PIONIC HYDROGEN and DEUTERIUM

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EXA 2021 15.9.2021

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

PIONS, NUCLEONS - INTERACTION in terms of QCD

χPT

CHiRAL

PERTURBATION

THEORY

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

$\pi N \Leftrightarrow \pi N$

$NN \Leftrightarrow NN$

… ⇔ …

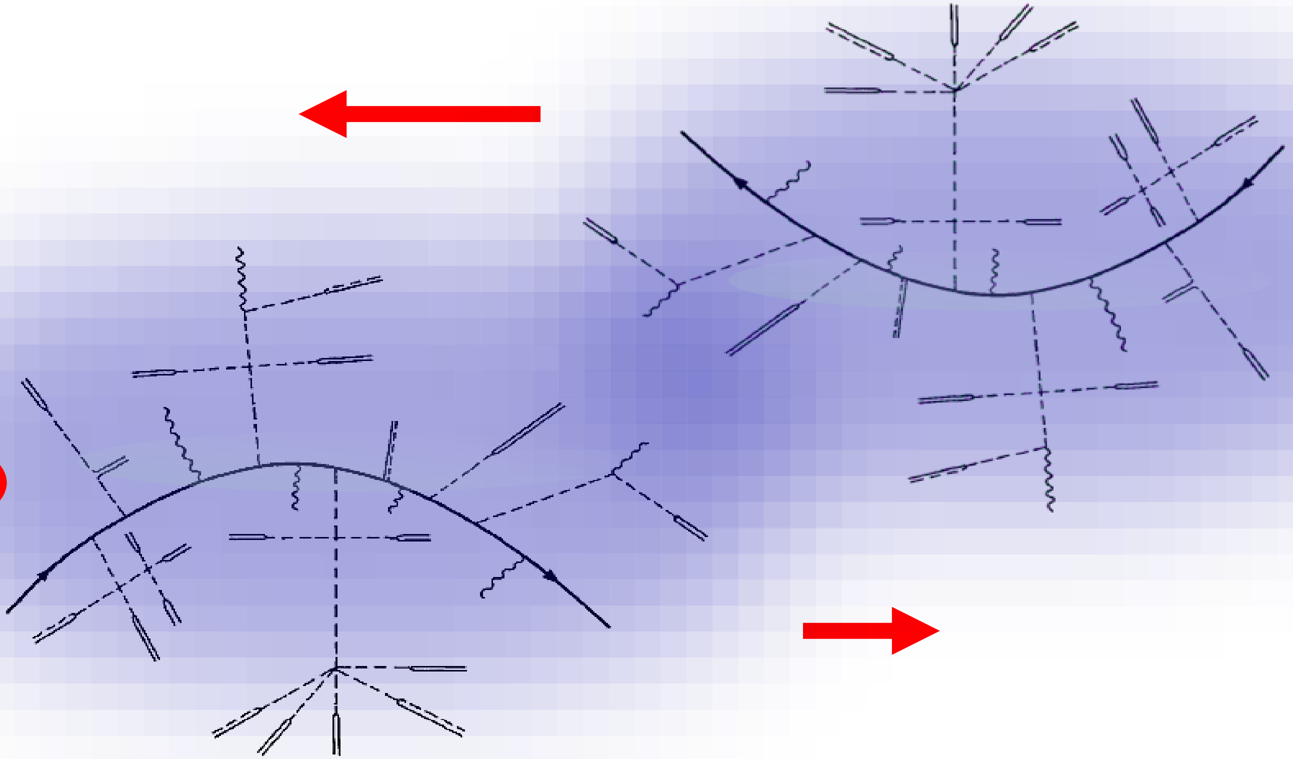


Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ——→—— nucleon; - - - pions; ∼∼∼ vector current; =·=·= axial vector current; —⊏ pseudoscalar density; ═══ scalar density.

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

PION-NUCLEON SCATTERING LENGTHS

$\pi \otimes N$ *isospin* **$1 \otimes 1/2 = 1/2 \oplus 3/2$**

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

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

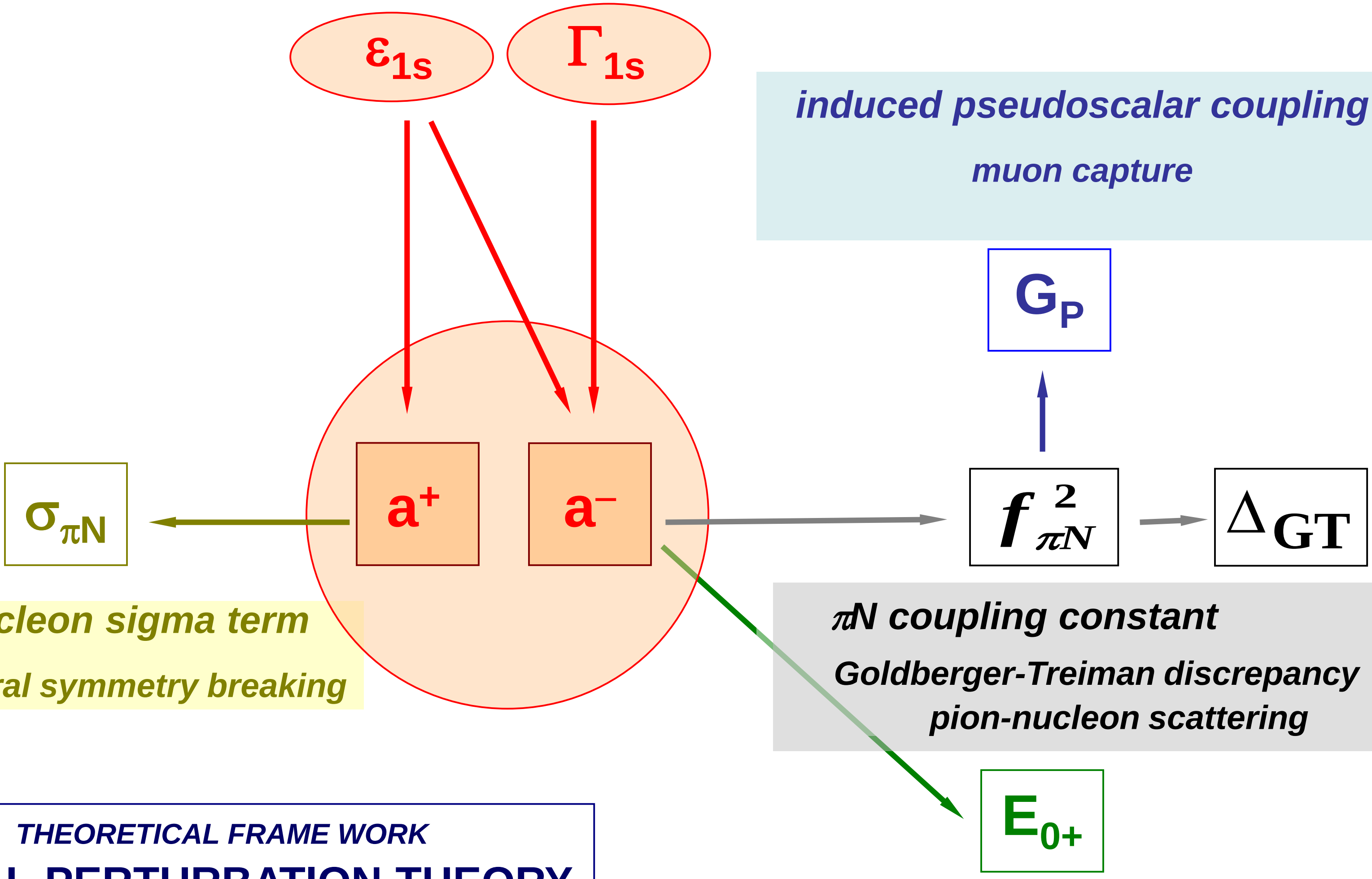
$$a_{\pi^- p \rightarrow \pi^0 n} = -\frac{\sqrt{2}}{3}\left(a_{1/2} - a_{3/2}\right) + \ldots = -\sqrt{2}\, a^- + \ldots$$

