

PIONIC HYDROGEN and DEUTERIUM

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- **WHY PIONIC HYDROGEN & ... ?**
- **EXPERIMENTAL APPROACH**
- **ANALYSIS**
- **RESULTS**
- **CONCLUSIONS**

PIONS, NUCLEONS - INTERACTION in terms of QCD

χ_{PT}

CHIRAL

PERTURBATION

THEORY

$\pi\pi \Leftrightarrow \pi\pi$

$\pi N \Leftrightarrow \pi N$

$NN \Leftrightarrow NN$

$\dots \Leftrightarrow \dots$

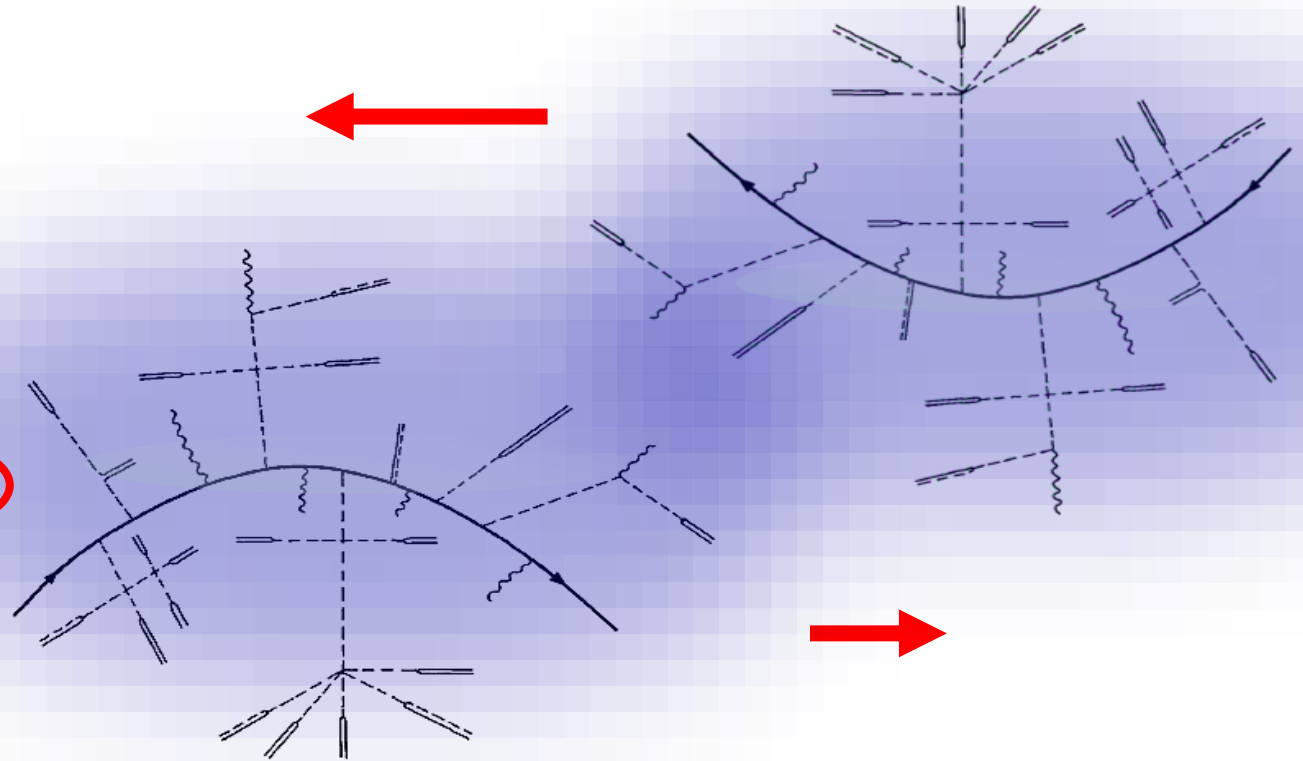


Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. $\longrightarrow$ nucleon; $--$ pions; $\sim$ vector current; $==$ axial vector current; $-$ pseudoscalar density; $===$ scalar density.

J. Gasser et al., Nucl. Phys. B307, 779 (1988)

PION-NUCLEON SCATTERING LENGTHS

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

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

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

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

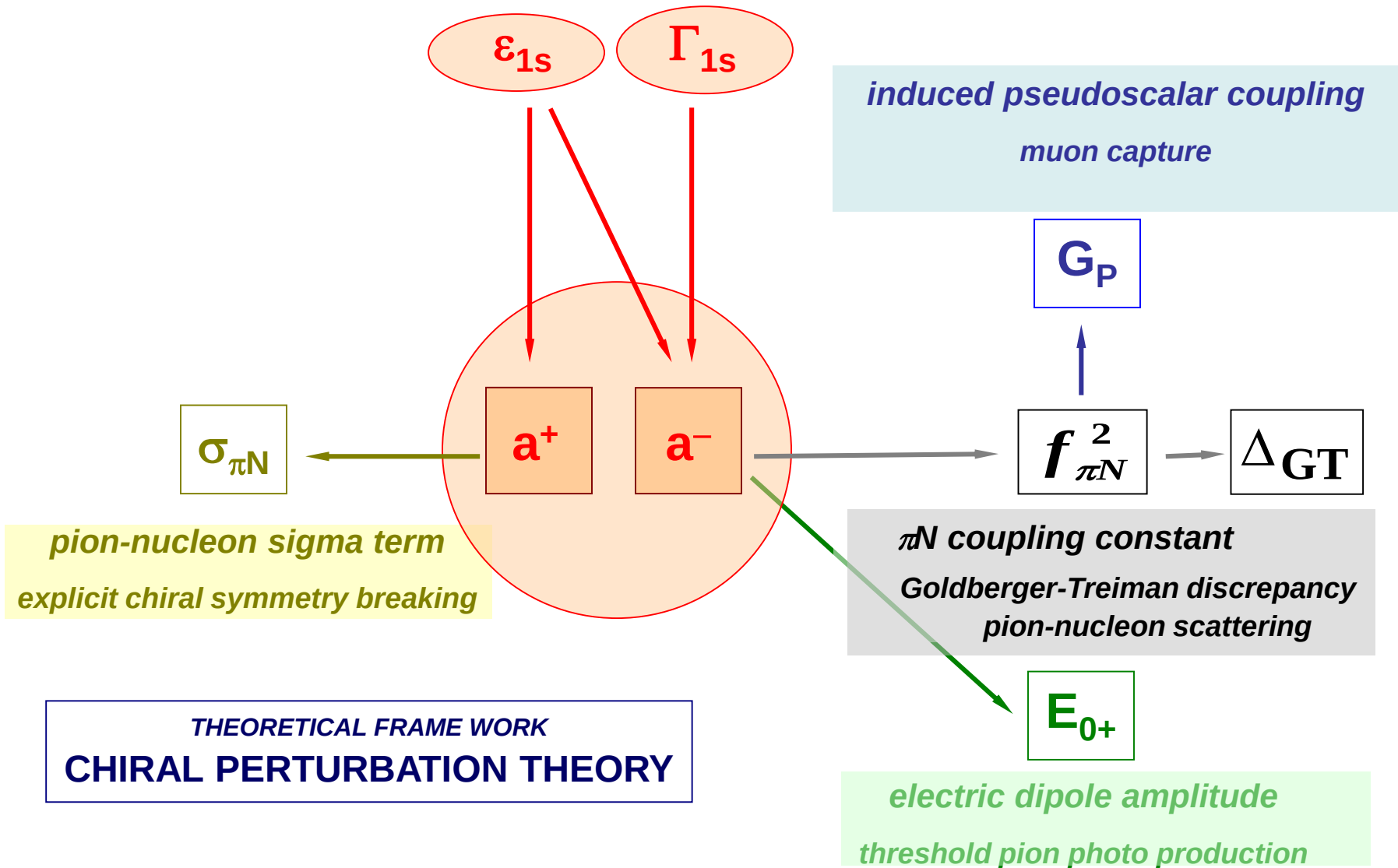
$$a_{\pi^- p} + a_{\pi^- n} = 2 \cdot \frac{1}{3} (a_{1/2} + 2a_{3/2}) + \dots = 2 \cdot a^+ + \dots$$

... : calculate within the framework of χPT

recent reviews theory: J. Gasser, V.E. Lyubovitskij, A. Rusetsky, Phys. Rep. 456, 167 (2008)
M. Hoferichter et al., Phys. Rep. 625, 1 (2016)

PION-NUCLEON SCATTERING LENGTHS

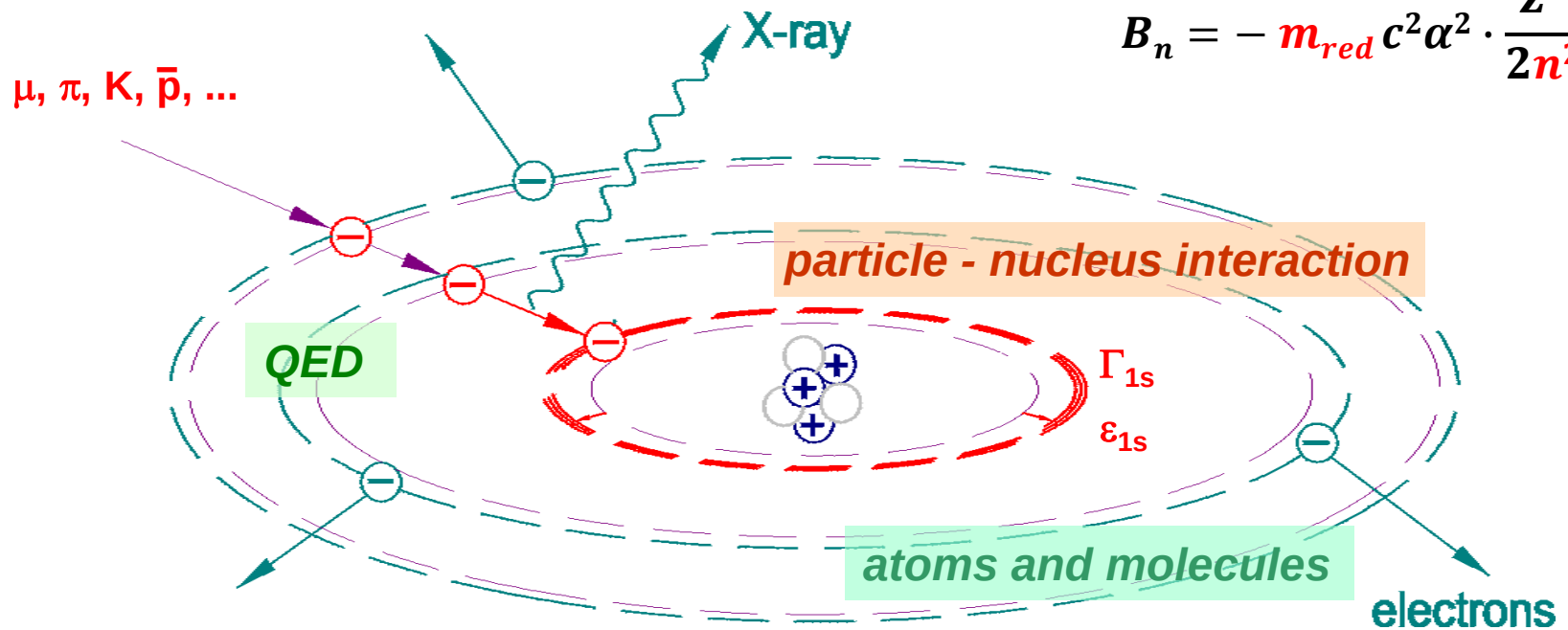
related quantities



LABORATORY: EXOTIC ATOMS

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

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



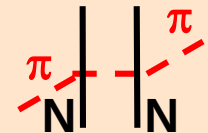
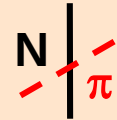
experiment X-ray energy, line width, and intensity

general review experiment: D. Gotta, Prog. Part. Nucl. Phys. Rep. 52, 133 (2004)

πH & πD - origin of shift ϵ_{1s}

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

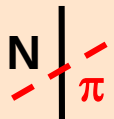
πD coherent sum $\pi^- p \rightarrow \pi^- p + \pi^- n \dots$



πH & πD - origin of broadening Γ_{1s}

πH scattering $\pi^- p \rightarrow \pi^0 n + n\gamma$
CEX = charge exchange

CEX scattering



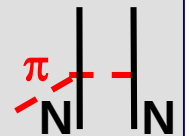
radiative capture



BR well known from experiment

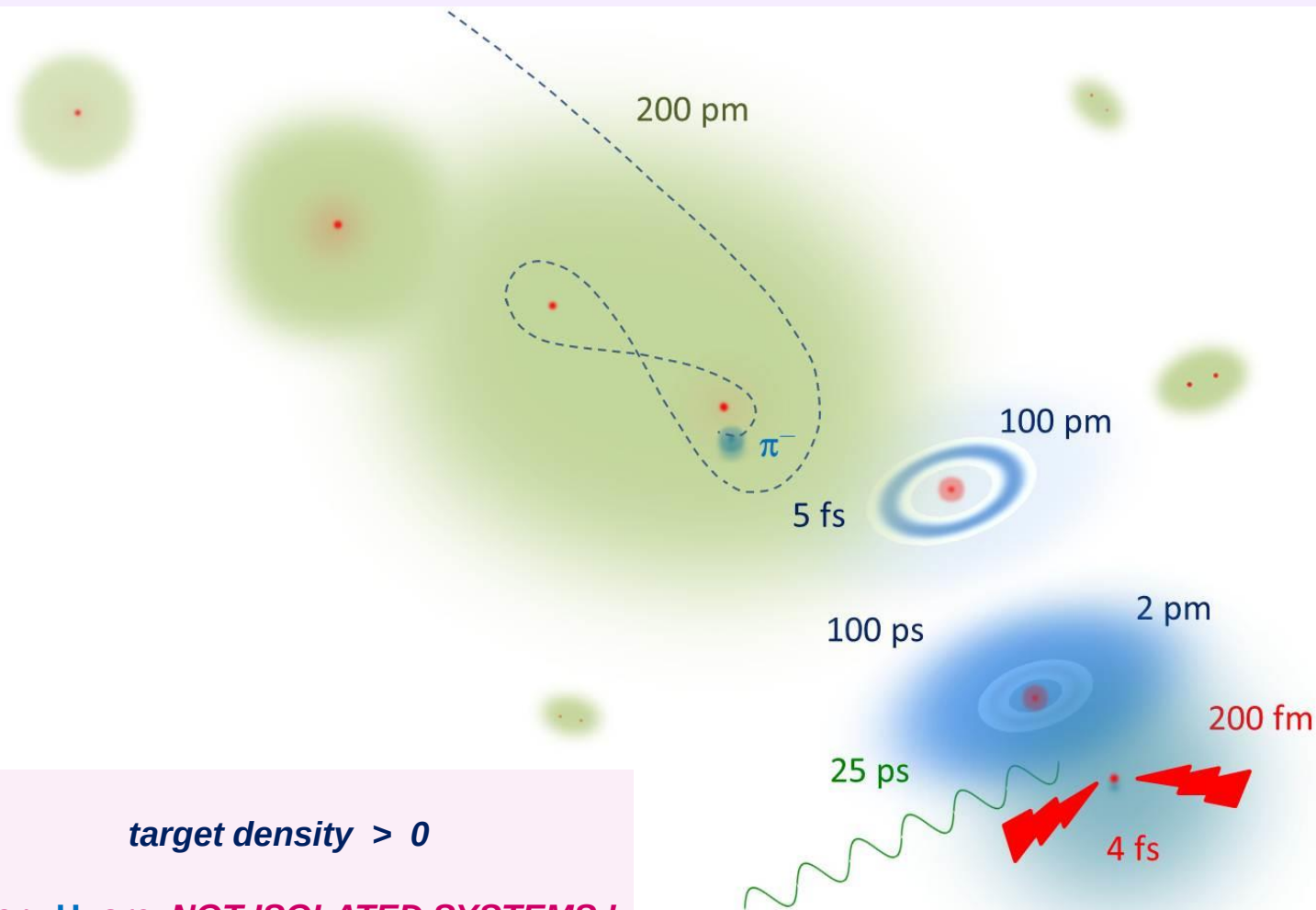
πD absorption $\pi^- d \rightarrow nn + nn\gamma$

