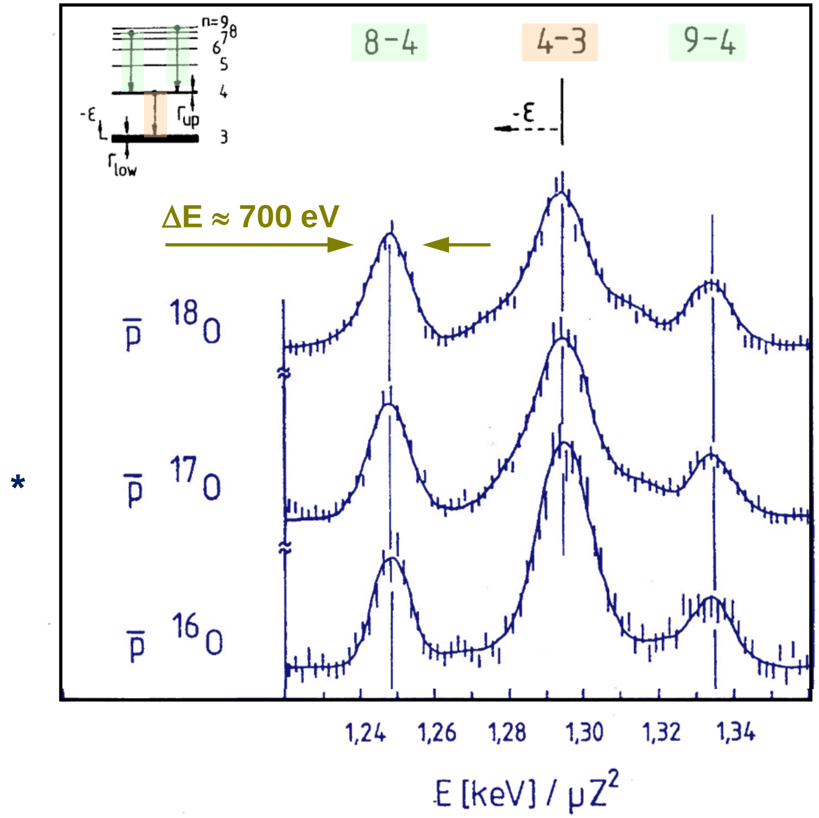
spin average	ε	Γ
$\bar{p}\,^6Li$ 2p	-215 ± 40	660 ± 180 eV
3d *		135 ± 16 meV
$\bar{p}\,^7Li$ 2p	-265 ± 25	690 ± 180 eV
3d *		129 ± 13 meV

** from intensity balance*

isotope effects ?

EXPERIMENT - ANTIPROTONIC OXYGEN

PS176 Th. Köhler et al., Phys. Lett. B 176 (1986) 327
D. Rohmann et al, Z. Phys. A 325 (1986) 261



spin average		ε	Γ
$\bar{p}$ O	2p state not accessible by X-rays		
$\bar{p}\,^{16}O$	3d	– 112 ± 20	495 ± 47 eV
$\bar{p}\,^{17}O$	3d	– 140 ± 47	540 ± 150 eV
$\bar{p}\,^{18}O$	3d	– 195 ± 21	640 ± 43 eV

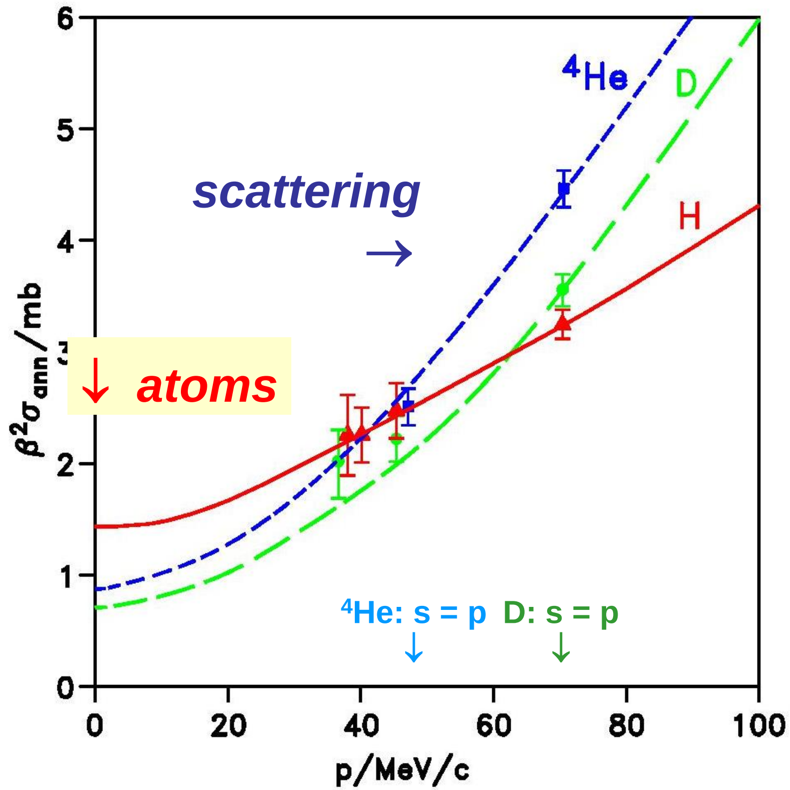
isotope effects visible

target H_2O

*** ^{16}O and ^{18}O contributions**

ANNIHILATION STRENGTH

ATOM DATA ⇔ LOW-ENERGY SCATTERING



data: LEAR – PS201(OBELIX)

hydrogen atom data
(Trueman formula)

	spin average	*effective range fit*
Im a_S	**- 0.69 ± 0.03**	**- 0.69 ± 0.04 fm**
Im a_p	**- 0.77 ± 0.06**	**- 0.75 ± 0.07 fm**

striking agreement, but spin average only!

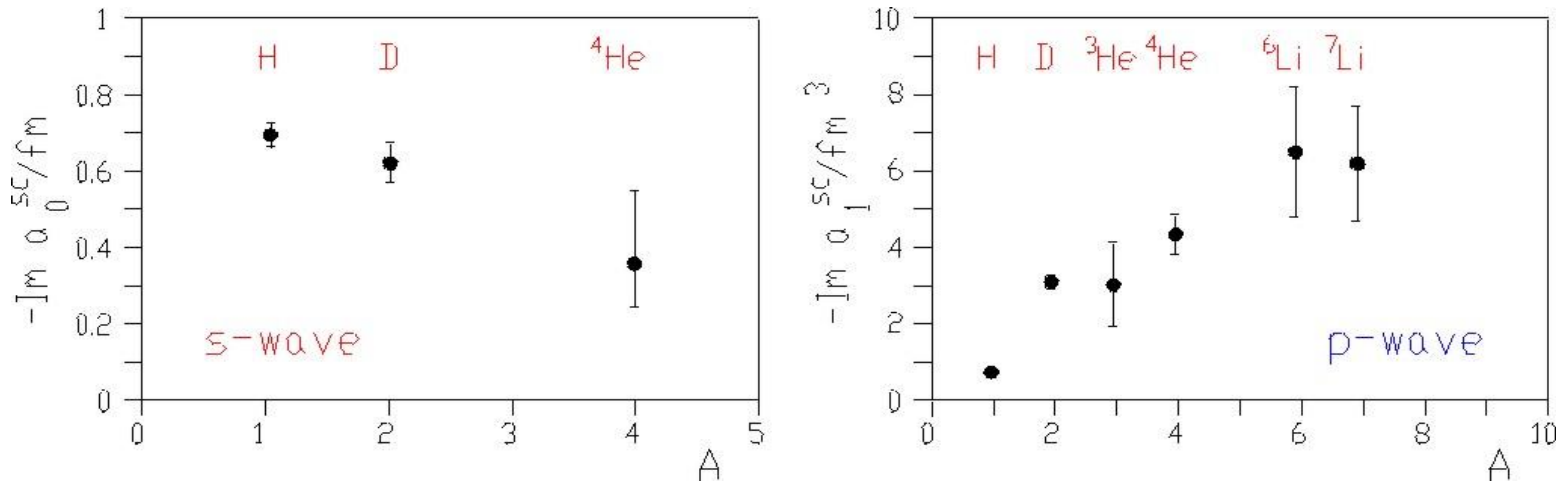
discussion and references: K. Protasov et al., Eur. Phys. J. A 7 (2000) 429

	HFS	*updated Paris potential HFS*
Im a_S	**- 0.64 ± 0.05**	**- 0.54 fm**
	reasonable	***?***

data: M. Augsburger et al., Nucl. Phys. A 658 (1999) 149

Paris pot.: El-Bennicj,Lacombe,Loiseau,Wycech, Phys. Rev. C 79 (2009) 054001

ANNIHILATION STRENGTH ⇔ NUCLEAR MASS



K. Protasov et al., Eur. Phys. J. A 7 (2001) 429

supplemantary data: PS176

saturation ?

seen also in optical potential analyses

$U_{opt} \propto a \cdot \rho(r)$

A. Gal, E. Friedman and C.J. Batty, Phys. Lett. B491 (2000) 219

qualitatively – strong annihilation suppresses wave function inside matter

e. g. $\varepsilon_{1s} < 0$ **for** $\bar{p}p$

$\bar{p}\ {}^4He \rightarrow {}^3He, T, D + X$

primordial nuclei abundancy

ANNIHILATION STRENGTH

and

ISOSPIN

Relative annihilation on p,n - isospin I = 0,1

$$R^{free}_{s-wave} = \frac{\bar{p}n}{\bar{p}p} = \frac{\Im\, a_{I=1}}{\tfrac{1}{2}\left(\Im\, a_{I=0} + \Im\, a_{I=1}\right)} = 1.14 \pm 0.13$$

$\bar{p}H$ & $\sigma_{\bar{n}p}$

input to neutron halo determination (FLAIR proposal)

?