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

… : calculabe 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*



ε_{1s}

Γ_{1s}

a^+

a^-

$\sigma_{\pi N}$

G_P

$f^2_{\pi N}$

Δ_{GT}

E_{0+}

induced pseudoscalar coupling

muon capture

pion-nucleon sigma term

explicit chiral symmetry breaking

πN coupling constant

Goldberger-Treiman discrepancy

pion-nucleon scattering

electric dipole amplitude

threshold pion photo production

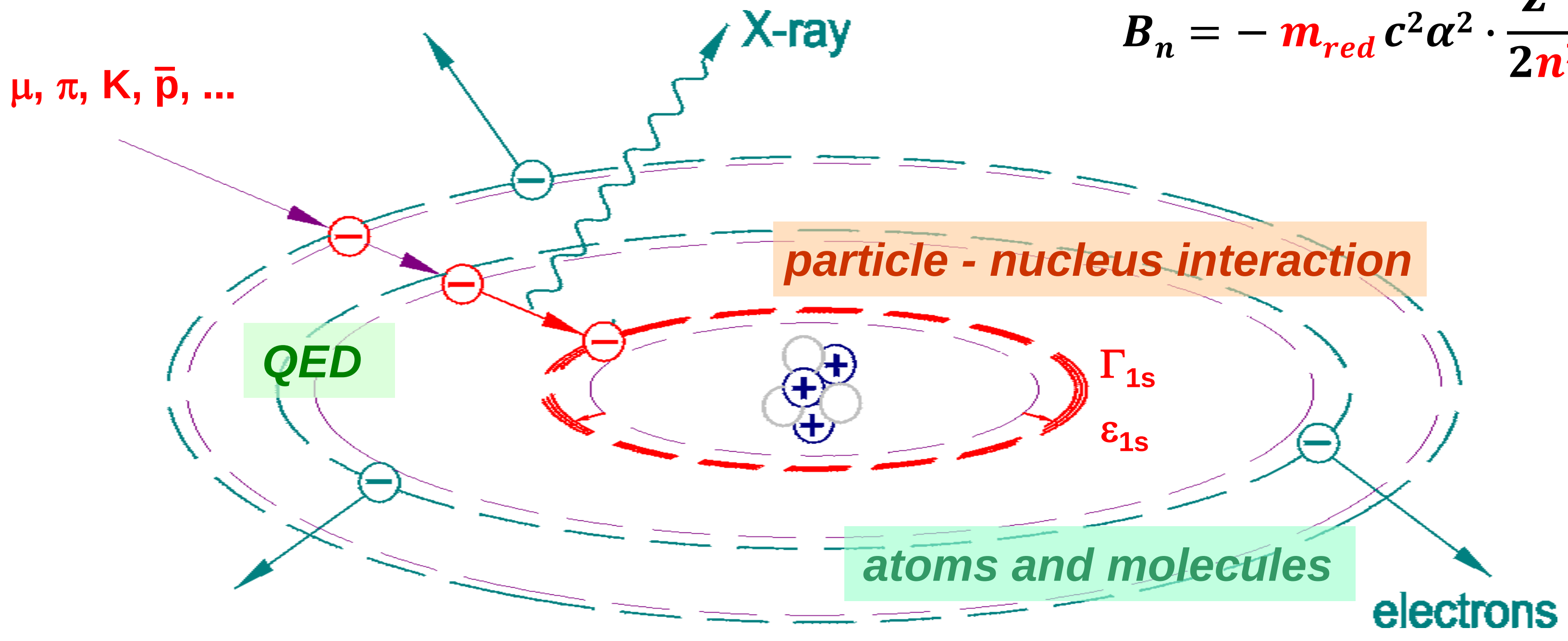
THEORETICAL FRAME WORK

CHIRAL PERTURBATION THEORY

LABORATORY: EXOTIC ATOMS

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

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



particle - nucleus interaction

QED

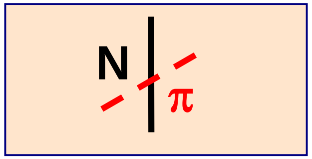
atoms and molecules

experiment **X-ray energy, line width, and intensity**

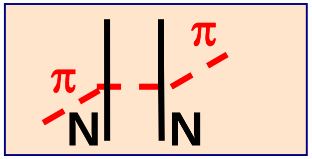
general review experiment: D. Gotta, Prog. Part. Nucl. Phys. Rep. 52, 133 (2004)

πH & πD - *origin of shift* ε_{1s}

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



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

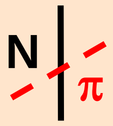


πH & πD - *origin of broadening* Γ_{1s}

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

CEX = charge exchange

CEX scattering

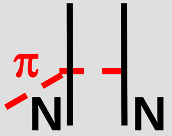


radiative capture

BR well known from experiment

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

„true“ absorption



- WHY PIONIC HYDROGEN & … ?
- **EXPERIMENTAL APPROACH**
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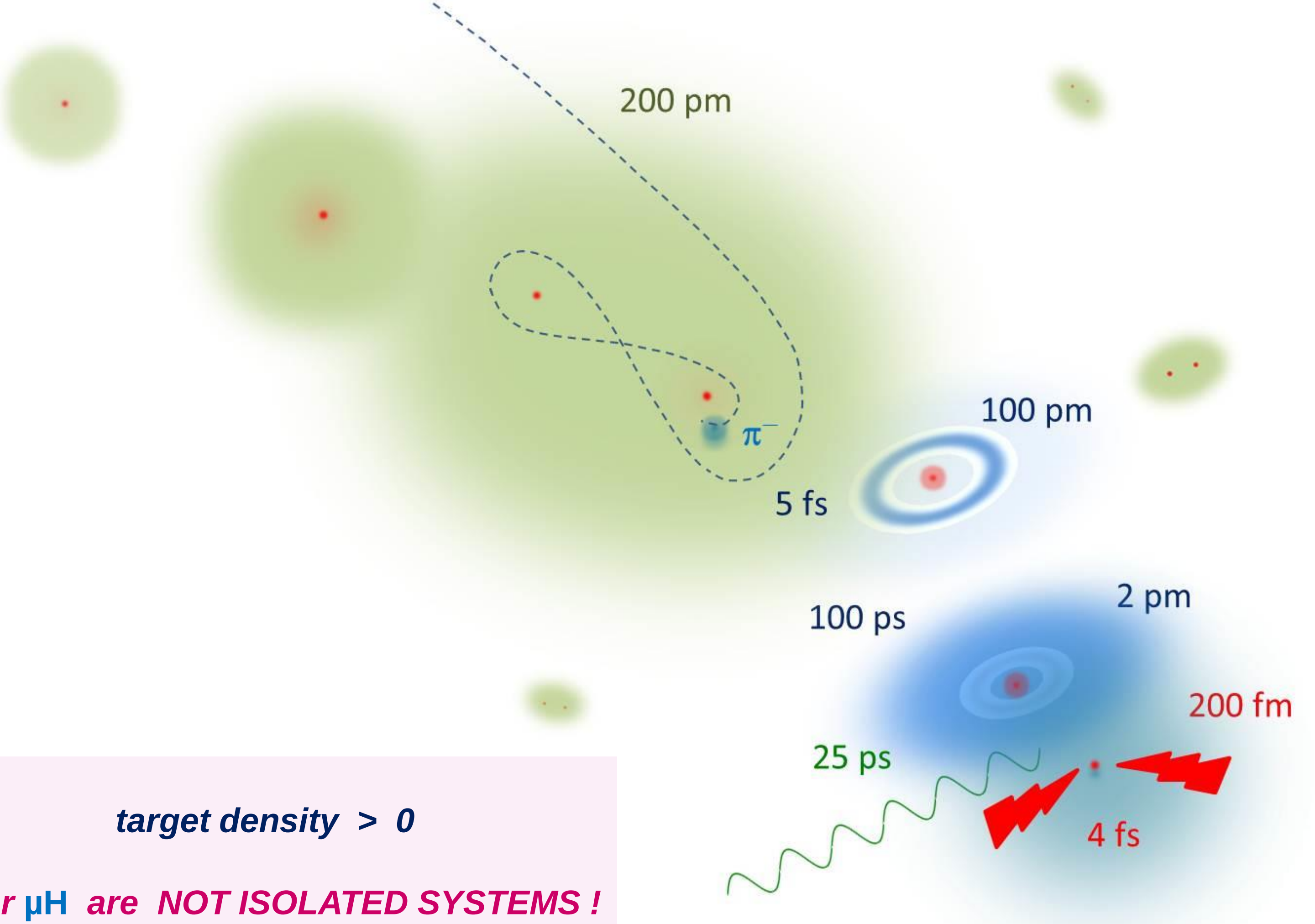
- RESULTS
- CONCLUSIONS

DE-EXCITATION CASCADE and COLLISIONAL EFFECTS



target density > 0

πH *or* μH *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 → II***
- ***cryogenic hydrogen target***
- ***minimize background***

