

EXOTIC ATOMS

25 years ultimate-resolution X-ray spectroscopy $\leq 10 \text{ keV}$

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Physics of fundamental Symmetries and Interactions 25.10.2019

- MOTIVATION \approx 1980
- EXOTIC ATOM
- EXPERIMENTAL APPROACH
- SOME RESULTS
- SUMMARY & OUTLOOK

CHARGED PION MASS

inconsistent results for $m_\pi \Rightarrow m_{\nu_\mu}$

- ν mass limits
- dark matter
- unstable ν
- requires $\approx 1\text{ppm}$

from

1) π^- exotic atoms solutions A and B with $\Delta = 15\text{ ppm}$

$$A \Rightarrow m_{\nu_\mu}^2 < 0!$$

Jeckelmann et al. NP A 457 (1986) 709, PL B 335 (1994) 326

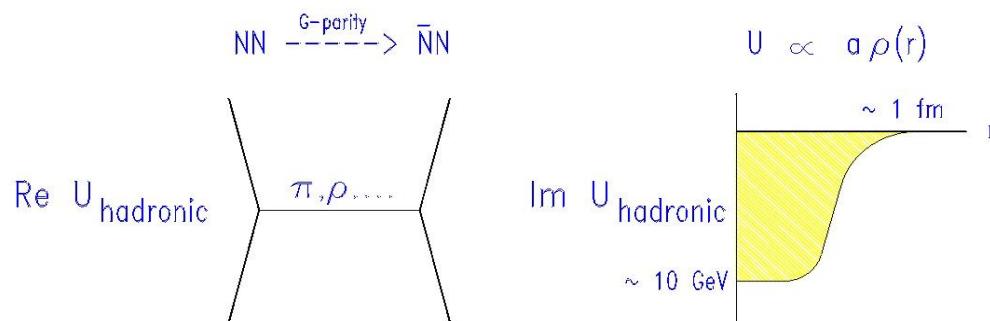
2) $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decay at rest

Assamagan et al. PR D 53 (1996) 6065

ANTINUCLEON - NUCLEON, ... , no microscopic theory

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

$U_{\text{hadronic}} = \text{meson exchange}$ + annihilation
 scattering: $\bar{p}p \leftrightarrow \bar{p}p$ $\bar{p}p \rightarrow \text{mesons}$
 $\bar{p}p \leftrightarrow \bar{n}n$



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

spin-spin "deuteron,, - problem
spin-orbit effects

no microscopic theory

☞ **check in particular spin dependence !**

PIONS, NUCLEONS - INTERACTION in terms of QCD

CHIRAL PERTURBATION THEORY (χ PT), ...

$\Delta_{\text{theory}} \approx \% !!!$

$\pi N \leftrightarrow \pi N$

scattering length

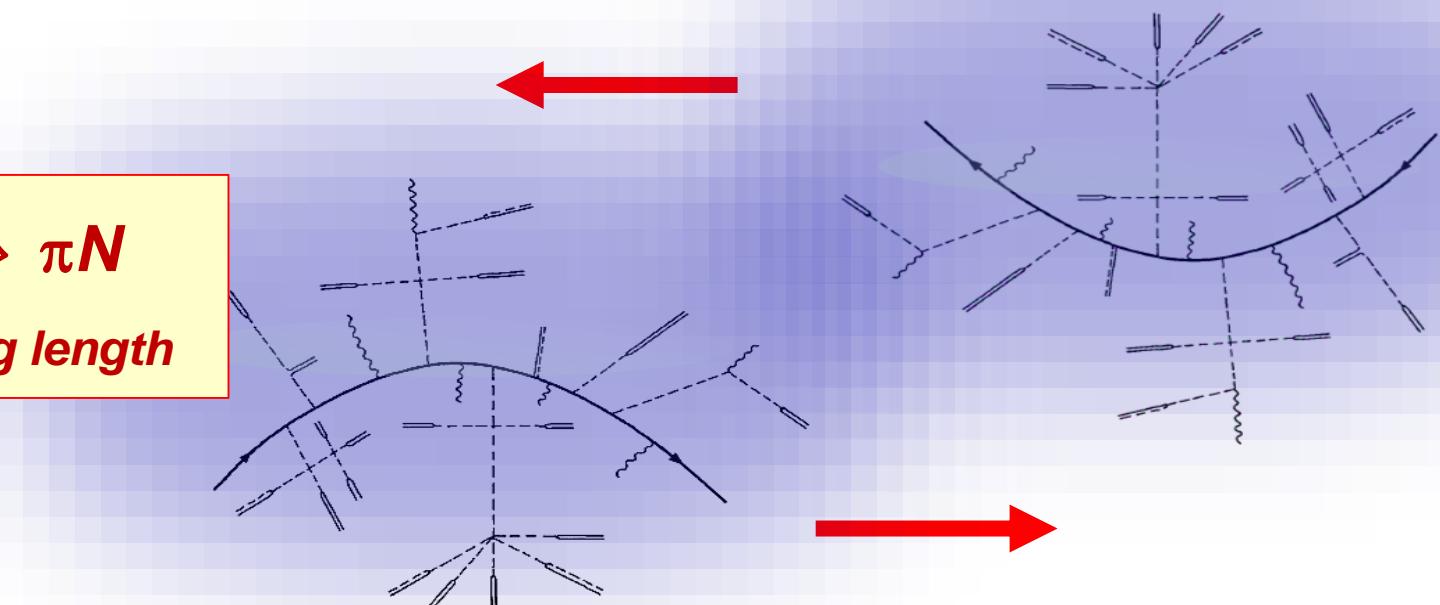


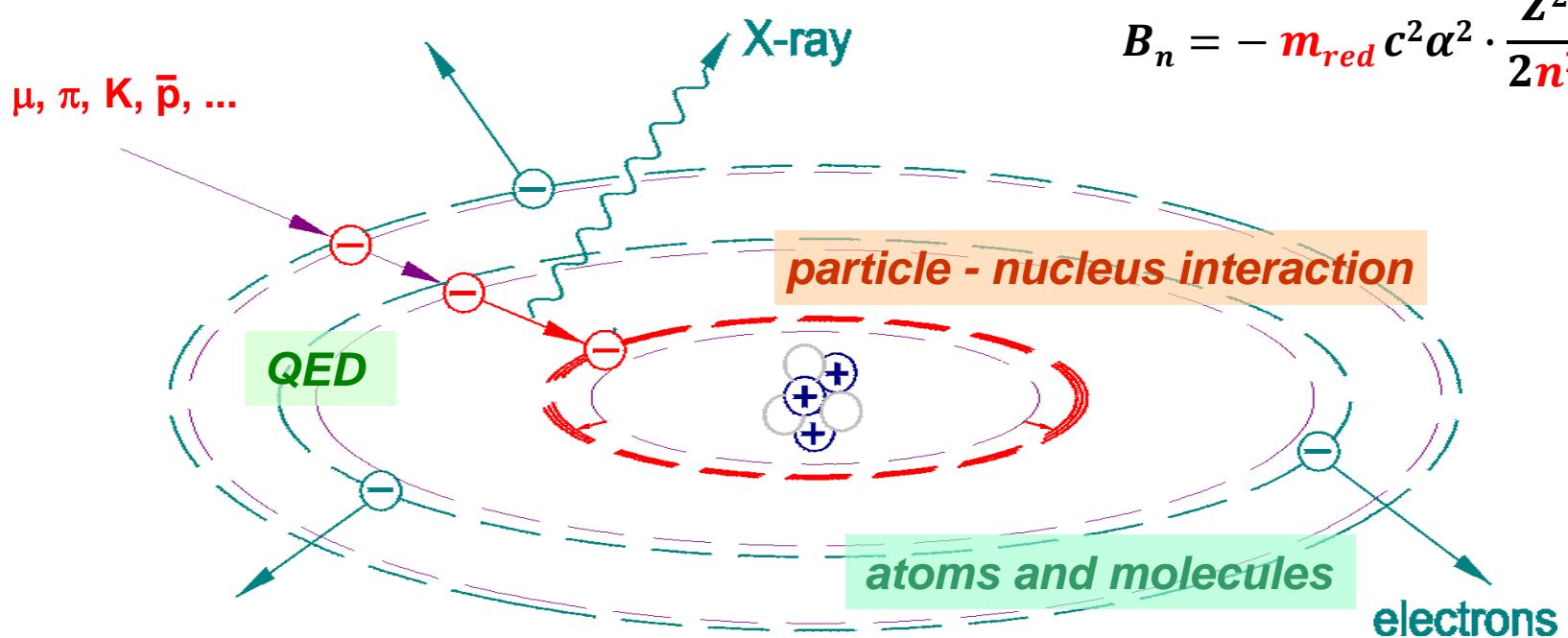
Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ————— nucleon; - - - pions; ~~~~ vector current; = = = axial vector current; - - pseudoscalar density; —— scalar density.

J. Gasser et al., Nucleons with chiral loops, Nucl. Phys. B307, 779 (1988)

LABORATORY: EXOTIC ATOMS

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

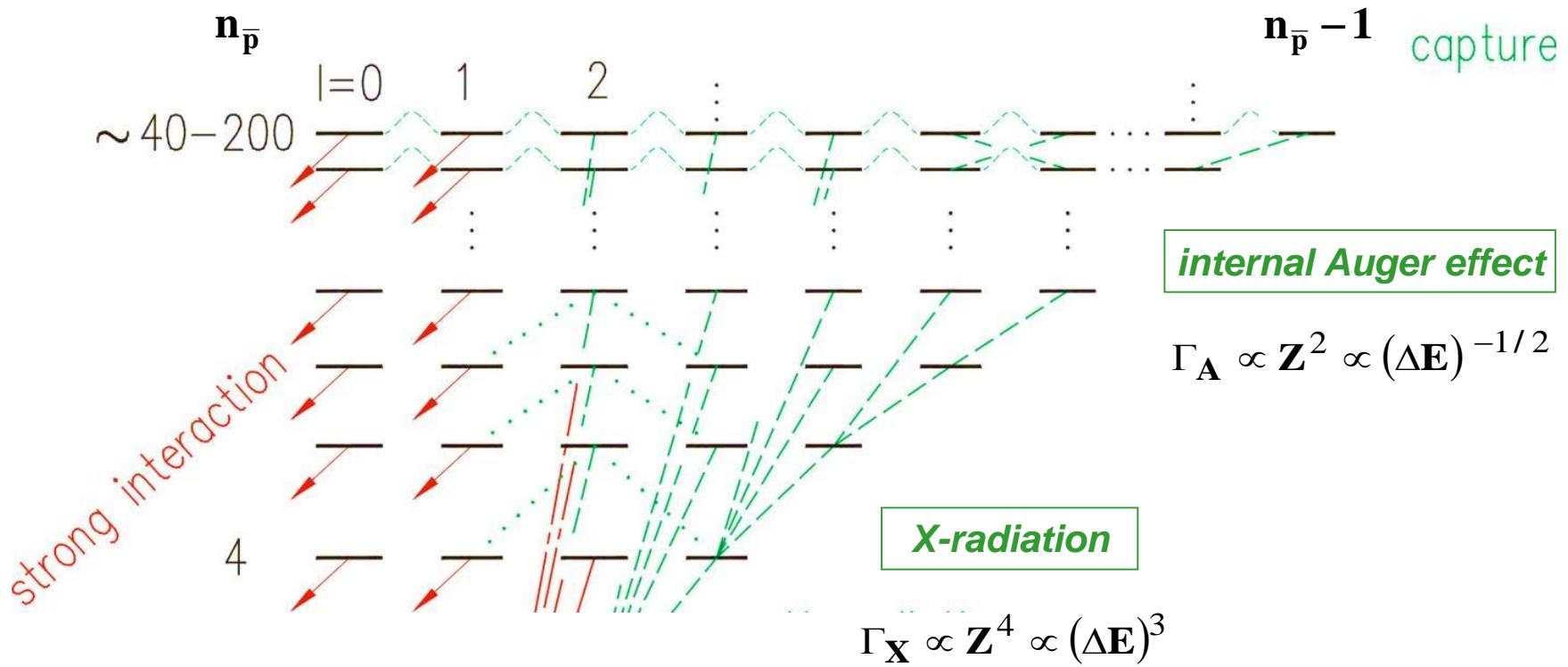
$$B_n = - m_{red} c^2 \alpha^2 \cdot \frac{Z^2}{2n^2}$$



experiment X-ray energy, line width, and intensity

- MOTIVATION
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CAPTURE and DE - EXCITATION



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

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

different de-excitation cascades for

leptons

μ

pure electromagnetic cascade

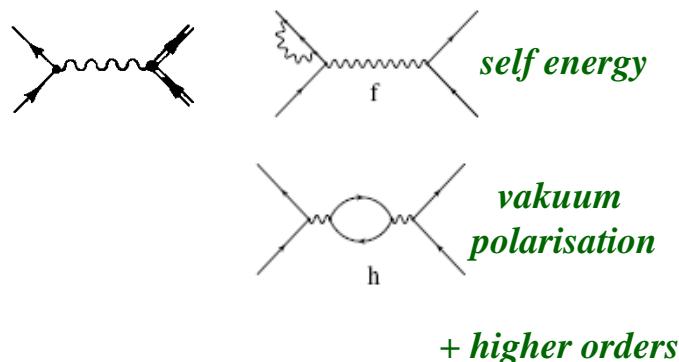
hadrons

π, K, p, \dots

... + nuclear reactions for low l - states

ATOMIC BINDING ENERGY

$$V_{total} = -\frac{Ze^2}{r} + \Delta V_{QED} + V_{strong\ interaction}$$

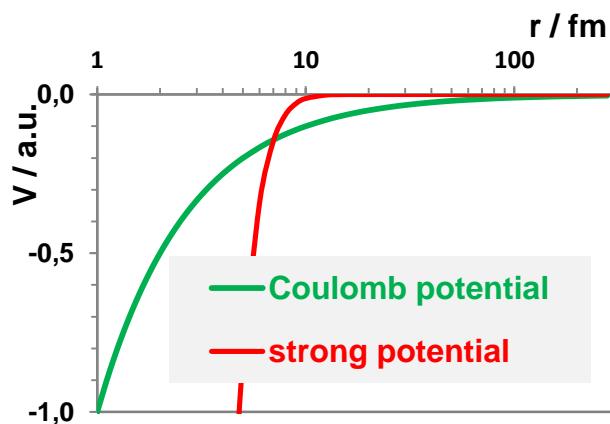


Yukawa potential

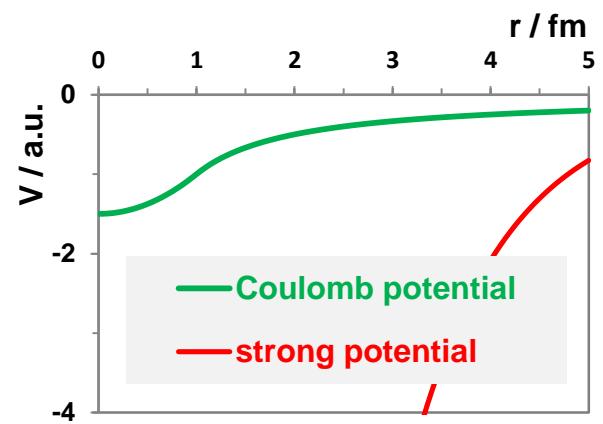
$$V_{strong} = g^2 \cdot \frac{e^{-\mu r}}{r}$$

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

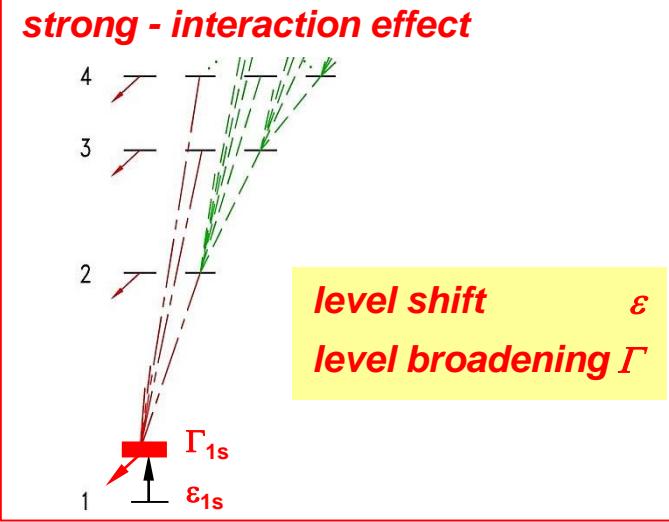
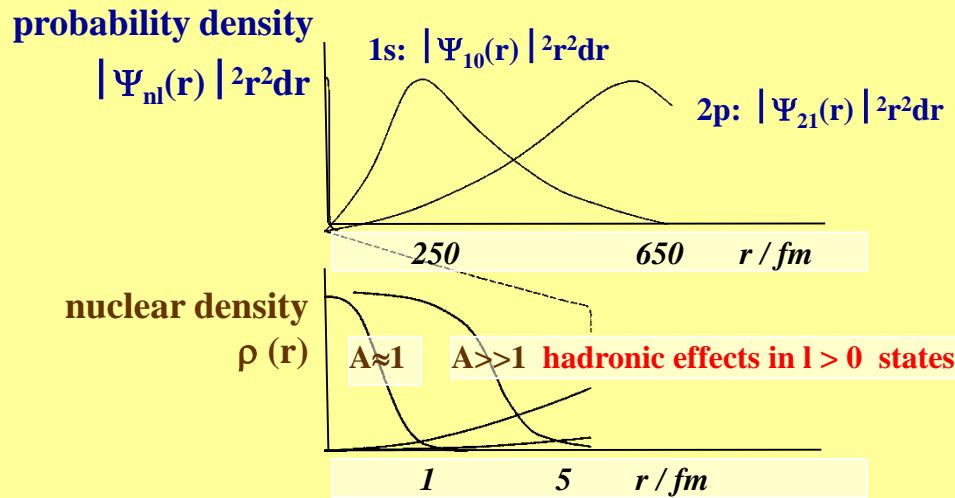
long range



short range



HADRONIC ATOM



$$\Delta E_{\text{strong}} = \epsilon - i \frac{\Gamma}{2} = \int |\Psi_{nl}|^2 |V_{\text{strong}}| dV \propto a_l \in \mathbb{C}$$

ΔE_{strong} reduces to complex numbers

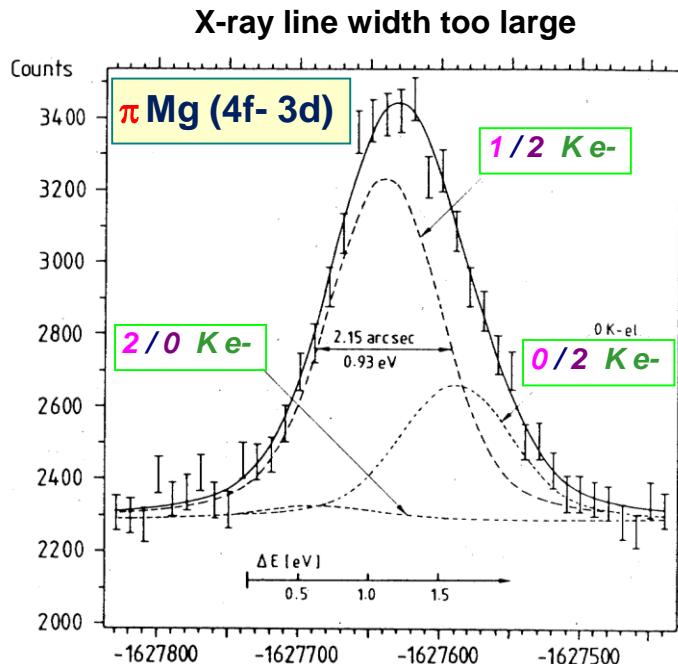
- scattering length a_s for s-waves
- scattering volume a_p for p-waves

- MOTIVATION
- EXOTIC ATOM
- EXPERIMENTAL APPROACH
- SOME RESULTS
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Starting conditions

- *low Z muonic/pionic atoms*
- *antiprotonic hydrogen*
- *pionic hydrogen*

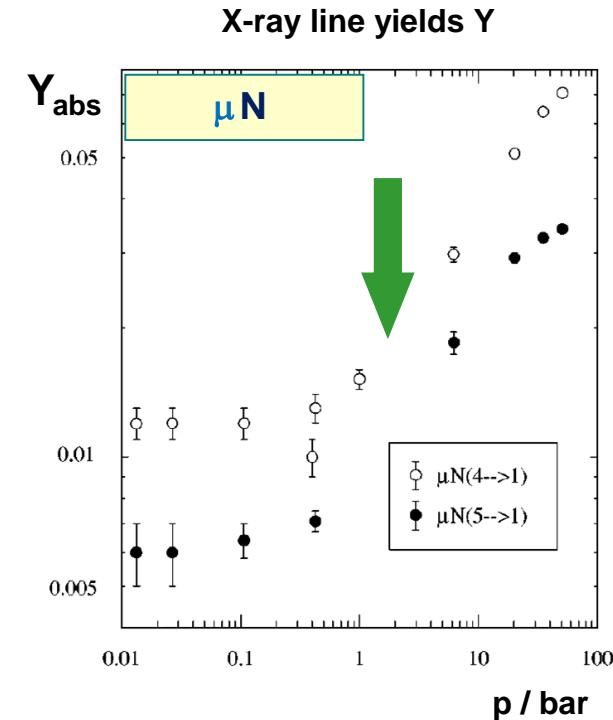
CHARGED PION MASS



Jeckelmann et al. NP A 457 (1986) 709
PL B 335 (1994) 326

How many K electrons ? 2!