ℓ dependence

$$R^{bound} = 0.78 \pm 0.03$$ $\bar{p}D$ **streamer chamber**

$$R^{bound} = 0.45 \pm 0.04$$ $\bar{p}\,^{3,4}He$

Final state charge

Balestra et al.
Nucl. Phys. A 491 (1989) 541
and ref. therein

$$\frac{\Gamma(\bar{p}\,^3He)}{\Gamma(\bar{p}\,^4He)} = 0.84 \pm 0.02$$

prediction from single nucleon approximation

$$\Gamma_{A(Z,N)} \propto Z \cdot \Gamma_{\bar{p}p} + N \cdot \Gamma_{\bar{p}n}$$

$$\frac{\Gamma(\bar{p}\,^3He)}{\Gamma(\bar{p}\,^4He)} = \frac{\Im\, a_{\bar{p}^3He}}{\Im\, a_{\bar{p}^4He}} = \frac{\Im\, a_{I=0} + 2\cdot\Im\, a_{I=1}}{\Im\, a_{I=0} + 3\cdot\Im\, a_{I=1}} \quad\Rightarrow\quad \left(\frac{\Im\, a_{I=1}}{\Im\, a_{I=0}}\right) = \frac{1 - \frac{\Gamma(\bar{p}\,^3He)}{\Gamma(\bar{p}\,^4He)}}{3\cdot\frac{\Gamma(\bar{p}\,^3He)}{\Gamma(\bar{p}\,^4He)} - 2}$$

$\bar{p}H$ & $\sigma_{\bar{n}p}$	$\rightarrow$	1.3 ± 0.2
$\bar{p}\,^{3,4}He$ 2p	$\rightarrow$	-1.3 ± 4.0 !
3d	$\rightarrow$	0.1 ± 1.6

Relative annihilation on p,n - isospin I = 0,1

relation to hadronic line width

$$\frac{\tilde{\Gamma}(\bar{p}\,^3He)}{\tilde{\Gamma}(\bar{p}\,^4He)} = \frac{2 + R^{bound}}{2 + 2R^{bound}}$$

$$R^{bound} \text{ from } \Gamma\left(\bar{p}\,^{3,4}He\right) \text{ if } \frac{\Delta\Gamma}{\Gamma} \approx \%$$

$$\tilde{\Gamma} = \Gamma \quad \text{corrected for different overlap} \quad (\approx \%)$$

result from X-ray data

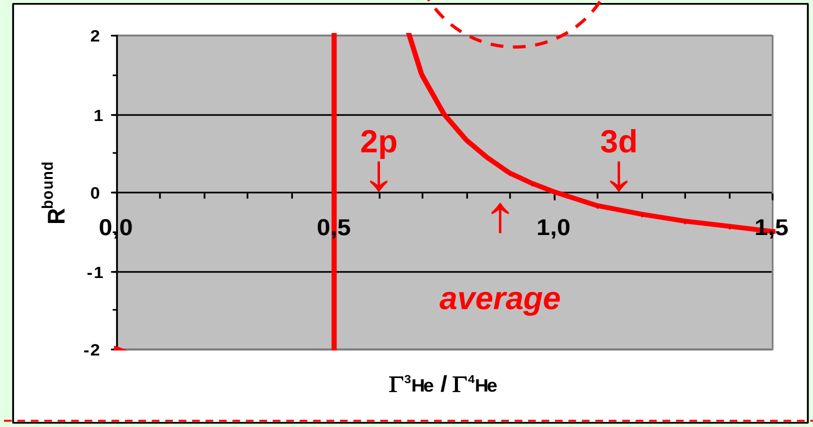
$$\frac{\Gamma(\bar{p}\,^3He)}{\Gamma(\bar{p}\,^4He)} = 0.83 \pm 0.12 \quad \Rightarrow \quad R^{bound} = 0.52\,^{+0.86}_{-0.41}$$

input from cascade theory

X-rays average 2p + 3d

atomic state: 50% p- + 50% d-wave

cascade calculation – G. Reifenröther et al., Th. Jensen



RECENT DEVELOPMENTS

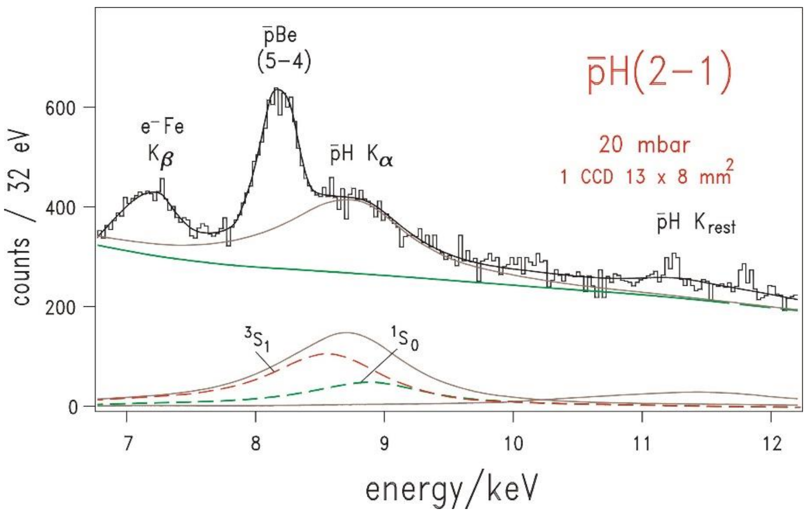
mainly from pionic X-ray measurements (PSI)

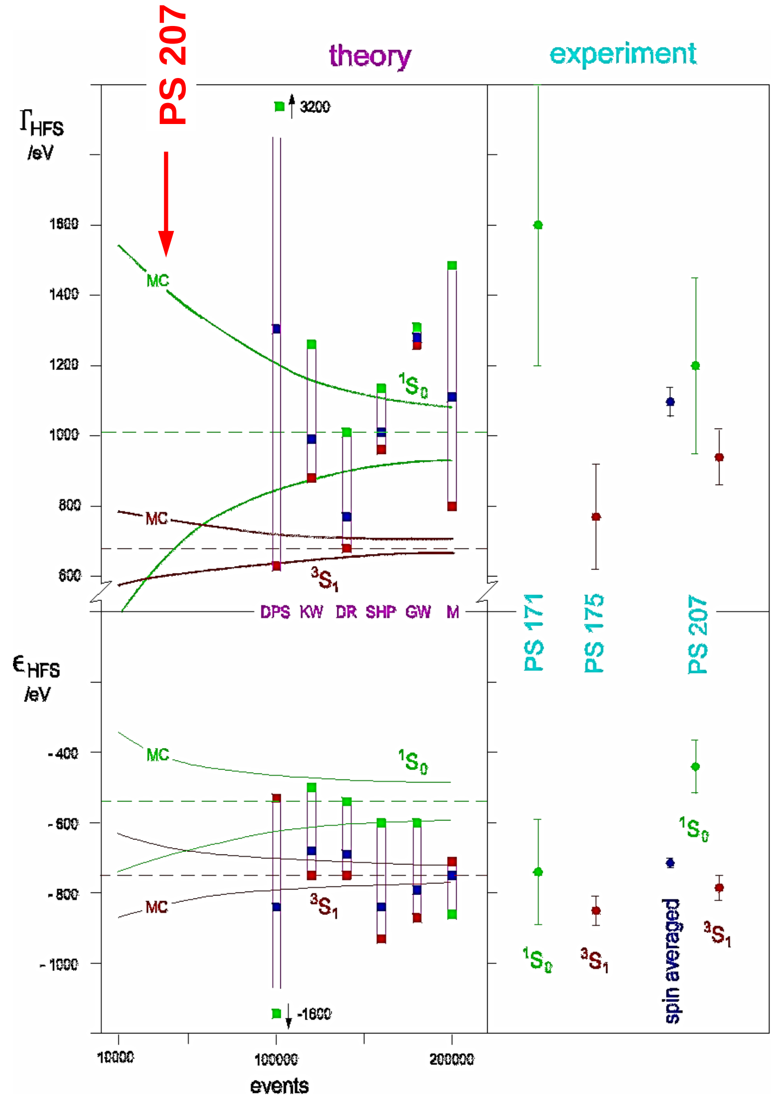
- R-94.01 π / μ mass ratio
- R-97.02 pion mass
- R-98.01 pionic & muonic hydrogen
- R-06.03 pionic deuterium

DETECTOR

again ***PROTONIUM ground state***

readout 1 frame / 10 s





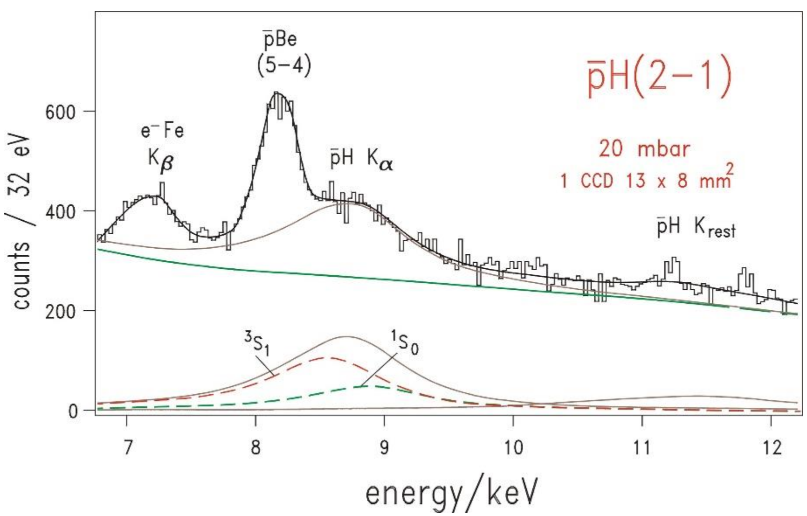
	ε / eV	Γ / eV
Spin average	- 714 ± 14	1097 ± 42
$^1S_0$	- 440 ± 75	1200 ± 250 *
$^3S_1$	- 785 ± 35	940 ± 80 *

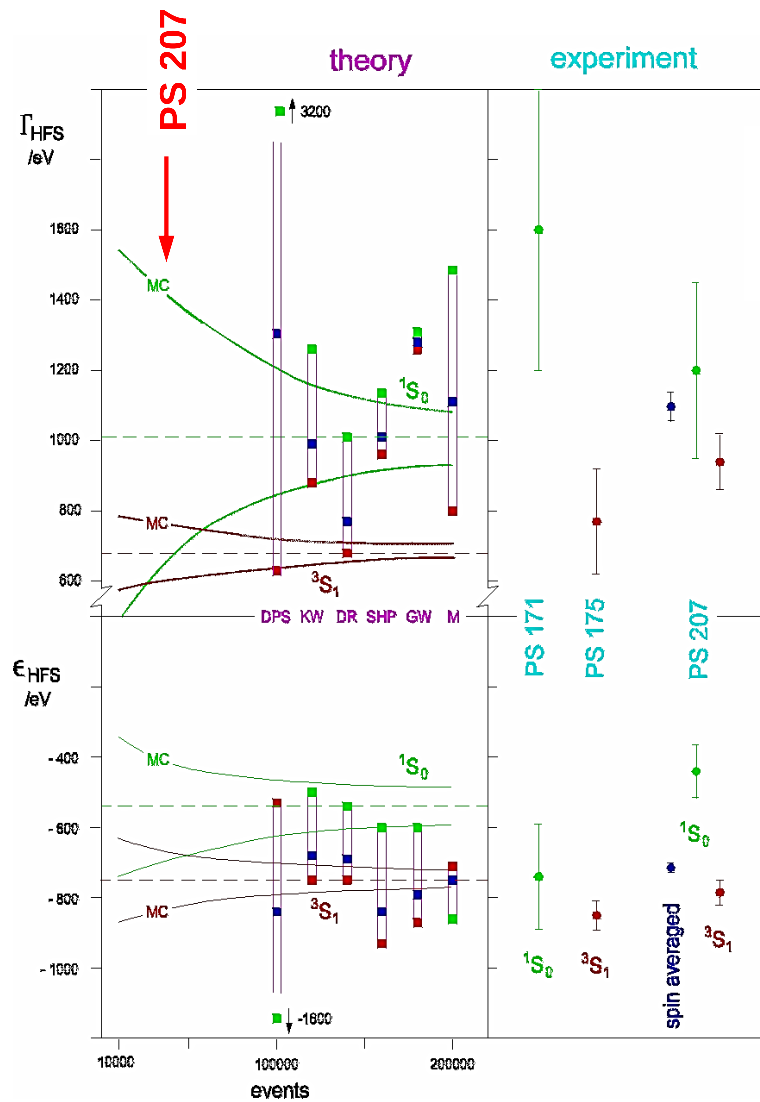
* fixed $^1S_0$ / $^3S_1$ ratio
background from p̄D