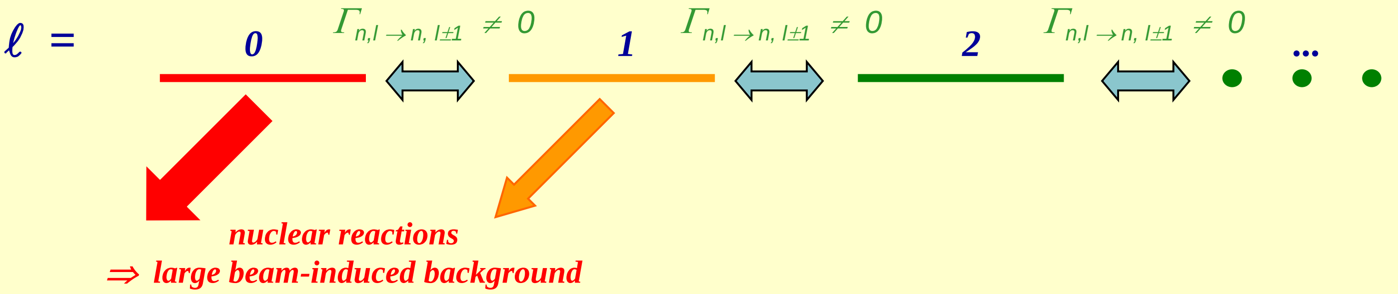
Sufficient energy resolution

- ***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)

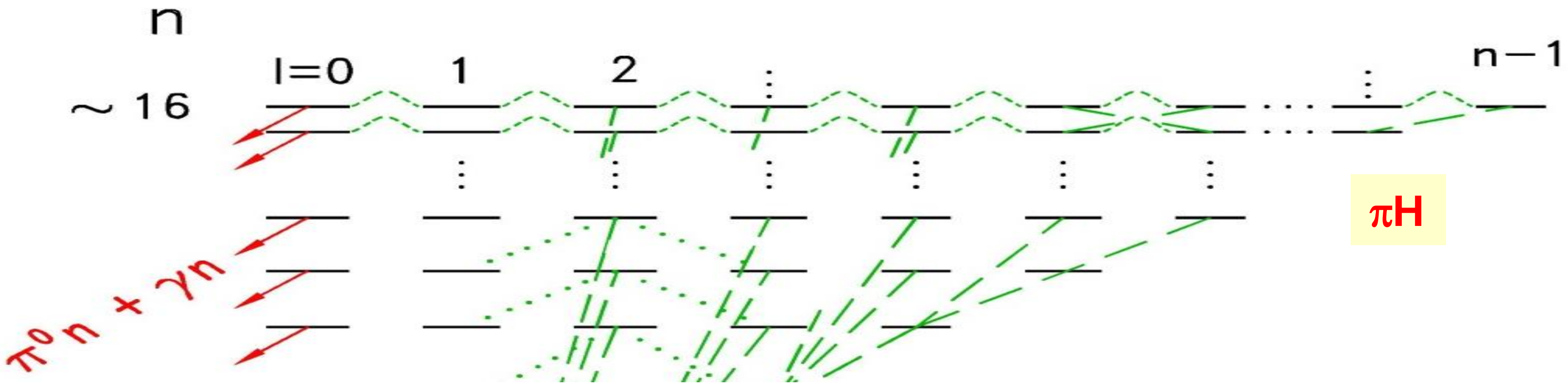
*collisions → electric field → **mixing of l states** Z = 1 (Z=2)*



ℓ = 0 $\Gamma_{n,l \to n,\, l\pm1} \neq 0$ 1 $\Gamma_{n,l \to n,\, l\pm1} \neq 0$ 2 $\Gamma_{n,l \to n,\, l\pm1} \neq 0$ ...

nuclear reactions

⇒ large beam-induced background



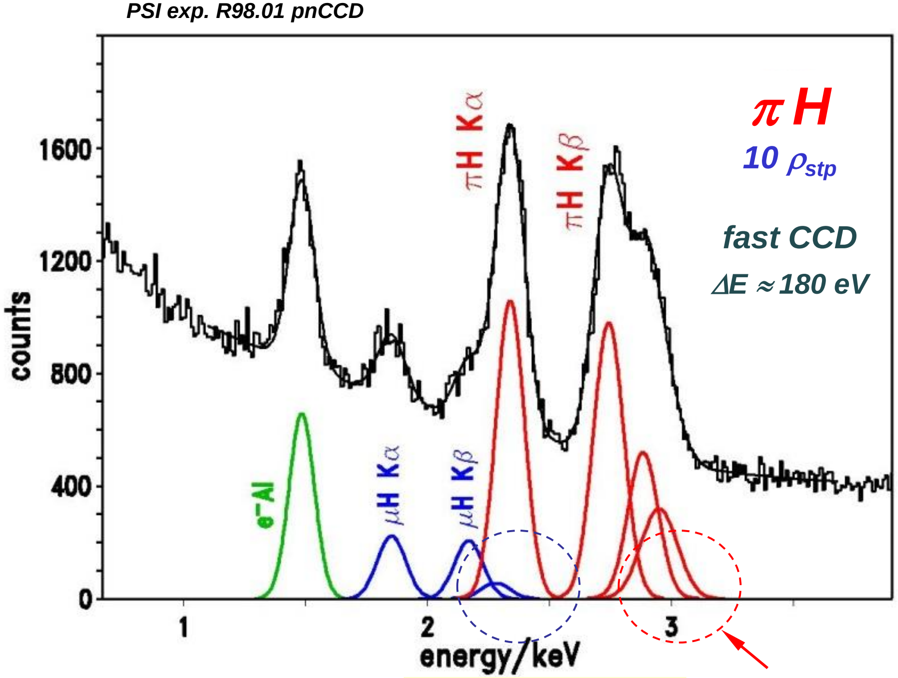
$\bar{p}$H ⇒ nuclear reactions in s and p states