„true“ absorption



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- RESULTS
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DE-EXCITATION CASCADE and COLLISIONAL EFFECTS



target density > 0

π H or μ H are NOT ISOLATED SYSTEMS !

pionic hydrogen

$\pi p \rightarrow \pi^0 + n / \rightarrow \gamma + n$ (39%)

Physics effects

Stark mixing

Molecular formation

Coulomb de-excitation

Apparative solution

Suitable X-ray source

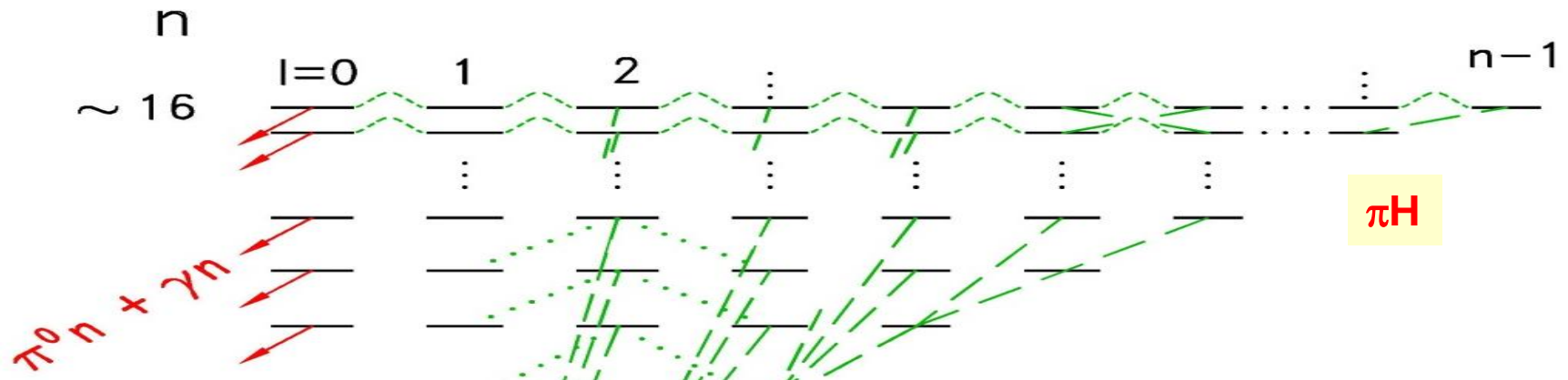
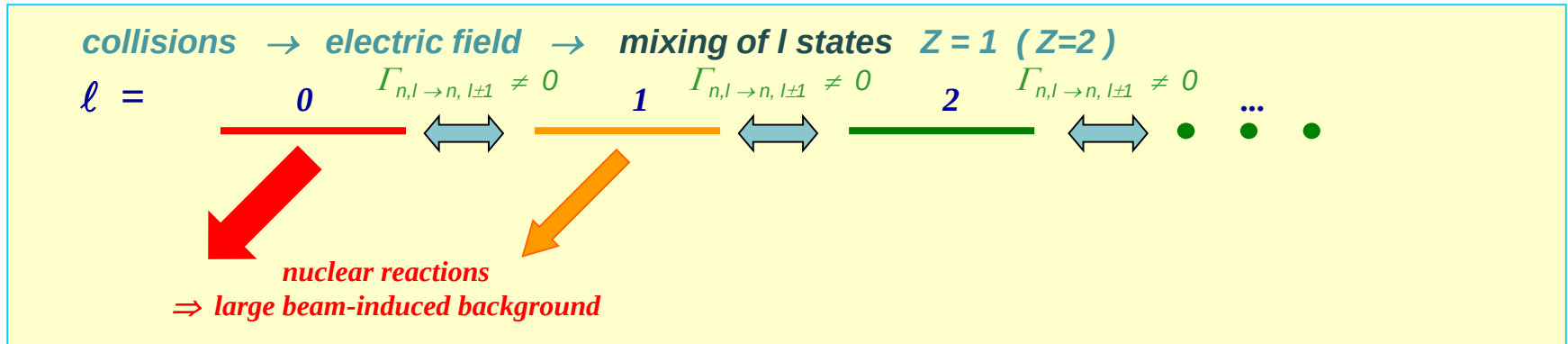
- ***cyclotron trap I $\rightarrow$ II***
- ***cryogenic hydrogen target***
- ***minimize background***

Sufficient energy resolution

- ***Bragg crystal spectrometer***
- ***ECR source: response from X-rays of He-like atoms***

STARK - MIXING

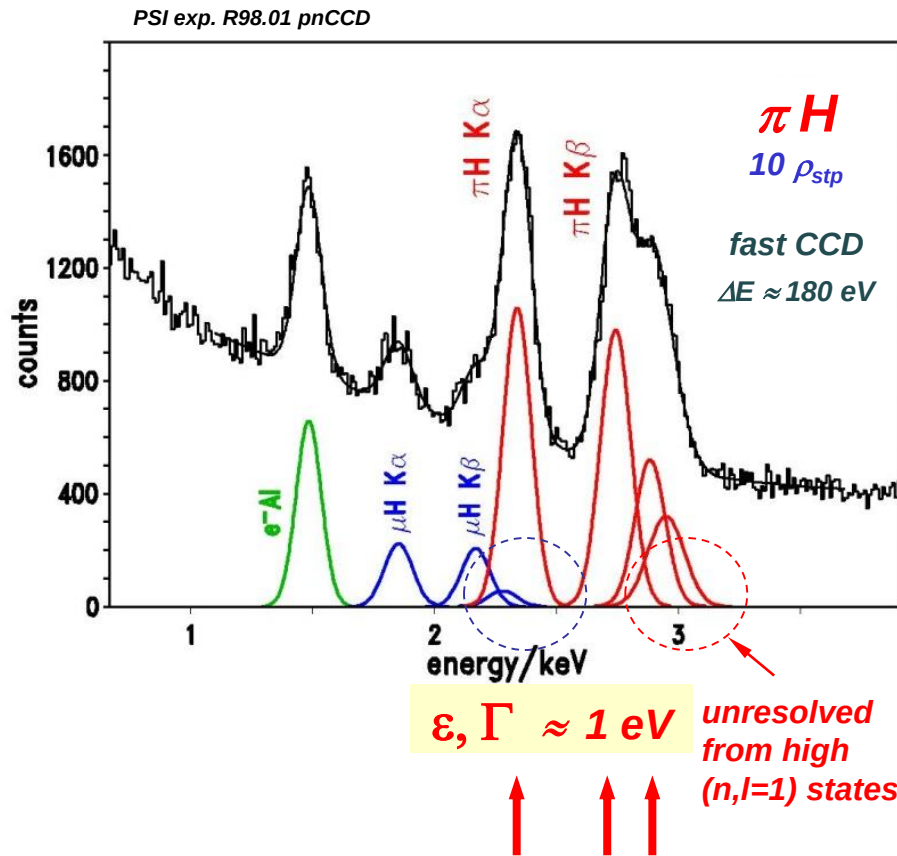
strong density dependence of yields for $Z = 1$ ($Z = 2$)



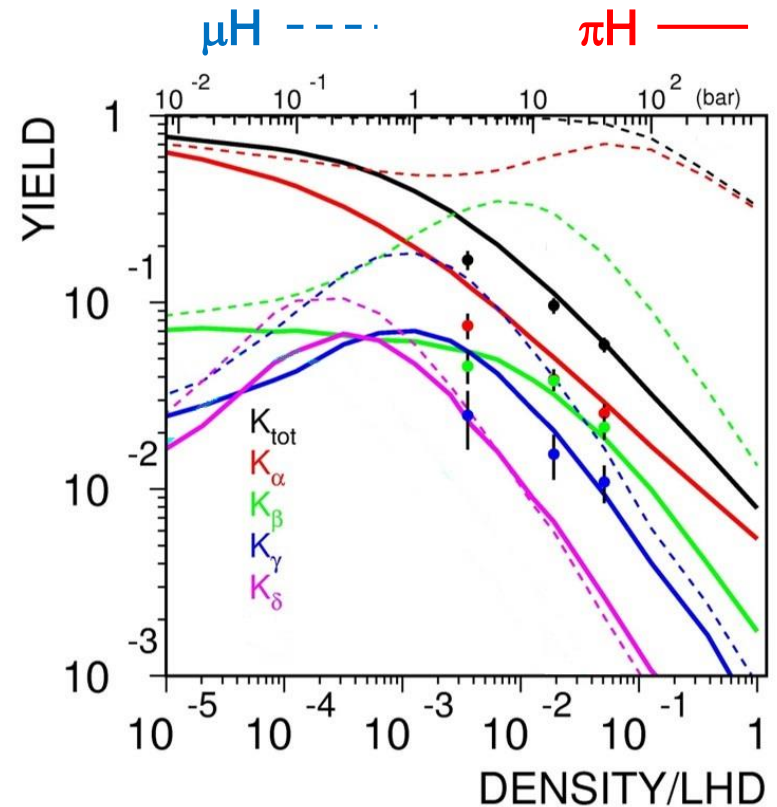
$\bar{p}H \Rightarrow$ nuclear reactions in s and p states

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

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



involve strong interaction effects



data:

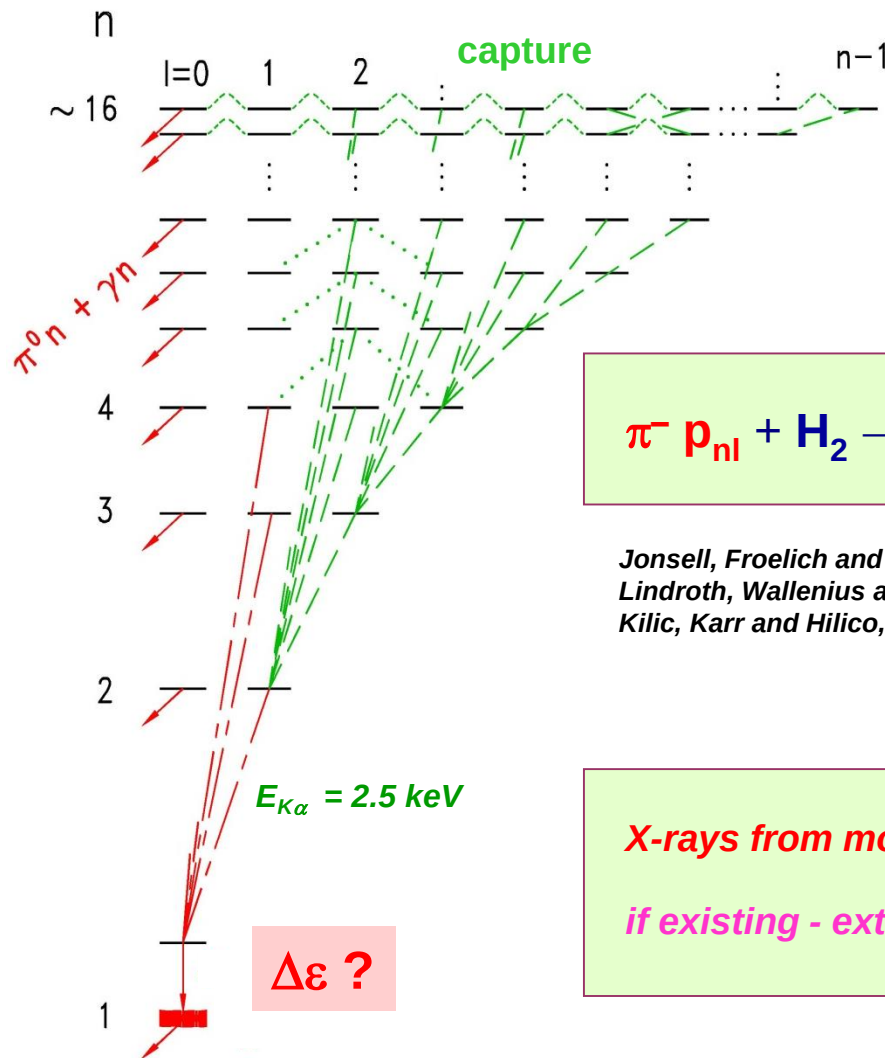
A.J. Rusi el Hassani et al., Z. Phys. A 351, 113 (1995)

cascade calculation:

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

MOLECULAR FORMATION

additional line shift



- known to exist from muon-catalysed fusion
- μH experiment quenching of μp_{2s} via $[(\mu pp)p]ee$ formation
R. Pohl et al., Phys. Rev. Lett. 97 (2006) 193402



Jonsell, Froelich and Wallenius for $n = 1, 2, 3$, Phys. Rev A 59 (1999) 3440
Lindroth, Wallenius and Jonsell, Phys. Rev A 68 (2003) 032502
Kilic, Karr and Hilico, Phys. Rev. A 70 (2004) 042506

X-rays from molecular states ? $\Rightarrow$ energy shift of np levels
if existing - extrapolation to density zero necessary!