M. Augsburger et al., NP A 658 (1999) 149

again ***PROTONIUM ground state***

readout 1 frame / 10 s





„new" theory
CHPT´based

L.Y-Dai,
J. Haidenbauer,
U.G. Meissner,
PRD 91 (2015),
JHEP 1707 (2017) 078 ,
…

	ε / eV	***Γ / eV***
Spin average	***- 714 ± 14***	***1097 ± 42***
$^1S_0$	***- 440 ± 75***	***1200 ± 250 ****
$^3S_1$	***- 785 ± 35***	***940 ± 80 ****

**** fixed*** $^1S_0 / ^3S_1$ ***ratio***
background from p̄D

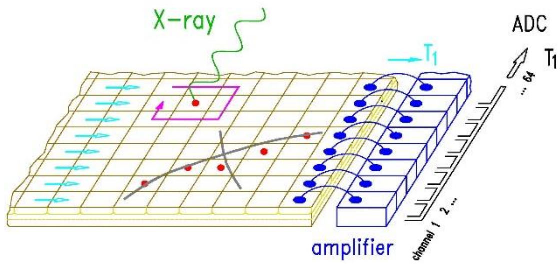
M. Augsburger et al., NP A 658 (1999) 149

FAST CCDs

for direct measurements

fully depleted fast CCD (pnCCD)

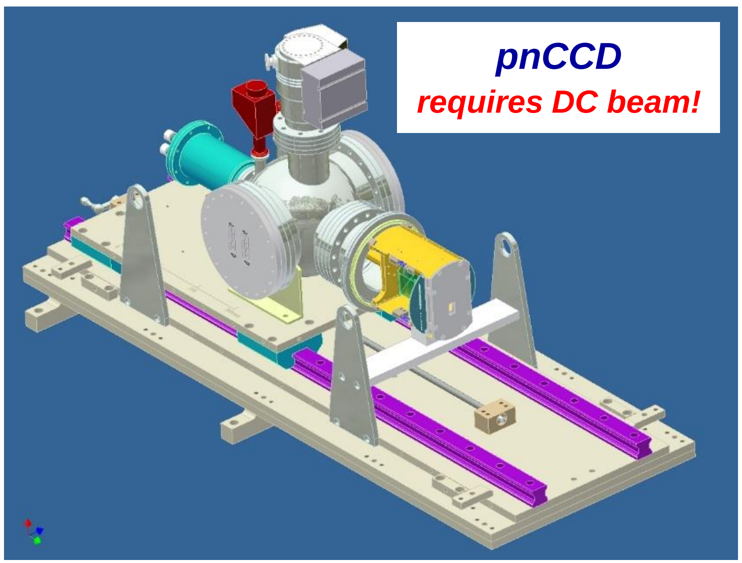
- *t = 300 - 500 µm*
- *high efficiency up to 25 keV*
- *64/128 channels parallel*
- *400/1000 frames/s*
- *150/75 µm pixel size*



prototype

1 cm^2
pixel size 150 µm
$\Delta E/E$ =180 eV
400 frames/s

π atoms PSI



A. Ackens et al., IEEE vol. 46 (1999) 1995
H. Gorke et al., AIP conf. proc. 793 (2005) 341
FZJ + MPI - Munich

10^5 $\bar{p}$/s!
AD?

?!

needed: statistics

$\bar{p}$H(2-1) 20.000 → > 200.000 events

$\bar{p}$D(2-1) 2000 → > 10.000 events

to confirm evidence for 1s shift and broadening

AD - ASACUSA/MUSASHI

slow extraction + gas cell
traps + atomic beam

- ELENA

<u>no</u> slow extraction!

FLAIR ≈ LEAR

Possible set-up (at AD) I

antiproton trap

↓

DC extraction

↓

re-accelaration

to 20 - 100 keV (25 keV ?)