πH ⇒ nuclear reactions in s states

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

PIONIC and MUONIC HYDROGEN

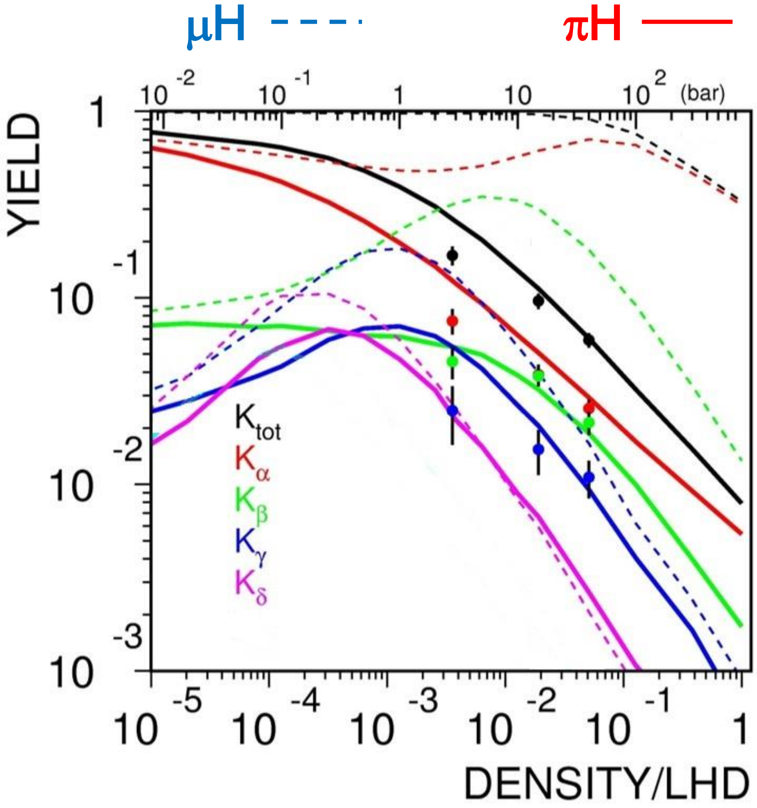
Lyman series



$\varepsilon, \Gamma \approx 1$ eV

unresolved from high (n,l=1) states

invove strong interaction effects



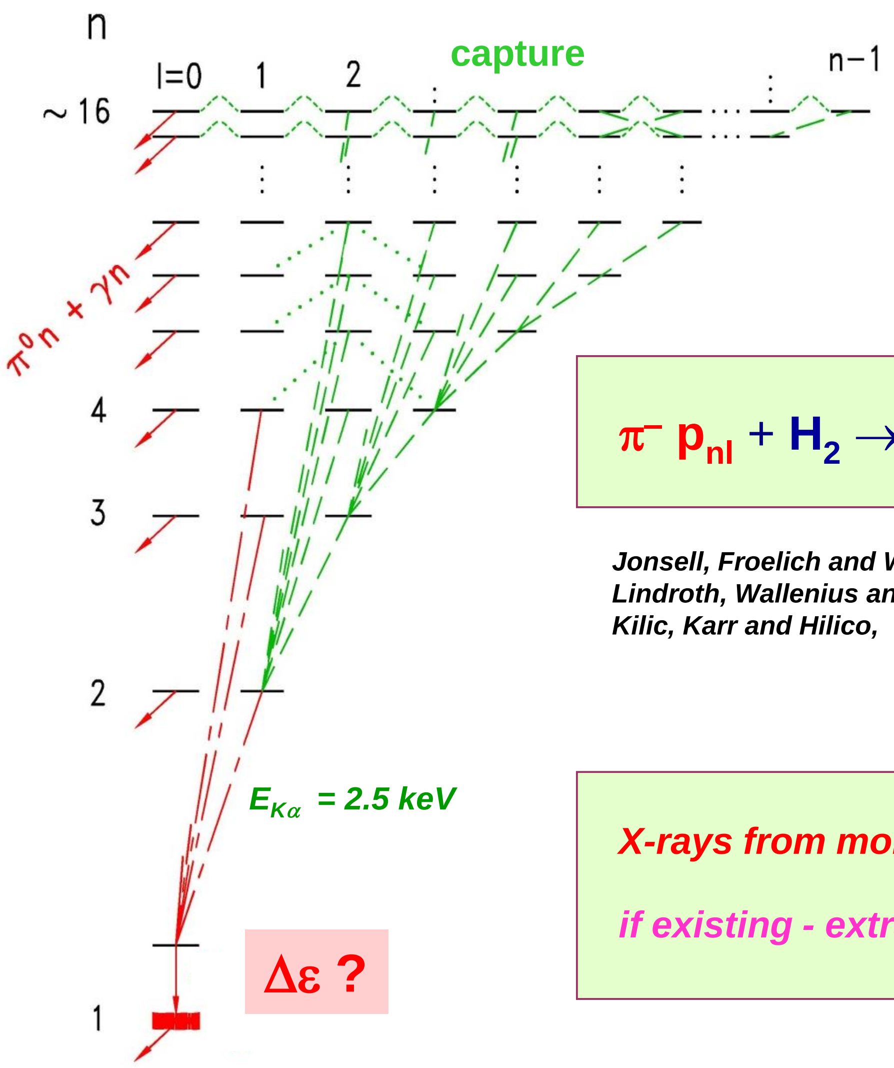
data:

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*



Δε ?

- *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

$$\pi^- p_{nl} + H_2 \rightarrow [(\pi^- pp)_{nj\nu} \cdot p]\ ee_{k\nu}$$ *decay usually by Auger process*

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. A70 (2004) 042506

X-rays from molecular states ? ⇒ energy shift of np levels

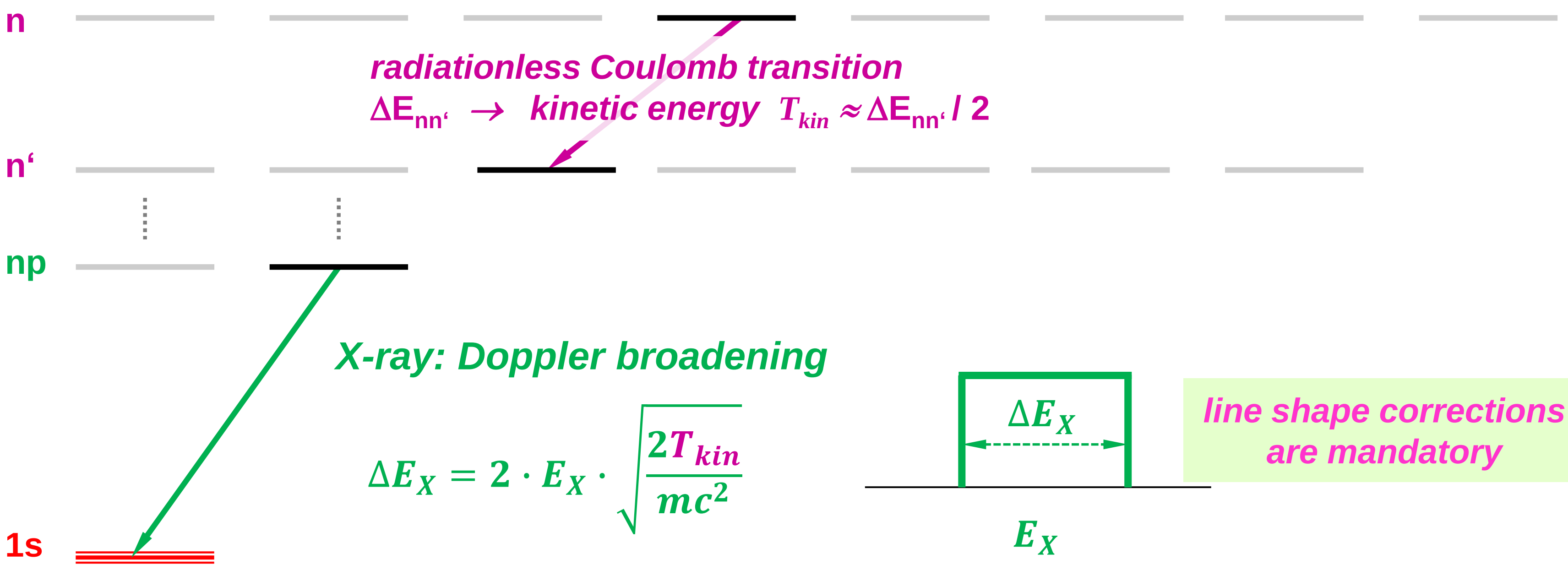
if existing - extrapolation to density zero necessary!

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)

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



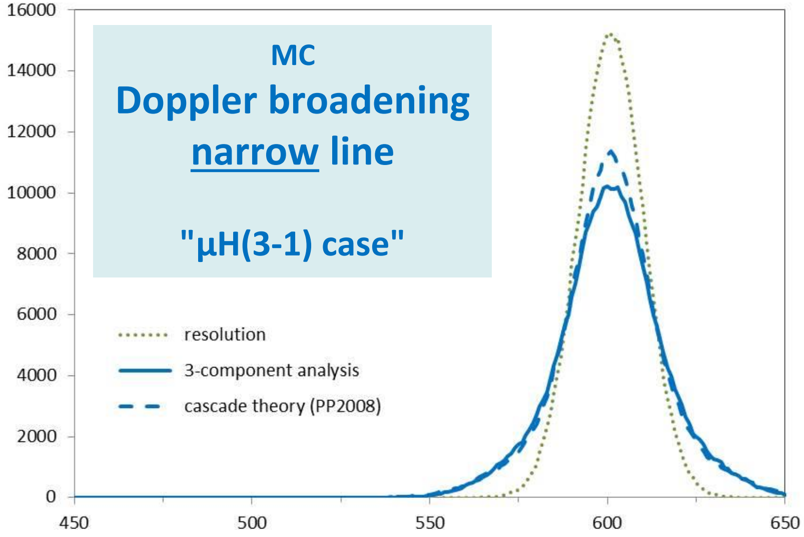
radiationless Coulomb transition
$\Delta E_{nn'} \rightarrow$ ***kinetic energy*** $T_{kin} \approx \Delta E_{nn'} / 2$