ΔE due to electron screening

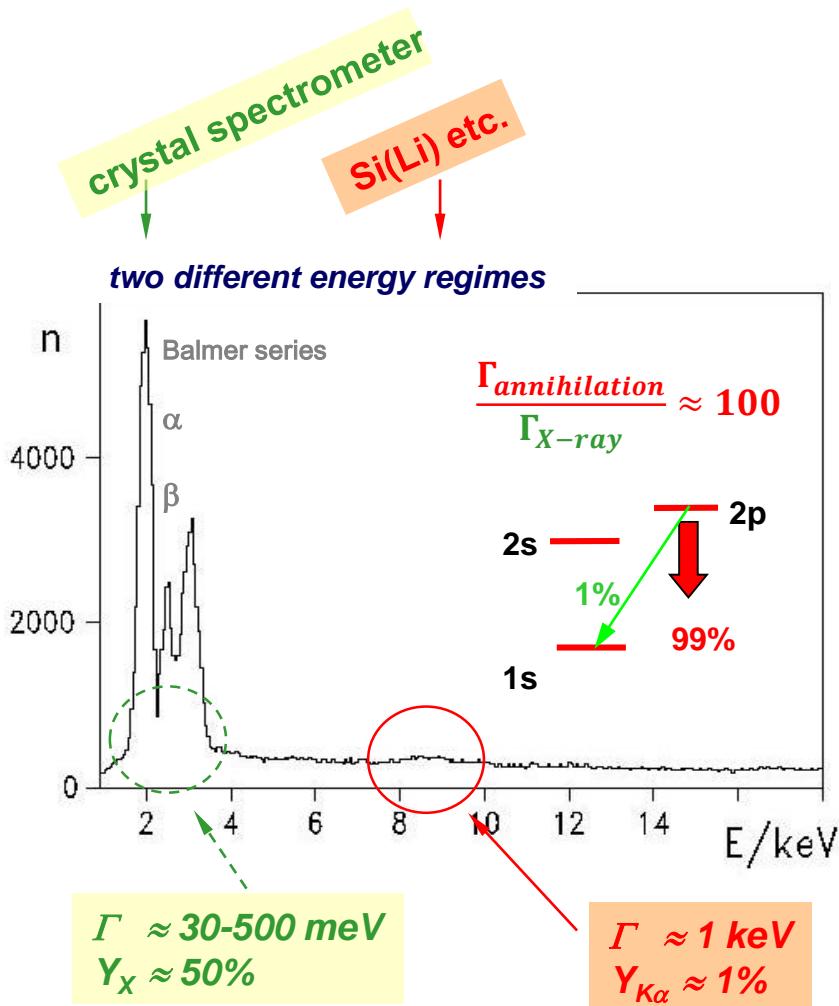


R. Bacher et al., Phys. Rev. Lett. 54 (1985) 2087
P. Ehrhart et al., Z. Phys. A 311 (1983) 259
K. Kirch et al., Phys. Rev. A 39 (1999) 3375

change due to electron refilling
internal Auger emission very fast

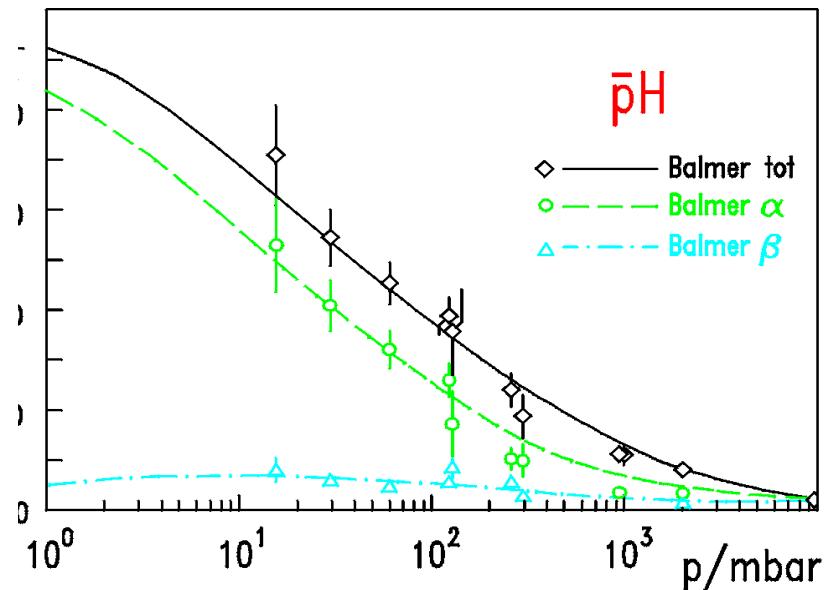
ANTIPROTONIC HYDROGEN

Lyman and Balmer series



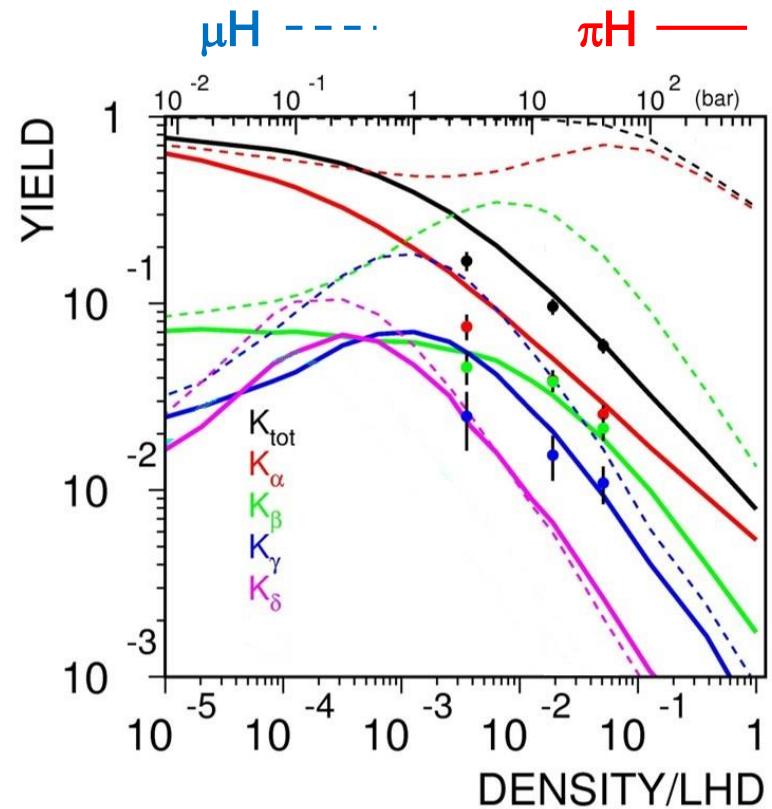
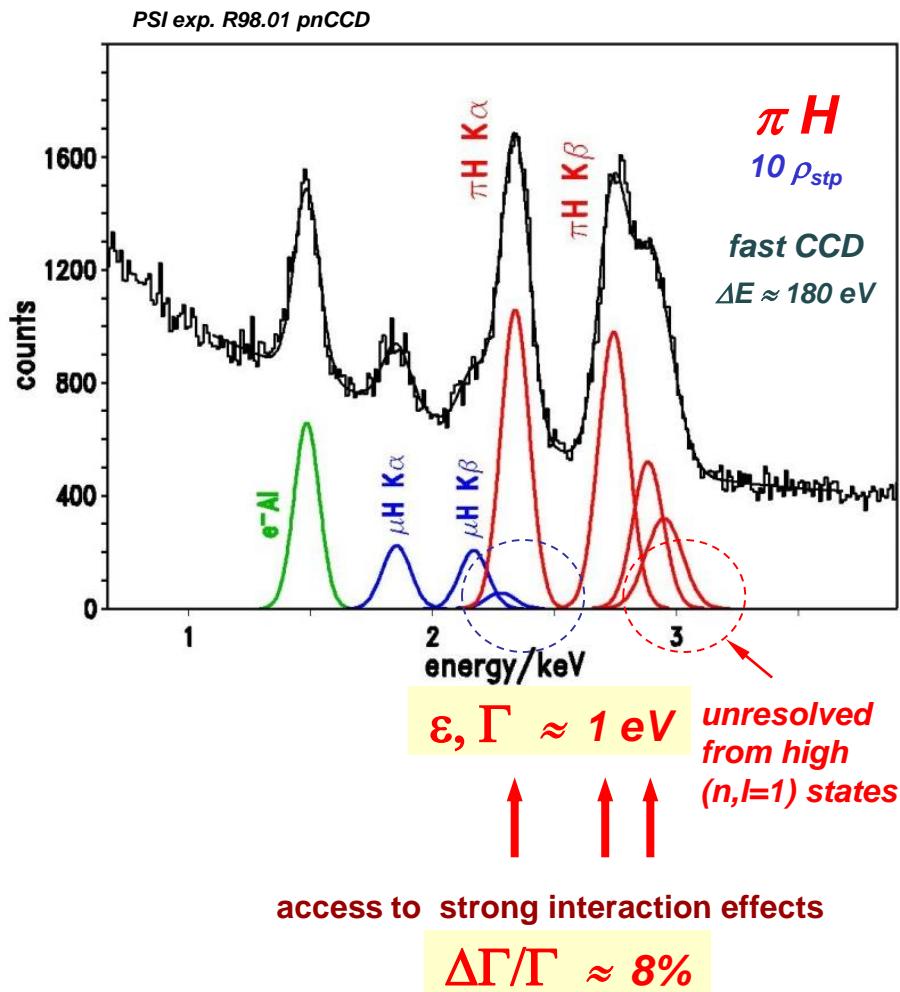
in addition

LINE YIELDS strong density dependence



PIONIC and MUONIC HYDROGEN

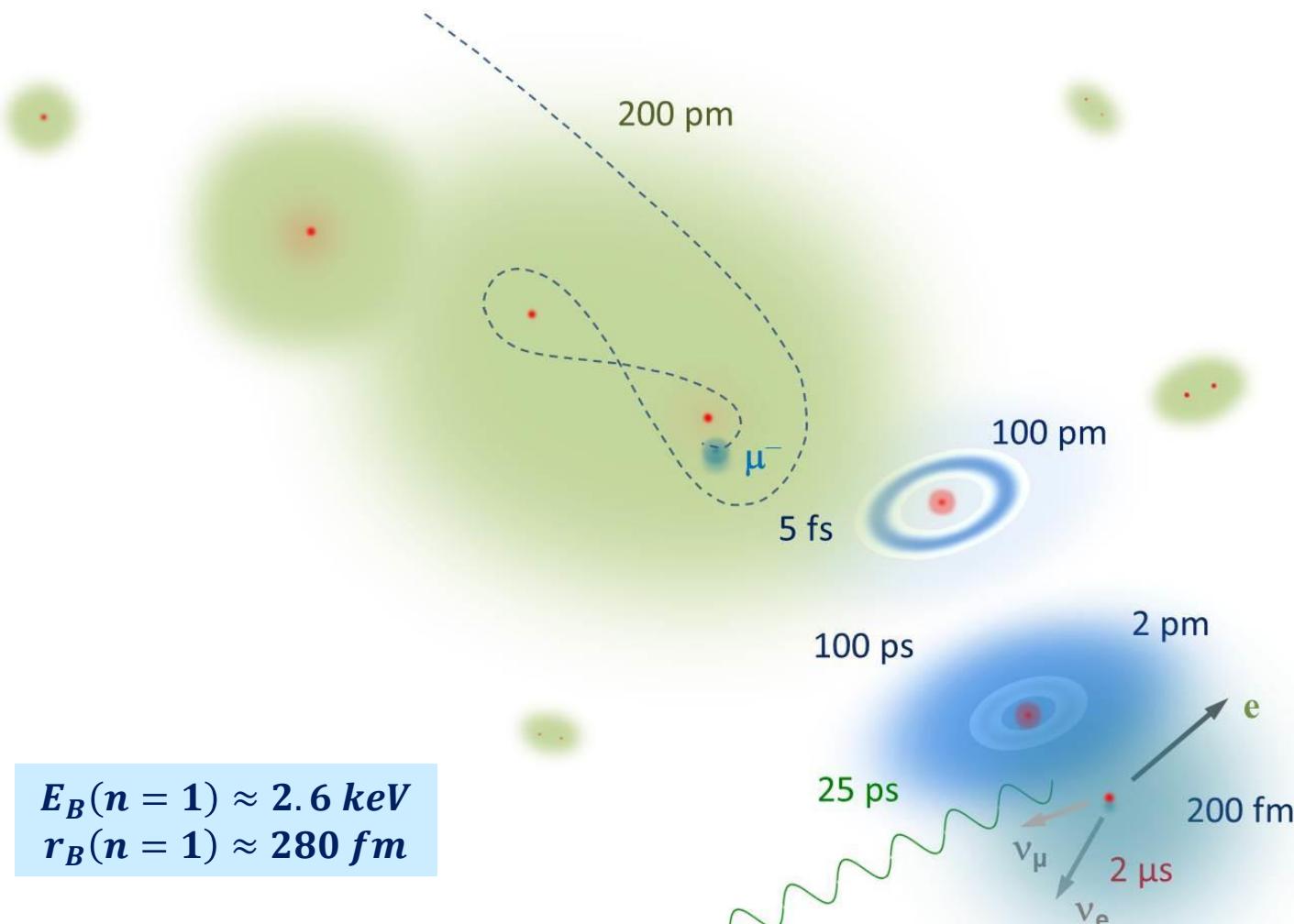
only Lyman series



data:
A.J. Rusi el Hassani et al., Z. Phys. A 351, 113 (1995)

cascade calculation:
V. E. Markushin and T.S. Jensen, Hyperfine Int. 138 (2001) 71

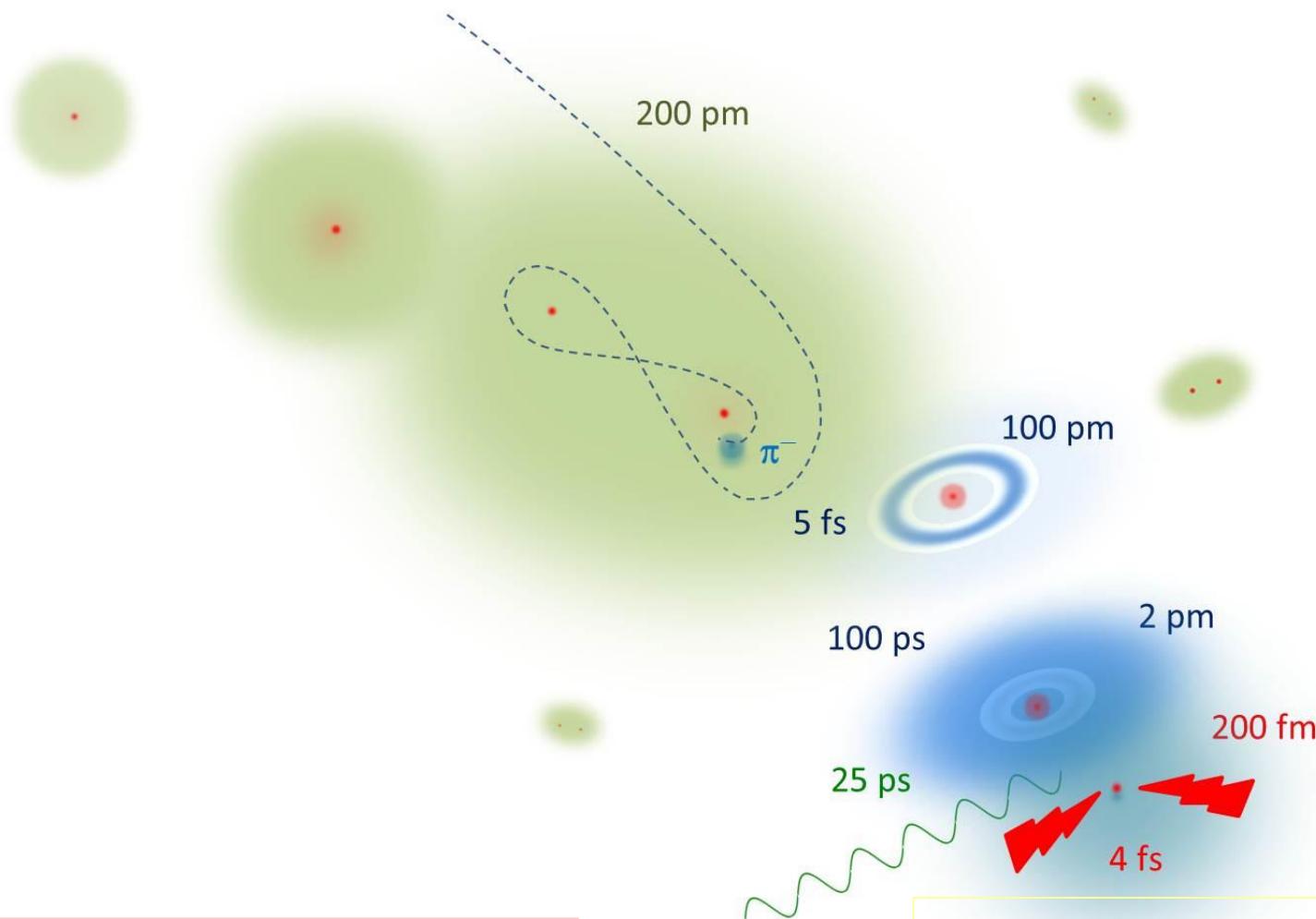
MUONIC HYDROGEN



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



PIONIC OR ANTIPIROTOMIC HYDROGEN



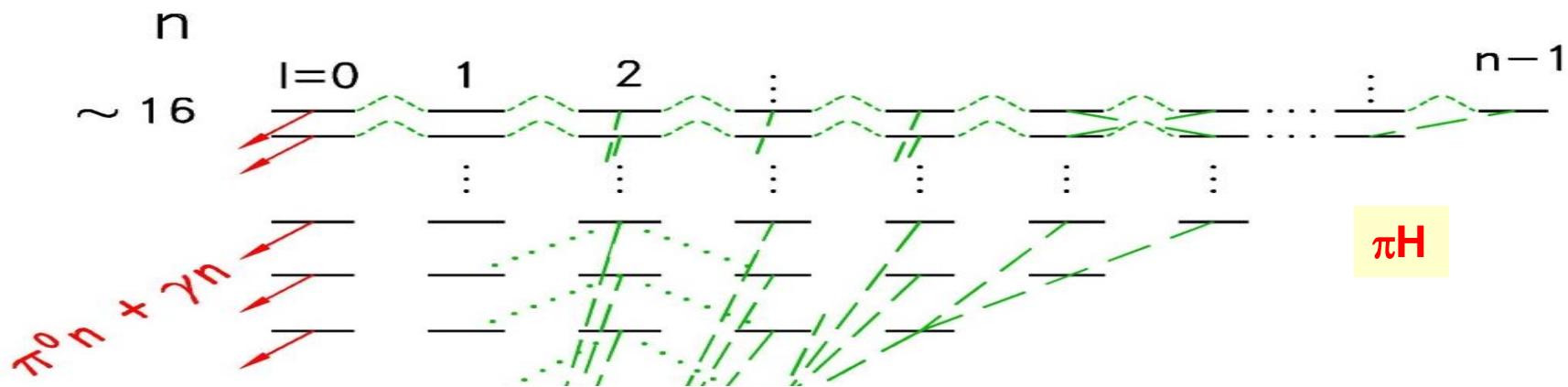
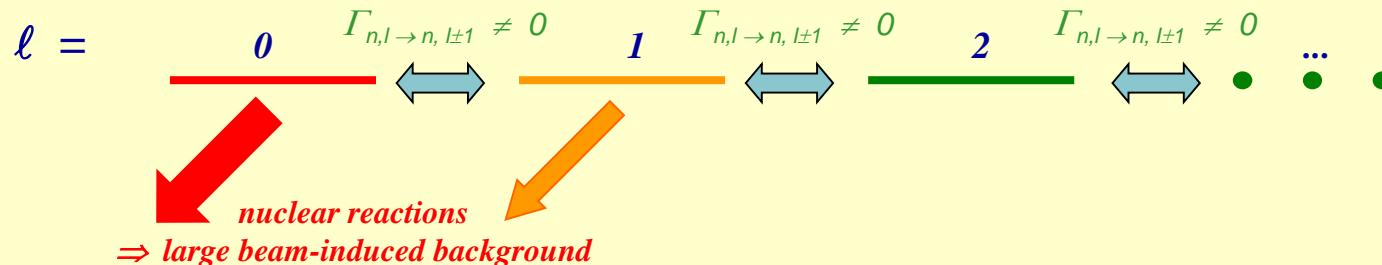
size and time scales for pions