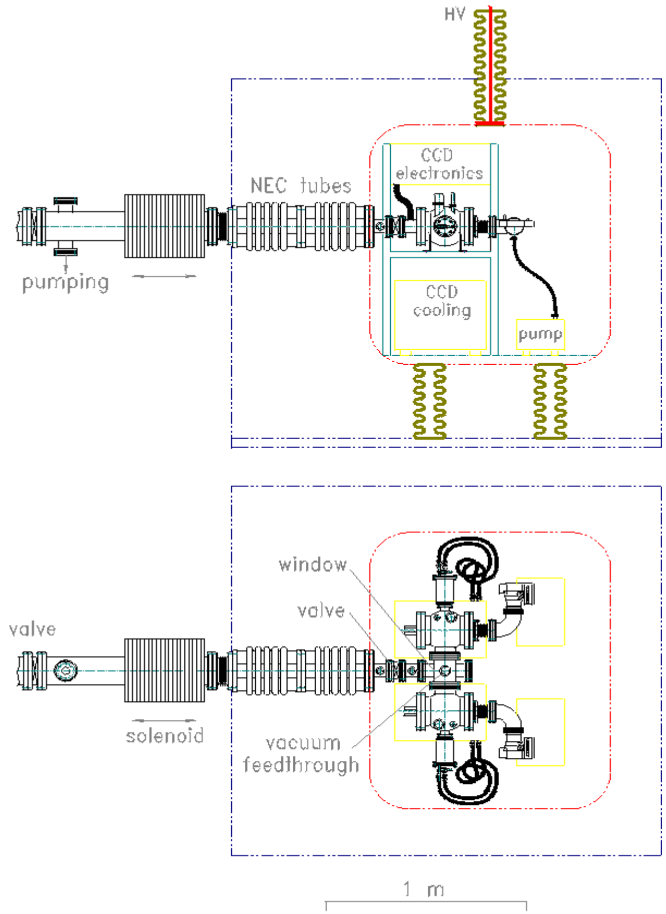
↓

gas cell (window) + fast CCD

$\bar{P}$

→

$T \approx$ kev



ASACUSA status report 2002,
CERN SPSC 2003-010

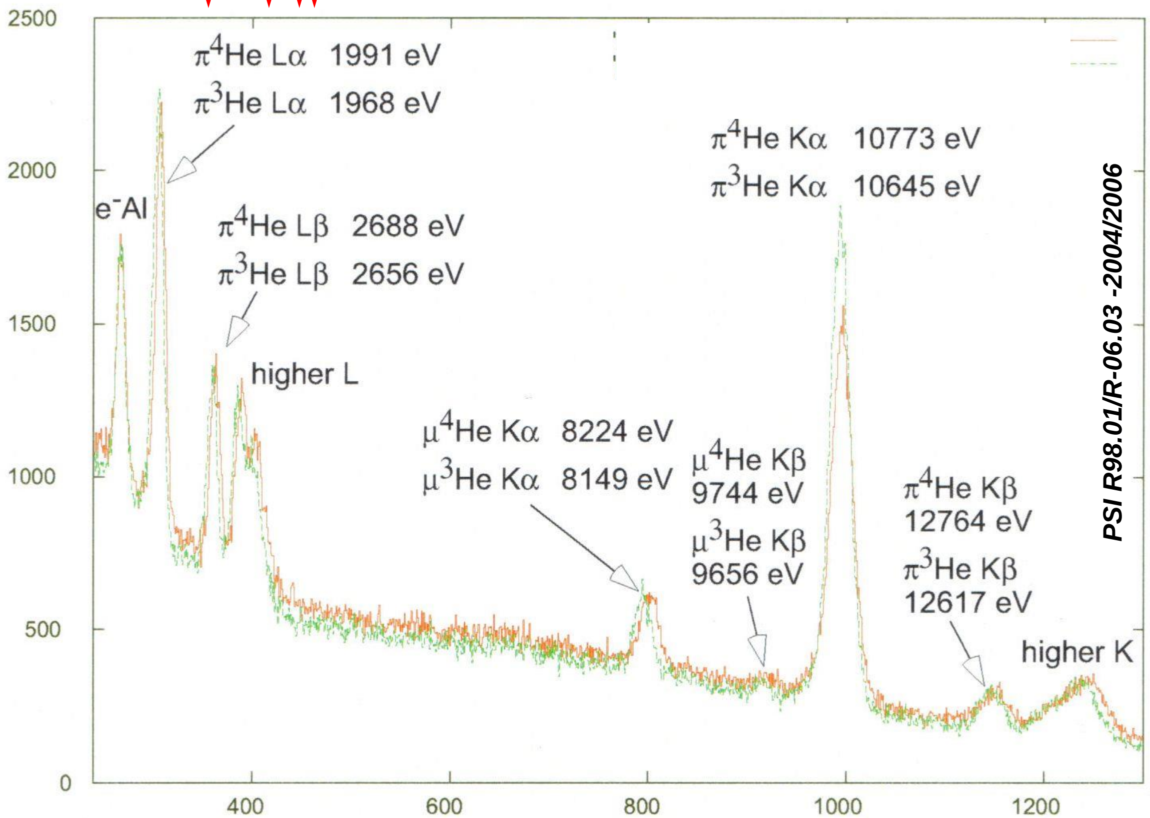
Possible set-up II

antiproton trap + gas jet + fast CCDs

"eat up" antiprotons

pnCCD raw data PSI 2006

broadening Γ_{2p} *from intensity balance $\Sigma L / K\alpha$*



π^4He

π^3He

accuracy → ≈ 1 eV

crystal spectrometer if sub eV precisision is needed

answer by theory

direct measurement: - **shift ε_{1s}**

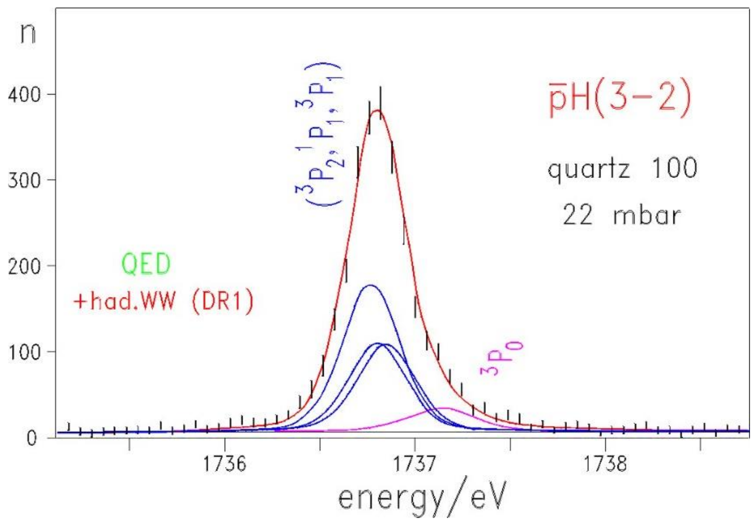
- **broadening Γ_{1s}**

BRAGG CRYSTAL

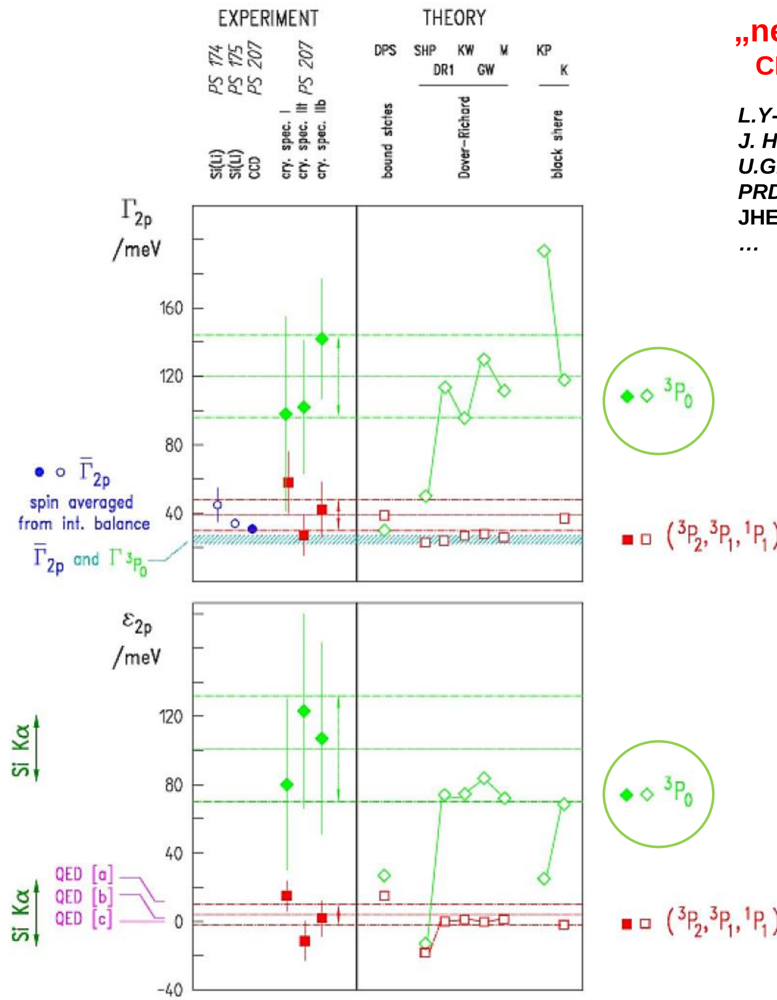
again PROTONIUM 2p - state

$\Delta E = 290 \pm 9$ meV

LEAR PS207: D.Gotta et al., NP A 660 (1999) 283



	ε / meV	Γ / meV
spin average	+ 15 ± 20	38.0 ± 2.8
$^3P_0$	+ 139 ± 38	120 ± 25

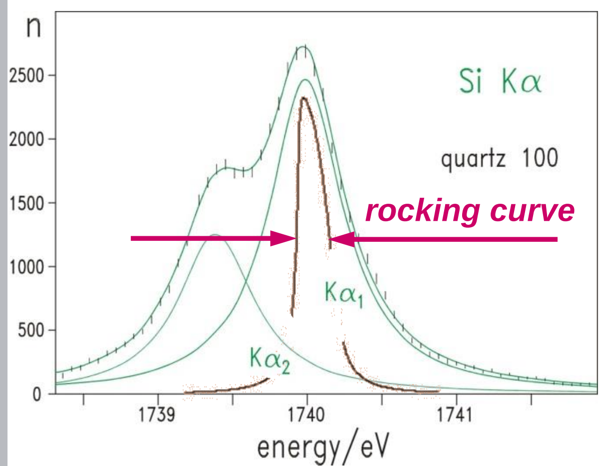


„new“ theory
CHPT´based

L.Y-Dai,
J. Haidenbauer,
U.G. Meissner,
PRD 91 (2015),
JHEP 1707 (2017) 078 ,
…

BRAGG CRYSTAL

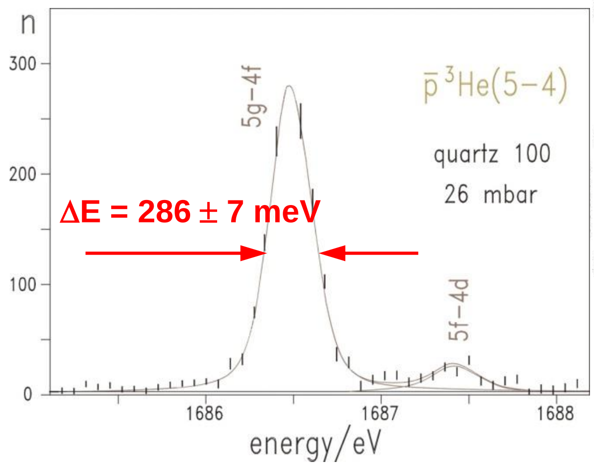
fluorescence X-rays
excited by means of X-ray tubes



problem

large natural line width and satellite lines

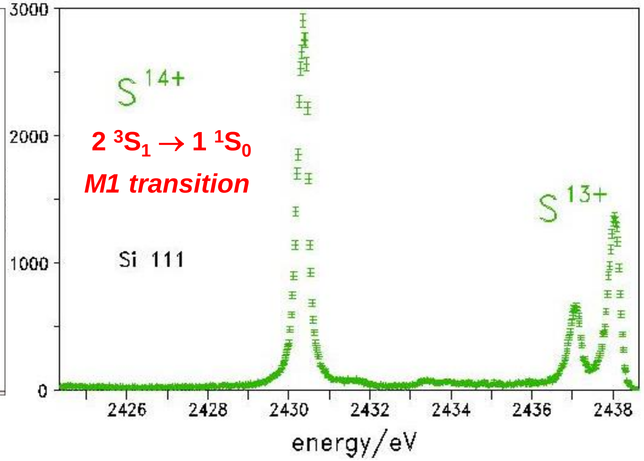
exotic-atom X-rays
from hydrogen-like systems



problem

rate

ECRIS
Electron Cyclotron Resonance Ion "Source"
=
cyclotron trap + hexapole magnet



solution: M1 transitions

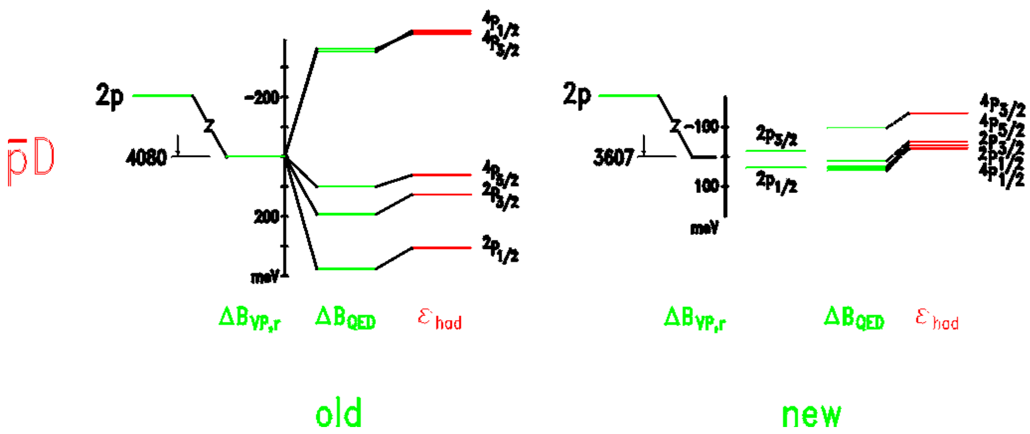
in He - like

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

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

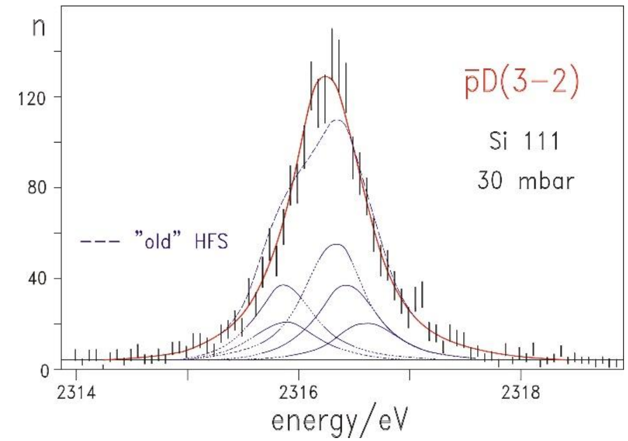
2p HYPERFINE SPLITTING - bound state QED

any splitting observable ?