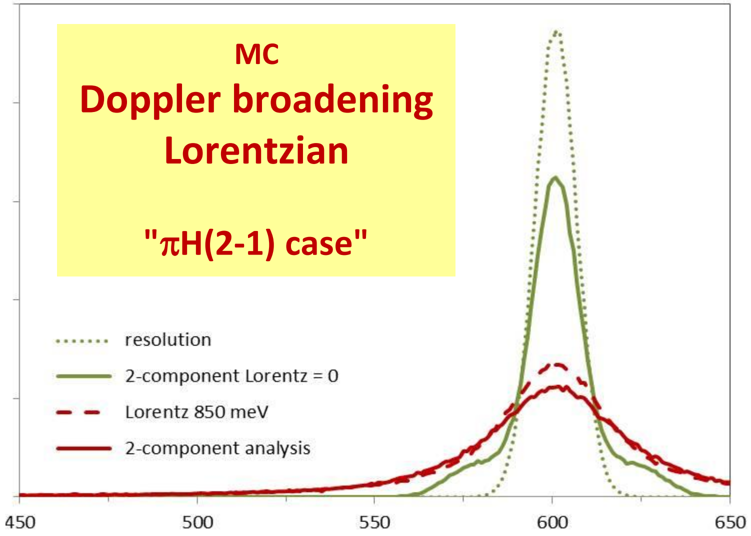
X-ray: Doppler broadening

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

line shape corrections are mandatory

EXEMPLIFICATION of Coulomb de-excitation





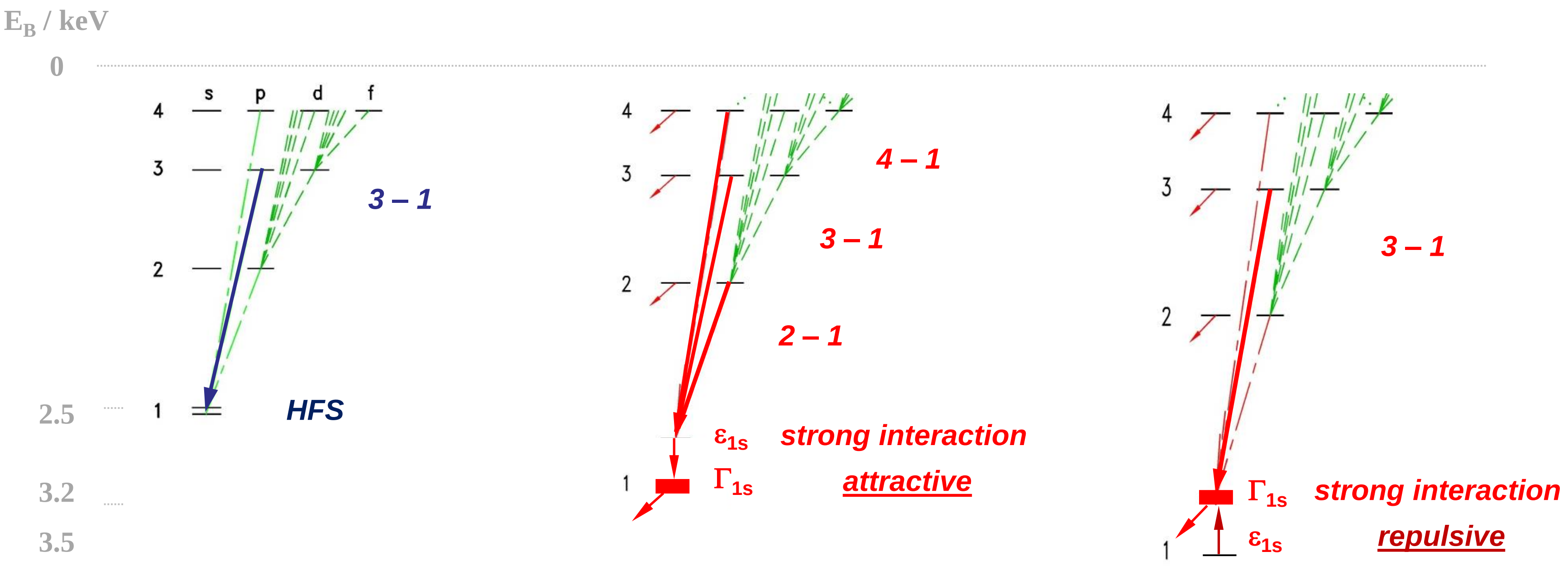
low background essential !

typical resolution (FWHM)

272 meV ***390 meV***

STRATEGY – VARY TRANSITION & VARY DENSITY

μH **πH** **πD**



3 – 1

HFS

4 – 1

3 – 1

2 – 1

strong interaction

attractive

3 – 1

strong interaction

repulsive

„dangerous“ cascade effects

Coulomb de-excitation

molecular formation

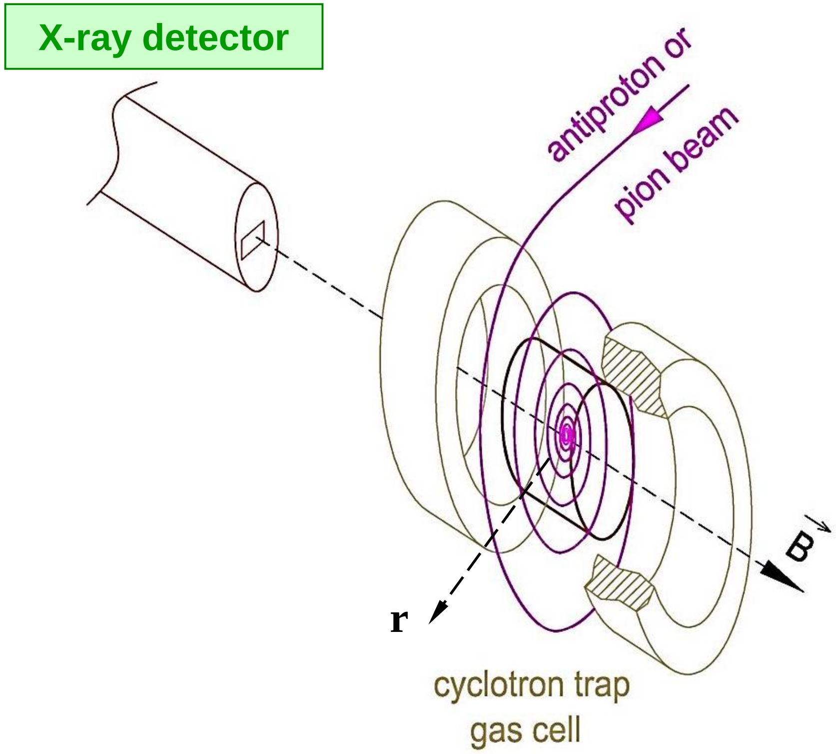
10 bar

3, 10, 28 bar and LH_2

3, 10 and 17 bar

X-ray source

CYCLOTRON TRAP concentrates particles



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

“wind up” range curve

in a (weakly) focusing magnetic field

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

increase in <u>stop density</u>

compared to a linear stop arrangement

pions (PSI)		**x 200**
antiprotons	**(LEAR)**	**x 10^6**

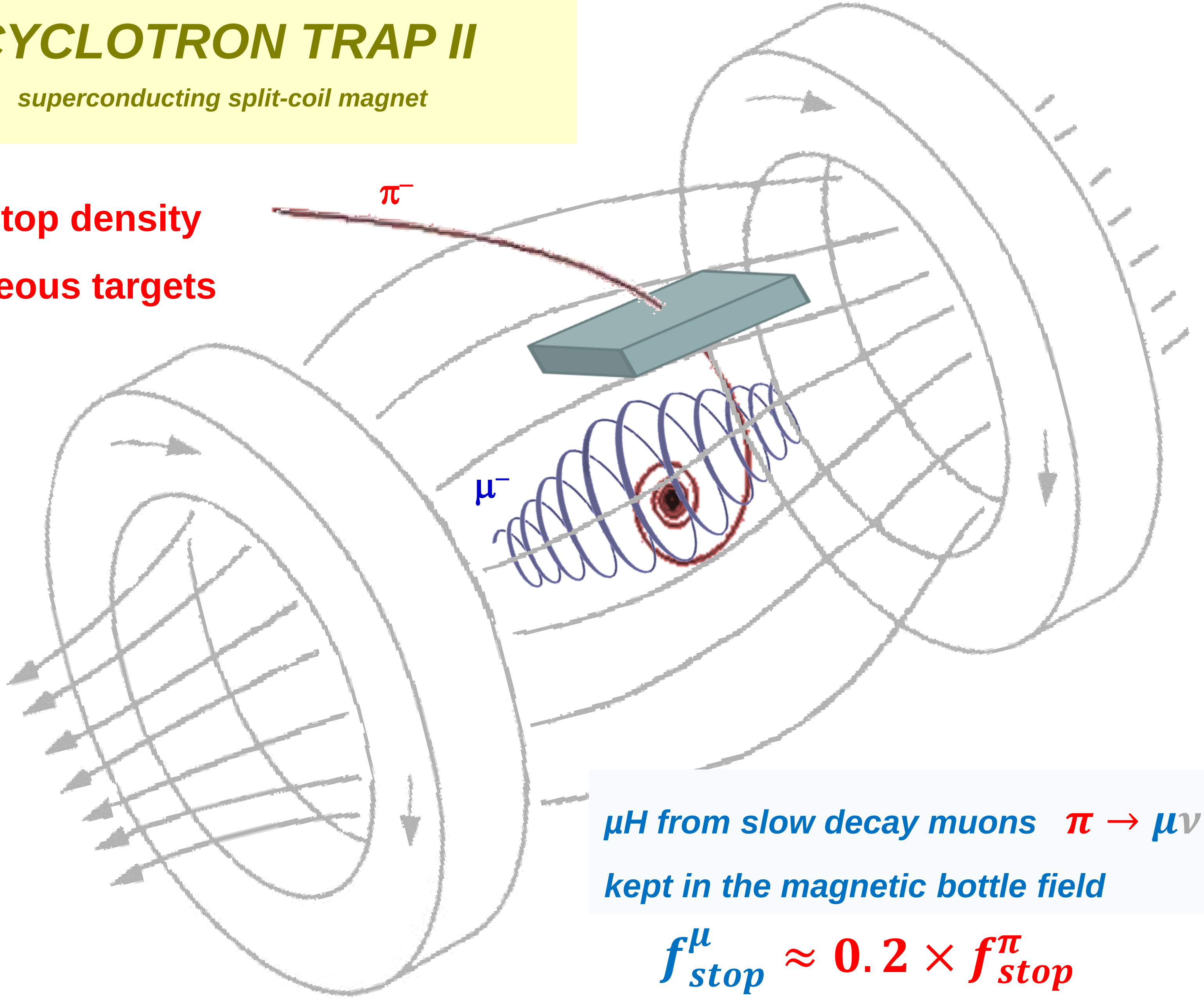
⇒ high X - ray line yields
⇒ bright X - ray source