STARK - MIXING

strong density dependence of yields for Z = 1 (Z=2)

collisions → electric field → mixing of l states Z = 1 (Z=2)



$\bar{p}H \Rightarrow$ nuclear reactions in s and p states

$\pi H \Rightarrow$ nuclear reactions in s states

$\mu H \Rightarrow$ muons come back from s states ⇒ $Y_{\mu H} \gg Y_{\pi H}$

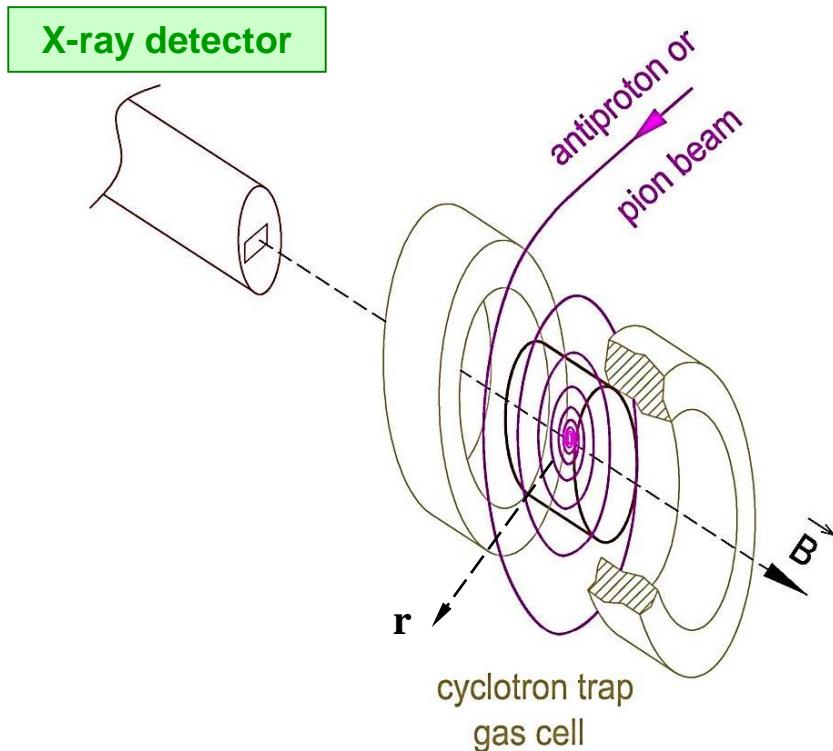
EXPERIMENT

*How to produce a suitable X-ray source
=*
many of exotic atoms?

How to achieve the ultimate resolution ?

CYCLOTRON TRAP

concentrates particles



"wind up" range curve

in a (weakly) focusing magnetic field

$$n = -\frac{\frac{\partial B}{\partial r}}{\frac{B}{r}} < 1 \quad \text{field index}$$

increase in stop density

compared to a linear stop arrangement

pions (PSI) $\times 200$

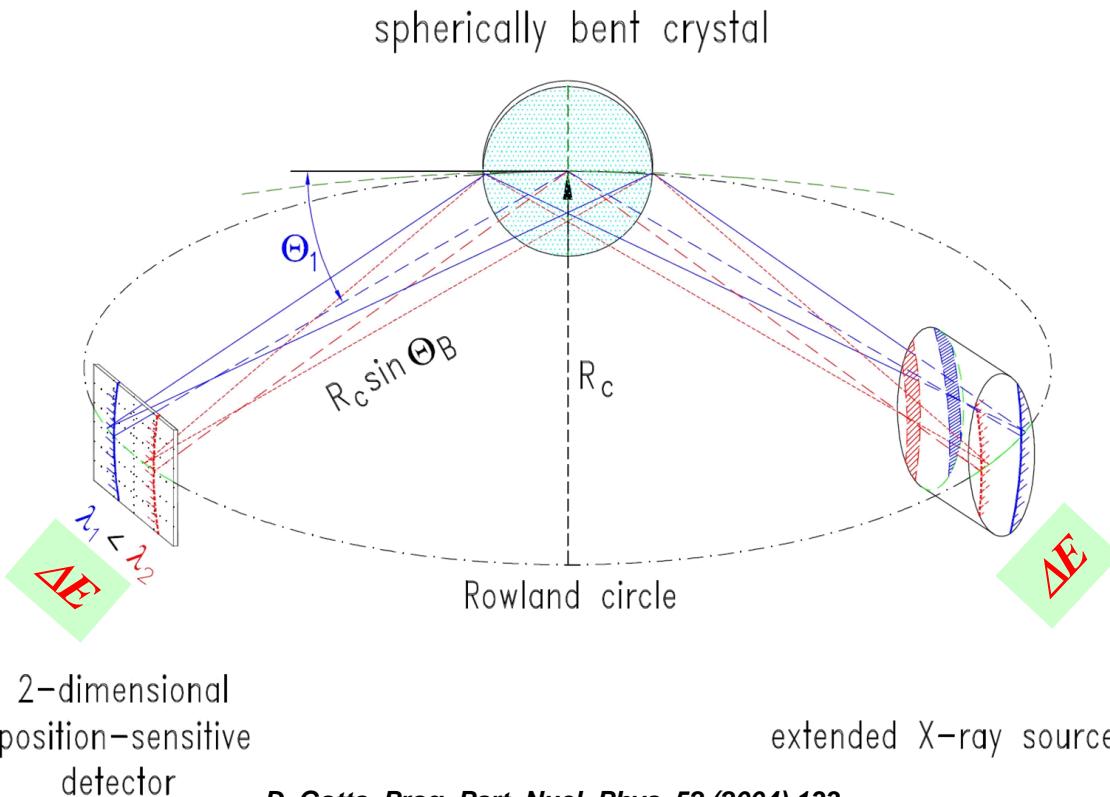
antiprotons (LEAR) $\times 10^6$

⇒ high X-ray line yields

⇒ bright X-ray source

JOHANN-TYPE CRYSTAL SPECTROMETER

simultaneous measurement of ΔE



$$\text{Bragg law} \quad n\lambda = 2d \cdot \sin\Theta_B$$

focussing conditions

horizontal $R_c \cdot \sin\Theta_B$ ✓

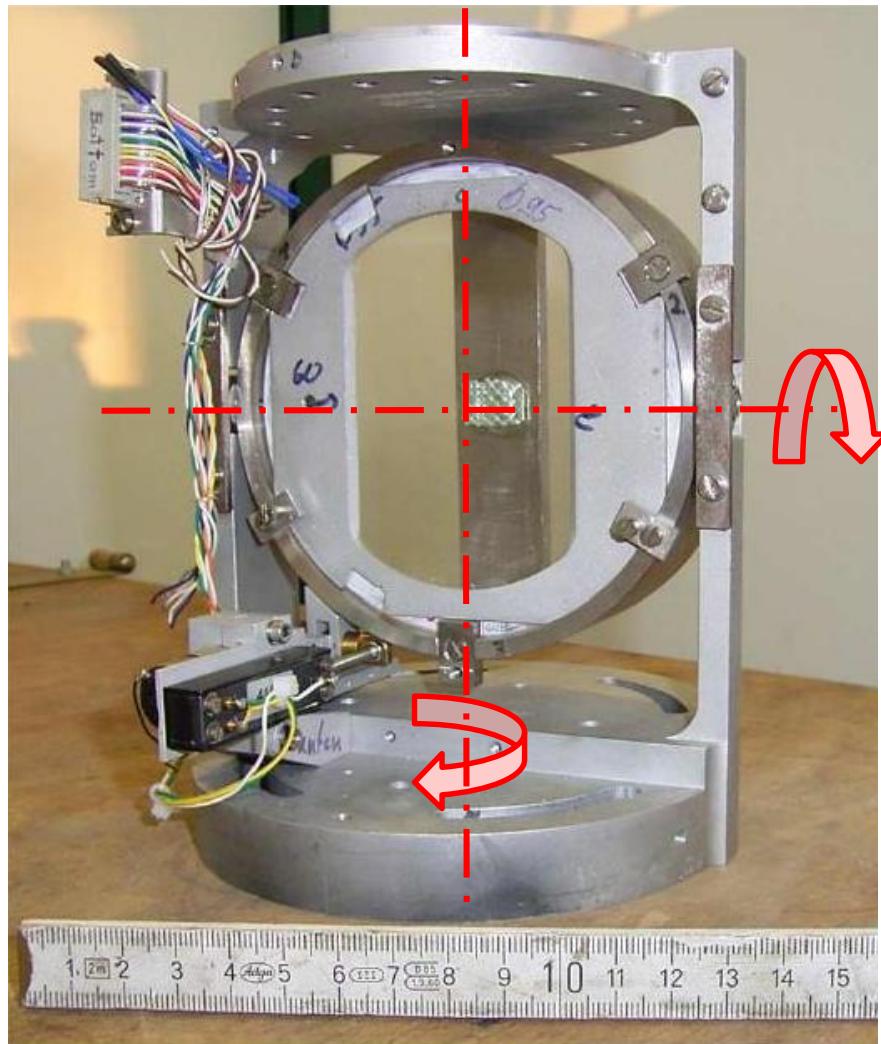
vertical $R_c \cdot \sin^2\Theta_B$
usually dismissed

angular dispersion

sym. plane $\frac{dE}{d\Theta} = -\frac{E}{\tan \Theta_B}$

BRAGG CRYSTALS

quartz or silicon



quartz (10-1)

$$R_c = (2982.6 \pm 0.4) \text{ mm}$$

quartz disk

thickness 0.2 mm

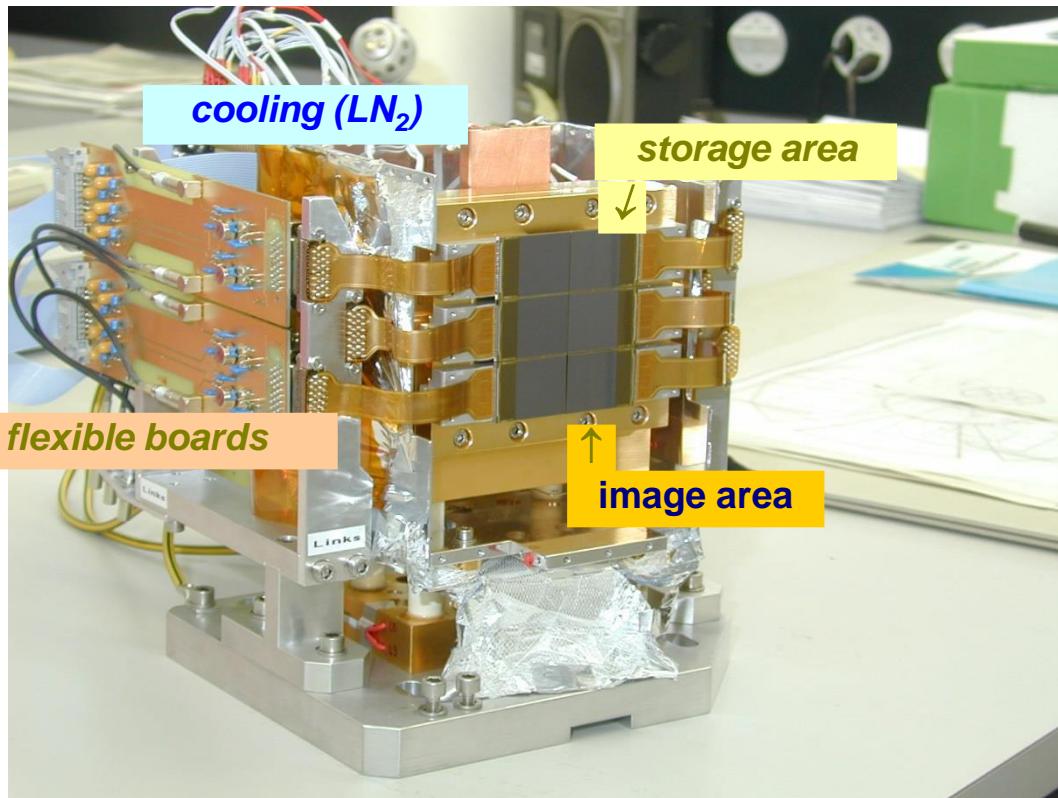
diameter 10 mm

attachment glueless

support glas lense $\phi 120 \text{ mm} \times 30 \text{ mm}$

2-DIM. POSITION-SENSITIVE DETECTOR

2×3 charge-coupled device (CCD) array



$x \times y: 600 \times 600$ pixels each

pixel size $40 \mu\text{m} \times 40 \mu\text{m}$

frame transfer ≈ 10 ms

data processing 2.4 s

operates at -100°C

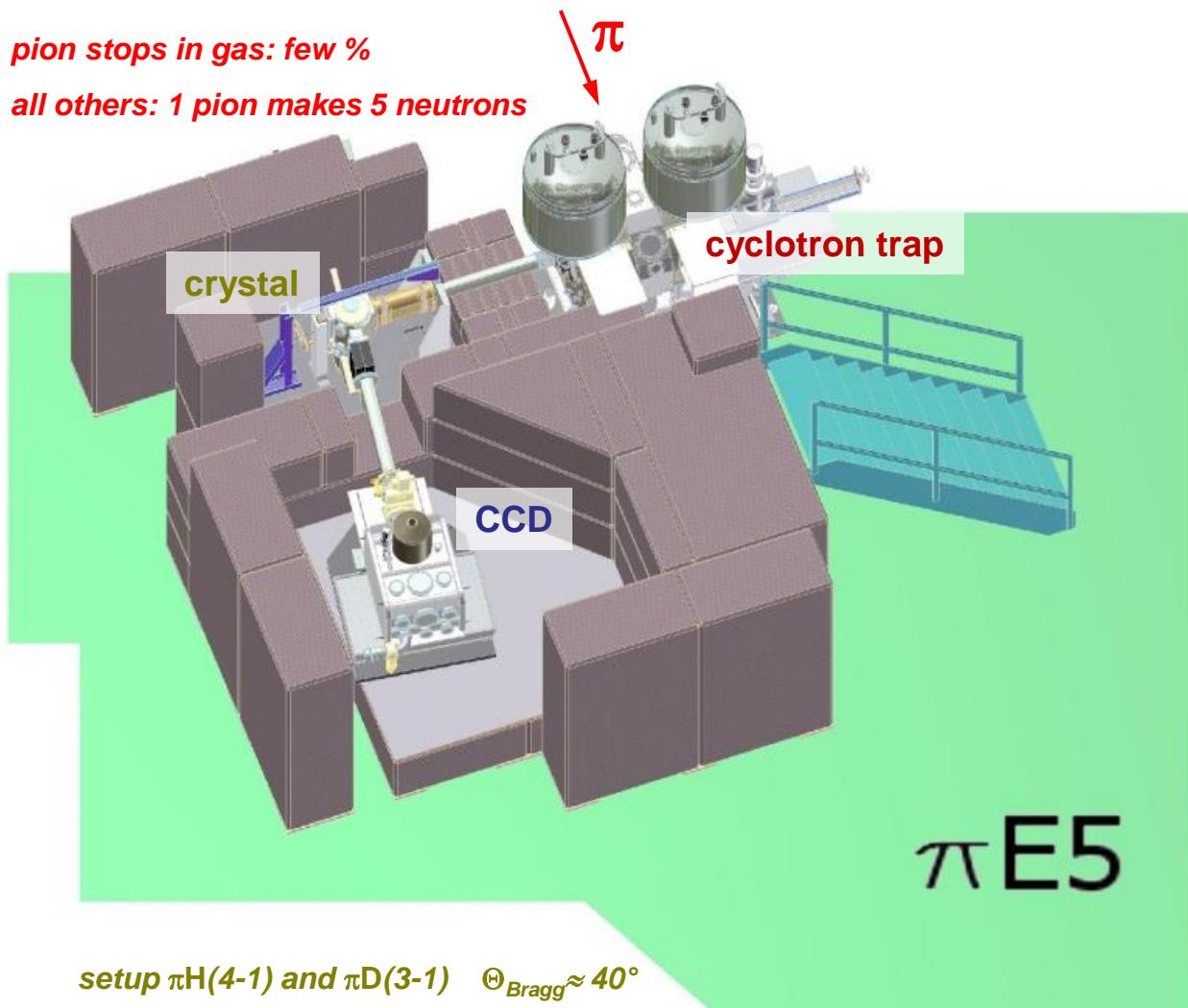
$\Delta E \approx 150$ eV @ 4 keV

$\varepsilon_{\text{q.e.}} \approx 90\%$

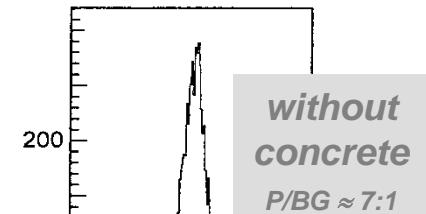
N. Nelms et al., Nucl. Instr. Meth. 484 (2002) 419

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

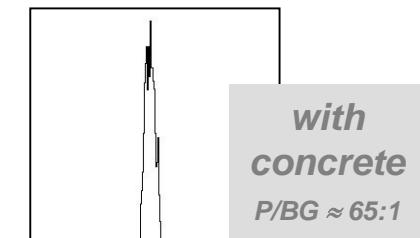
TYPICAL SET-UP at PSI



pionic hydrogen



peak/background $\times 10$



0
background reduction II

- MOTIVATION
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- **SOME RESULTS**
- SUMMARY & OUTLOOK