S. Boucard and P. Indelicato, to be published
Veitia, Pachucki, Phys. Rev A 69 (2004) 042501

discussion see D. Gotta, Prog.Part.Nucl.Phys. 52 (2004) 133



LEAR PS207: D. Gotta et al., Nucl. Phys. A 660 (1999) 283

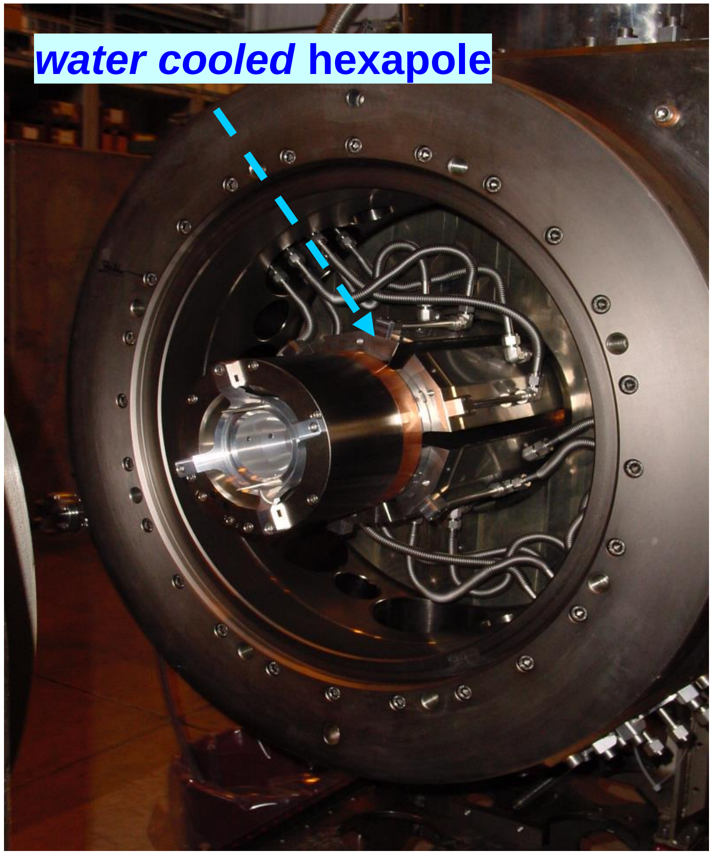
$$\Gamma_{2p}^{\bar{p}D} \approx 13 \cdot \Gamma_{2p}^{\bar{p}H}$$

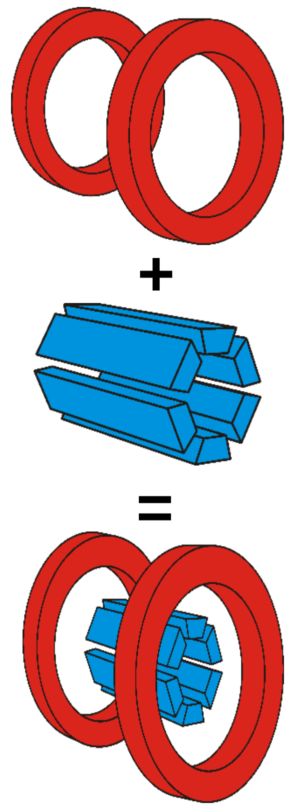
reasonable from larger overlap

$$\Gamma \propto \int \Im U_{had} |\Psi_{n\ell}|^2 \, dV$$

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*

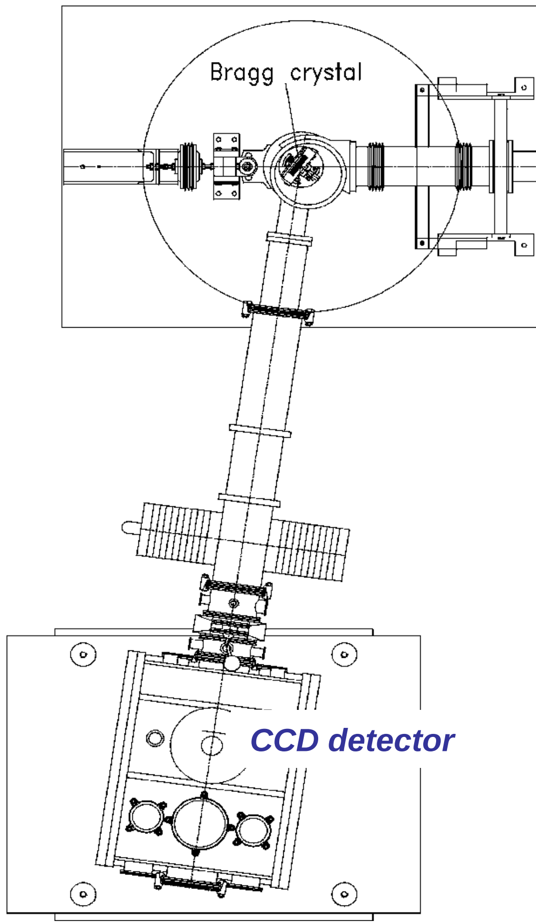
large mirror ratio = 4.3

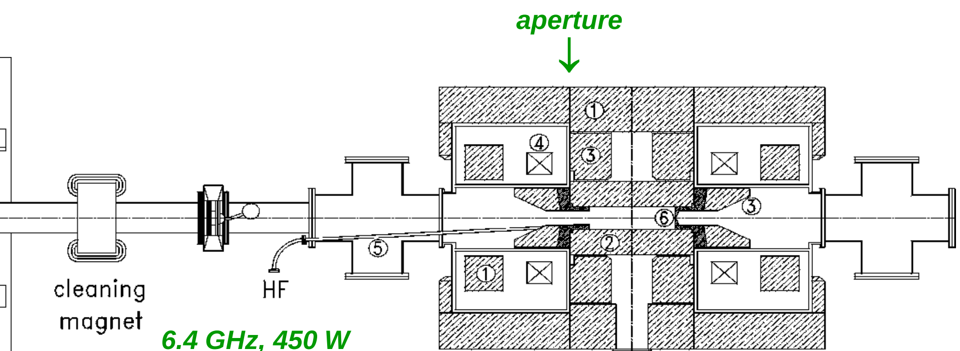
B_{max} / B_{min} *!*

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)





$T_{ion} \lesssim$ **5 eV** **"cold" plasma !**

He-like electronic atoms

$\Rightarrow$ **narrow X-ray transitions**

Γ_X = 10 - 40 meV

CRYSTAL SPECTROMETER and PSI ECRIT

Electron Cyclotron Resonance Ion Trap
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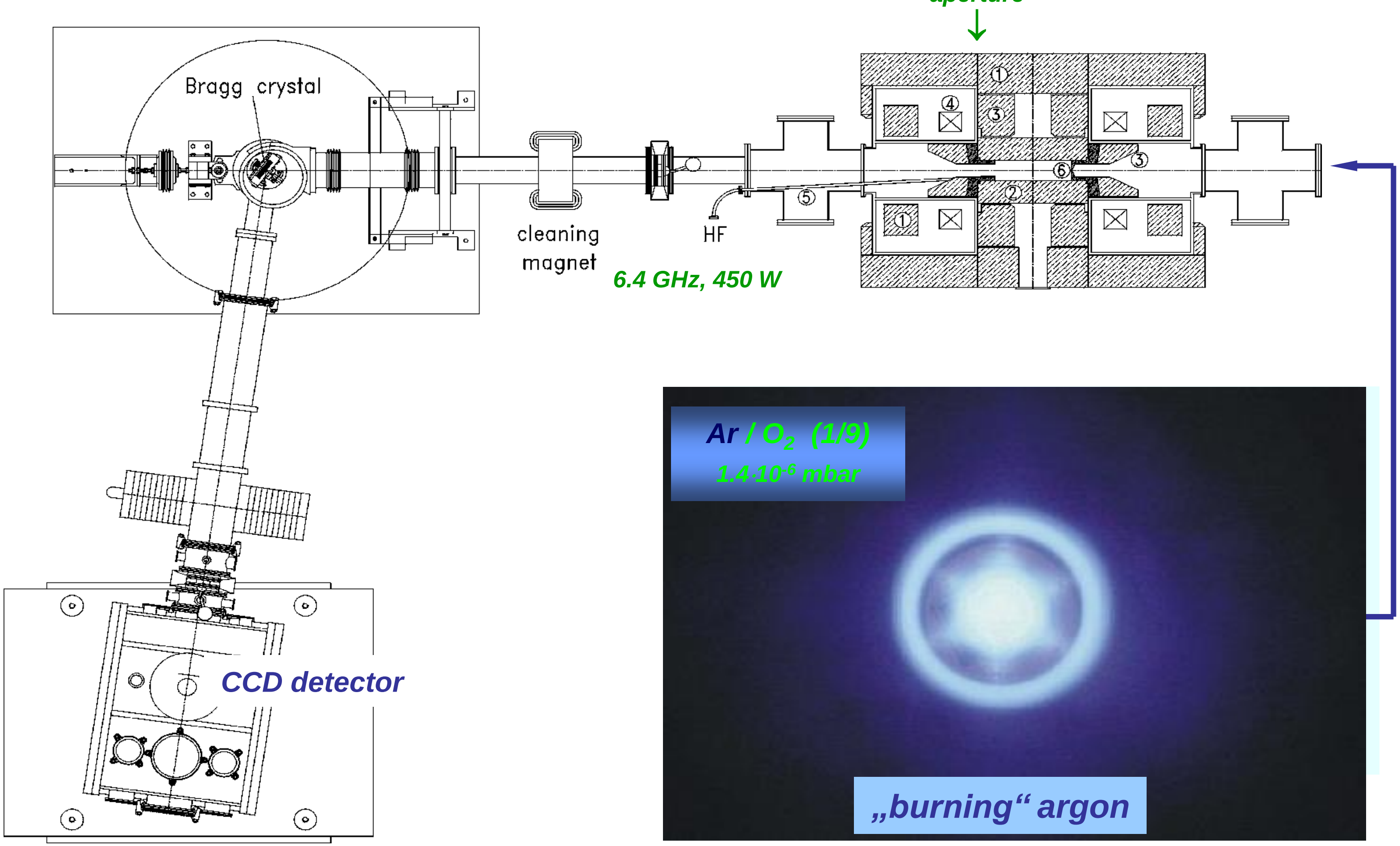
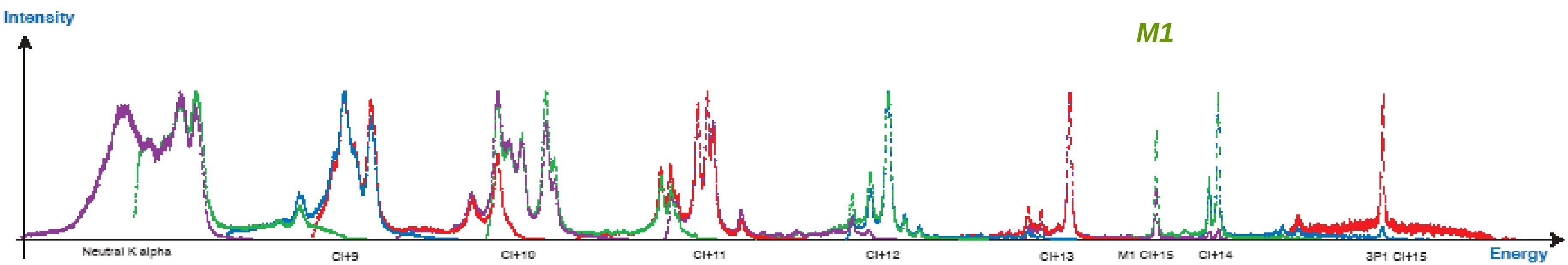