CYCLOTRON TRAP II

superconducting split-coil magnet

high stop density

in gaseous targets



μH from slow decay muons $\boldsymbol{\pi \to \mu\nu}$

kept in the magnetic bottle field

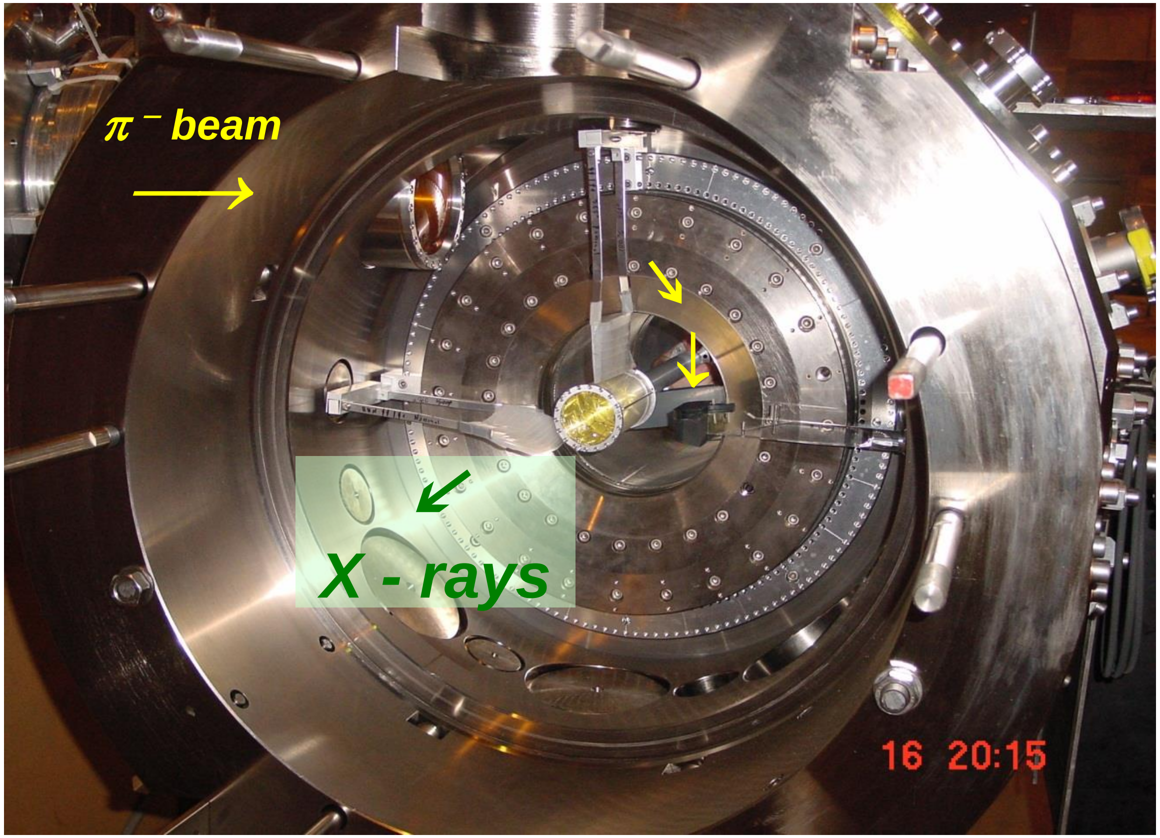
$$f^{\mu}_{stop} \approx 0.2 \times f^{\pi}_{stop}$$