CHARGED PION MASS

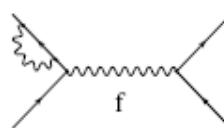
ATOMIC BINDING ENERGY

$$E_B = E_{\text{Coulomb}}$$

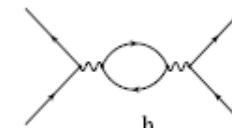
$$-\frac{Ze}{r}$$

QED calculations
± 1 meV

$$+ \Delta E_{\text{QED}}$$

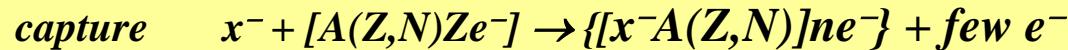


self energy



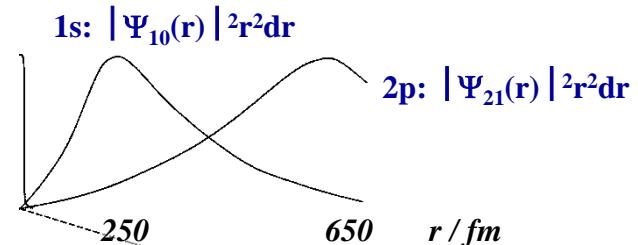
vakuum polarisation + higher orders

$$+ \Delta E_{\text{screening}}$$



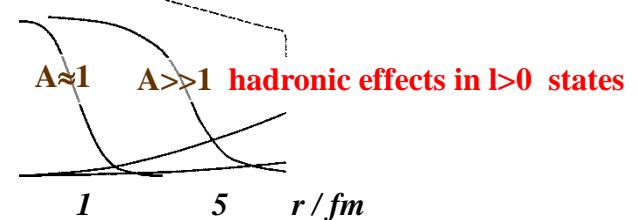
$$+ \Delta E_{\text{finite size}}$$

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



$$+ \Delta E_{\text{strong interaction}}$$

nuclear density
 $\rho(r)$



ATOMIC BINDING ENERGY

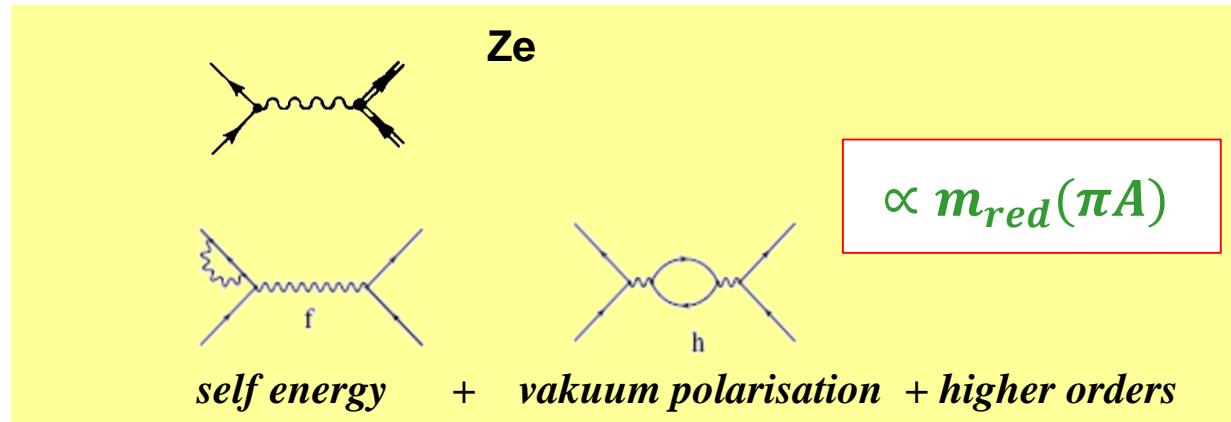
$$E_B = E_{\text{Coulomb}}$$

$$+ \Delta E_{\text{QED}}$$

~~$$+ \Delta E_{\text{screening}}$$~~

$$+ \Delta E_{\text{finite size}}$$

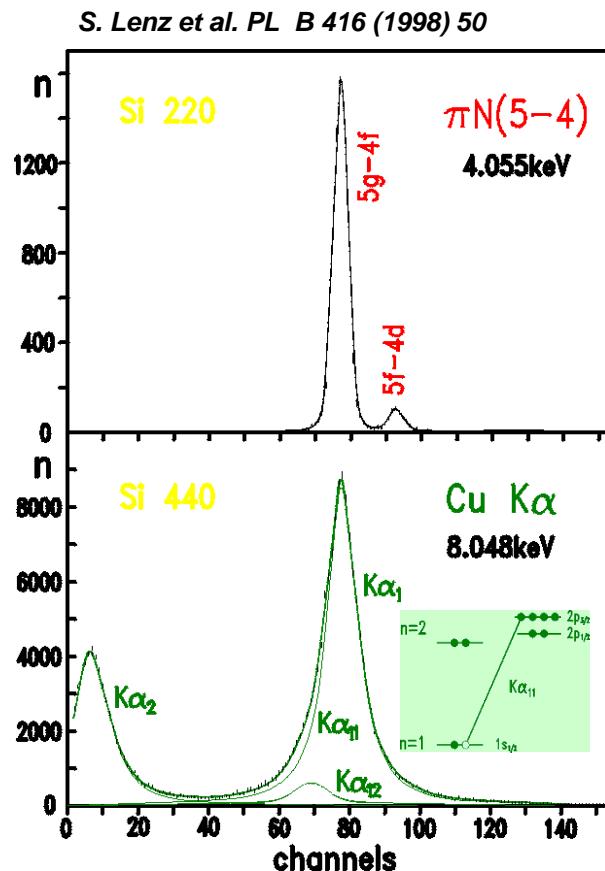
$$+ \Delta E_{\text{strong interaction}}$$



tiny corrections

FIRST STEP

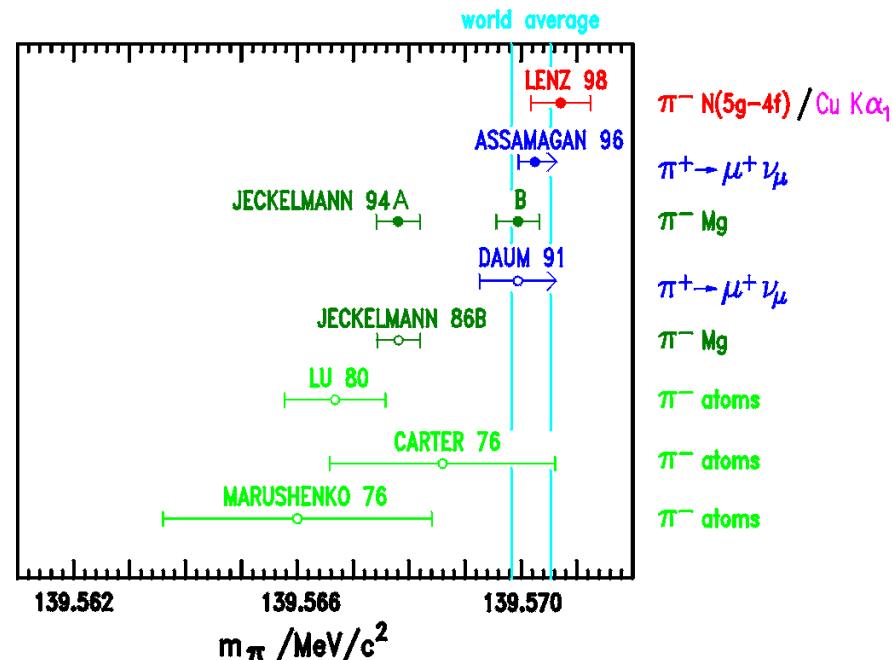
*N₂ gas target 1.4 bar
no electrons*



energy calibration: Cu $K\alpha$ standard
Deutsch et al. PR A 51 (1995) 283

$$\Delta m_\pi / m_\pi = 4 \text{ ppm}$$

discrepancy removed



Problems with calibration

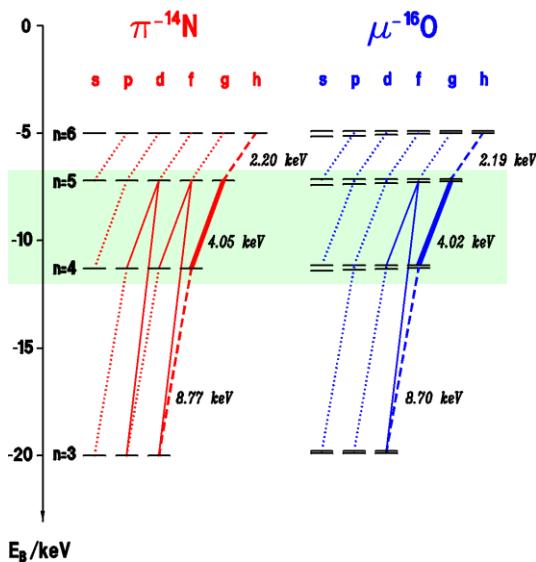
- large natural line width
- multiple ionisation \Rightarrow satellite lines

SECOND STEP

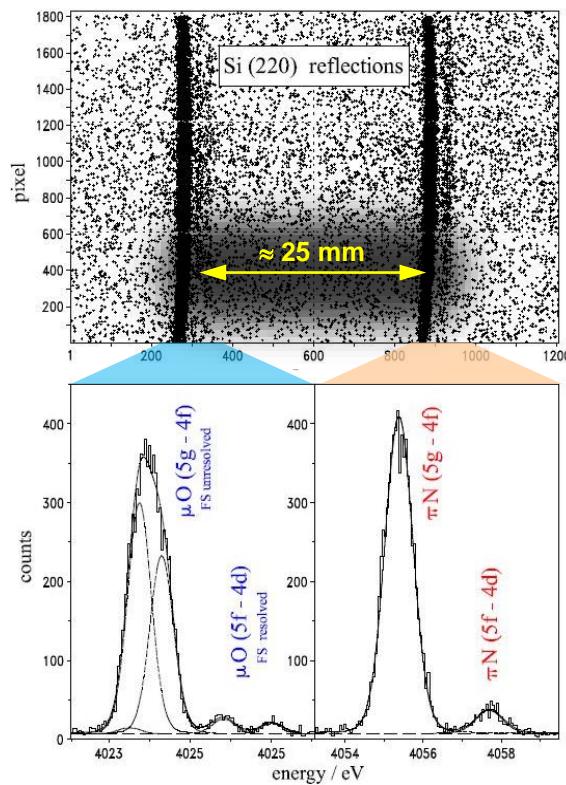
- + simultaneous measurement πN & μO
- low μO count rate cyclotron trap II

measurement calibration

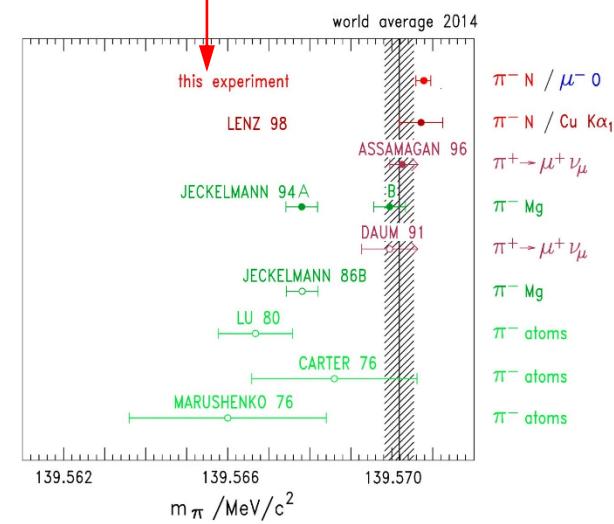
$$E_{\mu O(5g-4f)} / E_{\pi N(5g-4f)} = m_\mu / m_\pi + \dots$$



N_2/O_2 mixture (10% / 90%) @ 1.4 bar



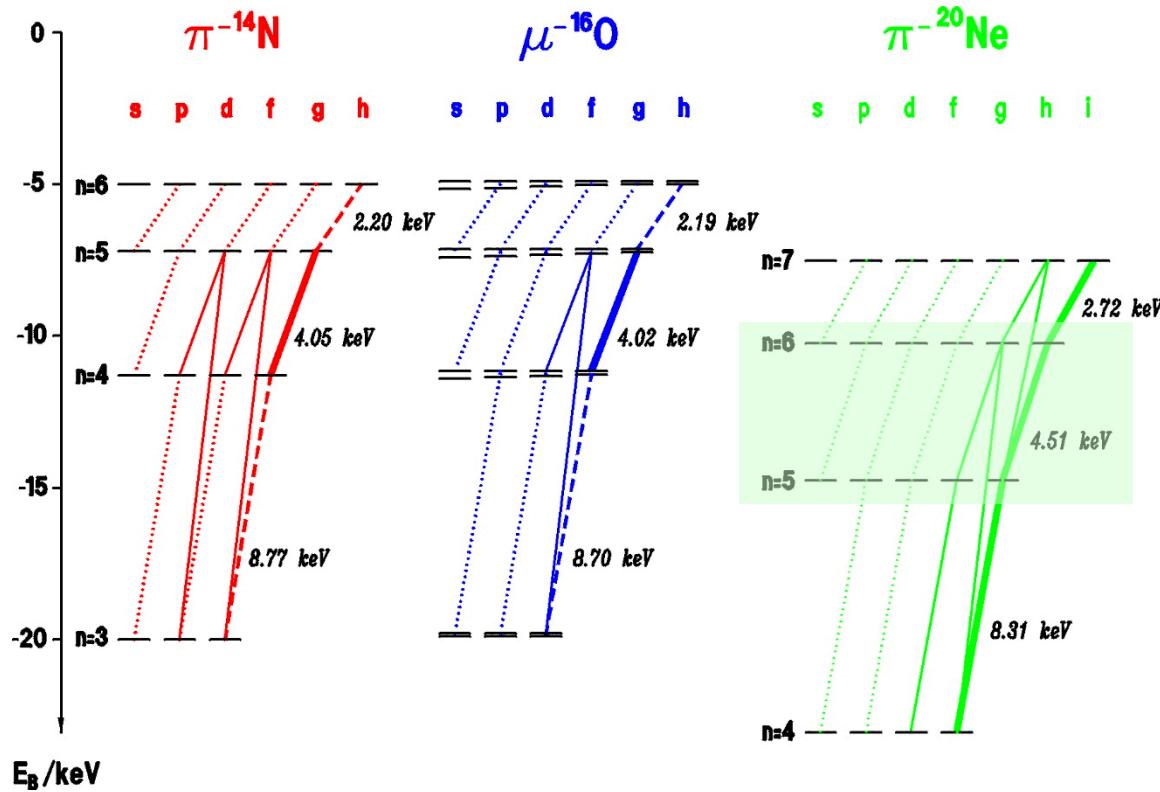
$$m_\pi = 139.57077 \pm 0.0018 \text{ eV} \\ (\pm 1.3\text{ppm})$$



M. Trassinelli et al., Phys. Lett. B 759 (2016) 583

line width ?

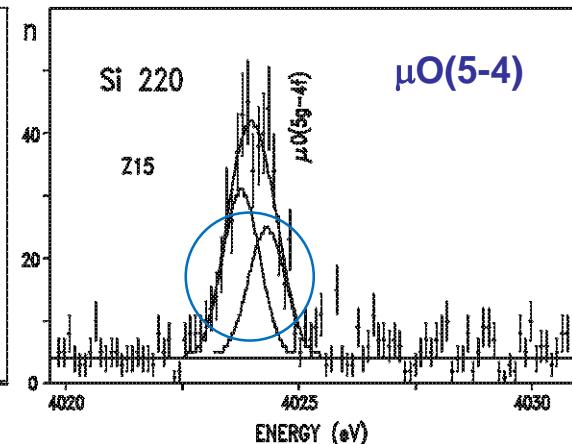
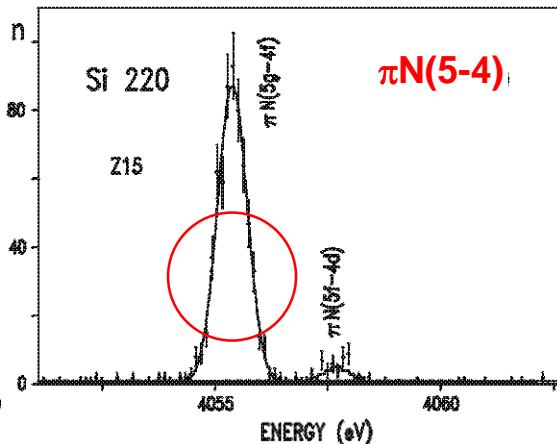
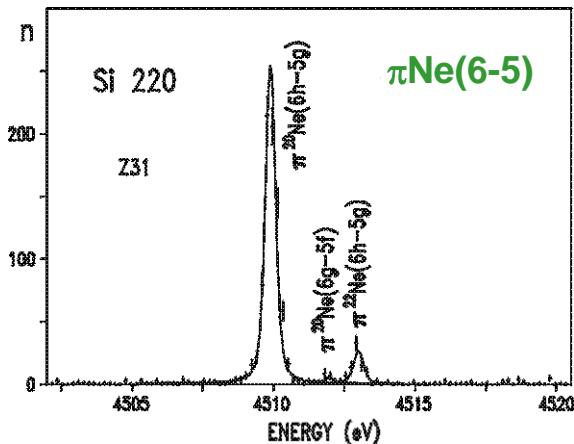
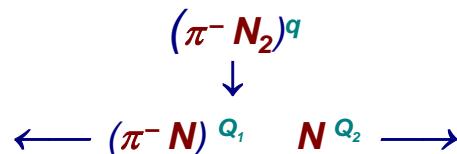
SPECTROMETER RESPONSE $\pi\text{Ne}(6g - 5f)$



COULOMB EXPLOSION - atoms ≠ molecules

response function
usable as X-ray standard

molecule fragmentation



$$\Delta E = 520 \text{ meV}$$

$$\begin{aligned} \Delta E_{\text{Doppler}} &\approx 800 \pm 100 \text{ meV} \\ \Rightarrow q_1 \cdot q_2 &\approx 9 \pm 2 \end{aligned}$$

$$\begin{aligned} &\approx 900 \pm 300 \text{ meV} \\ \Rightarrow q_1 \cdot q_2 &\approx 19 \pm 10 \end{aligned}$$

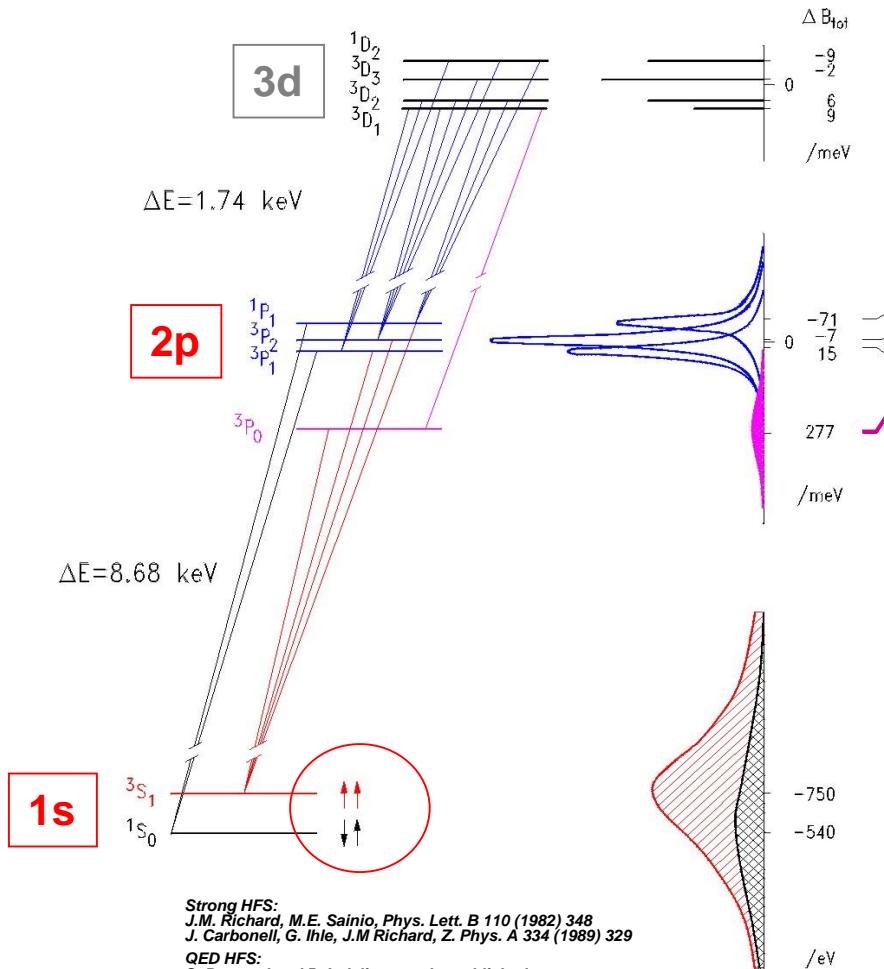
T. Siems et al., Phys. Rev. Lett. 84 (2000) 4573

explains density dependence onset of $\mu^- N$ line yields

NUCLEON - ANTINUCLEON

STRONG SPIN - SPIN and SPIN - ORBIT INTERACTION

PROTONIUM - hyperfine transitions



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

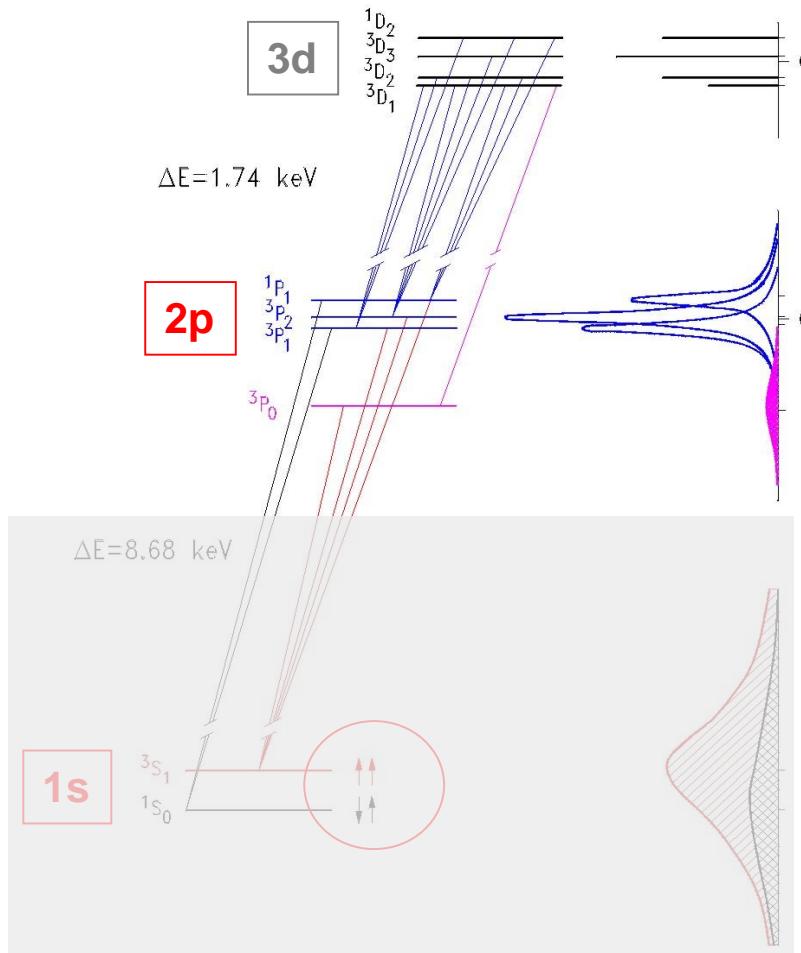
spin-spin interaction

$\epsilon > 0 (<0)$ = attractive (repulsive) interaction

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,
Veltia, Pachucki, Phys. Rev A 69 (2004) 042501