CHLORINE SKY LINE

Cl^{15+}

M1

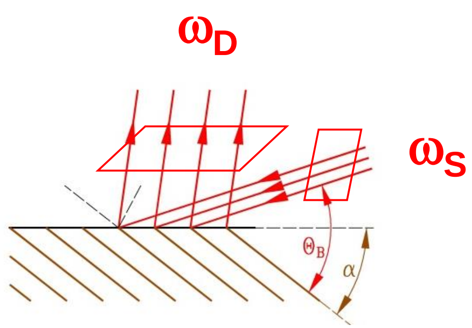


↑

RESPONSE FUNCTION
2757 ev

Asymmetric cut crystals

diffracting planes ≠ crystal surface



phase space

$$\omega_s \cdot \sqrt{b} = \omega_D \cdot / \sqrt{b}$$

asymmetry factor

$$b = \frac{\sin(\Theta_B - \alpha)}{\sin(\Theta_B + \alpha)}$$

resolution $\omega_D = \sqrt{b} \cdot \omega_0$

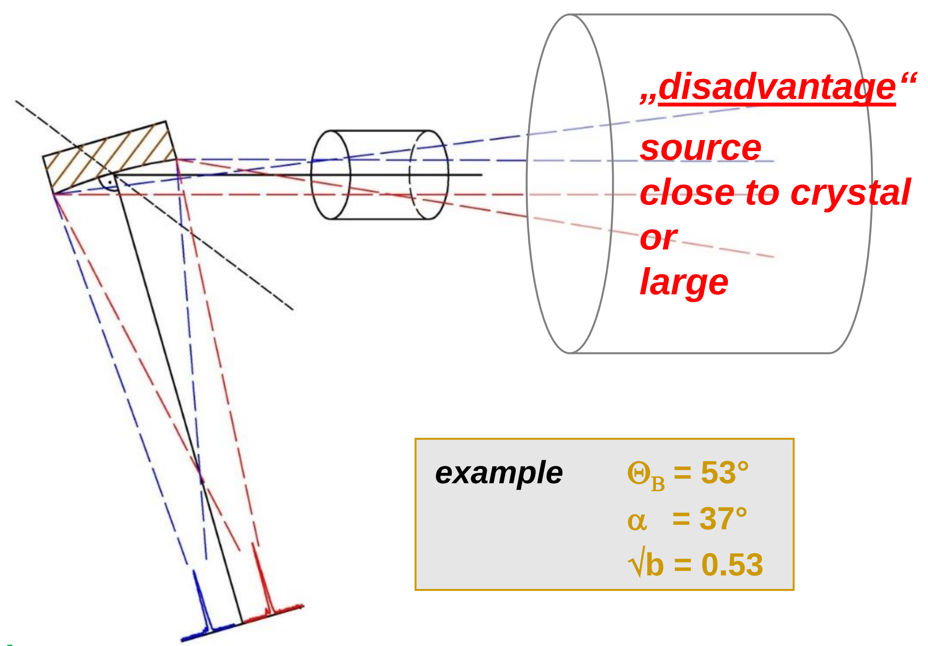
rate $R_I \Rightarrow \sqrt{b} \cdot R_I$

ω_0 *angular width accepted in the symmetric Bragg case*

Focusing conditions

Guinier 1946

$$\overline{SC} = R_C \sin(\Theta_B - \alpha)$$
$$\overline{CD} = R_C \sin(\Theta_B + \alpha)$$



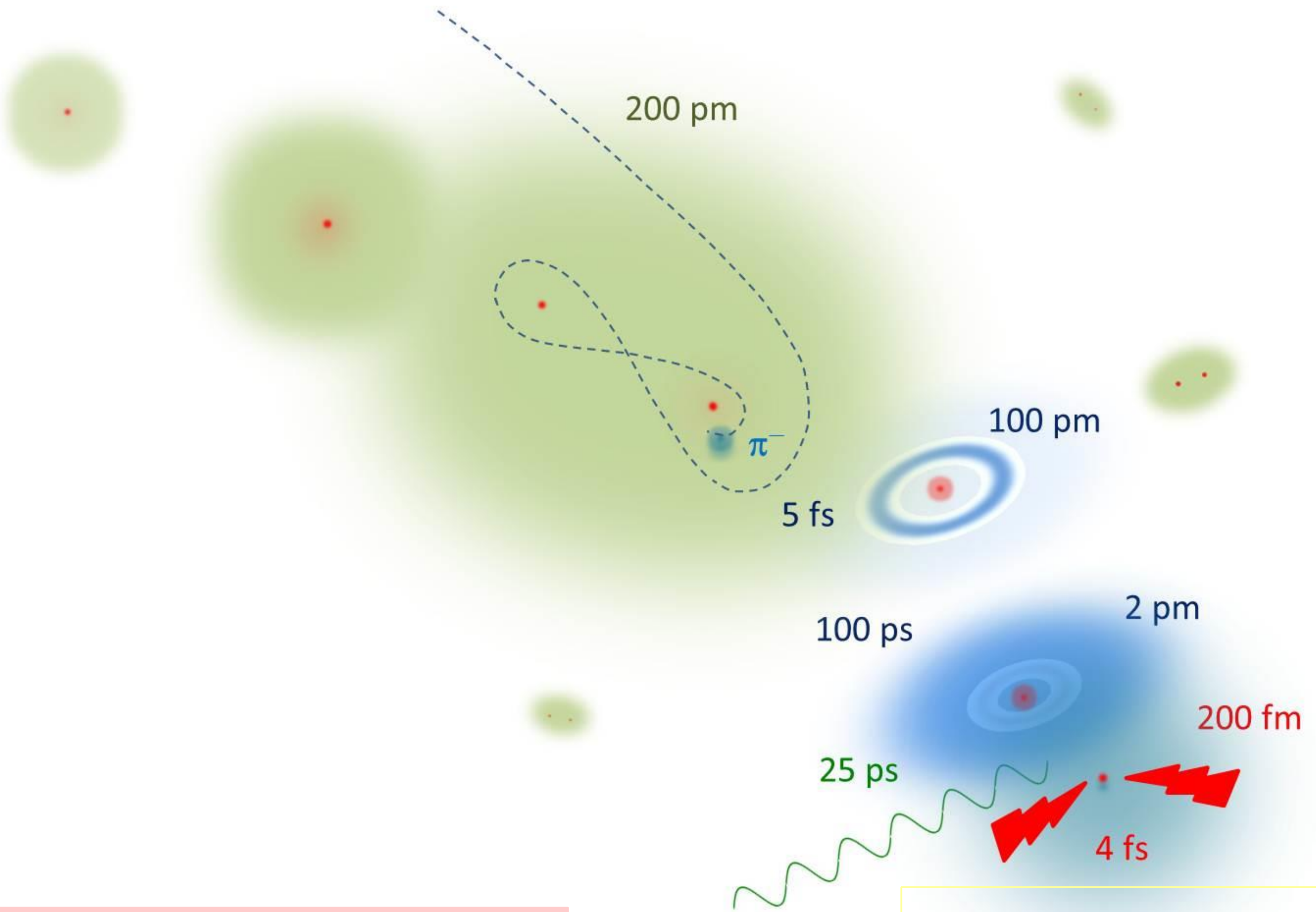
example $\Theta_B = 53°$
$\alpha = 37°$
$\sqrt{b} = 0.53$