Cryogenic target: density adjustmentby temperature variation

- **~1 bar**
- **~22 K**

density equivalent →

- **~12.5 bar**
- **~293 K**



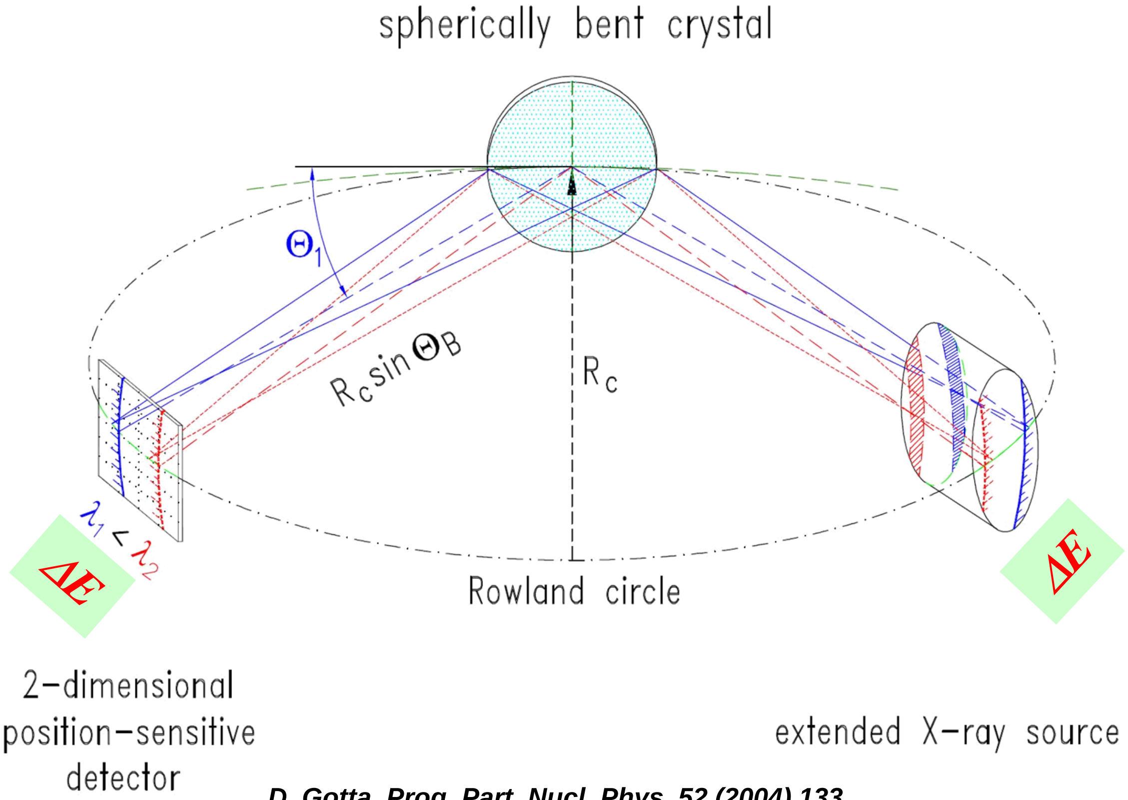
pion set-up 2002

Energy resolution

JOHANN-TYPE CRYSTAL SPECTROMETER

simultanuous measurement of ΔE

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



D. Gotta, Prog. Part. Nucl. Phys. 52 (2004) 133
D.E. Gotta, L.M.Simons, Spectrochim. Acta Part B 120 (2016) 9

focussing conditions

horizontal $R_c \cdot \sin\Theta_B$ ✓

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

usually dismissed

angular dispersion

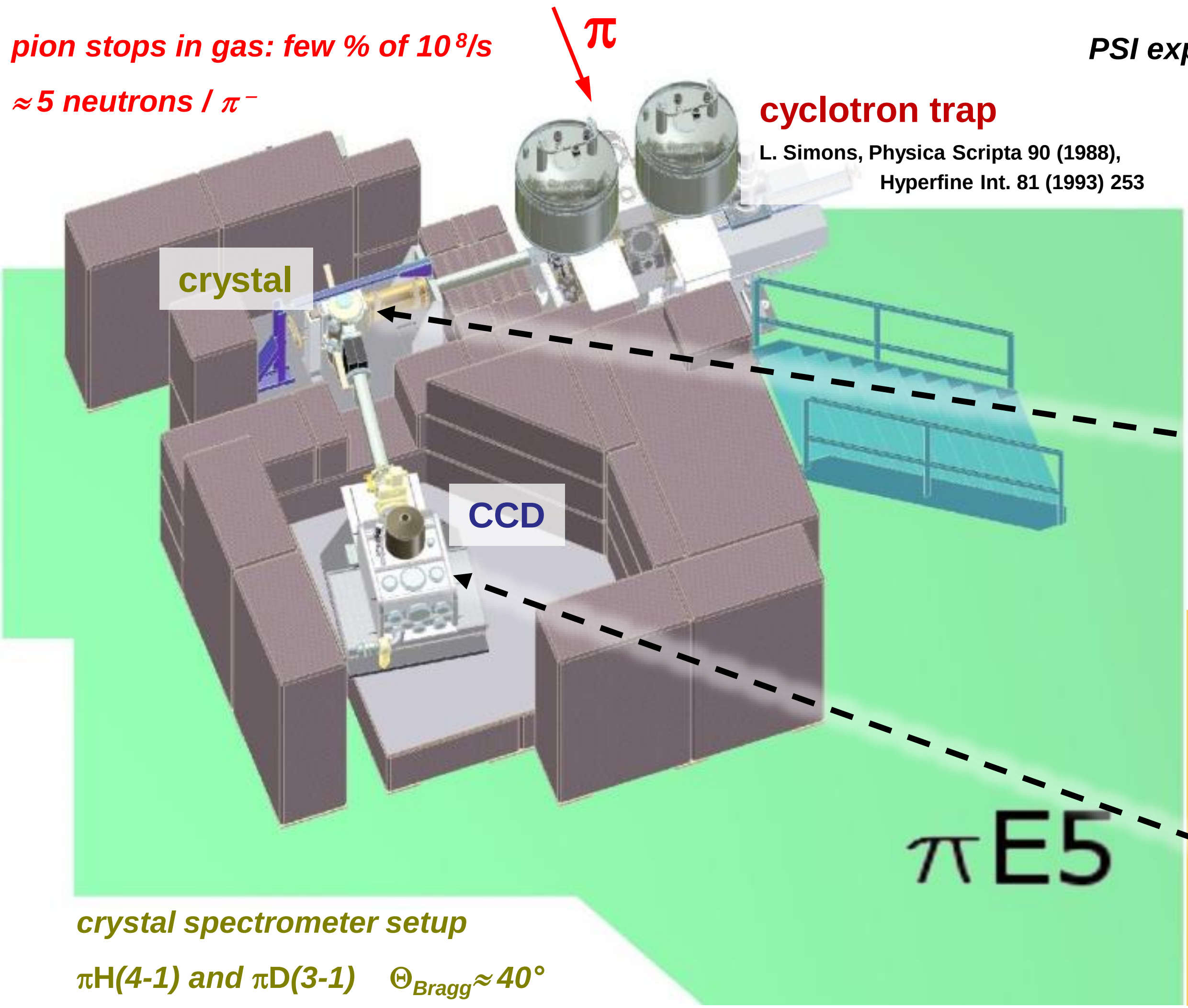
sym. plane $\frac{dE}{d\Theta} = -\frac{E}{\tan\Theta_B}$

TYPICAL SET-UP at PSI

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

$\approx$ 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 spectrometer setup