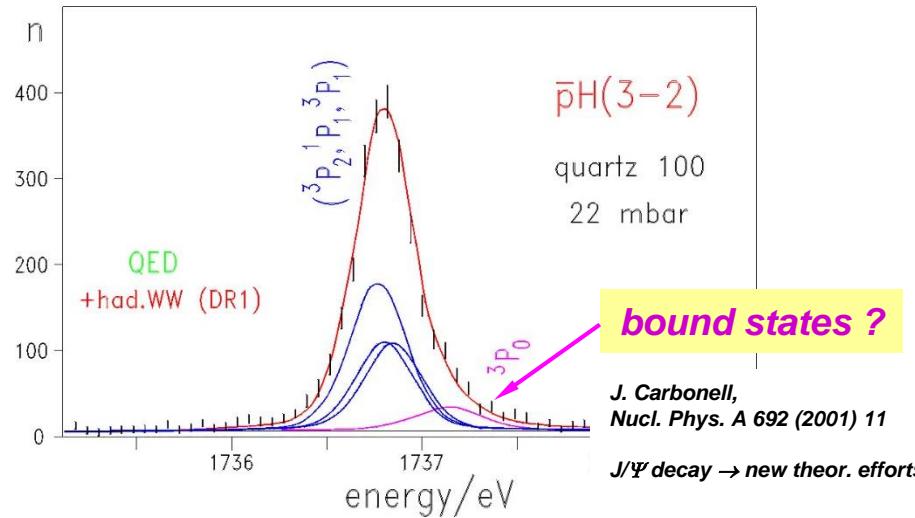
PROTONIUM 2p state



cyclotron trap + crystal spectrometer

$$\Delta E = 290 \pm 9 \text{ meV}$$

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



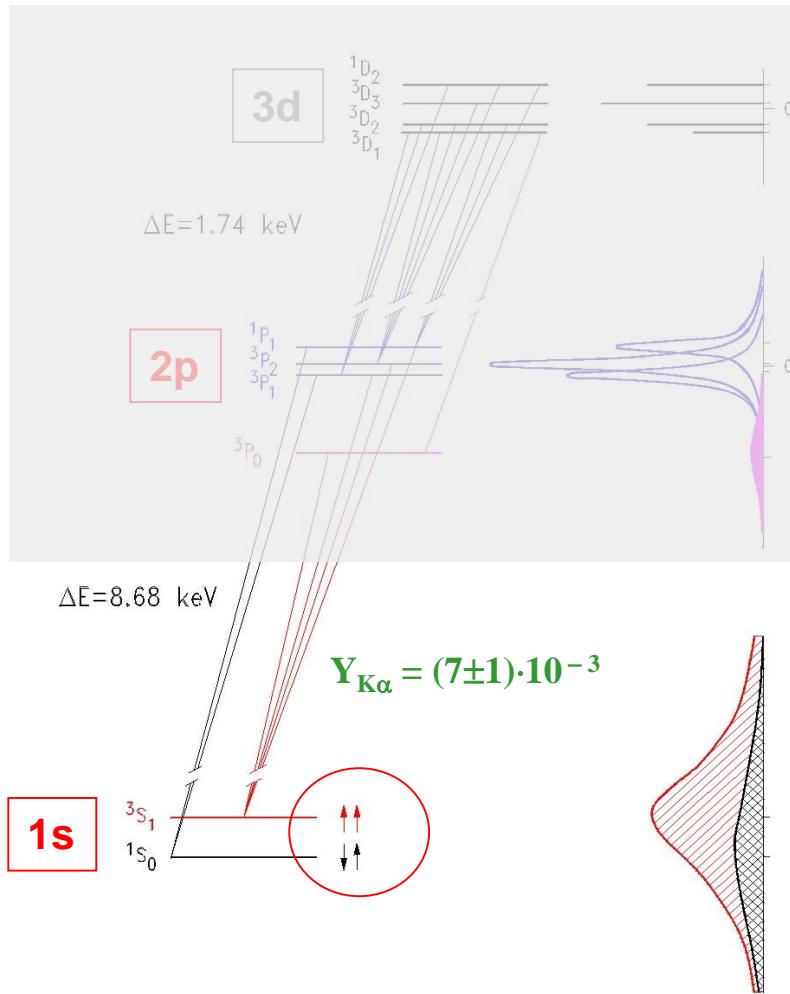
J. Carbonell,
Nucl. Phys. A 692 (2001) 11

J/Ψ decay \rightarrow new theor. efforts

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

PROTONIUM 1s state

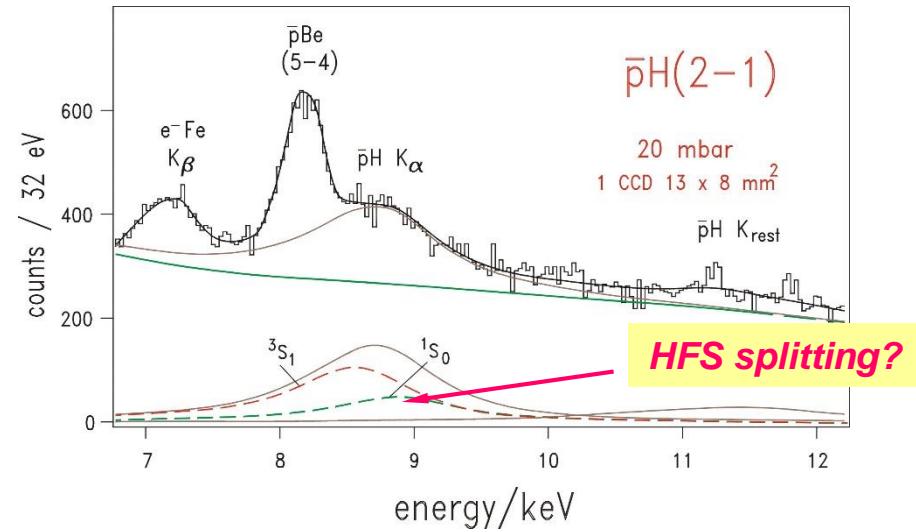
cyclotron trap + MOS CCD



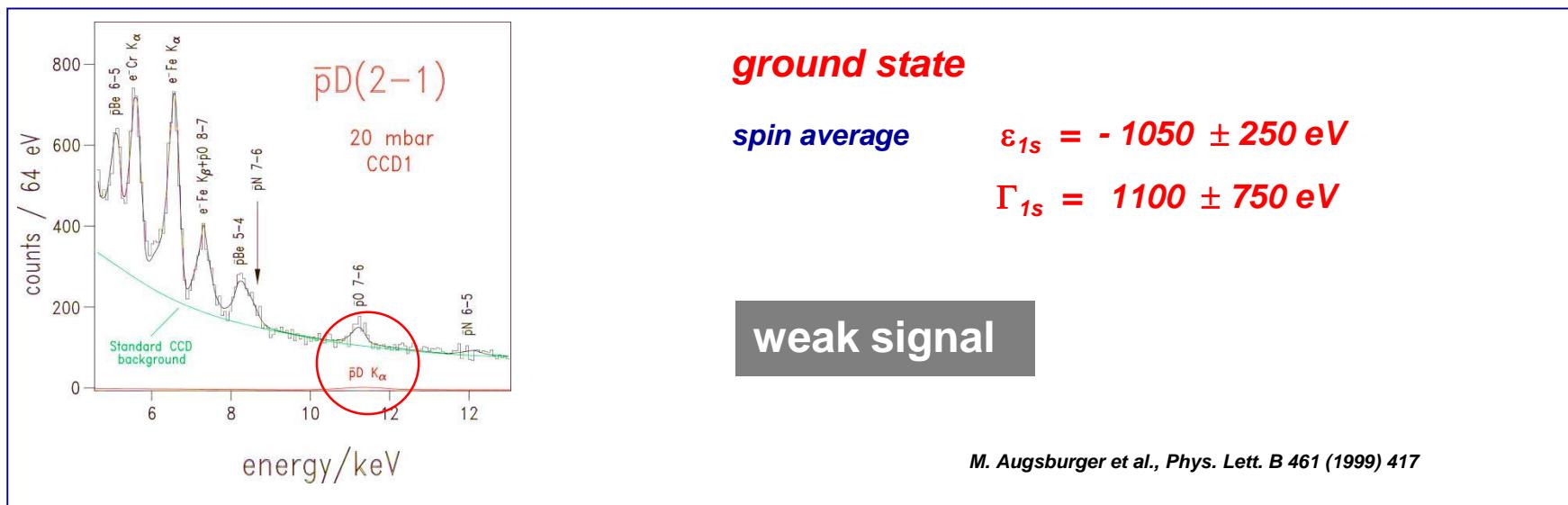
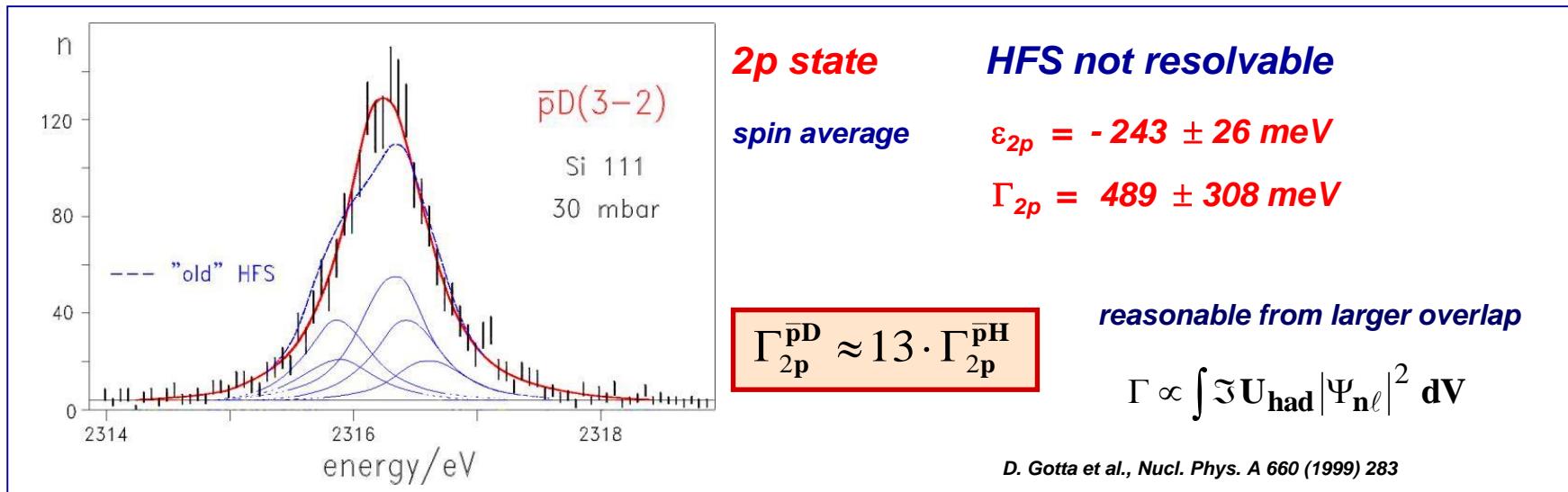
LEAR PS207: M. Augsburger et al., Nucl. Phys. A 658 (1999) 149

	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

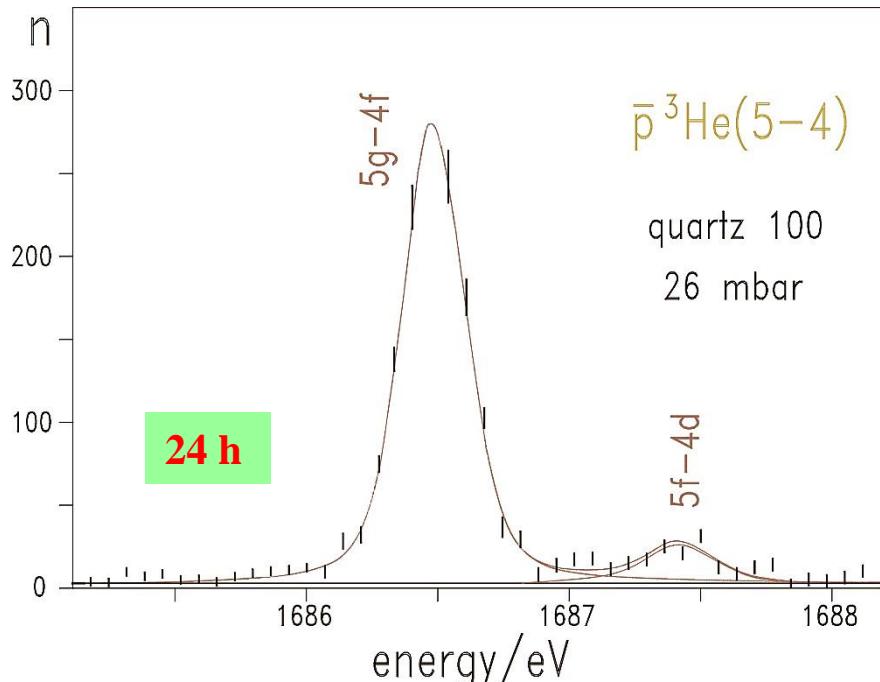


ANTIPROTONIC DEUTERIUM $2p$ and $1s$ state



EXPERIMENTAL RESOLUTION

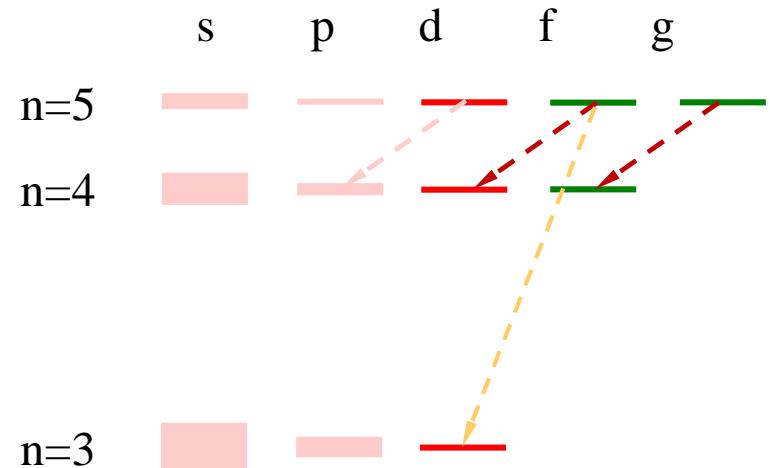
CASCADE



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

$$\eta_{\text{calculated}} = 5.5 \cdot 10^{-7}$$

$$\eta_{\text{measured}} = (7 \pm 3) \cdot 10^{-7}$$



$$\text{Intensity ratio } \frac{Y(5f-4d)}{Y(5g-4f)} = (7.7 \pm 0.6)\%$$

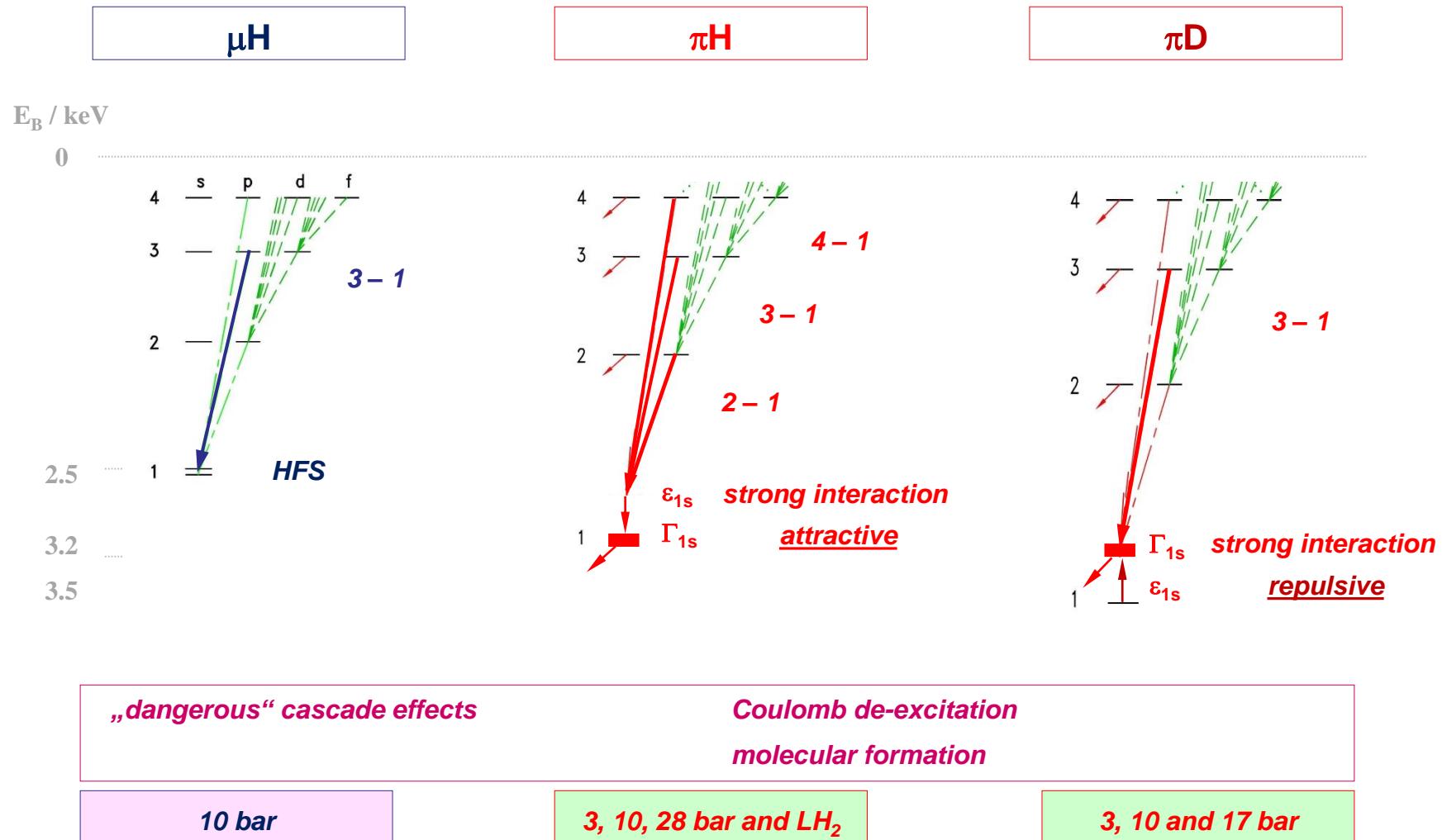
$$\text{Relative population } \frac{\text{pop}(5f)}{\text{pop}(5g)} = (21 \pm 2)\%$$

PIONIC HYDROGEN & DEUTERIUM

,,QCD Lamb shift“

PION – NUCLEON SCATTERING LENGTHS

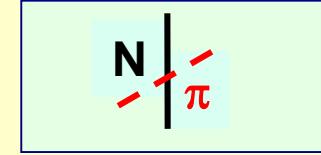
STRATEGY – VARY TRANSITION & DENSITY



HYDROGEN & DEUTERIUM - ORIGIN OF ε_{1s}

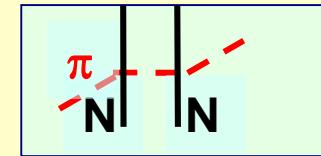
πH elastic scattering $\pi^- p \rightarrow \pi^- p$

+ ...