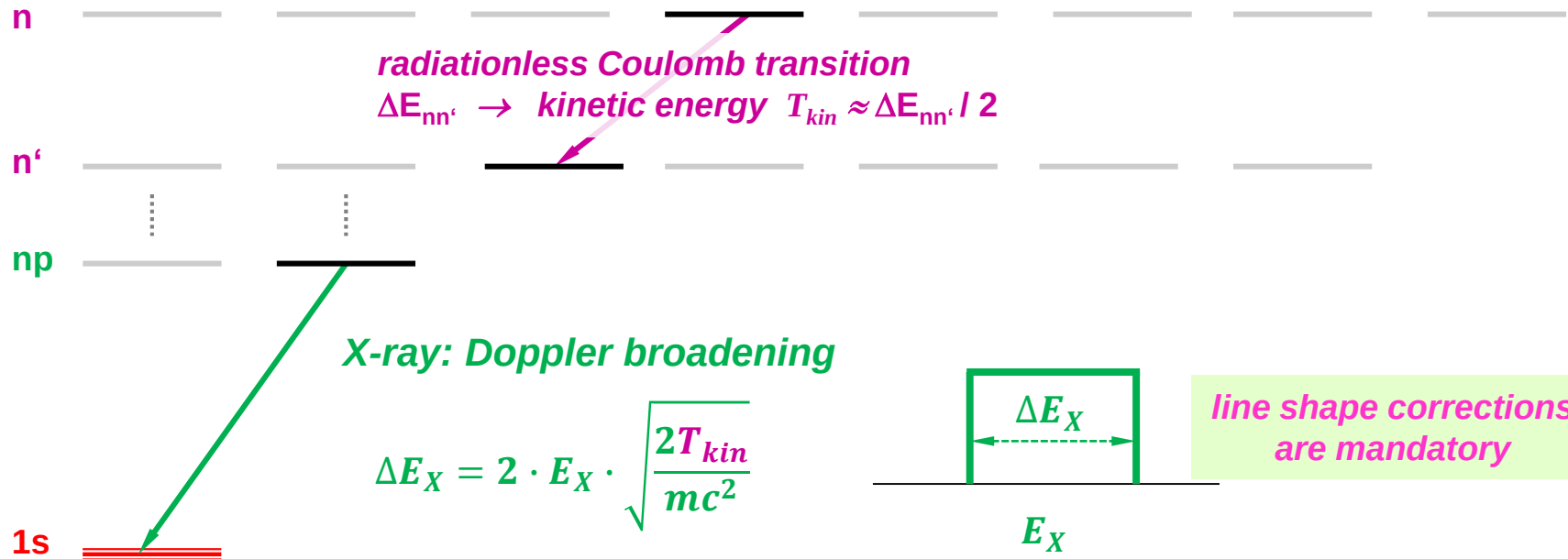
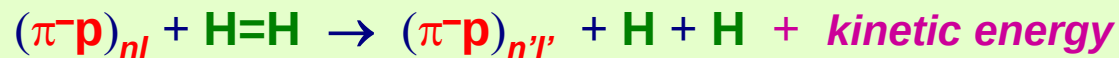
COULOMB DE-EXCITATION

additional line broadening

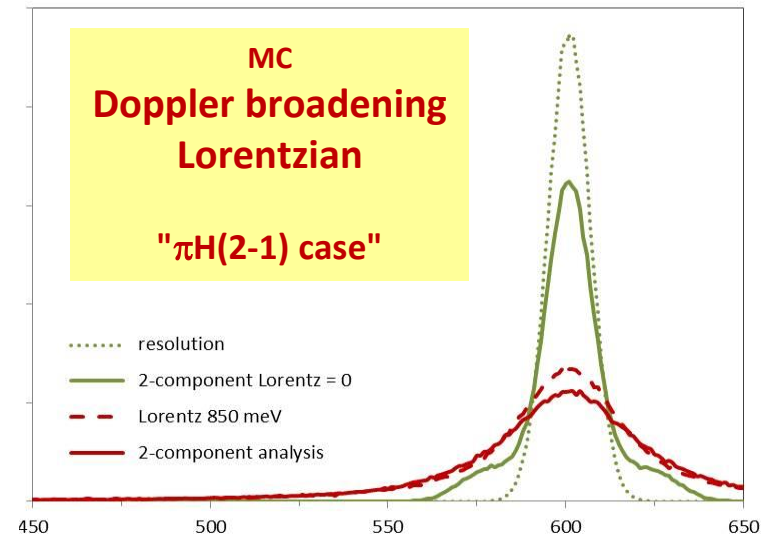
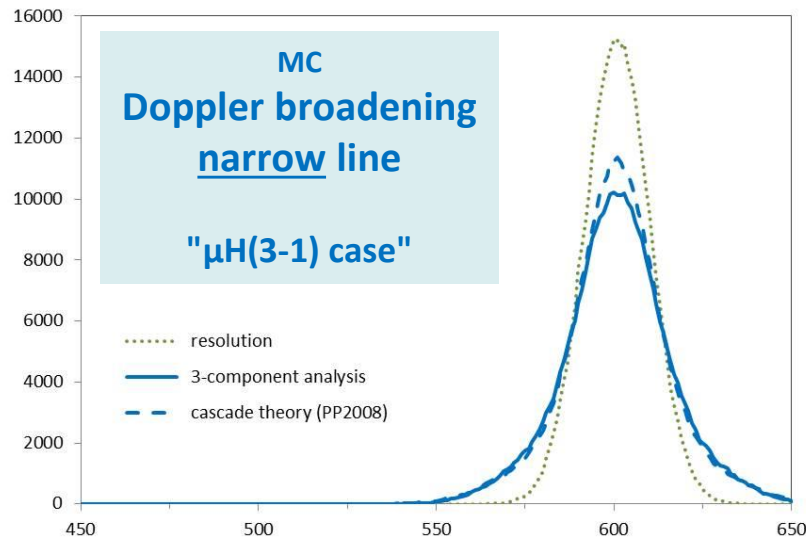
first observed from NEUTRON - TOF

J.B. Czirr et al., Phys. Rev. 130, 341 (1963)

A. Badertscher et al., Eur. Phys. Lett. 54 (2001) 313 (status)



EXEMPLIFICATION of Coulomb de-excitation



low background essential !

typical resolution (FWHM)

272 meV

390 meV

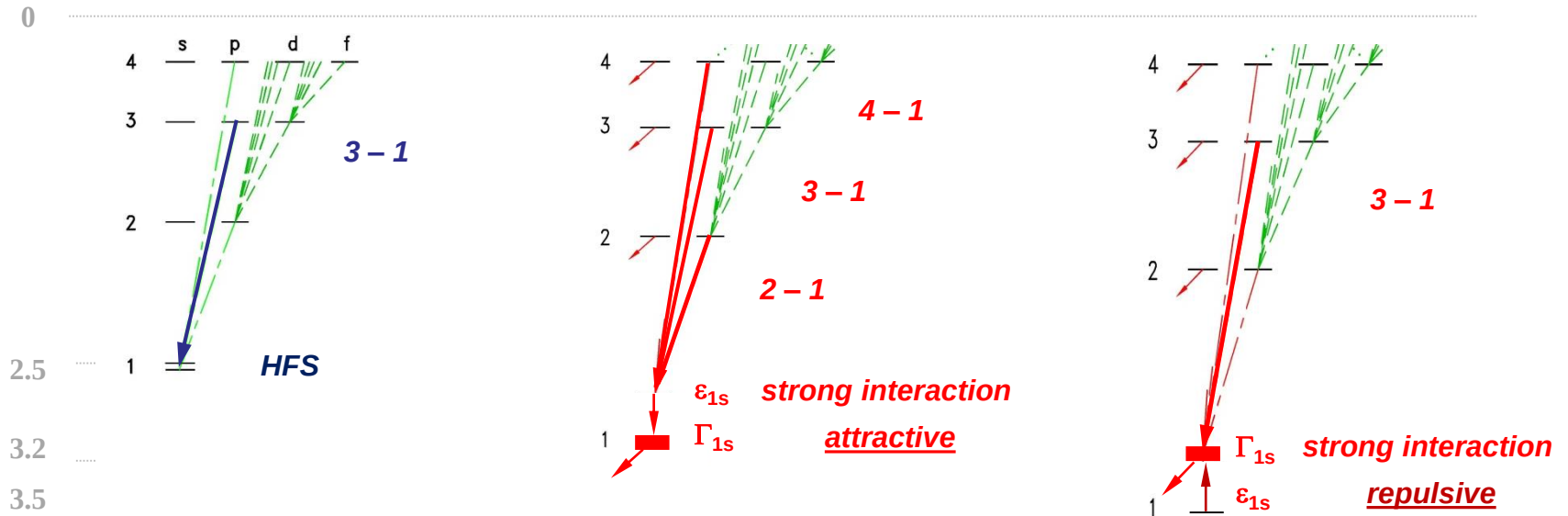
STRATEGY – VARY TRANSITION & VARY DENSITY