advantage

no defocusing for $\Theta_B + \alpha \approx 90°$

ATOMIC CASCADE IN HYDROGEN

PIONIC OR ANTIPROTONIC HYDROGEN

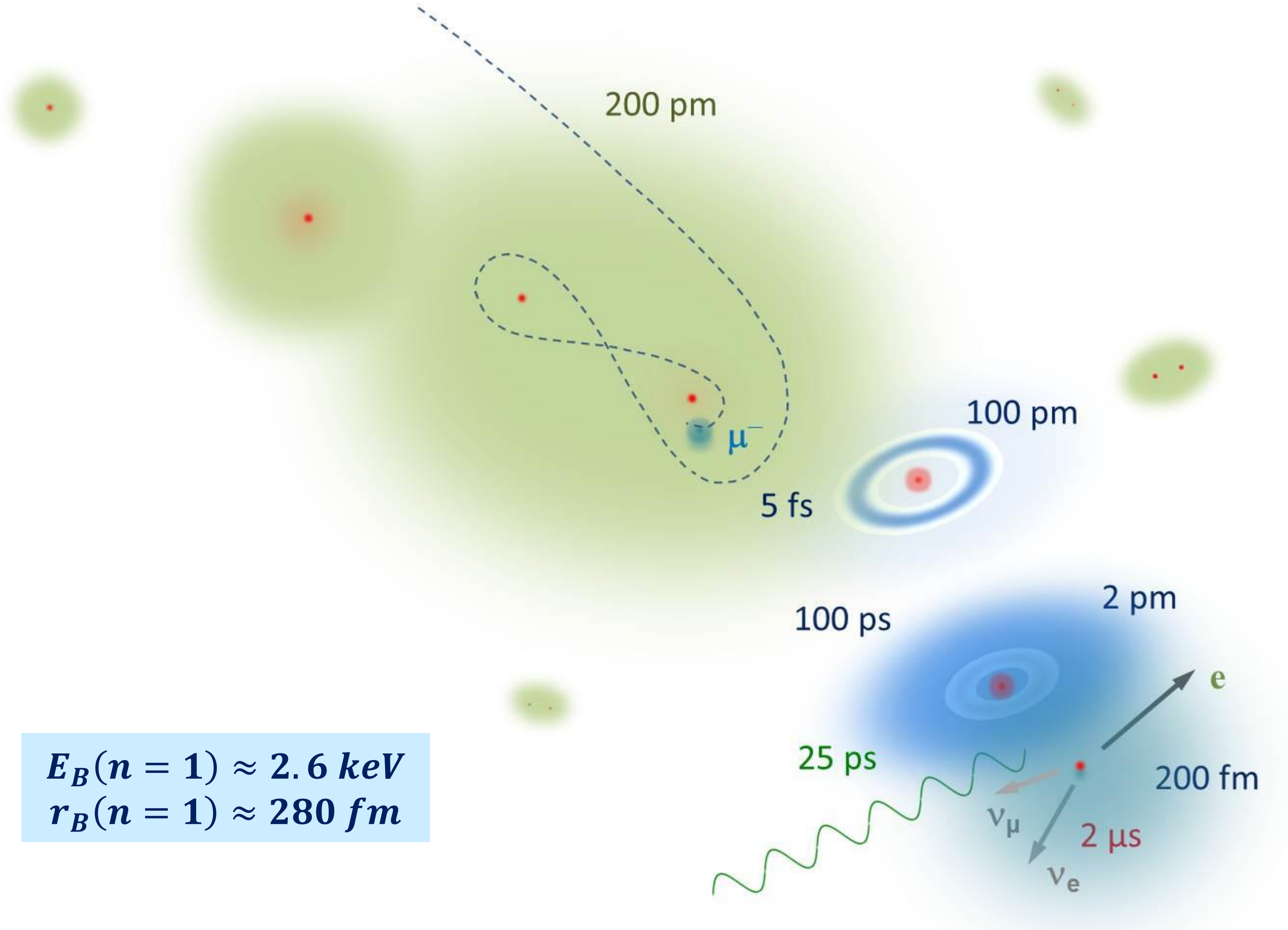


size and time scales for pions

$$\pi p \rightarrow \pi^0 + n \,/\, \gamma + n$$

$$\bar{p}p \rightarrow 5.5\,\pi \text{ in average}$$

MUONIC HYDROGEN



$$E_B(n = 1) \approx 2.6\ keV$$
$$r_B(n = 1) \approx 280\ fm$$

μp → eνν + p

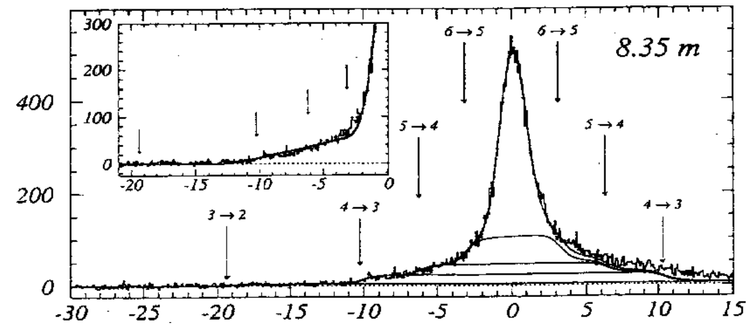
COULOMB DE-EXCITATION

$(\pi^- p)_n$ + H=H $\rightarrow$ $(\pi^- p)_{n'}$ + H + H + *kinetic energy*

$(\pi^- p)_{ns} \rightarrow \pi^0 n$

↑

moving neutron source



neutron – TOF / ns

MUONIC HYDROGEN

$(\pi^- p)_{np} \rightarrow (\pi^- p)_{1s} + \gamma$

↑

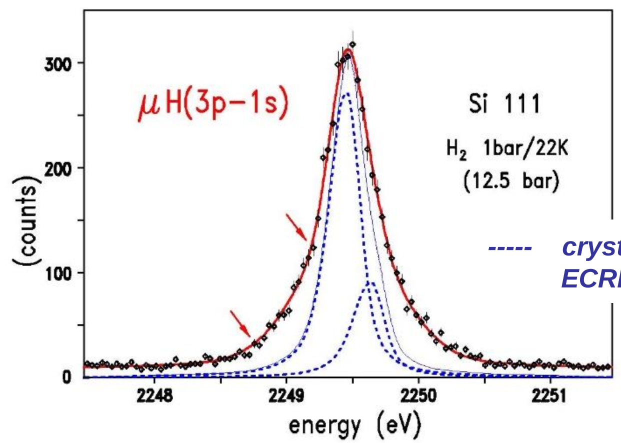
moving X-ray source

new cascade theory (ESCM)

Markushin, Jensen

new cross sections

Popov, Pomerantsev



----- *crystal response ECRIT 2004*

results - **model free determination of Coulomb Doppler contributions**

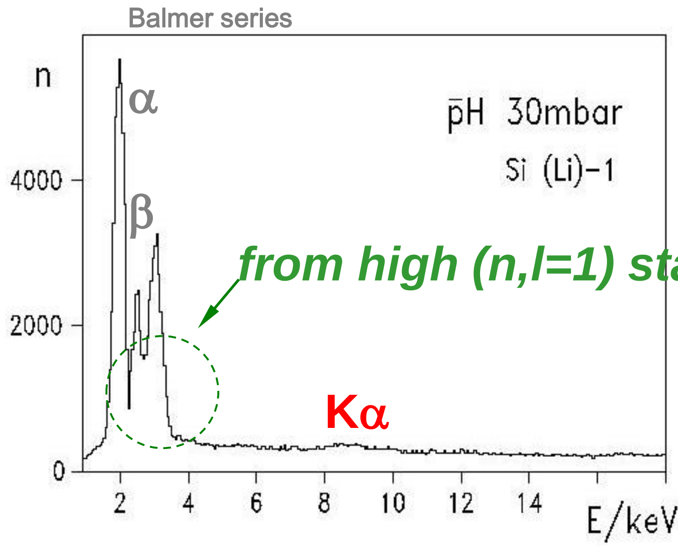
- **$^1S_0$ / $^3S_1$ population = 1 : (2.94 ± 0.24)** *statistical 1:3*

- **ΔE_{HFS} = 194 ± 12 meV** *QED 183 meV*

D. Covita, PhD thesis Coimbra (2008)
D. Covita et al.,
Phys. Rev. Lett.. 102 (2009) 023401

ANTIPROTONIC HYDROGEN - series limit

high np states populated in contrast to μH, πH



from high (n,l=1) states

Kα

$$n_{max} \approx \sqrt[3]{2n_f^2 / \left(\Delta E / E_{\infty - n_f}\right)}$$

$n_{max} \approx 40$ for $\Delta E = 300$ meV

n_{max} : resolvable state

n_f : final state

ΔE : energy resolution

$E_{\infty - n_f}$: transition energy from series limit

Coulomb de-excitation

state dependent !

OUTLOOK

$\bar{p}p$ $^1S_0$ / $^3S_1$

$\bar{p}d$ ground state

$\bar{p}p$, $\bar{p}d$ p-states

$\bar{p}A(N,Z)$

bound-state QED

capture and cascade

AD ?

+ FLAIR

↑ initial steps

↑ crystal spectrometer

antiproton „beams“

AD *MUSASHI* — *antiproton trap → DC extraction → gas cell*

direct measurements

FLAIR — *high intensity DC beams*

direct measurements + crystal spectrometer

future option — *traps and gas jets*

X-ray detector *direct measurement* — fast pnCCDs

→ pixel size 75 μm

MOS CCDs 3 frames / minute → 600 frames / s

crystal spectrometer

2 – 3 keV ultimate resolution — ΔE = 300* → 200 (100) meV

asymmetric cut crystals

10 keV „bad“ resolution — 300* → „1 eV“

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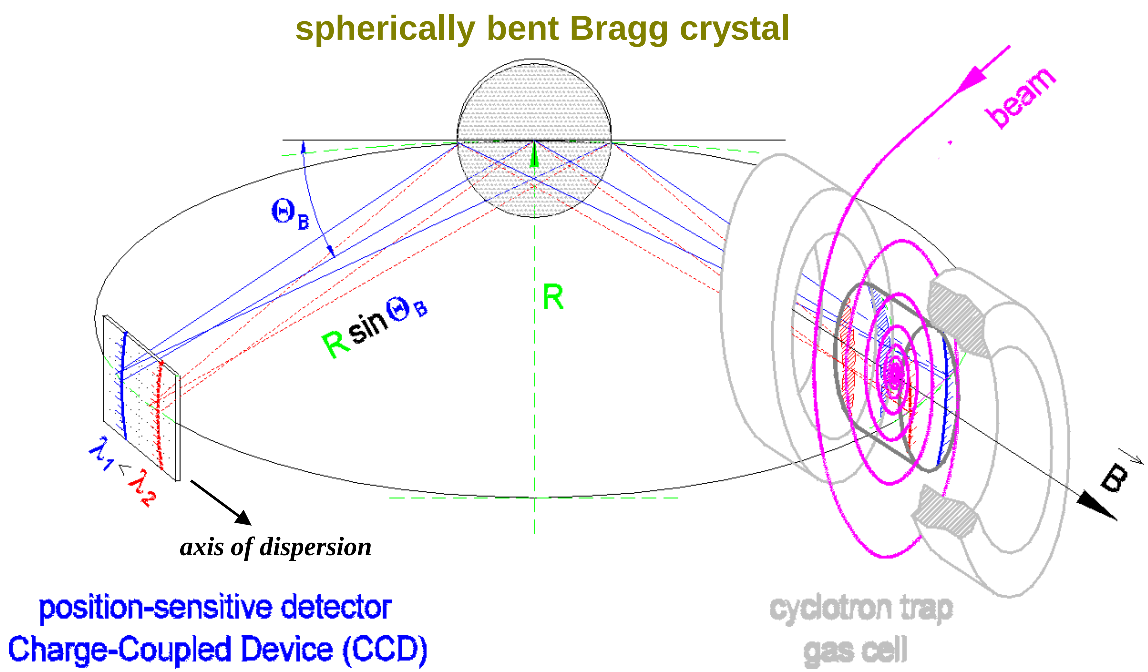
* PSI ECRIT

CRYSTAL SPECTROMETER JOHANN SET-UP



300 keV beam

replace cyclotron trap by gas cell

count rate	≈	**beam**	×	**stop efficiency**	×	**line yield**	×	**spectrometer efficiency**
	≈			ca. %	×	ca. %	×	10^{-8} - 10^{-6}
	≈					1 - 100 / hour		