πD coherent sum $\pi^- p \rightarrow \pi^- p + \pi^- n$

+ ...



HYDROGEN - ORIGIN OF Γ_{1s}

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

$CEX = \text{charge exchange}$

CEX scattering



BR P well known from experiment

$$P = \pi^0 n / n\gamma = 1.546 \pm 0.009$$

radiative capture



PION-NUCLEON SCATTERING LENGTHS

$$\pi \otimes N \text{ isospin} \quad 1 \otimes 1/2 = 1/2 \oplus 3/2$$

$$a^\pm \equiv \frac{1}{2} (a_{\pi^- p} \pm a_{\pi^+ p})$$

$$a_{\pi^- p} = \frac{1}{3} (2a_{1/2} + a_{3/2}) = a^+ + a^-$$

$$a_{\pi^- p \rightarrow \pi^0 n} = -\frac{\sqrt{2}}{3} (a_{1/2} - a_{3/2}) = -\sqrt{2} a^-$$

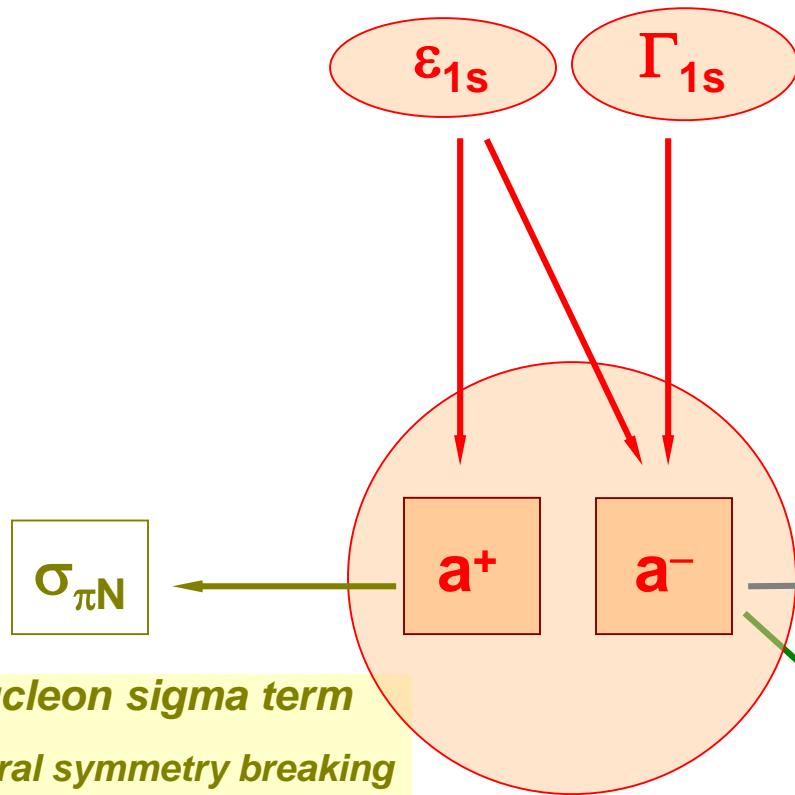
$$a_{\pi^+ p} = a_{\pi^- n} = a_{3/2} = a^+ - a^-$$

$$\begin{aligned} \chi\text{PT} \quad a^+ &\rightarrow a^+ + \Delta a^+ \\ a^- &\rightarrow a^- + \Delta a^- \end{aligned}$$

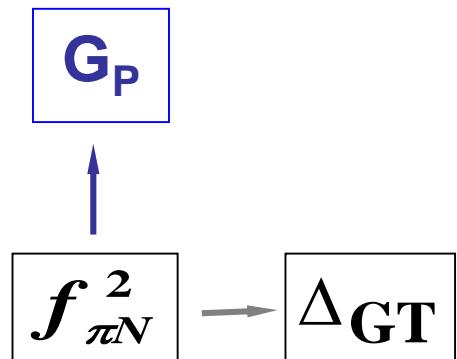
review theory: J. Gasser, V.E. Lyubovitskij, A. Rusetsky, Phys. Rep. 456, 167 (2008)

PION-NUCLEON SCATTERING LENGTHS

related quantities



induced pseudoscalar coupling
muon capture

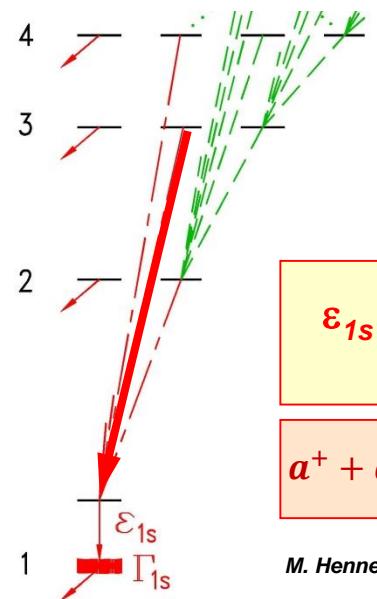
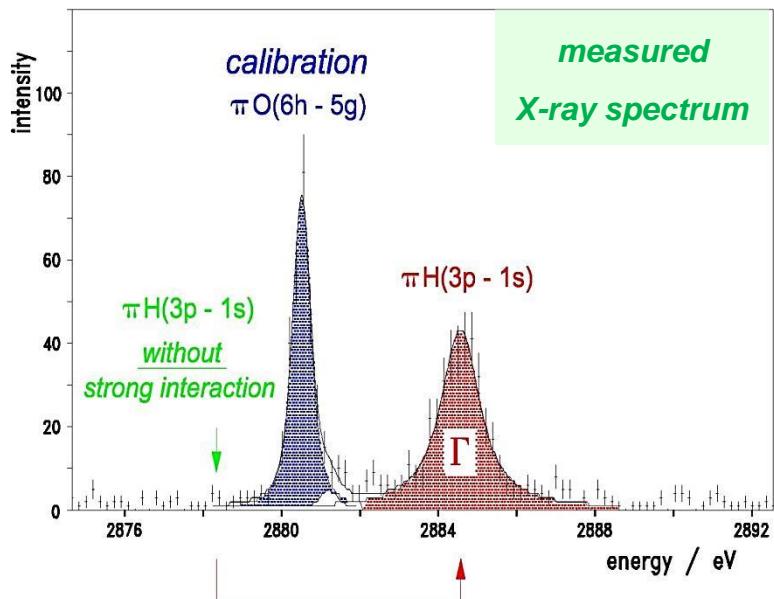


πN coupling constant
Goldberger-Treiman discrepancy
pion-nucleon scattering



electric dipole amplitude
threshold pion photo production

PIONIC HYDROGEN ε_{1s}



$$\varepsilon_{1s} = +7.086 \pm 0.009 \text{ eV}$$

($\pm 0.13\%$)

$$a^+ + a^- = (93.0 \pm 3.3) \cdot 10^{-3} m_\pi^{-1}$$

M. Hennebach et al. et al., Eur. Phys. J. A 50 (2014) 190
Eur. Phys. J. A 55 (2019) 24 (E)

scattering lengths

$$\pi H \quad \varepsilon_{1s} \propto a_{\pi-p \rightarrow \pi-p} \propto a^+ + a^- + \dots$$

$$\Gamma_{1s} \propto (a_{\pi-p \rightarrow \pi^0 n})^2 \propto (a^-)^2 + \dots$$

$$\pi D \quad \varepsilon_{1s} \propto a_{\pi-d \rightarrow \pi-d} \propto 2 \cdot a^+ + \dots$$

experiment

$\pm 0.2\%$

$\pm 2.5\%$

$\pm 1.3\%$

Trueman correction

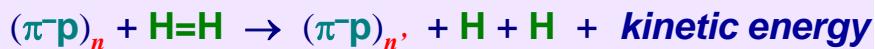
$$\chi PT \quad \dots \approx 1\% \quad + (-9.0 \pm 3.5)\%$$

$$\dots \approx 1\% \quad + (+0.5 \pm 1.0)\%$$

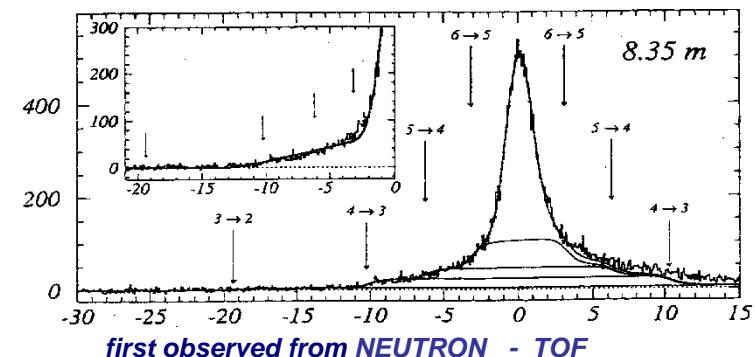
$$\dots \approx 1\% \quad + \quad \pm 4\%$$

* 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

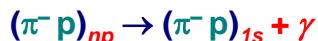
COULOMB DE-EXCITATION



moving neutron source



MUONIC HYDROGEN



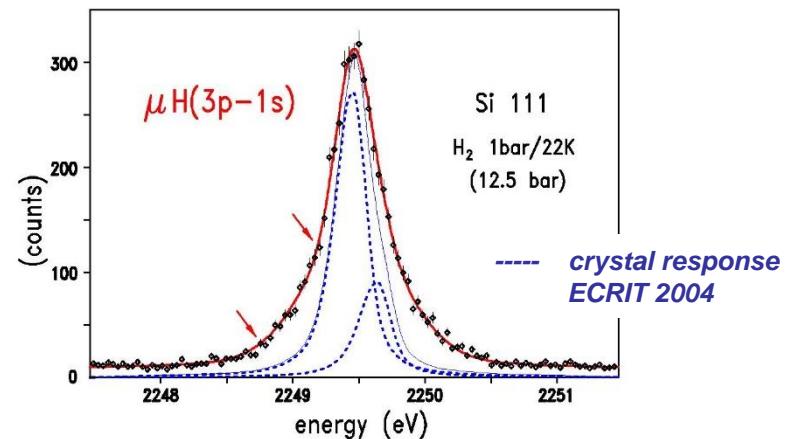
moving X-ray source

new cascade theory (ESCM)

Markushin, Jensen

new cross sections

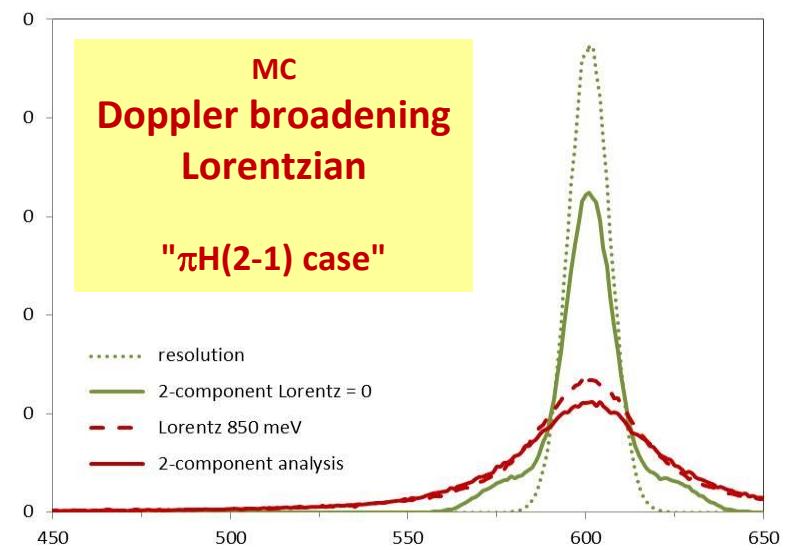
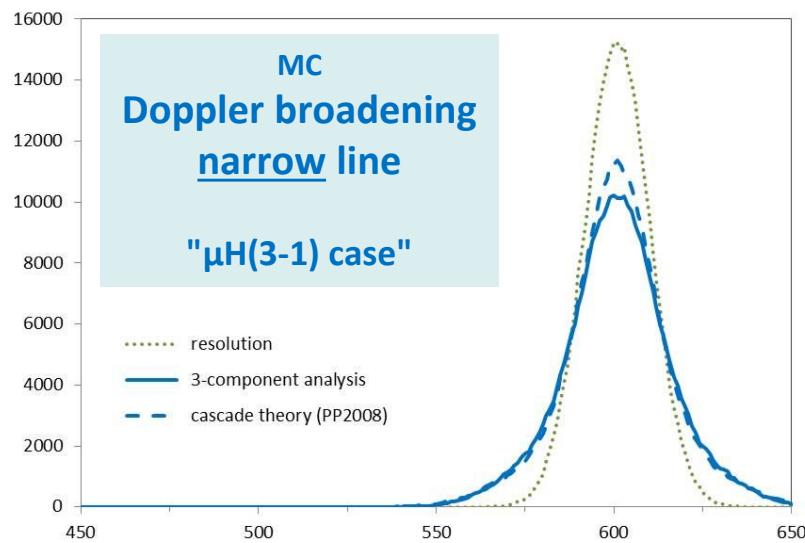
Popov, Pomerantsev



$$\Delta E_X = 2 \cdot E_X \cdot \sqrt{\frac{2T_{kin}}{mc^2}}$$

D. Covita, PhD thesis Coimbra (2008)
D. Covita et al., Phys. Rev. Lett. 102 (2009) 023401,
Eur. Phys. J. D 72 (2018) 72

EXEMPLIFICATION



low background essential !

typical resolution (FWHM)
272 meV

390 meV

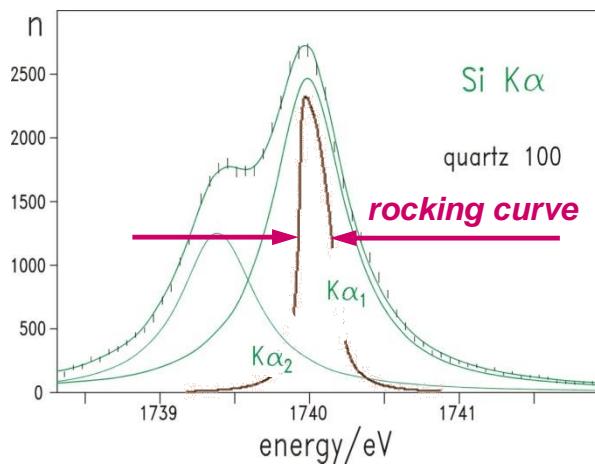
INTERMEZZO

EXPERIMENT

How to achieve ultimate precision for the spectrometer response?

CRYSTAL RESPONSE - NO SOLUTION

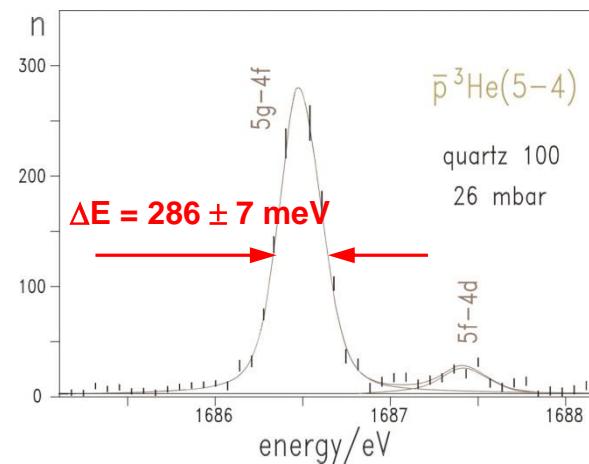
fluorescence X-rays
excited by means of X-ray tubes



problem

**large natural line width
and
satellite lines**

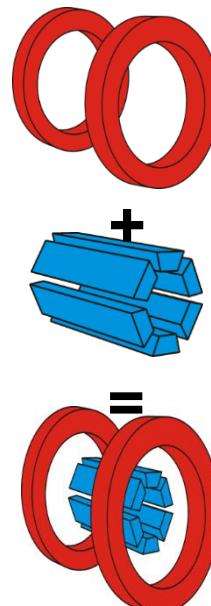
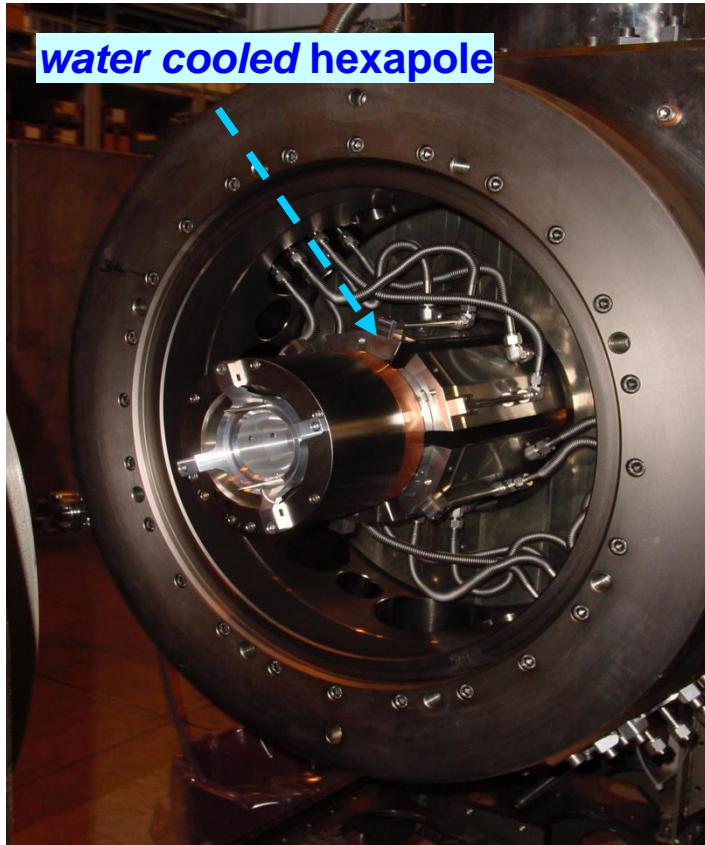
exotic-atom X-rays
from hydrogen-like systems



problem

rate

MEASURE SPECTROMETER RESPONSE new approach



ECRIS

*Electron Cyclotron Resonance Ion
“Source”*
=
cyclotron trap + hexapole magnet

superconducting coils

- cyclotron trap

permanent hexapole

- AEGR-U type
- 1 Tesla at the hexapole wall
- open structure

large mirror ratio = 4.3

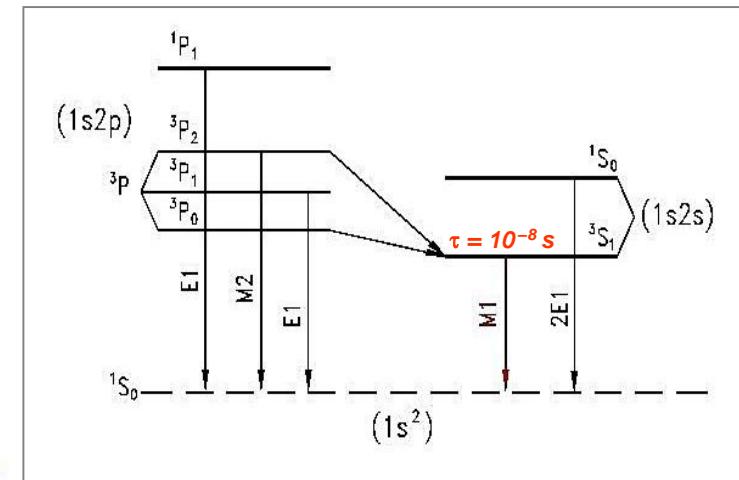
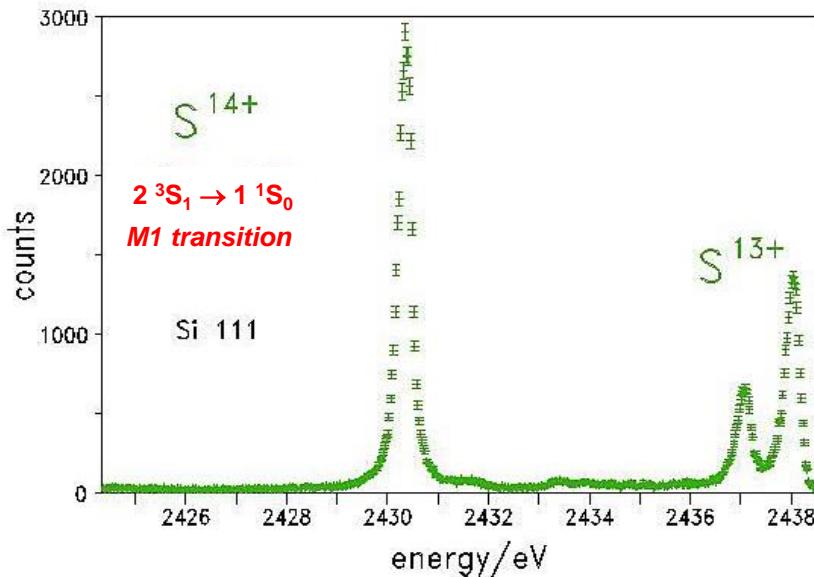
B_{max} / B_{min} !