μH

πH

πD

E_B / keV



„dangerous“ cascade effects

Coulomb de-excitation
molecular formation

10 bar

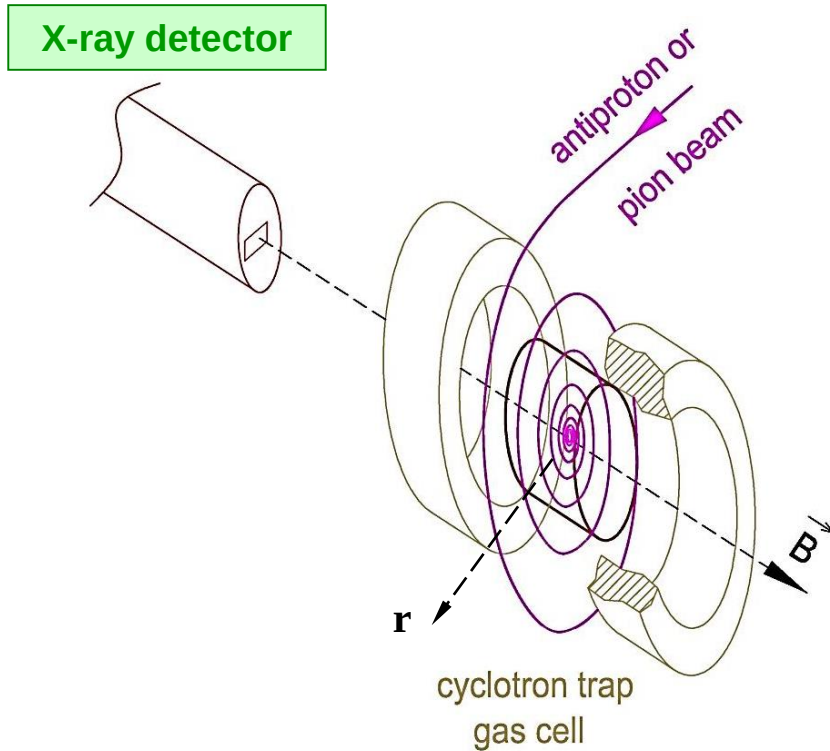
3, 10, 28 bar and LH_2

3, 10 and 17 bar

X-ray source

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) $\times 10^6$

$\Rightarrow$ high X - ray line yields

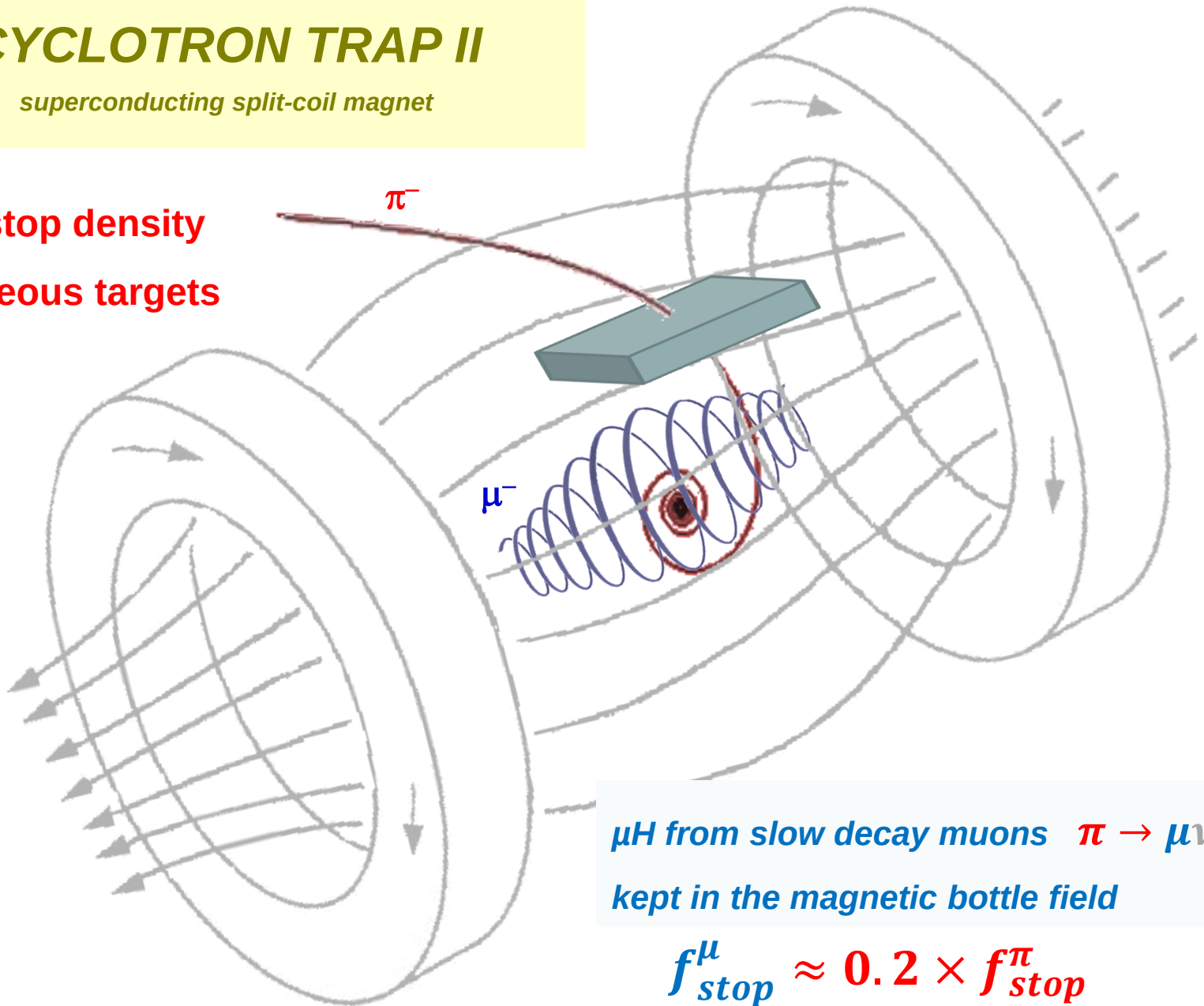
$\Rightarrow$ bright X - ray source

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

CYCLOTRON TRAP II

superconducting split-coil magnet

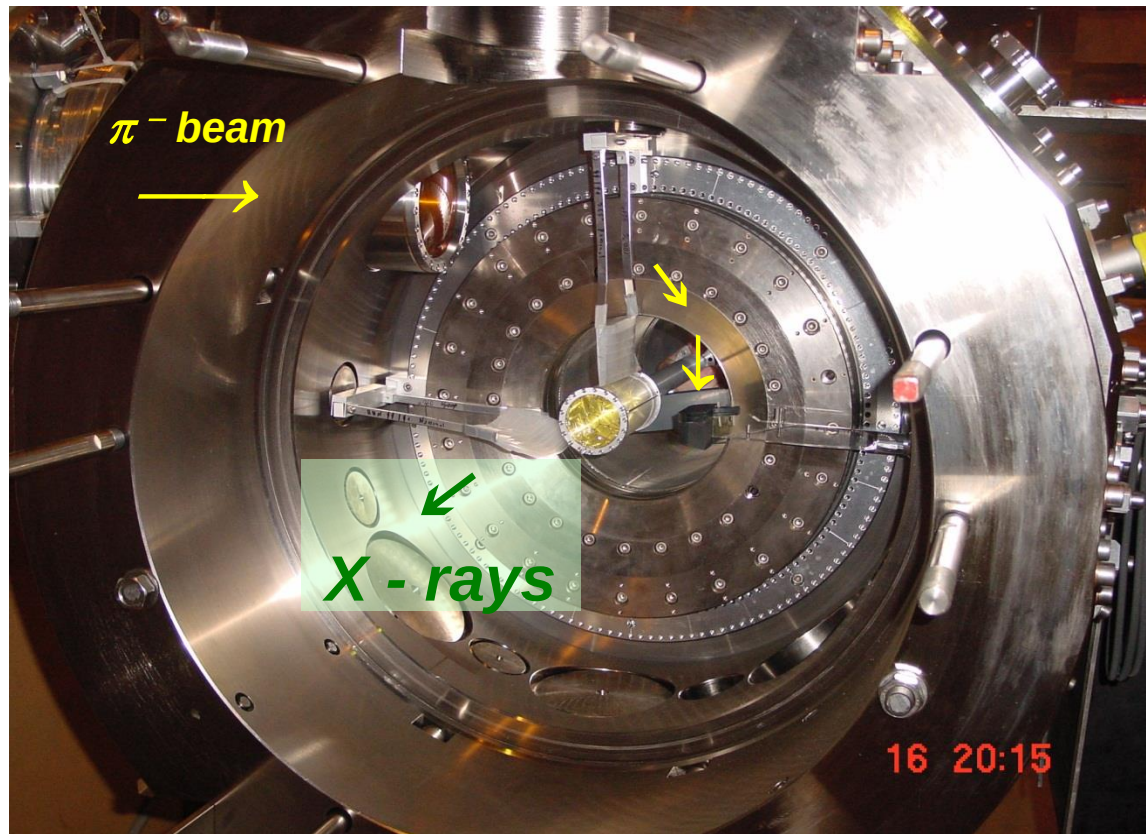
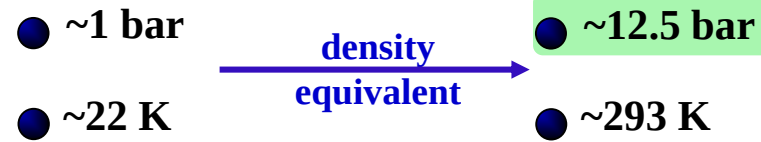
high stop density
in gaseous targets



μH from slow decay muons $\pi \rightarrow \mu \nu$
kept in the magnetic bottle field

$$f_{stop}^{\mu} \approx 0.2 \times f_{stop}^{\pi}$$

Cryogenic target: density adjustment by temperature variation



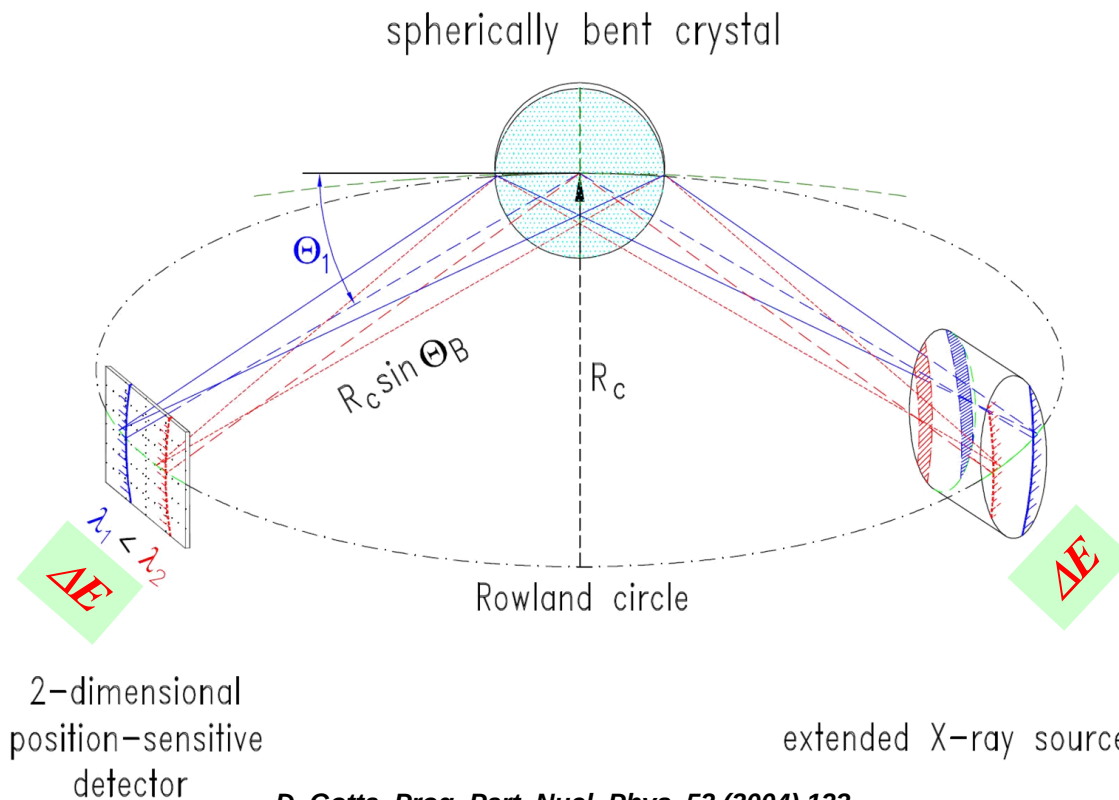
pion set-up 2002

Energy resolution

JOHANN-TYPE CRYSTAL SPECTROMETER

simultaneous measurement of ΔE

Bragg law $n\lambda = 2d \cdot \sin\Theta_B$



focussing conditions

horizontal $R_c \cdot \sin\Theta_B \checkmark$

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

angular dispersion

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

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

D.E. Gotta, L.M. Simons, Spectrochim. Acta Part B 120 (2016) 9

TYPICAL *SET-UP* at PSI

*pion stops in gas: few % of $10^8/s$
 ≈ 5 neutrons / π^-*

PSI experiments R-98.01 and R-06.03

cyclotron trap

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

crystal

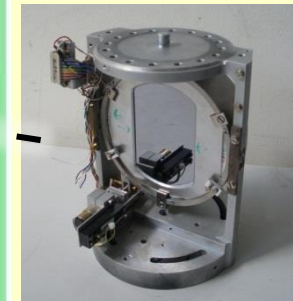
CCD

π E5

crystal spectrometer setup

π H(4-1) and π D(3-1) $\Theta_{\text{Bragg}} \approx 40^\circ$

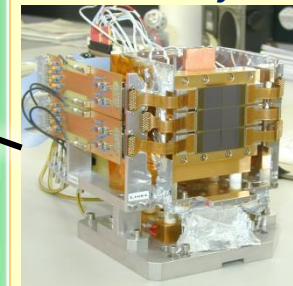
BRAGG CRYSTAL
spherically bent



Si or quartz

$R = 3 \text{ m}$
 $\Phi = 10 \text{ cm}$

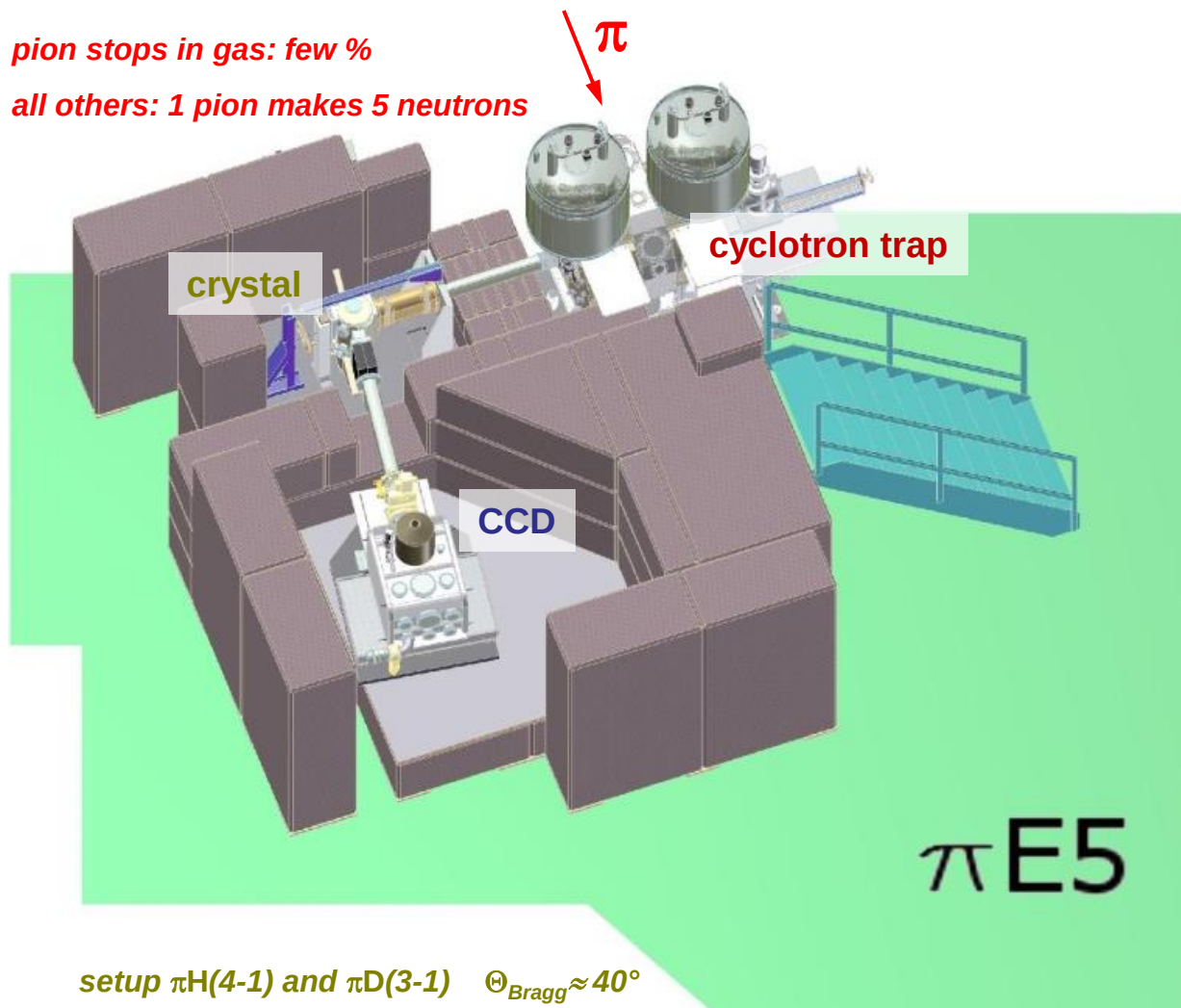
FOCAL PLANE DETECTOR
 3x2 CCD array



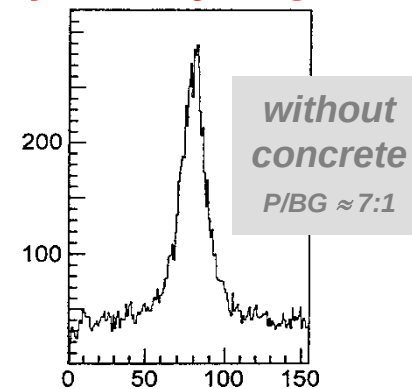
pixel size
 $40 \mu\text{m} \times 40 \mu\text{m}$

N. Nelms et al. Nucl. Instr. Meth. A484 (2002) 419

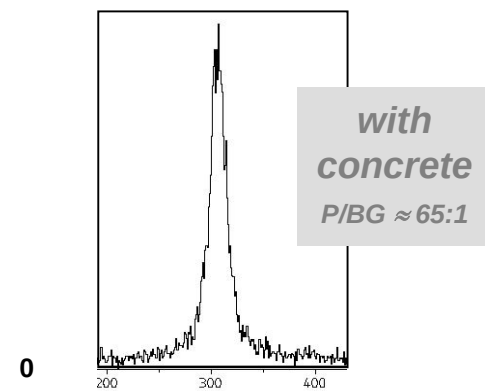
TYPICAL SET-UP at PSI



pionic hydrogen



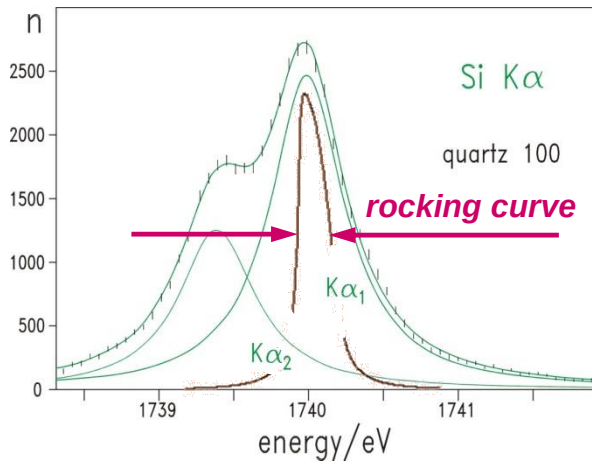
peak/background x 10



background reduction II

CRYSTAL RESPONSE - NO SOLUTION

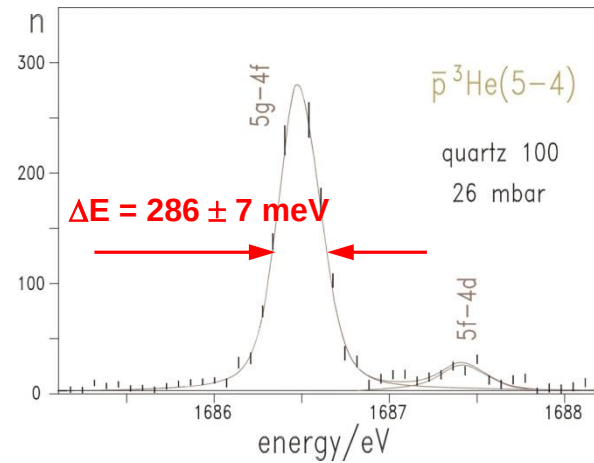
fluorescence X-rays
excited by means of X-ray tubes