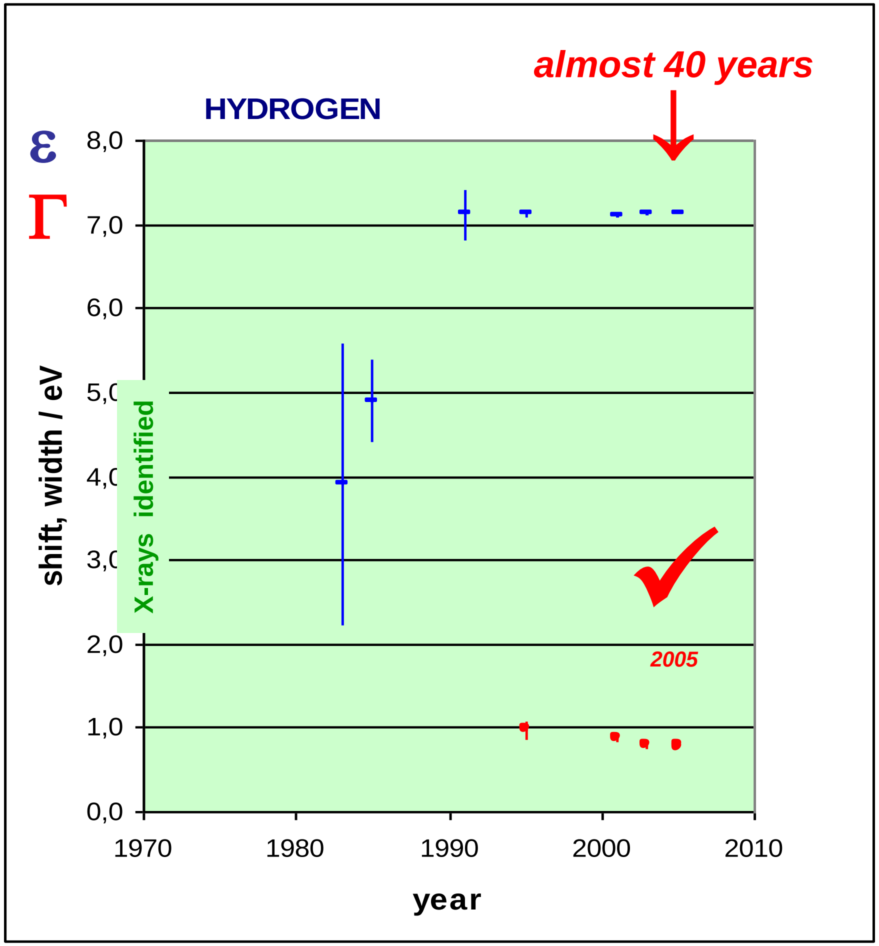
	ΔE	$\Delta\Omega \times \varepsilon$
fast CCD	300* → 150 eV	10^{-3}
crystal spectrometer *asymmetrically cut Bragg crystals*	300* → 150 meV	10^{-6}

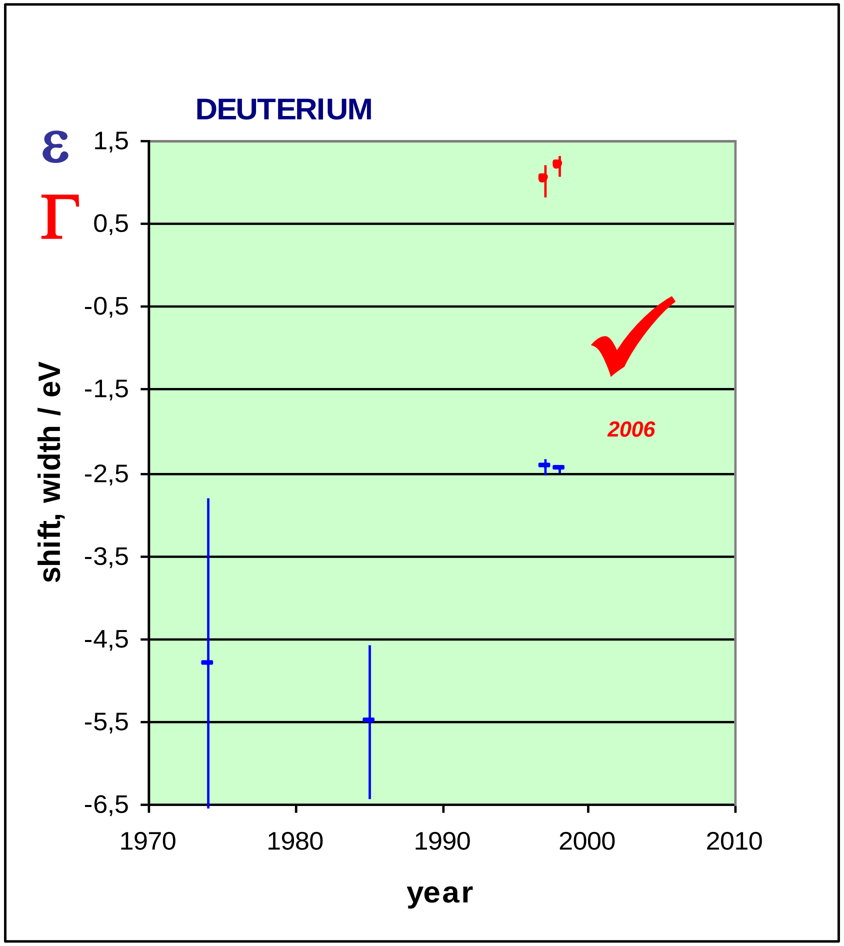
			yield	*counts*	$\bar{p}_{stopped}$		
$\bar{p}H$	$^1S_0 / {}^3S_1$	$K\alpha$	*1%*	*200 000*	$2 \cdot 10^{10}$		*CCD*
$\bar{p}D$		$K\alpha$	*0.1%*	*20 000*	$2 \cdot 10^{10}$		*CCD*
$\bar{p}H$	*2p HFS*	$L\alpha$	*50%*	*20 000*	$4 \cdot 10^{10}$		*cry spec*
$\bar{p}\ {}^{3,4}He$	*2p*	$L\alpha$	*25%***	*20 000*	$2 \cdot 10^{8}$	*1. step*	*CCD*
				5000	$1 \cdot 10^{10}$	*2. step*	*cry spec*

* PS 207
** 50% 3d annihilation

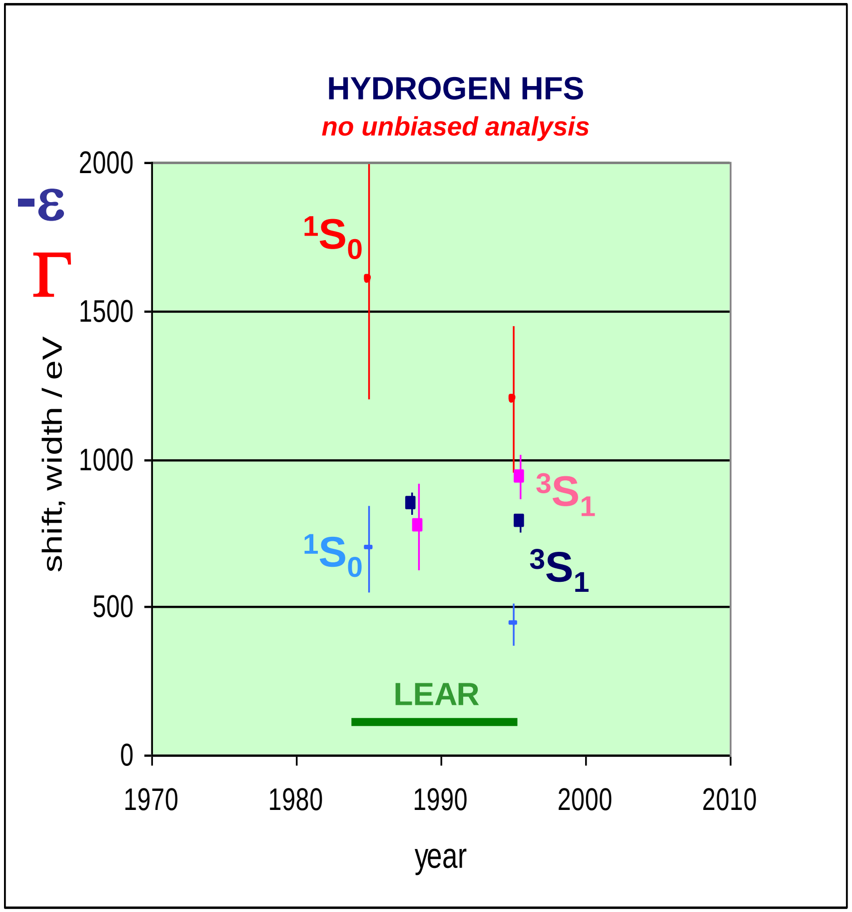
SUMMARY

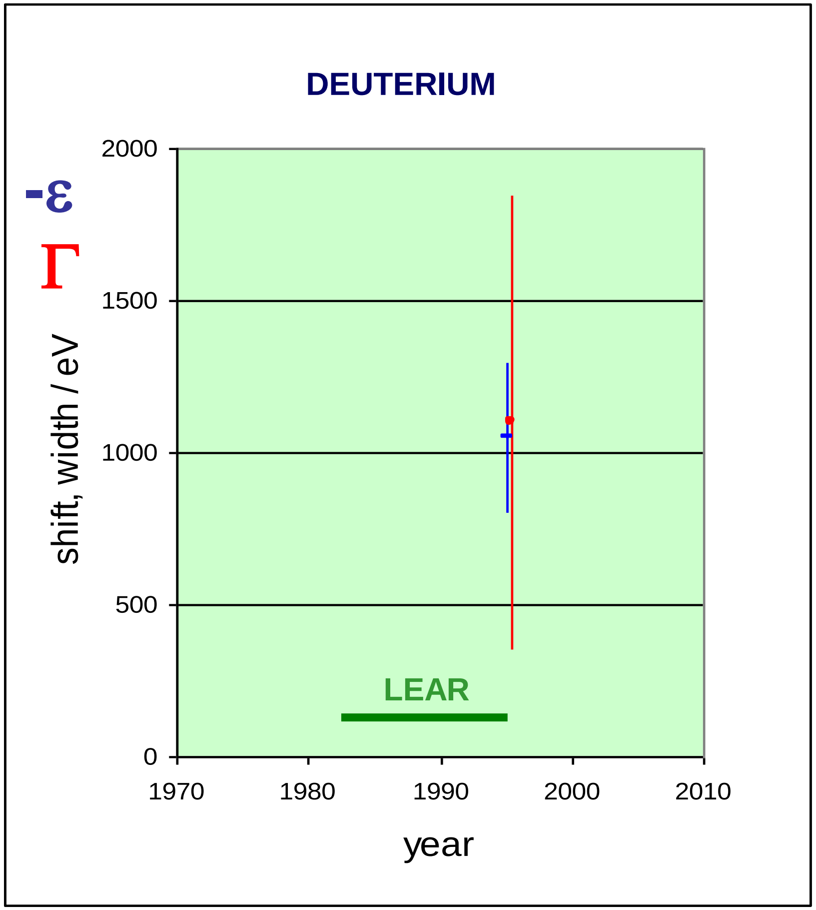
PIONIC HYDROGEN STORY





ANTIPROTONIC HYDROGEN STORY *s-wave*





still a lot to do !

THANK YOU