„burning“ argon

Ar / O₂ (1/9)
1.4 · 10⁻⁶ mbar

SPECTROMETER RESPONSE at πH Lyman ENERGIES

M1 transitions in He - like S \leftrightarrow $\pi H(2p-1s)$
 Cl \leftrightarrow $\pi H(3p-1s)$
 Ar \leftrightarrow $\pi H(4p-1s)$



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

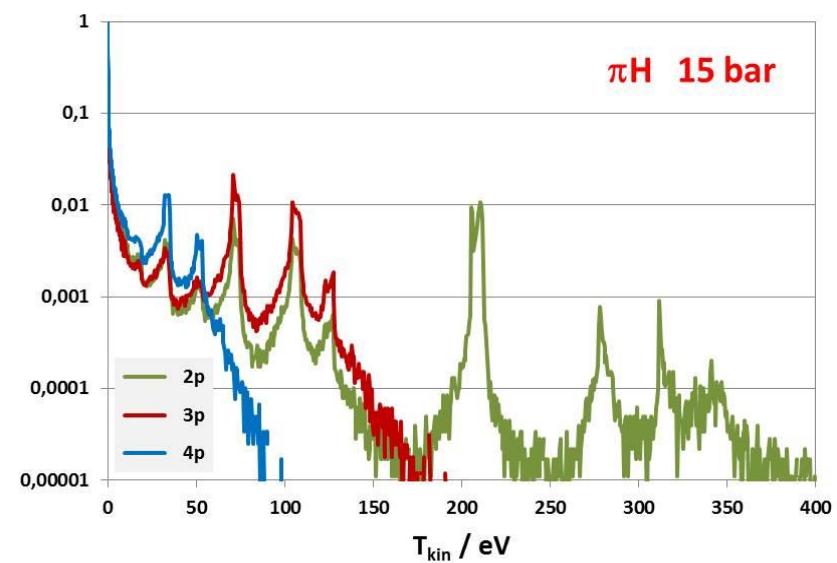
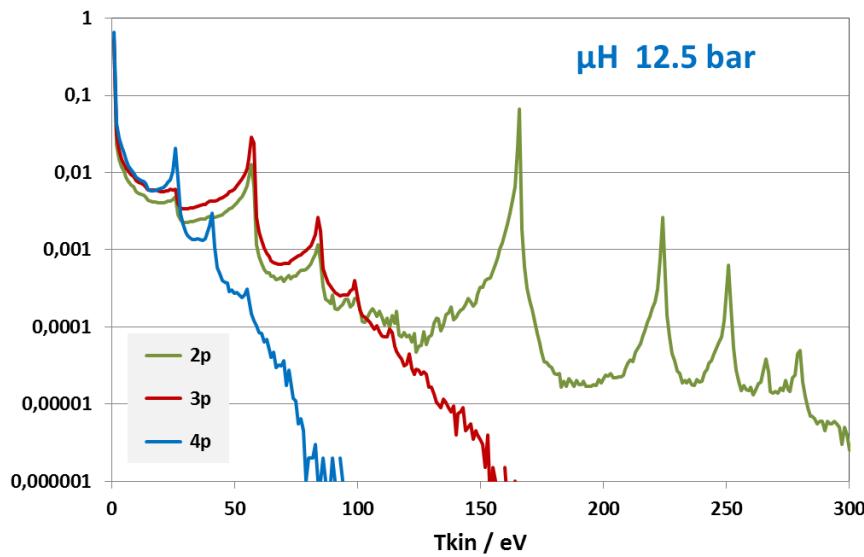
EXTRACTION OF Γ_{1s}

=

find model for Coulomb de-excitation

Prediction from cascade theory

ESCM (extended standard cascade model) model follows development of kinetic energy



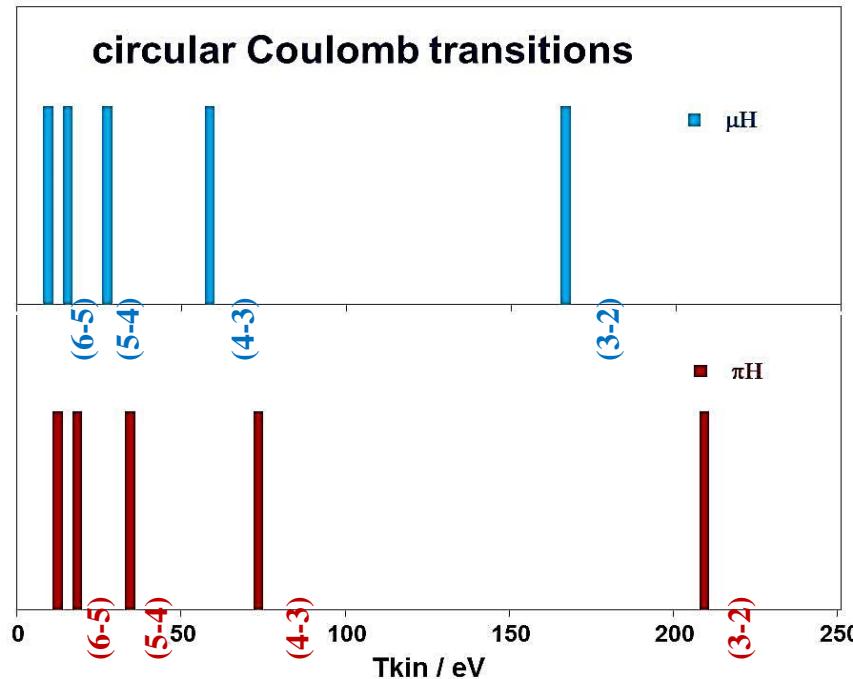
T.Jensen and V.Markushin

introduction of ESCM

V.N. Pomerantsev and V.P. Popov

new collision cross sections

STRATEGY - *phenomenological approach*



neglected here: possible $\Delta n=2$ Coulomb transitions

maximal Doppler broadening of X-ray line

$$\Delta E_{X,max} = 1,5 \text{ eV} \quad \mu\text{H}(3\text{p} - 1\text{s})$$

$$\Delta E_{X,max} = 3.0 \text{ eV} \quad \pi\text{H}(2\text{p} - 1\text{s})$$

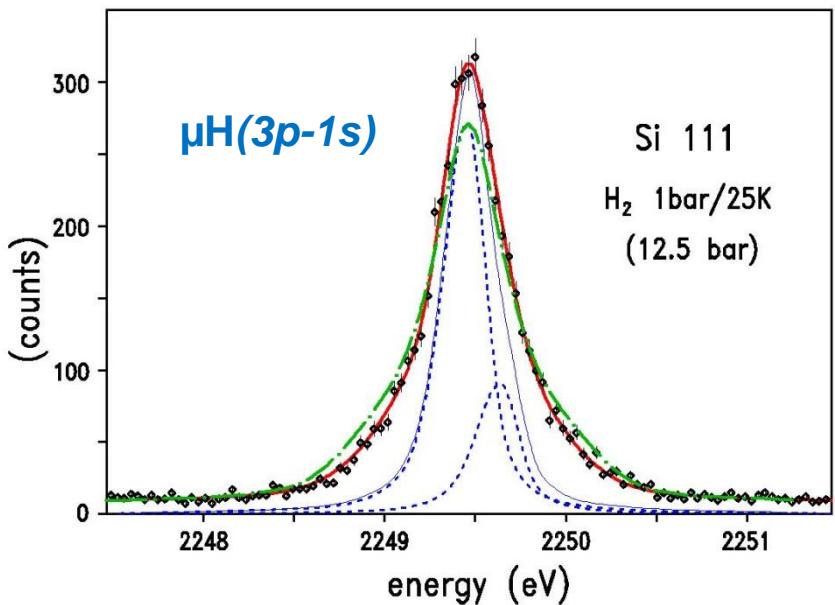
$$\Delta E_{X,max} = 2.1 \text{ eV} \quad \pi\text{H}(3\text{p} - 1\text{s})$$

$$\Delta E_{X,max} = 1.5 \text{ eV} \quad \pi\text{H}(4\text{p} - 1\text{s})$$

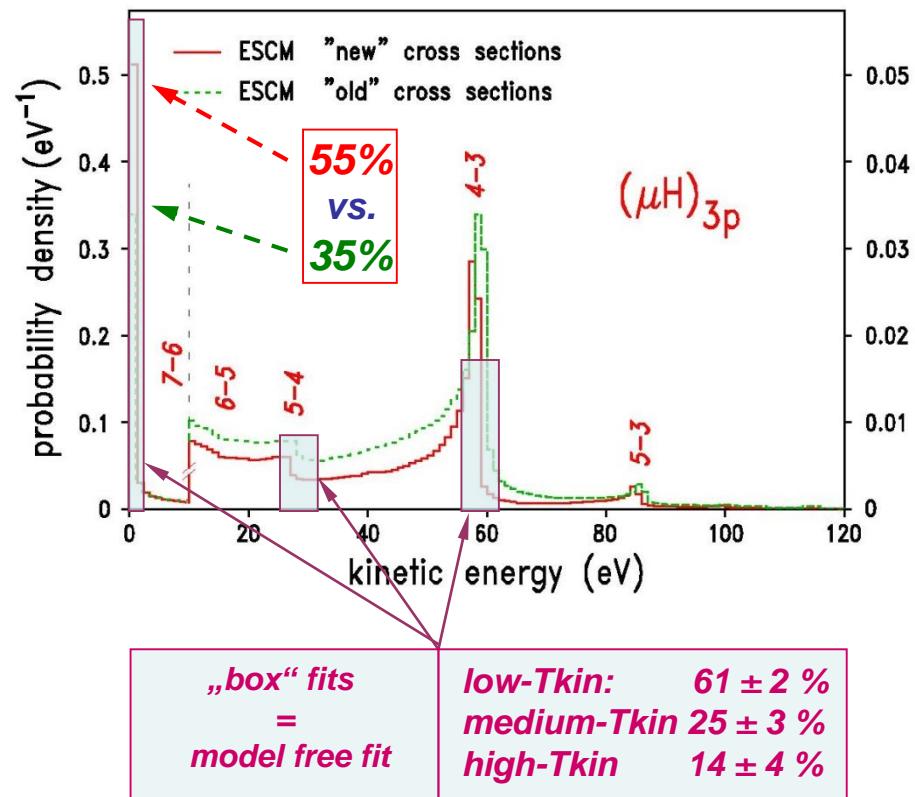
2 analysis methods

1. χ^2 fit frequentist approach
2. Bayesian method

ANALYSIS - $\mu\text{H}(3p - 1s)$



re-calculation of cross sections



ESCM:

extended standard cascade calculation and cross sections

T.S.Jensen and V.E.Markushin, Eur. Phys. J. D 19, 165 (2002); *ibid.* D 21, 261 (2002); *ibid.* D 21, 271 (2002)

new cross sections

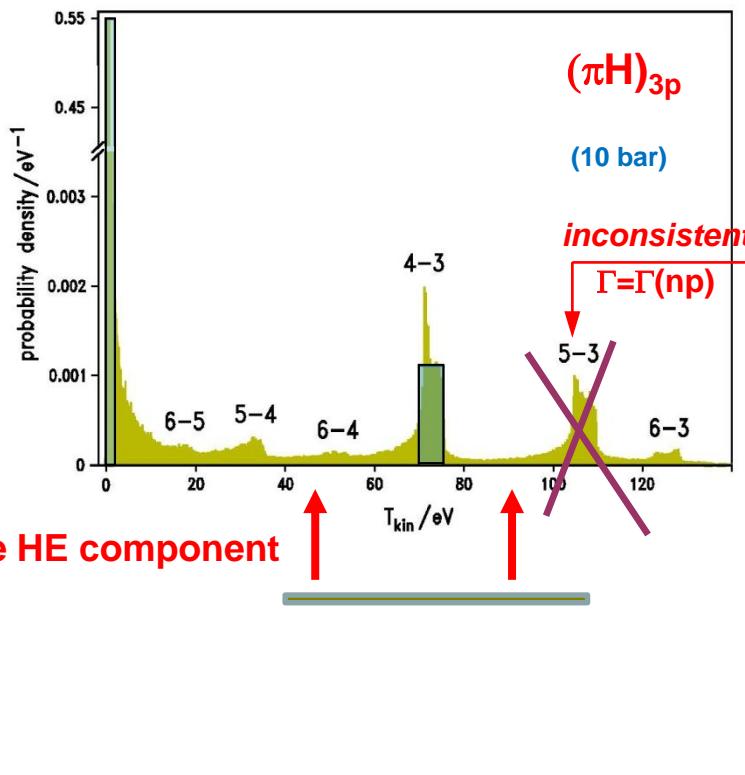
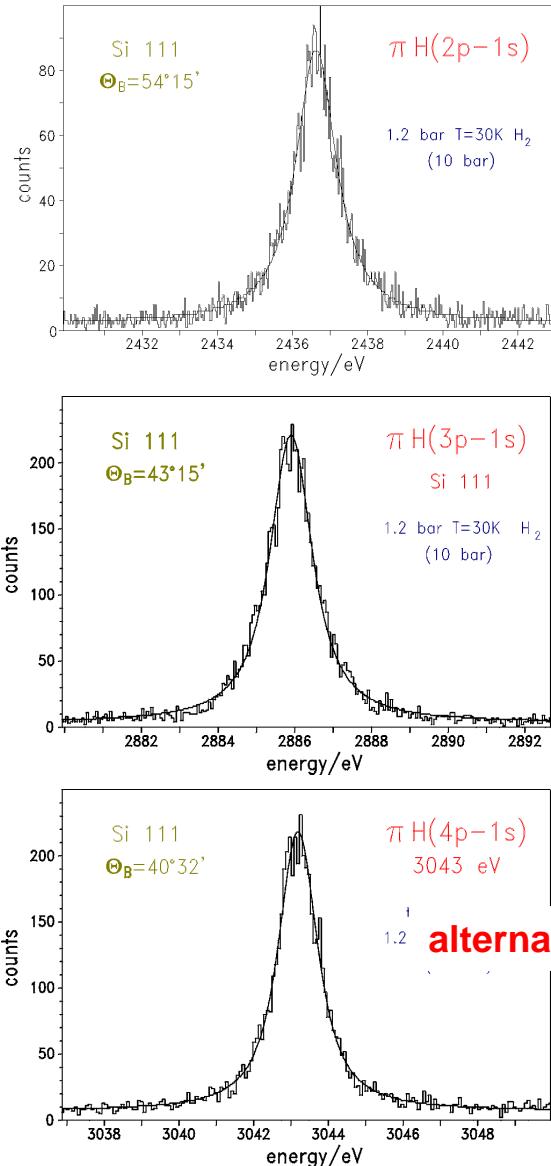
G.Ya. Koreman, V.N. Pomerantsev and V.P. Popov, JETP. Lett. 81, 543 (2005)

V.N. Pomerantsev and V.P. Popov, Phys. Rev A 73, 040501 (2006)

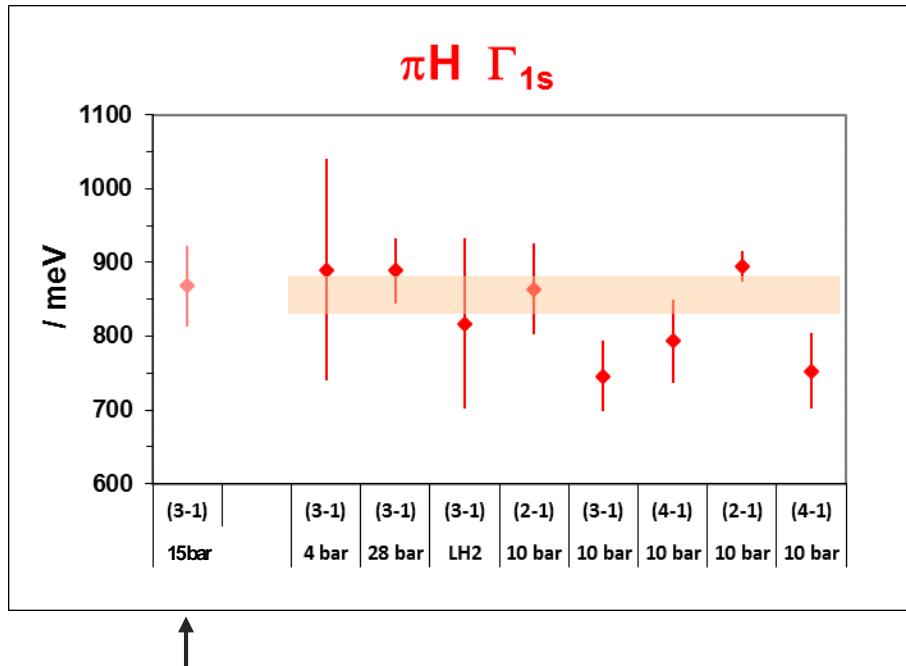
V.P. Popov and V.N. Pomerantsev, arXiv:0712.3111v1[nucl-th] (2007)

V.P. Popov and V.N. Pomerantsev, Phys. Rev A 86, 052520 (2012)

ANALYSIS - $\pi H(np - 1s)$ Γ_{1s}



Coulomb transition	
low-energy	$\approx 50\%$
5-4	---
6-4	---
4-3	$\approx 50\%$
3-2	?
low-energy	$\approx 55\%$
5-4	---
6-4	---
4-3	$\approx 45\%$
5-3	---
low-energy	$\approx 50\%$
6-5	---
5-4	$\approx 50\%$
6-4	---



D. Sigg et al., Phys. Rev. Lett. 75 (1995) 3245,
H.-Ch. Schröder et al., Phys.Lett. B 469 (1999) 25;
Eur. Phys. J. C 21 (2001) 433

phenomenological
approach

2 or 3 - component model

all measurements

$$\Gamma_{1s} = (0.85 \pm 0.03) \text{ eV}$$

$$-\sqrt{2} \cdot a^- = (124 \pm 3) \cdot 10^{-3} m_\pi^{-1}$$

PION

PRODUCTION / ABSORPTION

$$NN \Leftrightarrow \pi NN$$

$\pi D(3p - 1s)$ Γ_{1s}

πD *absorption*



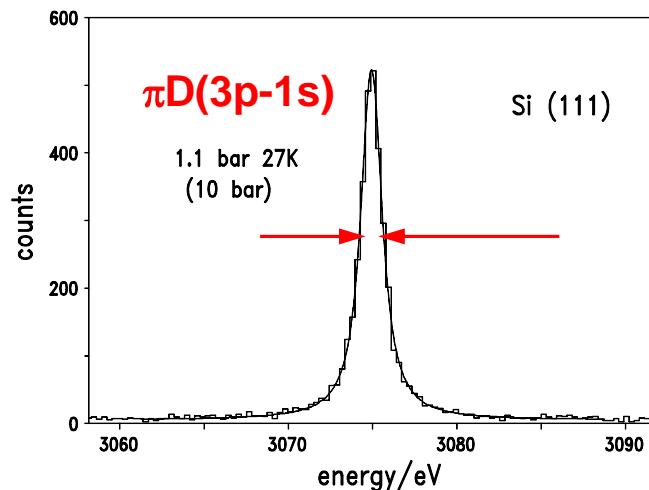
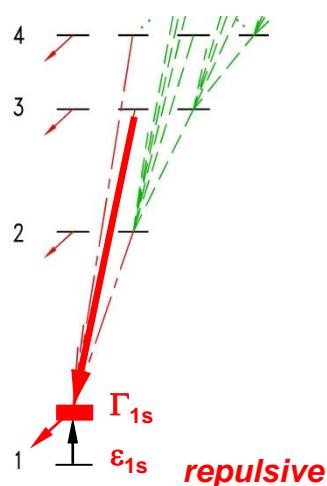
„true“ absorption π^- 

radiative capture

BR well known from experiment



strong interaction



PhD thesis: Th. Strauch, Cologne 2009
 Th. Strauch et al., Phys. Rev. Lett. 104 (2010) 142503;
 Eur. Phys. J. A 47 (2011) 88

$$\Gamma_{1s} = (1.171 \pm 0.023 \text{ } ^{+ 2\%}_{- 4\%}) \text{ eV}$$

$$\Im a_{\pi^-d} = (6.22 \pm 0.12) \cdot 10^{-3} m_\pi^{-1}$$

error budget

- ± 23 meV statistics
- ± 43 meV Coulomb de-excitation
(≤ 10% !)

cascade theory

Coulomb de-excitation small!