problem

**large natural line width
and
satellite lines**

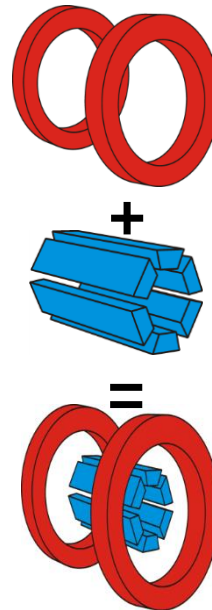
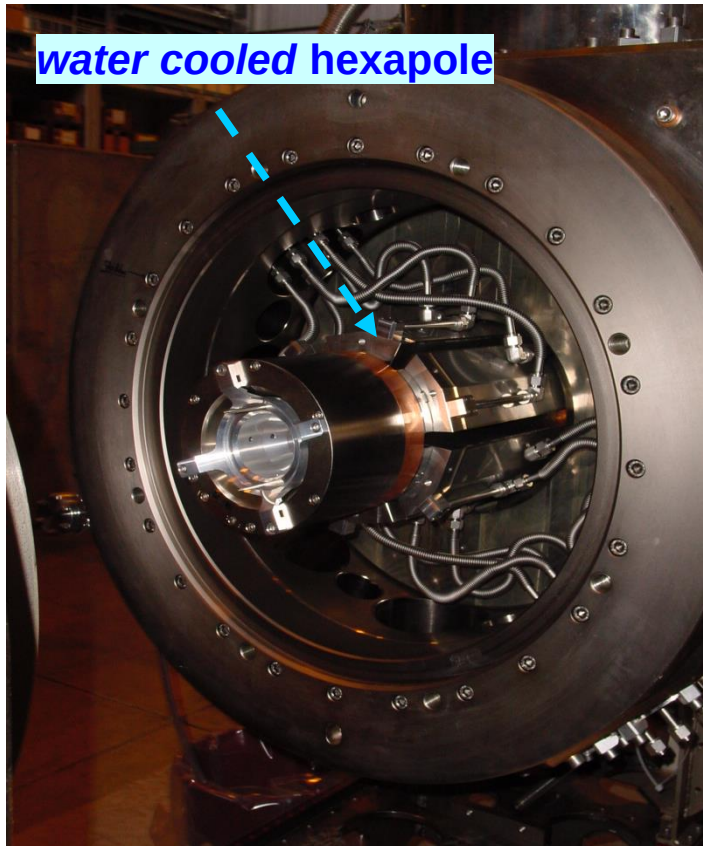
exotic-atom X-rays
from hydrogen-like systems



problem

rate

MEASURE SPECTROMETER RESPONSE *new approach*



ECRIS

*Electron Cyclotron Resonance Ion
"Source"*

=
cyclotron trap + hexapole magnet

superconducting coils

- *cyclotron trap*

permanent hexapole

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

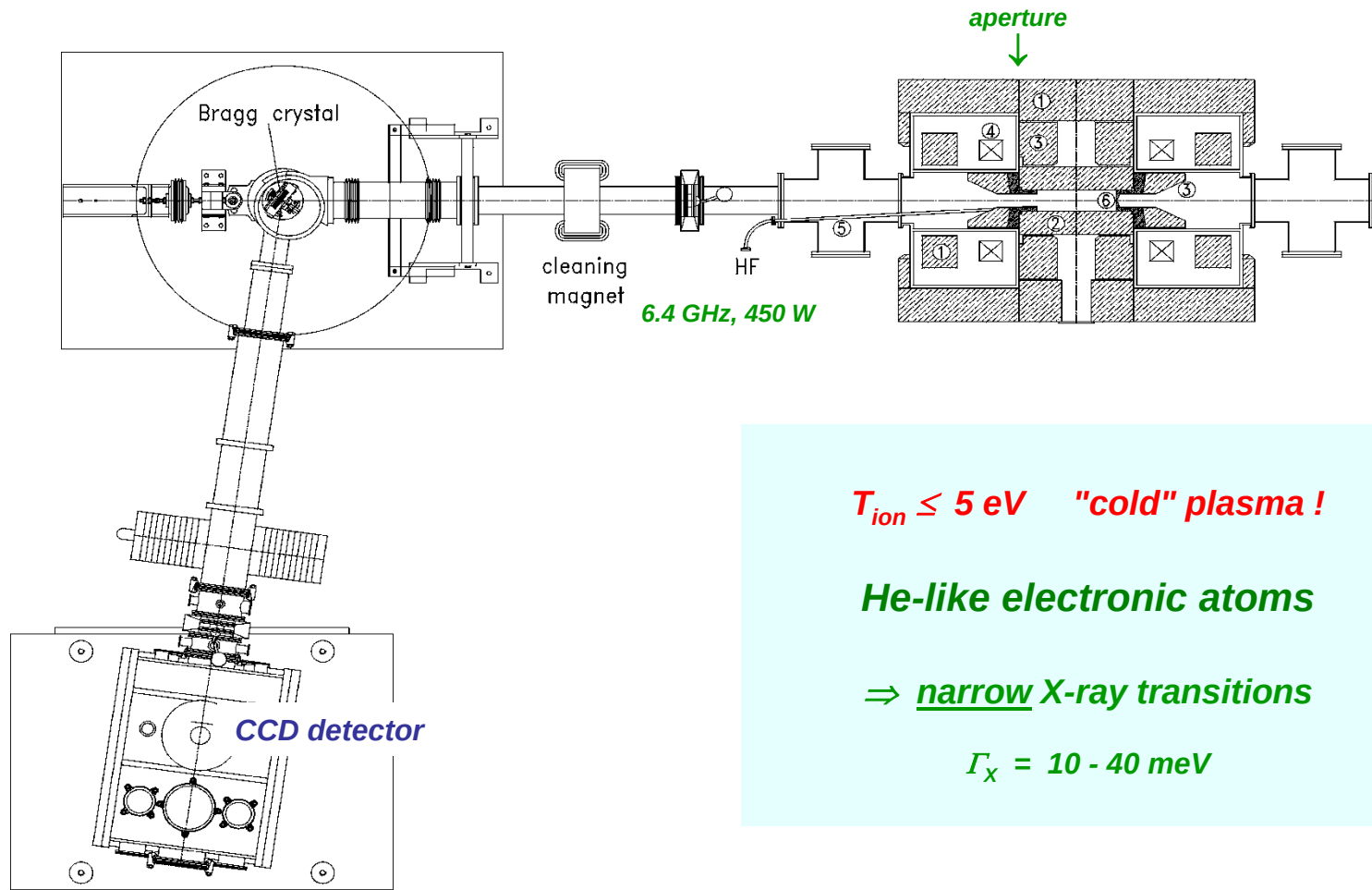
large mirror ratio = 4.3

$B_{\max} / B_{\min} !$

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)



$T_{ion} \leq 5 \text{ eV}$ "cold" plasma !

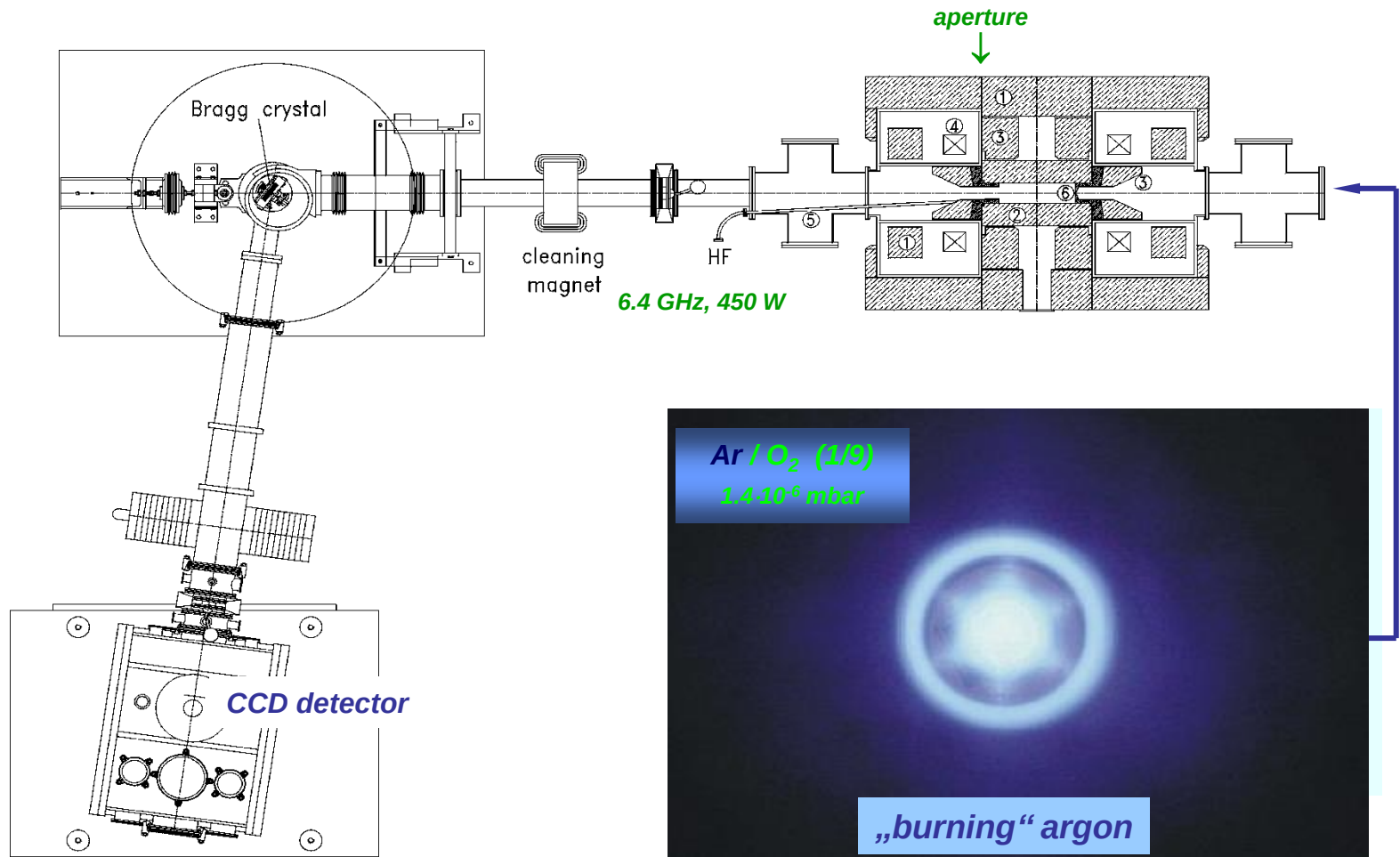
He-like electronic atoms

⇒ narrow X-ray transitions

$$\Gamma_x = 10 - 40 \text{ meV}$$

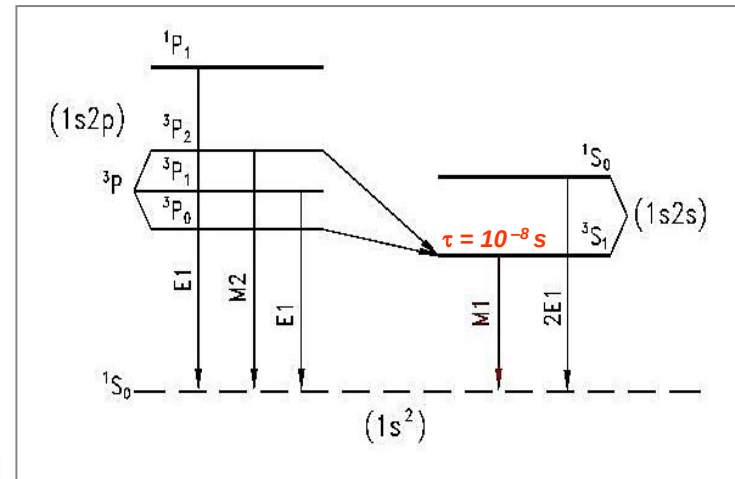
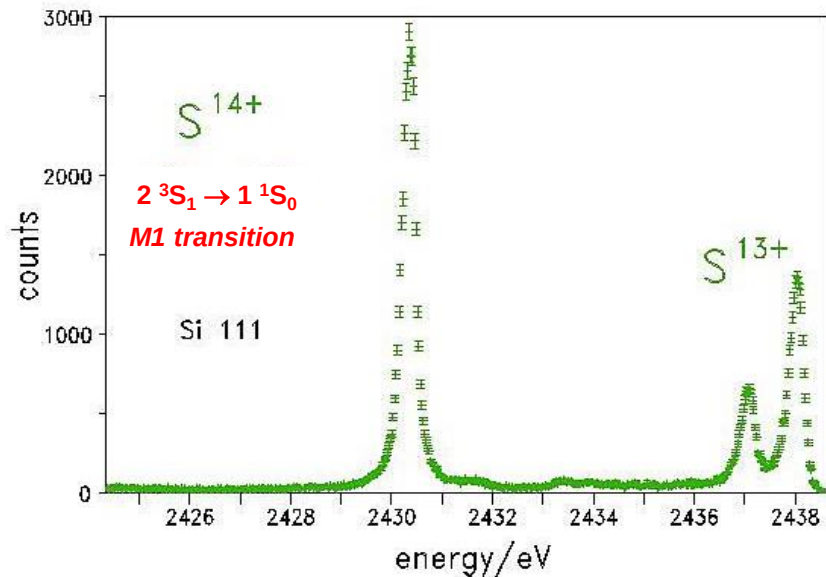
CRYSTAL SPECTROMETER and PSI ECRIT

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



SPECTROMETER RESPONSE at π H Lyman ENERGIES

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

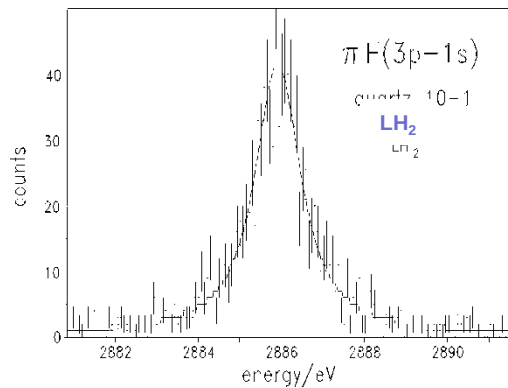
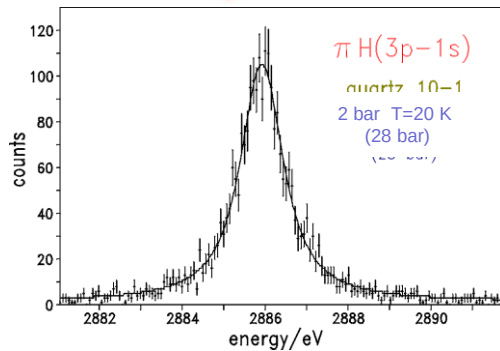
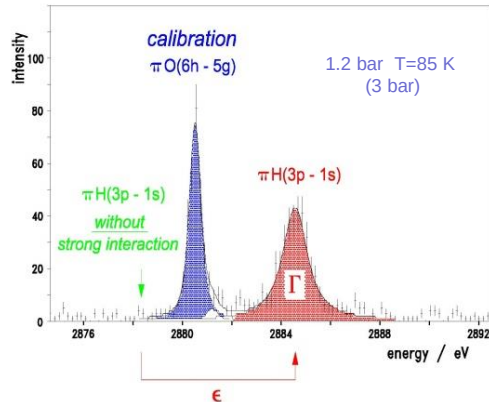
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DETERMINATION OF ϵ_{1s}

=

find angle difference to reference line

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



energy calibration

$\pi\text{H} / \pi\text{O}$ mixture

mixture H_2 / O_2 (98% / 2%)

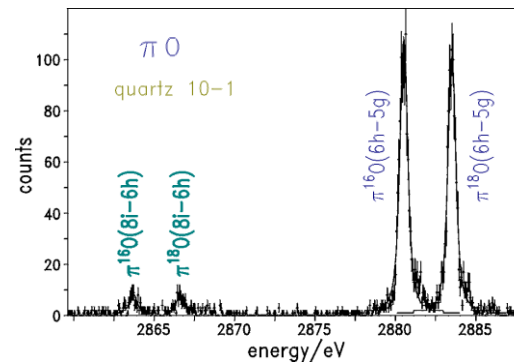
1.2 bar @ $T = 85\text{ K}$

energy calibration simultaneously

$\pi\text{H} / \pi\text{O}$ alternating

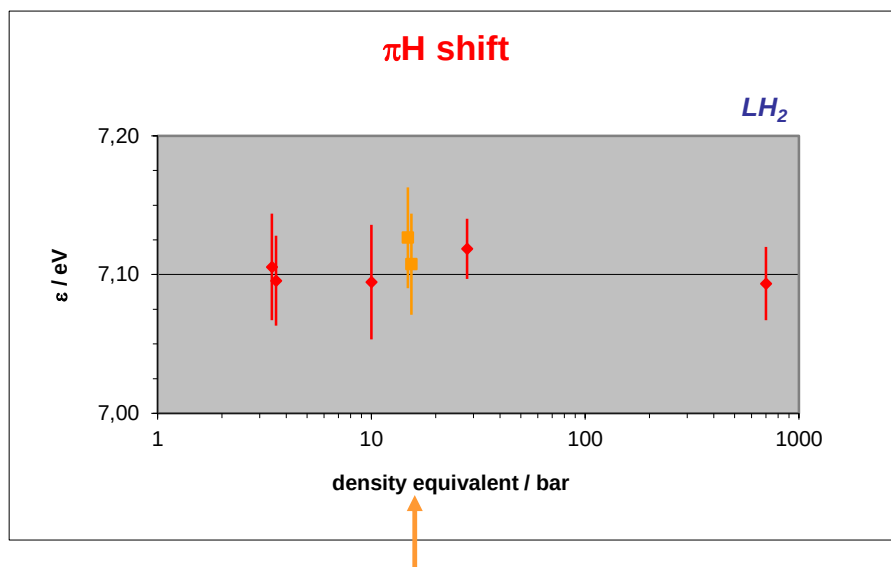
mixture $^4\text{He} / ^{16}\text{O}_2 / ^{18}\text{O}_2$ ($\approx 80\%$ / 10% / 10%)

2 bar @ $T = 86\text{ K}$



$\pi\text{H}(3p - 1s) \quad \epsilon_{1s}$

no density dependence identified $\Rightarrow$ “no” X-ray transitions from molecular states



previous experiment – Ar K α
ETHZ-PSI H.-Ch.Schröder et al.
Eur.Phys.J.C 1(2001)473

$$\epsilon_{1s} = + 7.0858 \pm 0.0096 \text{ eV } (\pm 0.14\%)$$

$$a_{\pi^-p} = (85.26 \pm 0.12) \cdot 10^{-3} m_{\pi}^{-1}$$

$$a^+ + a^- = (93.4 \pm 0.12_{\text{exp}} \pm 2.8_{\text{th}}) \cdot 10^{-3} m_{\pi}^{-1}$$

M. Hennebach, PhD thesis, Cologne 2003
M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190

most recent value for $m_{\pi} \pm 1.3\text{ppm}$

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

$$\Rightarrow \Delta\epsilon_{m\pi} = \pm 0.8 \text{ meV} !$$

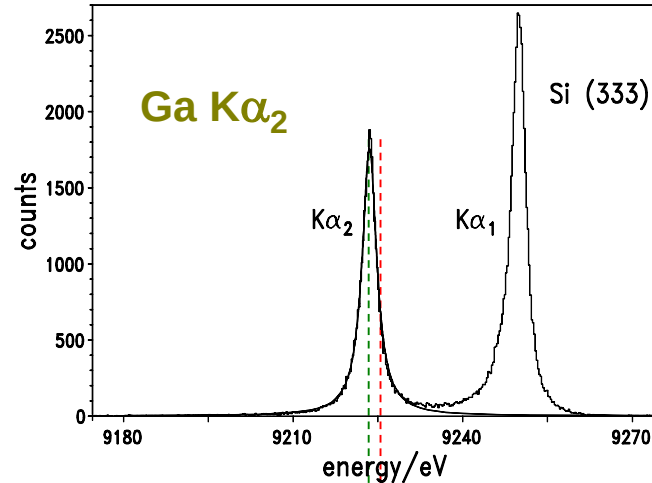
new QED value $\Delta\epsilon_{\text{QED}} = \pm 1.4 \text{ meV}$

S. Schlessler et al. Phys. Rev. C 84 (2011) 015211

$$\Rightarrow - 22 \text{ meV} !$$

$\pi D(3p - 1s)$ ϵ_{1s}

energy calibration

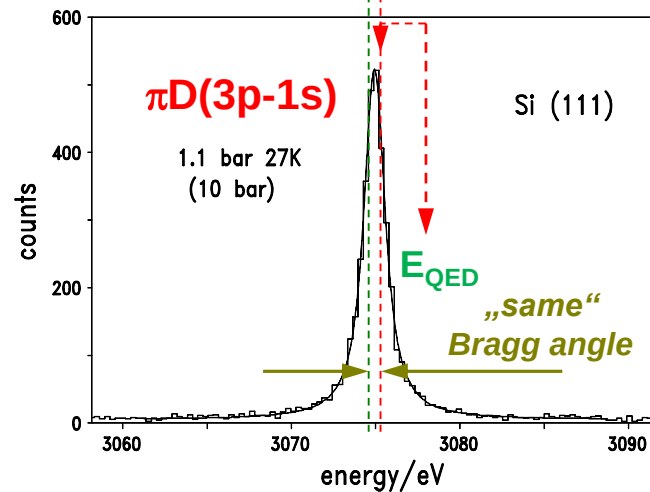
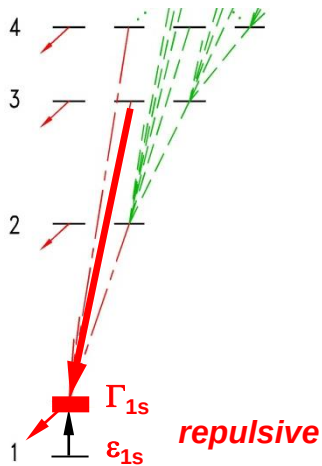


3 bar
10 bar
22 bar } no molecule formation seen

error budget

± 27 meV	Ga $K\alpha_2$
± 10 meV	statistics
± 8 meV	pion mass
± 5 meV	systematics
± 2 meV	QED

strong interaction



$$\epsilon_{1s} = (-2.356 \pm 0.031) \text{ eV } (\pm 1.3\%)$$

$$\Re a_{\pi-d} = (25.0 \pm 0.3) \cdot 10^{-3} m_{\pi}^{-1}$$

PhD thesis: Th. Strauch, Cologne 2009

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

$$\text{line shape} = \text{Lorentzian} \otimes \text{RESPONSE} \otimes \sum_i D_i$$

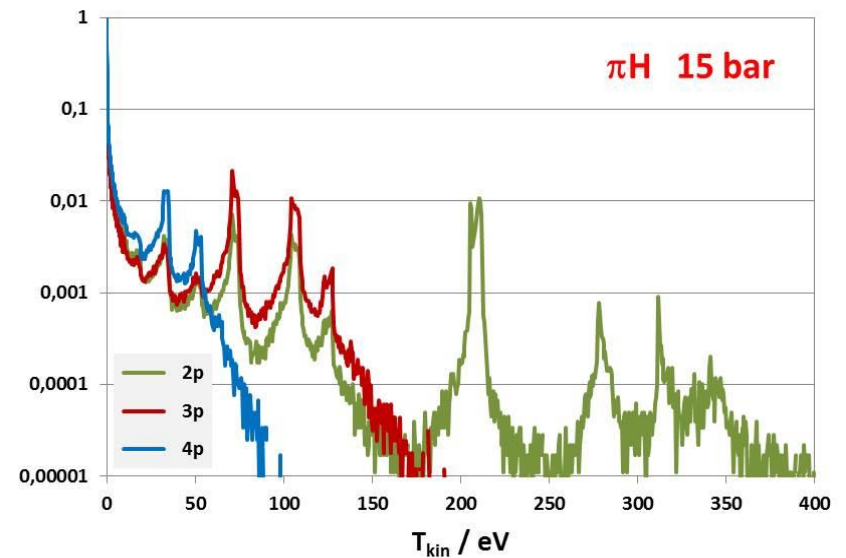
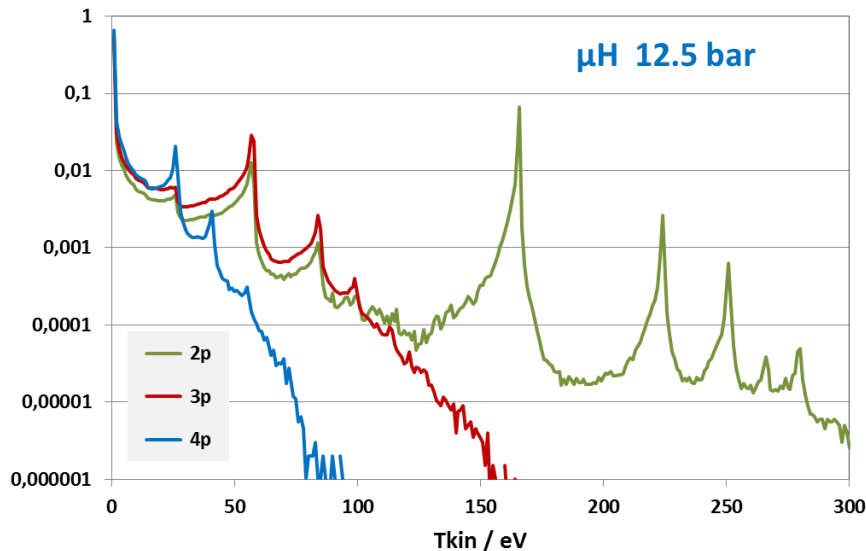
EXTRACTION OF Γ_{1s}

=

find model for Coulomb de-excitation

Prediction from cascade theory

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



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

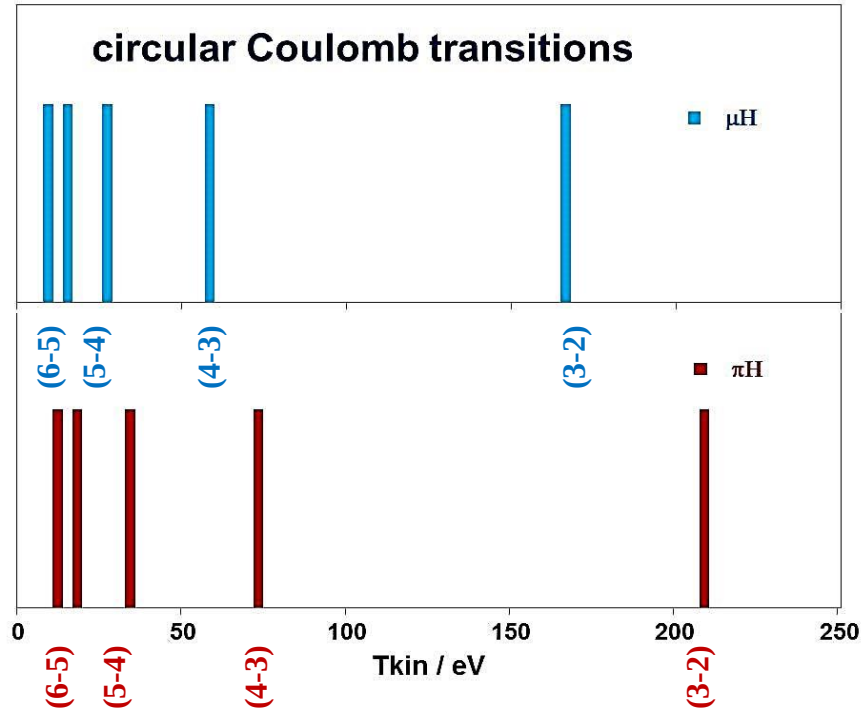
G.Ya. Koreman, V.N. Pomerantsev and V.P. Popov, *JETP. Lett.* 81, 543 (2005)

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)

STRATEGY - phenomenological approach



maximal Doppler broadening of X-ray line

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

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

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

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

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

ANALYSIS METHODS

I MAXIMUM LIKELIHOOD „FIT“

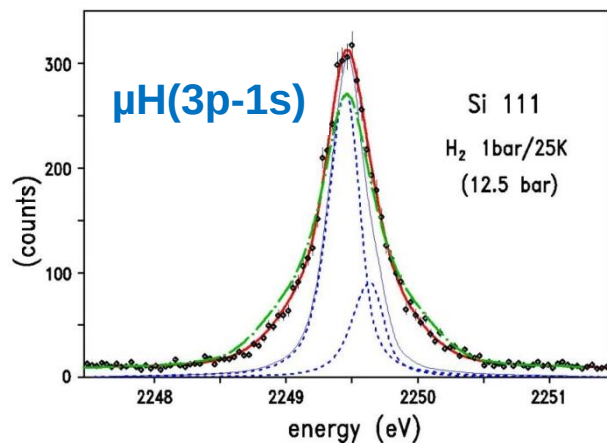
„MINUIT“ χ^2 analysis

„bias“ problem

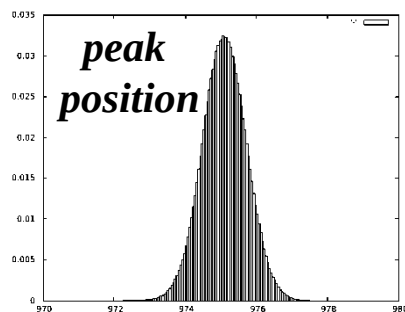
II BAYESIAN APPROACH

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

comparison: 3-component model



„obvious“ parameters
look like Gaussian



χ^2 analysis

[0-2] 61 ± 2

[24-27] 25 ± 3

[57-58] 14 ± 4

HFS free 211 ± 19

T/S 3.6 ± 0.6

HFS fixed

T/S 2.9 ± 0.2

Bayesian approach

[0-4] 65^{+3}_{-4}

[23-25] 24^{+4}_{-10}

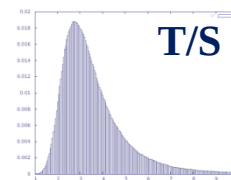
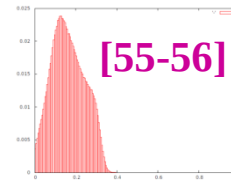
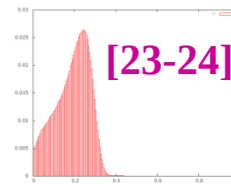
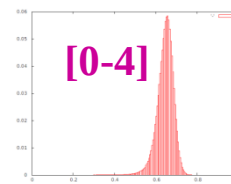
[55-57] 16^{+10}_{-4}