V. P. Popov* and V. N. Pomerantsev,
 Phys. Rev. A 95, 022506 (2017)

NN \leftrightarrow π NN threshold parameter α

<i>charge symmetry</i>	\leftrightarrow	<i>detailed balance (T invariance)</i>
$\sigma_{\pi^- d \rightarrow nn}$	\leftrightarrow	$\sigma_{\pi^+ d \rightarrow pp}$

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

$$\Gamma_{1s} \propto \Im a_{\pi^- d} \propto \alpha(pp \rightarrow \pi^+ d) = (251 {}^{+5}_{-11}) \mu b \quad ({}^{+20\%}_{-4\%})$$

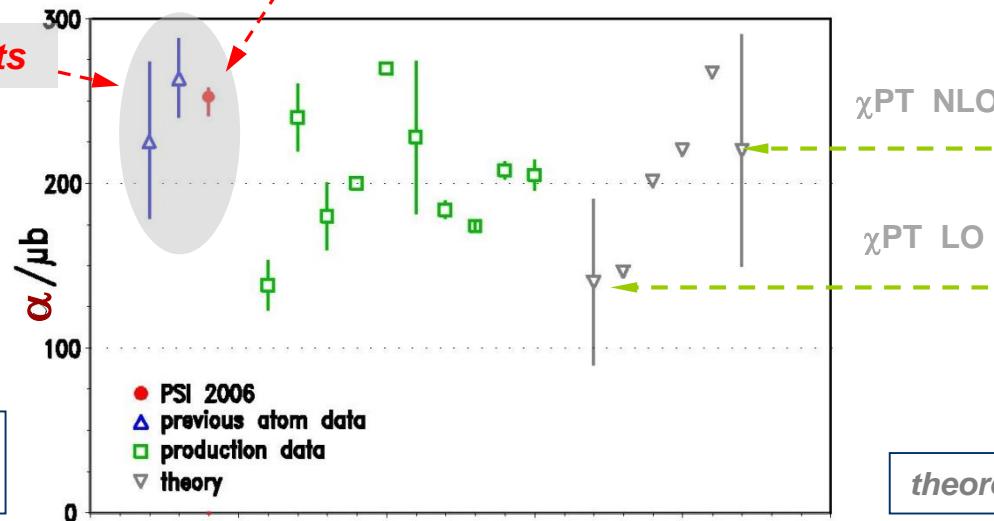
all exotic-atom results

Th. Strauch,
PhD thesis, Cologne 2009

Th. Strauch et al.,
Phys. Rev. Lett. 104 (2010) 142503

Th. Strauch et al.,
Eur. J. Phys. 47 (2011) 88

Outlook experiment
 $\Delta\Gamma/\Gamma \rightarrow 1\%$



χ PT
at present
 $\Delta\alpha/\alpha \approx 30\%$
 \rightarrow few % !?

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

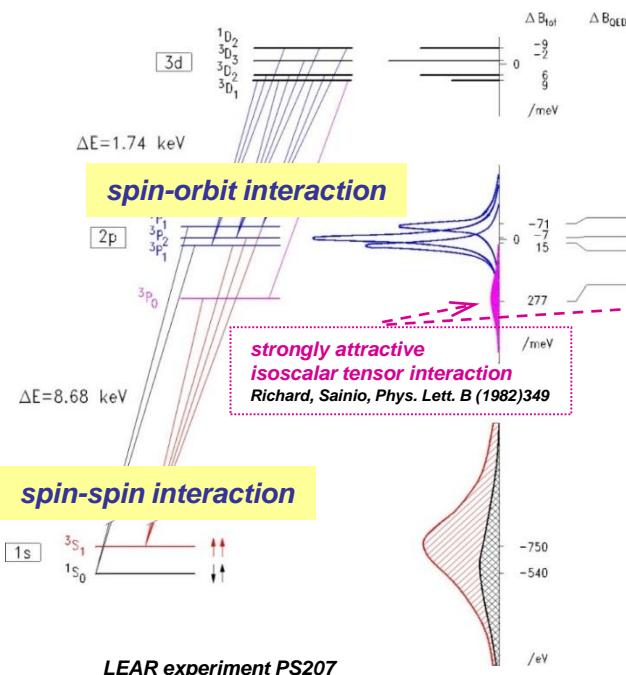
theoretical progress needed

- MOTIVATION
- EXOTIC ATOM
- EXPERIMENTAL APPROACH
- SOME RESULTS
- SUMMARY & OUTLOOK

CHARGED PION MASS

- reassessment of $\pi^+ \rightarrow \mu^+ \nu_\mu$ ($m_\nu \approx 0$)
 $\Delta m/m \rightarrow 1.0\text{pm}$ *2.4 σ discrepancy to πN result (2019)* ✓
- $\pi^- \text{Ne}$ (*no Coulomb explosion*) + *double flat crystal spectrometer* ?
 $\Delta m/m \rightarrow 0.5\text{ppm}$
- *Laser - induced excitation of metastable $\pi^- \text{He}$ states* *ongoing PSI proposal*
 $\Delta m/m \rightarrow 0.1\text{ppm}$

PROTONIUM - SEARCH for HFS

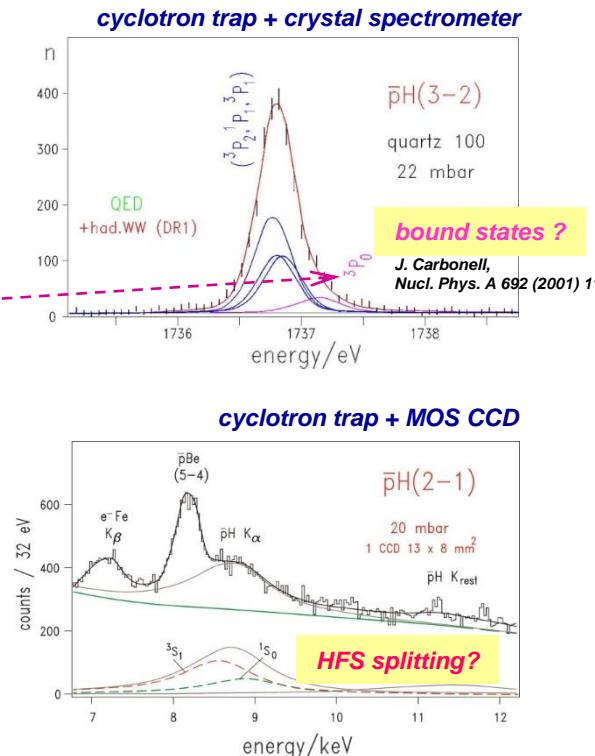


new „ χ PT inspired“ calculations

$\bar{p}^{\text{3,4}He}$ Γ_{2p} \Rightarrow relative annihilation strength

LEAR data not precise enough

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

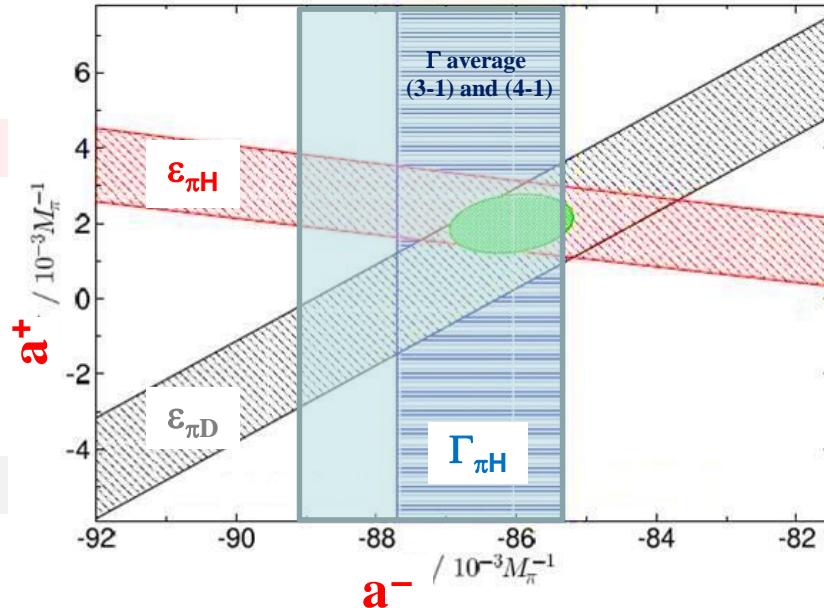


Outlook

- 2p state:
better resolution
factor of 2 possible
- 1s state:
much higher statistics
lower background
fast read-out CCDs
- mandatory:
 \geq LEAR-type beams

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

$\Delta \text{exp} \ll \Delta \text{theory}$



$\Delta \text{exp} \ll \Delta \text{theory}$

$\Delta \text{exp} (\text{Coulomb de-excitation}) \approx 3 \times \Delta \text{theory}$

- consistency ✓
- $\varepsilon_{\pi D}$ decisive constraint
- $a^+ > 0 !$

large discrepancy between pionic-atoms analysis and
 $a^+ = -15 \cdot 10^{-3} M_\pi^{-1}$ from lattice σ -term

Hoferichter et al., arXiv: 1602.07688v2
 Crivellin et al., Phys. Rev. D 89, 054021 (2014)
 Ellis et al., Phys. Rev. D, 065026 (2008)
 ...

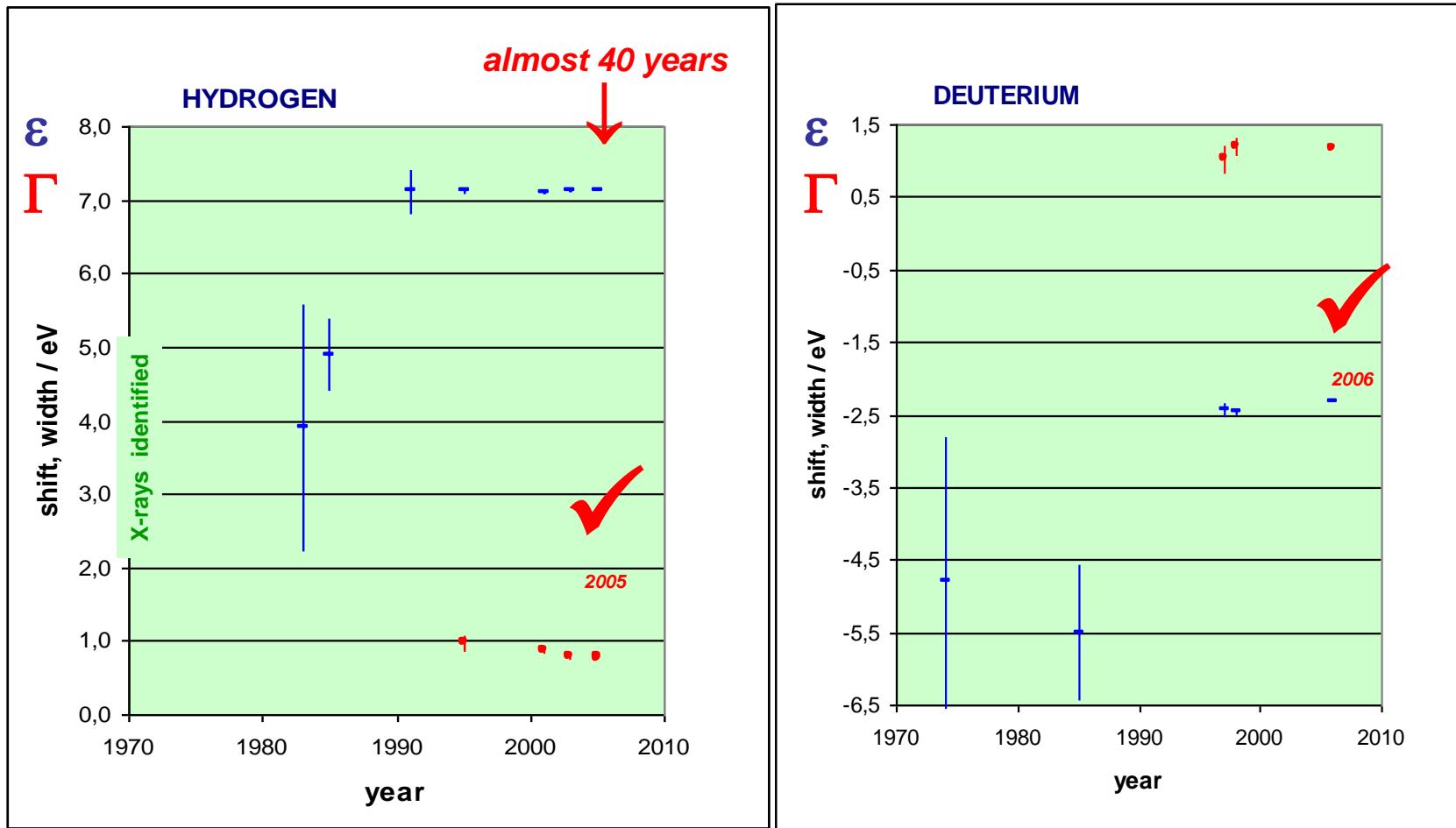
FIG. 2: Combined constraints in the $\tilde{a}^+ - a^-$ plane from data on the width and energy shift of πH , as well as the πD energy shift.

χPT : 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
 data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (2008) 165
 M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190
 πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88

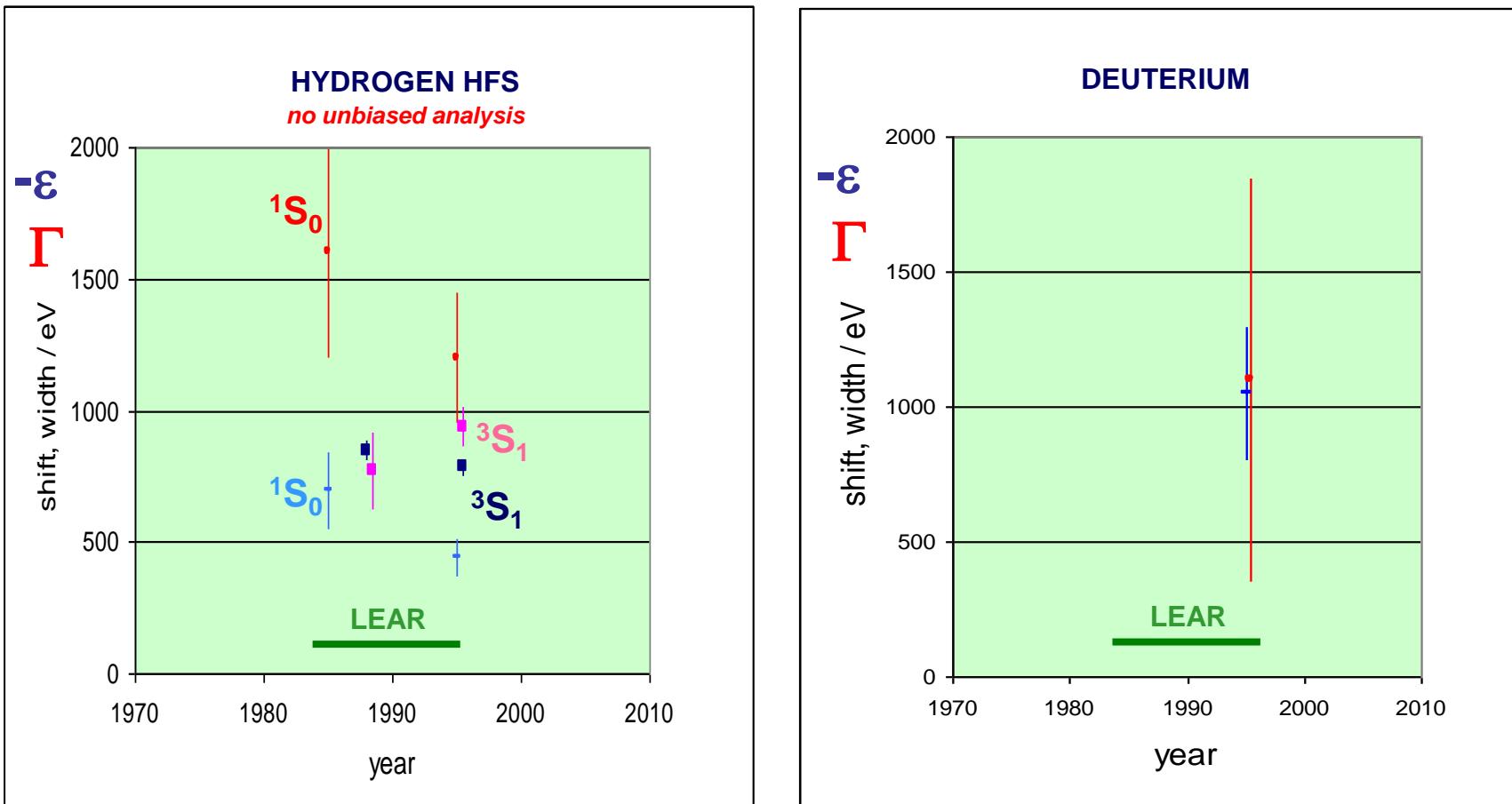
Outlook - high statistics experiment of $\pi H(4-1)$ and $\pi H(5-1)$ lines:
less Coulomb de-excitation

$\Delta\Gamma/\Gamma$ 3% → 1%

PIONIC HYDROGEN STORY



ANTIPROTONIC HYDROGEN STORY s -wave



still a lot to do !

DATA FROM EXPERIMENTS

\bar{p}

<i>collaboration</i>	<i>measurements</i>
PS 175 CERN antiprotonic atoms	1984 – 1988

PS 207 CERN	antiprotonic atoms	1994 – 1996
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μ/π

R-94.01 PSI	π / μ mass ratio	1994 – 1997
R-97.02 PSI	pion mass	1999 – 2000
R-98.01 PSI	pionic hydrogen	2000 – 2006
	muonic hydrogen	2004
R-06.03 PSI	pionic deuterium	2006

Coimbra, Debrecen, Ioannina, FZ Jülich, Leicester, MSU Moscow, Neuchatel, LKB Paris, PSI, SMI Vienna, Univ. Zürich