$^{+23}_{-21}$

$212^{+1.6}_{-0.7}$

3.2

$^{+1.1}_{-0.5}$
2.5

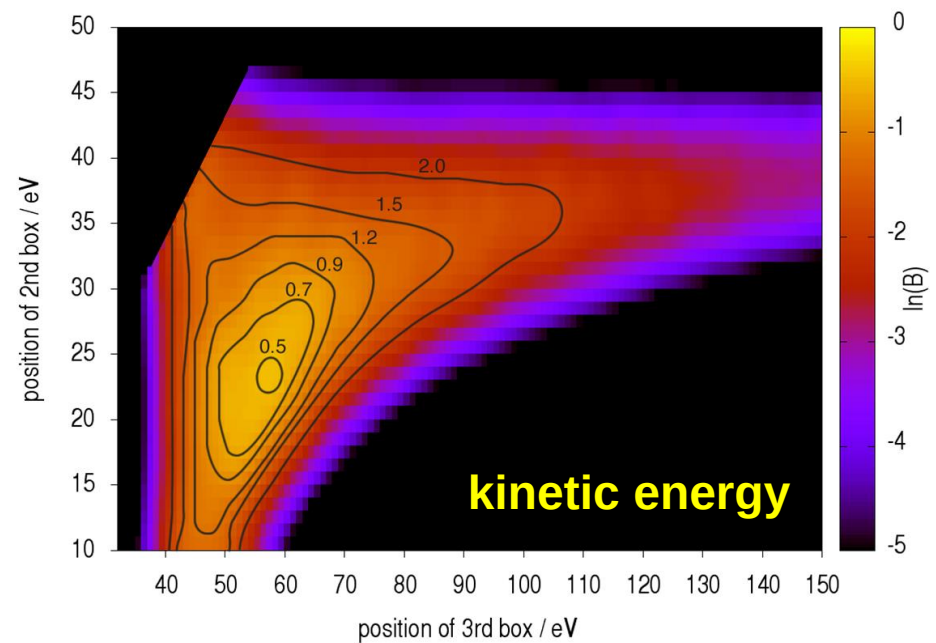
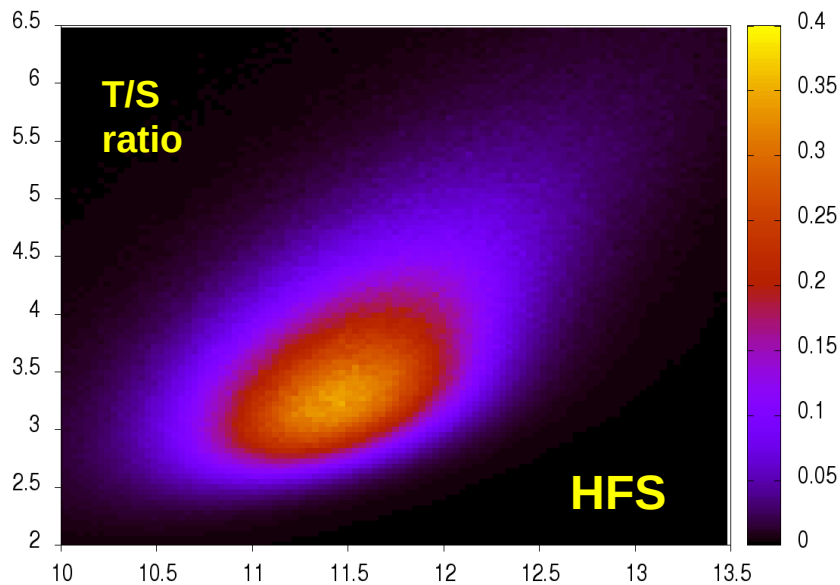


ANALYSIS - $\mu\text{H}(3p - 1s)$

Bayesian approach: two-dimensional posterior probability

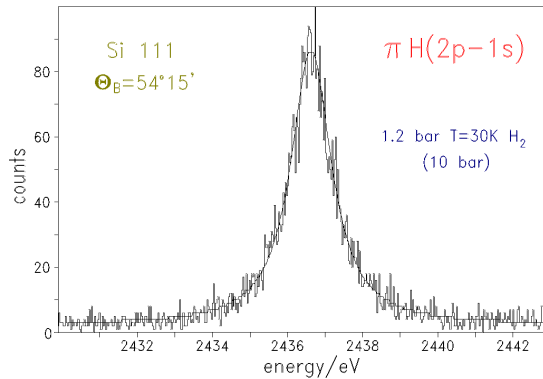
HFS free 212 $+23$
 -21
T/S 3.2 $+1.6$
 -0.7

2 high-energy components

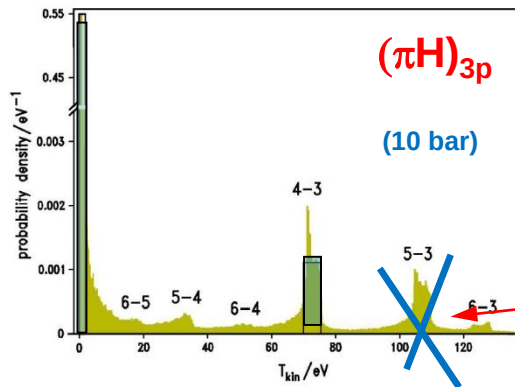
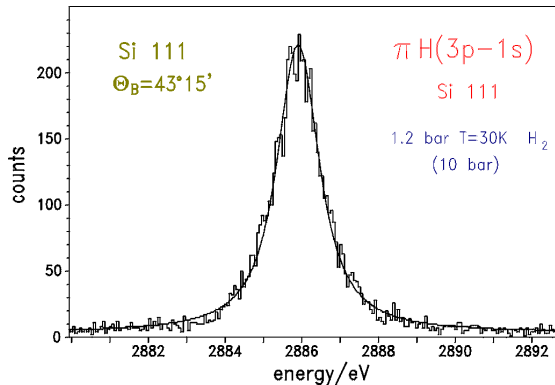


D.S. Covita, PhD thesis Coimbra 2008
D.S. Covita et al., Phys. Rev. Lett. 102, 023401 (2009)
M.Theisen, Diploma thesis FZJ 2013
D.S. Covita et al., Eur. Phys. J. D 72, 72 (2018)

ANALYSIS - $\pi H(np - 1s) \Gamma_{1s}$



alternative HE components

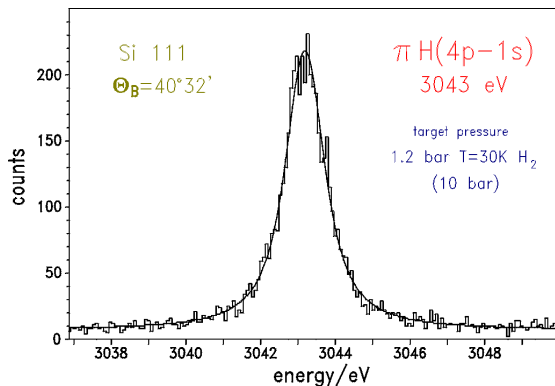


„FIT“ →

Coulomb transition

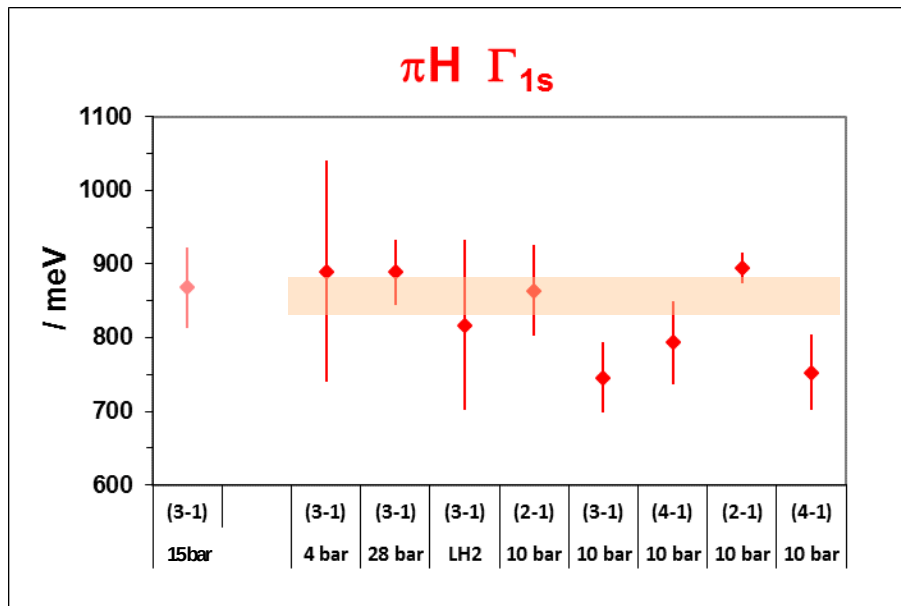
low-energy $\approx 50\%$
 5-4 ---
 6-4 ---
 4-3 $\approx 50\%$
 3-2 ?

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 ---

$\pi H(np - 1s) \quad \Gamma_{1s}$



↑
previous
experiment

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

$$\Gamma_{1s} = 856 \pm 27 \text{ meV } (\pm 3.1\%)$$

$$a_{\pi^- p}^{cex} = (-124.4 \pm 2.0) \cdot 10^{-3} m_{\pi}^{-1}$$

$$a^- = (88.2 \pm 1.4_{exp} \pm 0.6_{th}) \cdot 10^{-3} m_{\pi}^{-1}$$

A. Hirtl, PhD thesis, TU Vienna, 2008
A. Hirtl et al., Eur. Phys. J. A 57 (2021) 70

Γ_{1s} / meV

„FIT“ bias corrected 852 ± 22

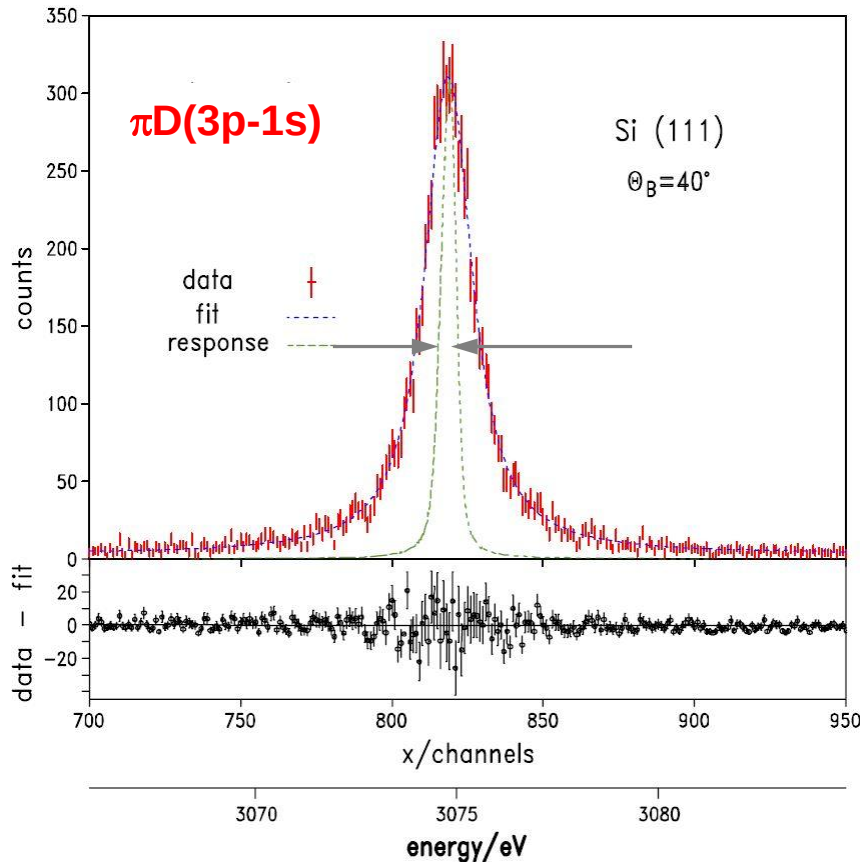
Bayesian approach 856 ± 27

Kln. energy distribution from cascade theory

$$\Gamma_{1s} = 781 - 963 \pm (7 - 20) \text{ meV}$$

no solution!

$\pi D(3p - 1s) \quad \Gamma_{1s}$



$$\Gamma_{1s} = (1.171 \pm 0.023) \text{ eV} \quad \left(\begin{array}{l} + 2\% \\ - 4\% \end{array} \right)$$

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

error budget

$\pm 23 \text{ meV}$ statistics

$\pm 43 \text{ meV}$ Coulomb de-excitation ($\leq 10\%$!)

PhD thesis: Th. Strauch, Cologne 2009

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

Eur. Phys. J. A 47 (2011) 88

recent cascade theory

Coulomb de-excitation small!

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

- WHY PIONIC HYDROGEN & ... ?
- EXPERIMENTAL APPROACH
- ANALYSIS
- **RESULTS**
- CONCLUSIONS

PION – NUCLEON

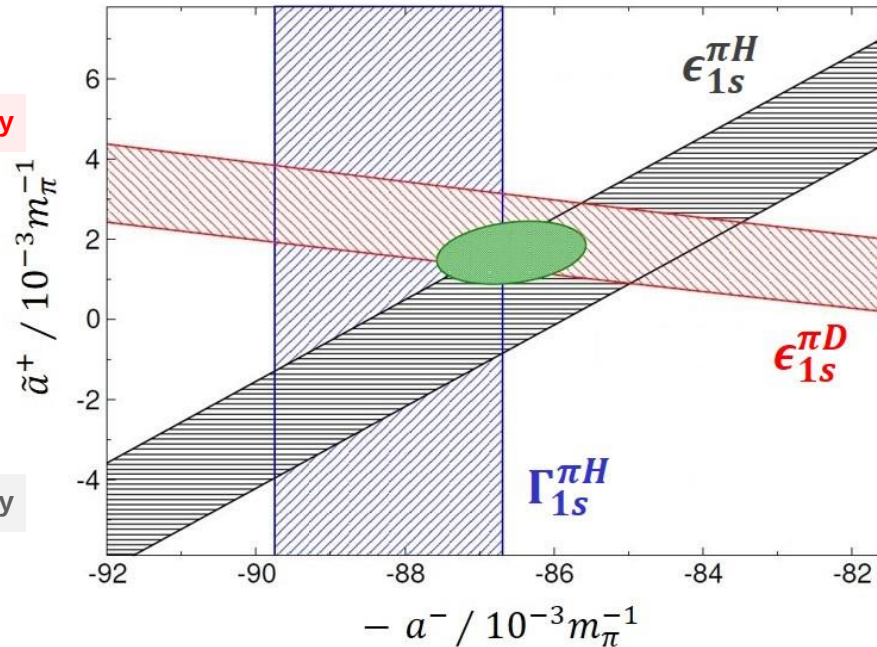
SCATTERING LENGTHS

$$\pi N \Leftrightarrow \pi N$$

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

$\Delta \text{ exp (Coulomb de-excitation)} \approx 2 \times \Delta \text{ theory}$

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



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

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

χ_{PT} : 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 : M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190
A. Hirtl et al., Eur. Phys. J. A 57 (2021) 70
 πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88

PION

PRODUCTION / ABSORPTION



$NN \leftrightarrow \pi NN$ threshold parameter α

charge symmetry

detailed balance (T invariance)

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

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

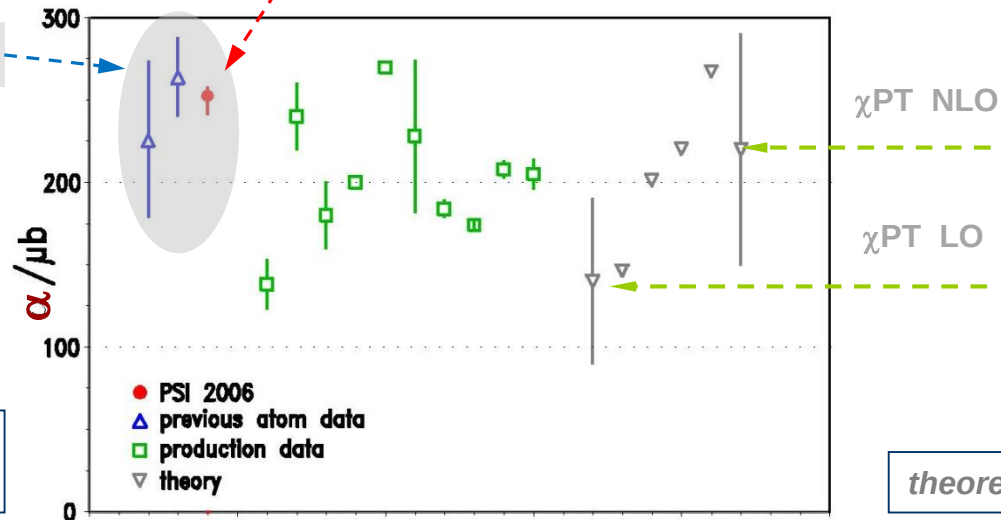
$$\Gamma_{1s} \propto \Im a_{\pi^- d} \propto \alpha(pp \rightarrow \pi^+ d) = (251^{+5}_{-11}) \mu b \quad (+20\%)$$

exotic-atom results

Th. Strauch,
PhD thesis, Cologne 2009

Th. Strauch et al.,
Phys.Rev.Lett.104 (2010)142503;
Eur.J.Phys.47 (2011)88

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



χ^{PT}

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

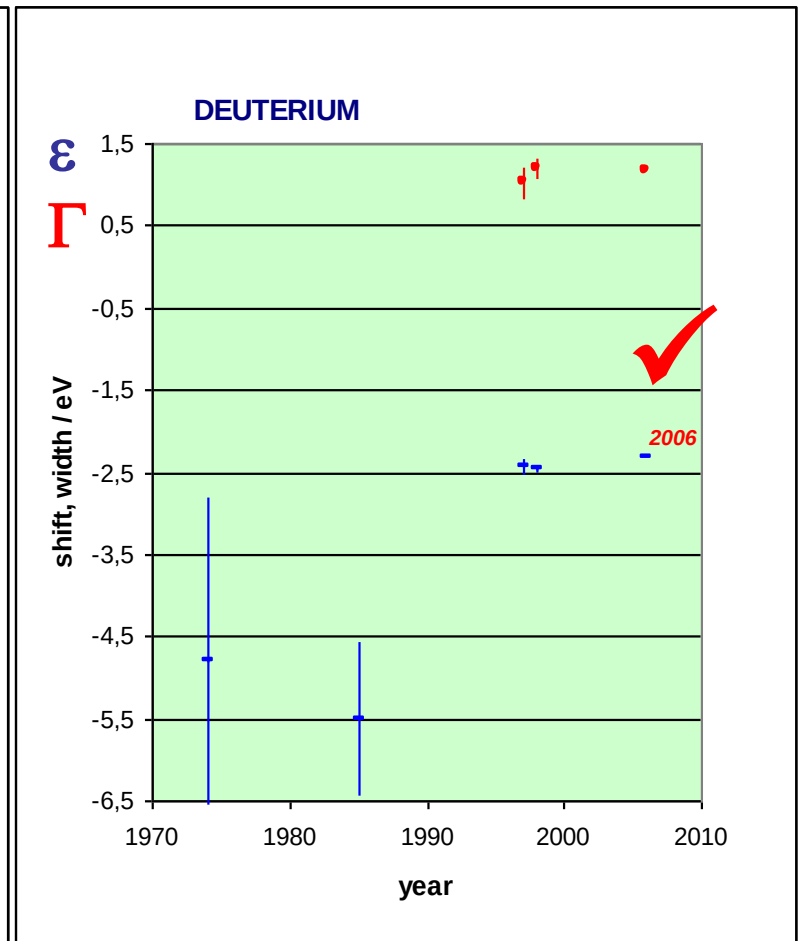
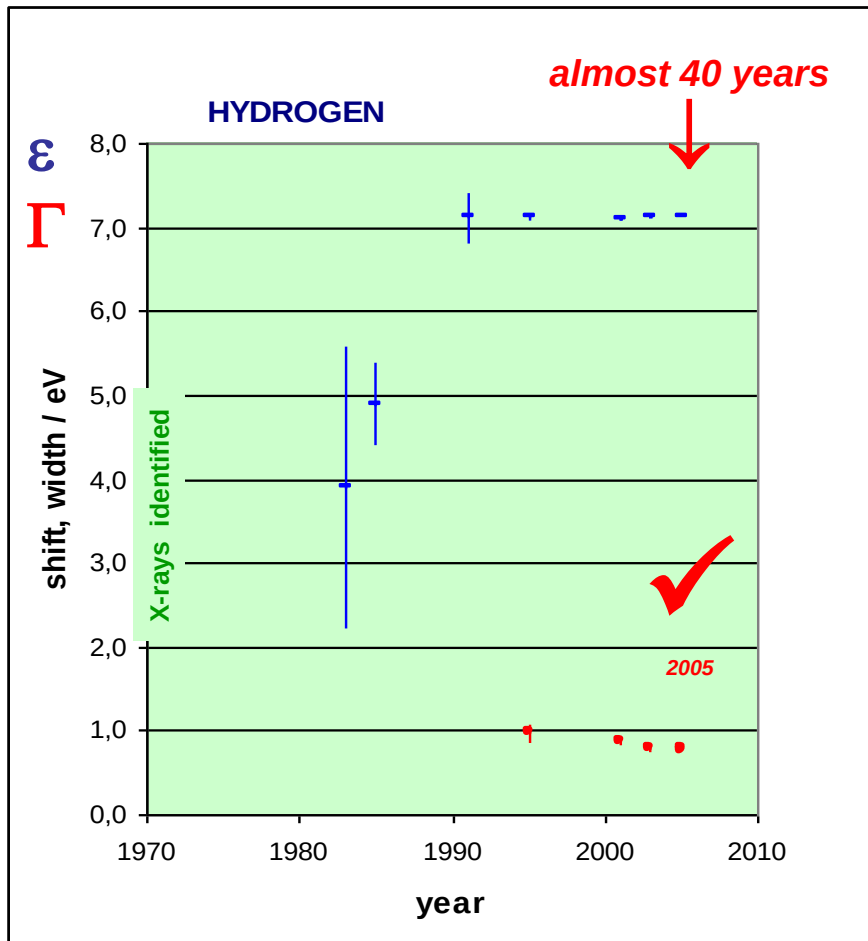
$\rightarrow$ few % !?

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

theoretical progress needed

- WHY PIONIC HYDROGEN & ... ?
- EXPERIMENTAL APPROACH
- ANALYSIS
- RESULTS
- **CONCLUSIONS**

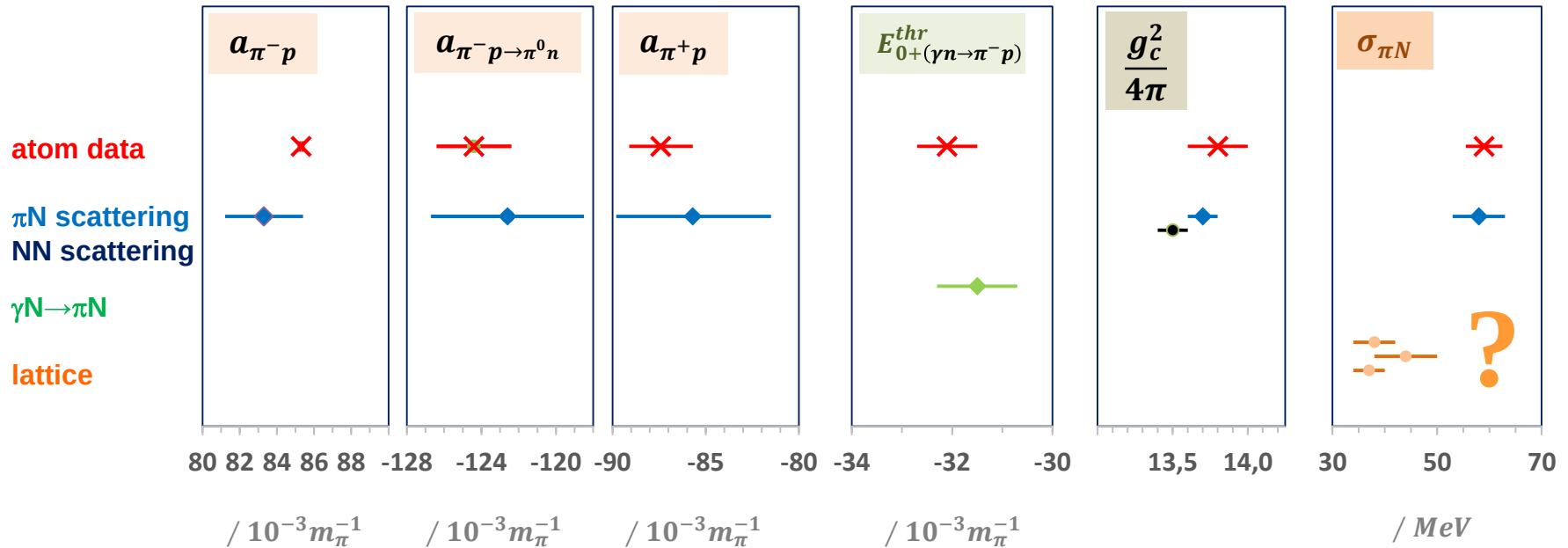
PIONIC HYDROGEN STORY





- π N scattering length: bands cross
- s - wave π - production strength
- μ H – singlet / triplet
 - ΔE_{HFS}
 - cascade theory $\approx$ line shape
- atomic & π N scattering data etc. highly consistent

Comparison of various inputs

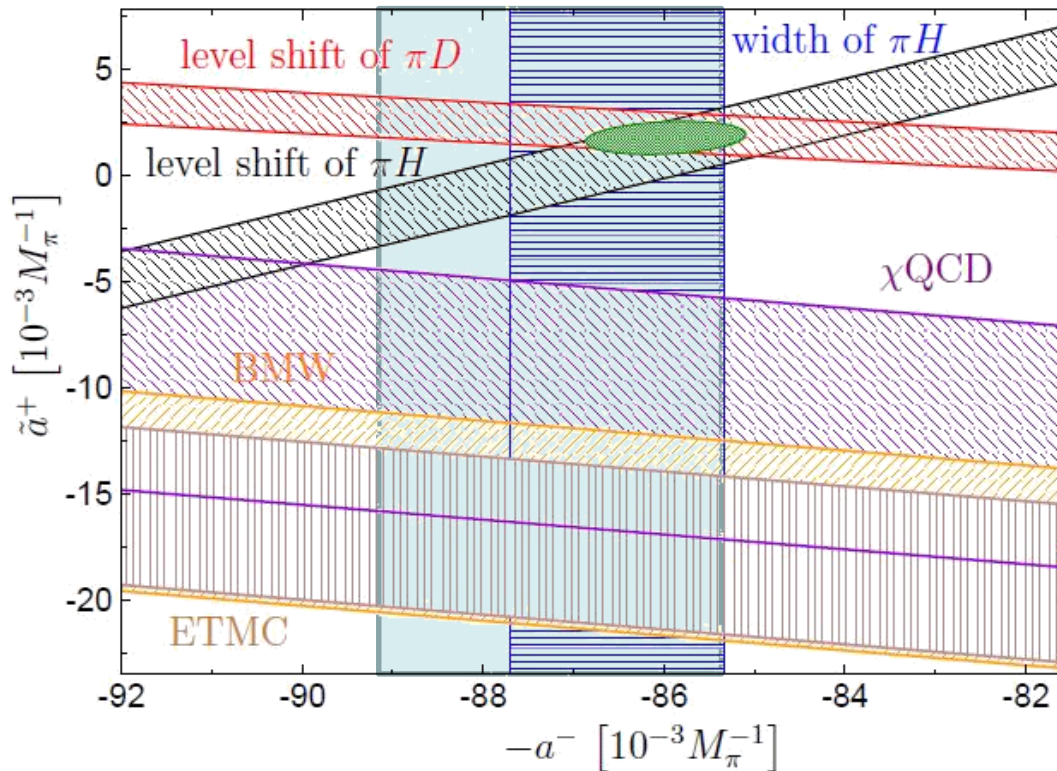


analyses involve input from χ^{PT}

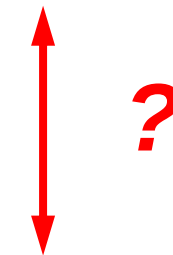
refs see A. Hirtl et al., *Eur. Phys. J. A* 57 (2021) 70

lattice S. Dürr et al. (BMW), *Phys. Rev. Lett* 116, 172001 (2016)
 Y.B. Yang et al. (χ QCD), *Phys. Rev. D* 94, 0540503 (2016)
 A. Abdel-Rehim et al. (ETM), *Phys. Rev. Lett.* 116, 252001 (2016)

$\sigma_{\pi N} \Leftrightarrow$ WIMP – nucleon scattering



← *pionic atoms analysis*



← *lattice*

Figure 1: Constraints on the πN scattering lengths from pionic atoms (black: level shift in πH , blue: width of πH ground state, red: level shift in πD) and from lattice σ -terms (orange: BMW [20], violet: χ QCD [21], brown: ETMC [22]).

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



πH – error of Γ_{1s} unsatisfactory

details of the high-energy components

- *are not accessible* 🙅
- *are not critical for the numerical result of Γ_{1s}* 👍
- *limit the accuracy for Γ_{1s} to about 3%* 🙅

WHAT TO DO?

$\Gamma_{1s} \rightarrow 1\%$

minimize Coulomb de-excitation

$\pi\text{H}(4p-1s)$

$\pi\text{H}(5p-1s) ?$

set-up

increase resolution

quartz 10-2

exploit higher pion fluxes at PSI

cascade

understand even better
kinetic energy distribution

$\mu\text{H}, \mu\text{D}$

T_{kin} -distribution as input possible?

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 and R-06.03

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Cascade theory

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→ Diploma and PhD thesis ←

THANK YOU