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

BRAGG CRYSTAL

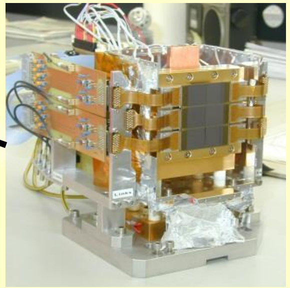
spherically bent

Si or quartz

$R = 3$ m
$\Phi = 10$ cm

FOCAL PLANE DETECTOR

3×2 CCD array



pixel size

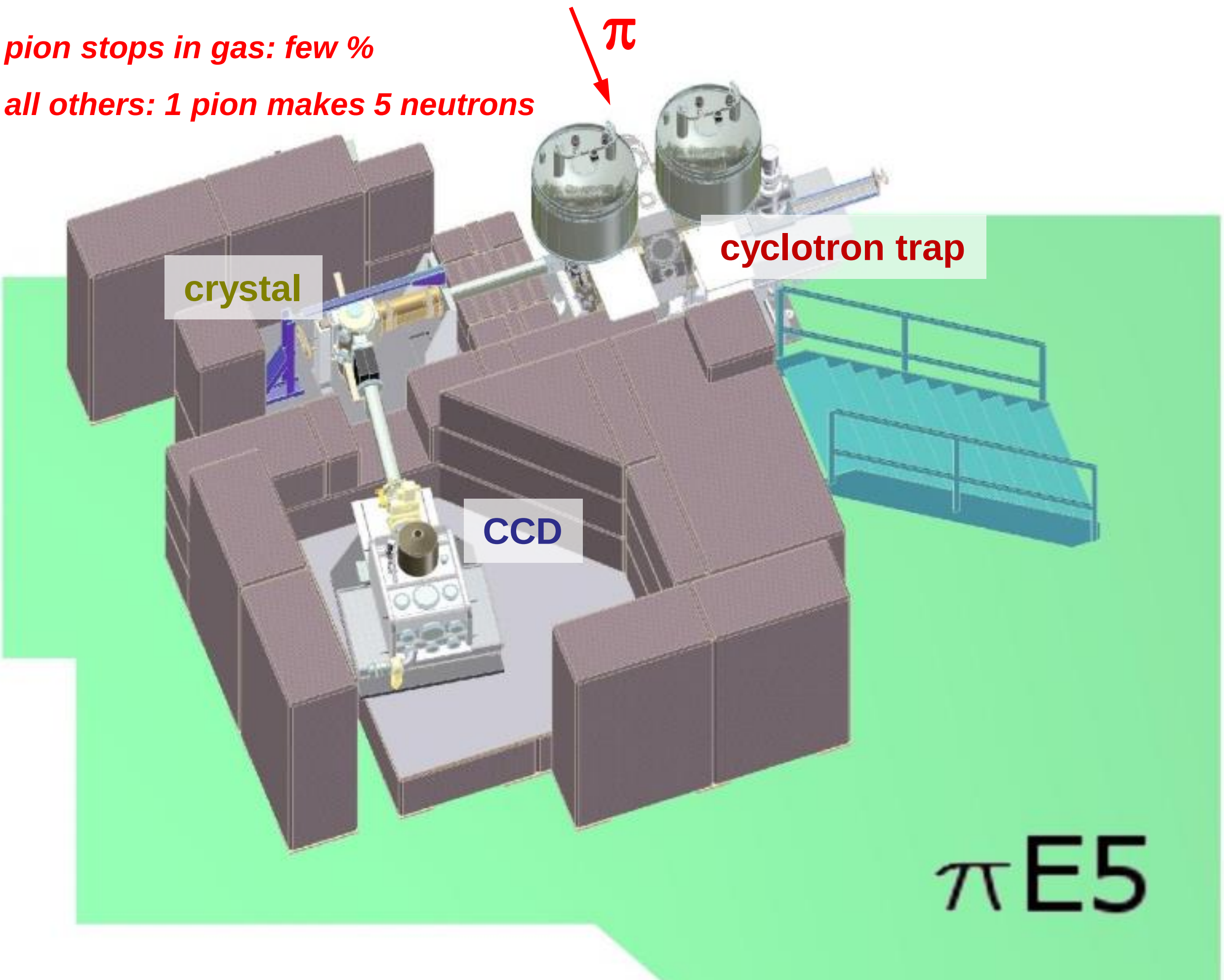
40 µm × 40 µm

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

TYPICAL SET-UP at PSI

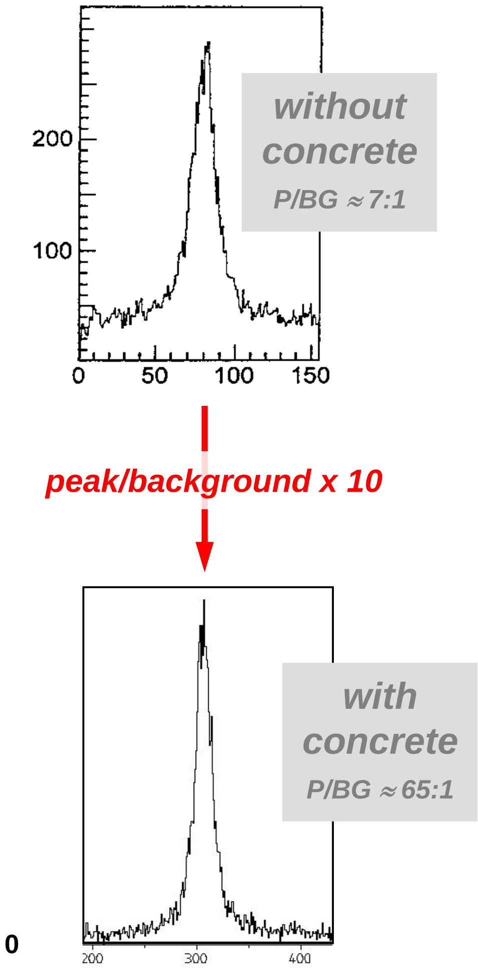
pion stops in gas: few %

all others: 1 pion makes 5 neutrons



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

pionic hydrogen



without concrete

P/BG ≈ 7:1

peak/background x 10

with concrete

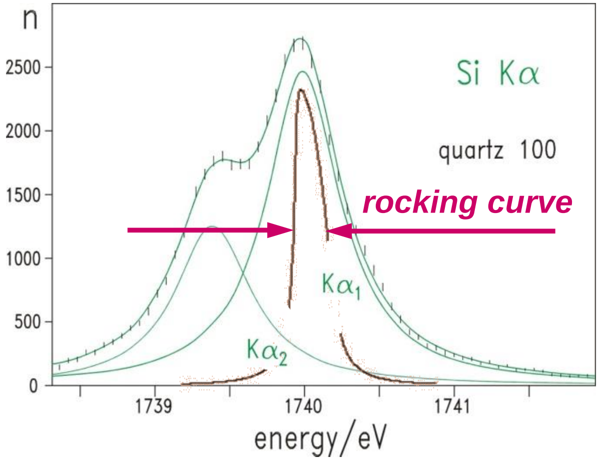
P/BG ≈ 65:1

background reduction II

CRYSTAL RESPONSE - NO SOLUTION

fluorescence X-rays

excited by means of X-ray tubes

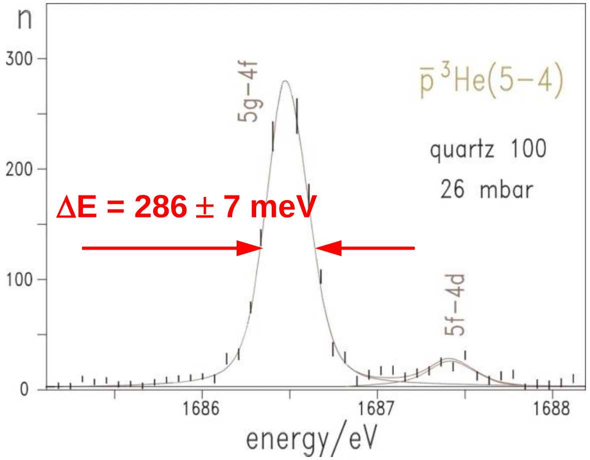


problem

large natural line width
and
satellite lines

exotic-atom X-rays

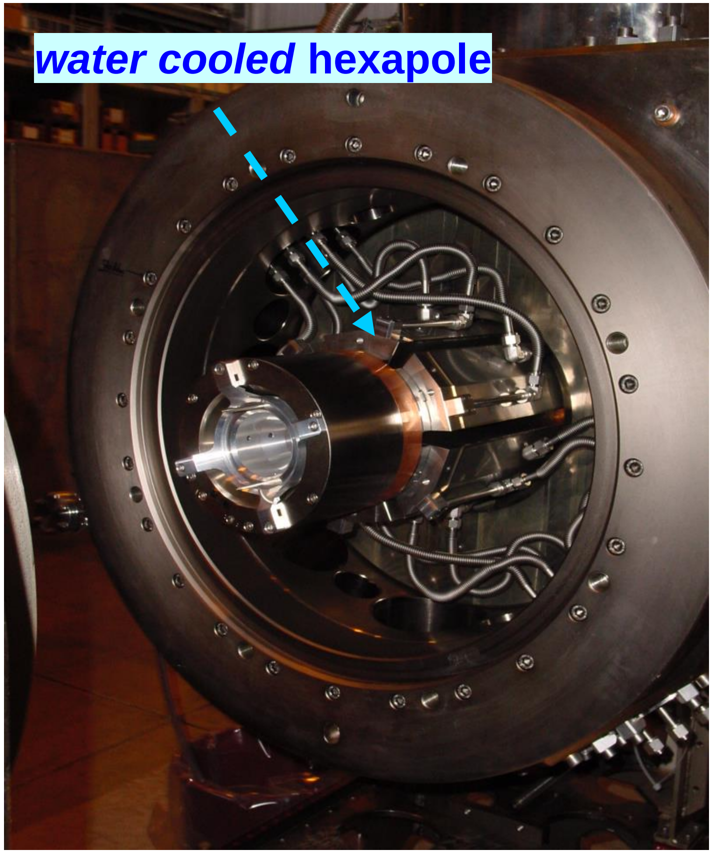
from hydrogen-like systems

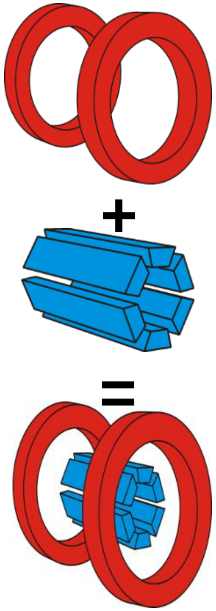


problem

rate

MEASURE SPECTROMETER RESPONSE new approach





ECRIS

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

superconducting coils

- ***cyclotron trap***

permanent hexapole

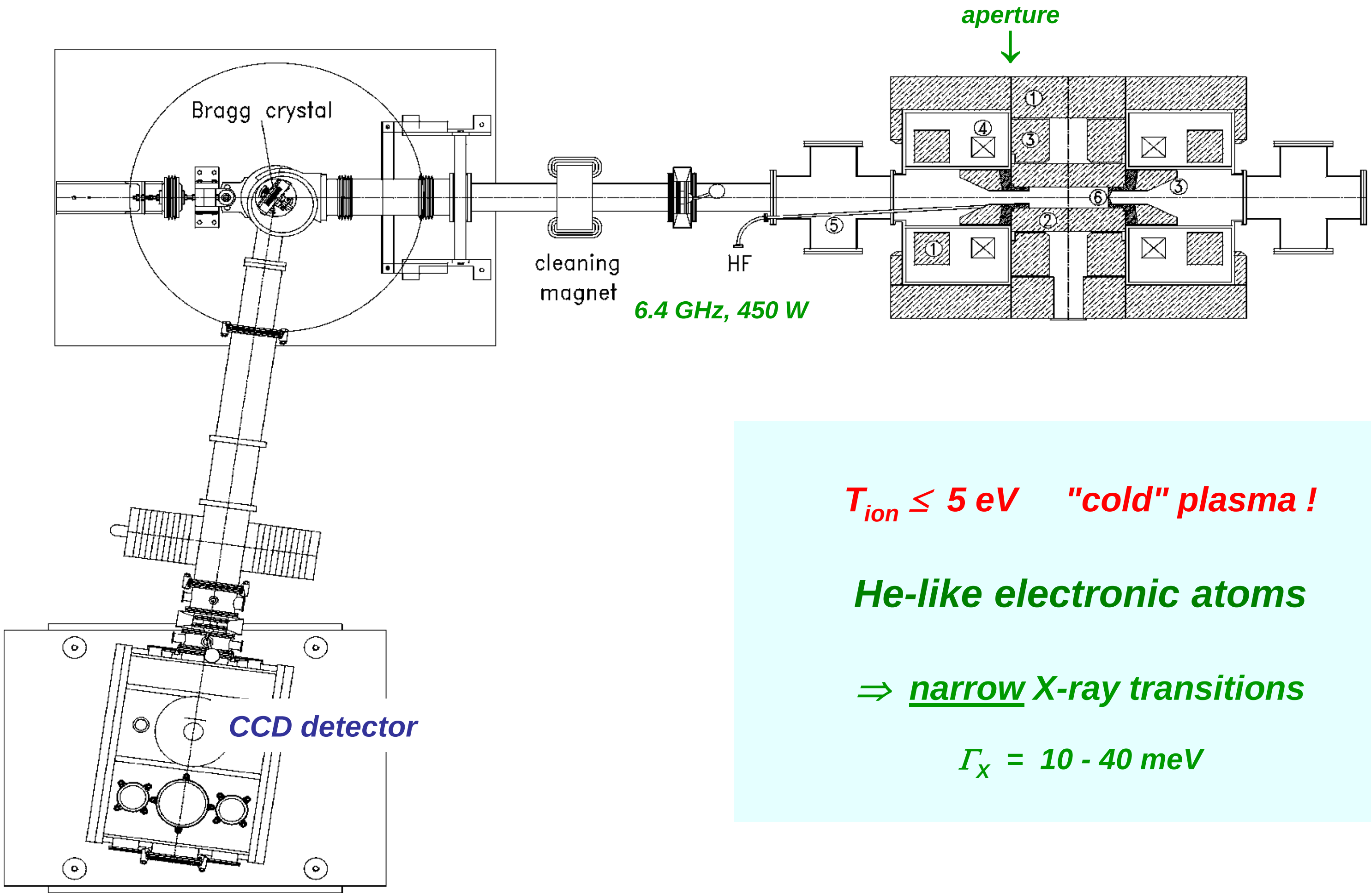
- ***AECR-U type***
- ***1 Tesla at the hexapole wall***
- ***open structure***

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)



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

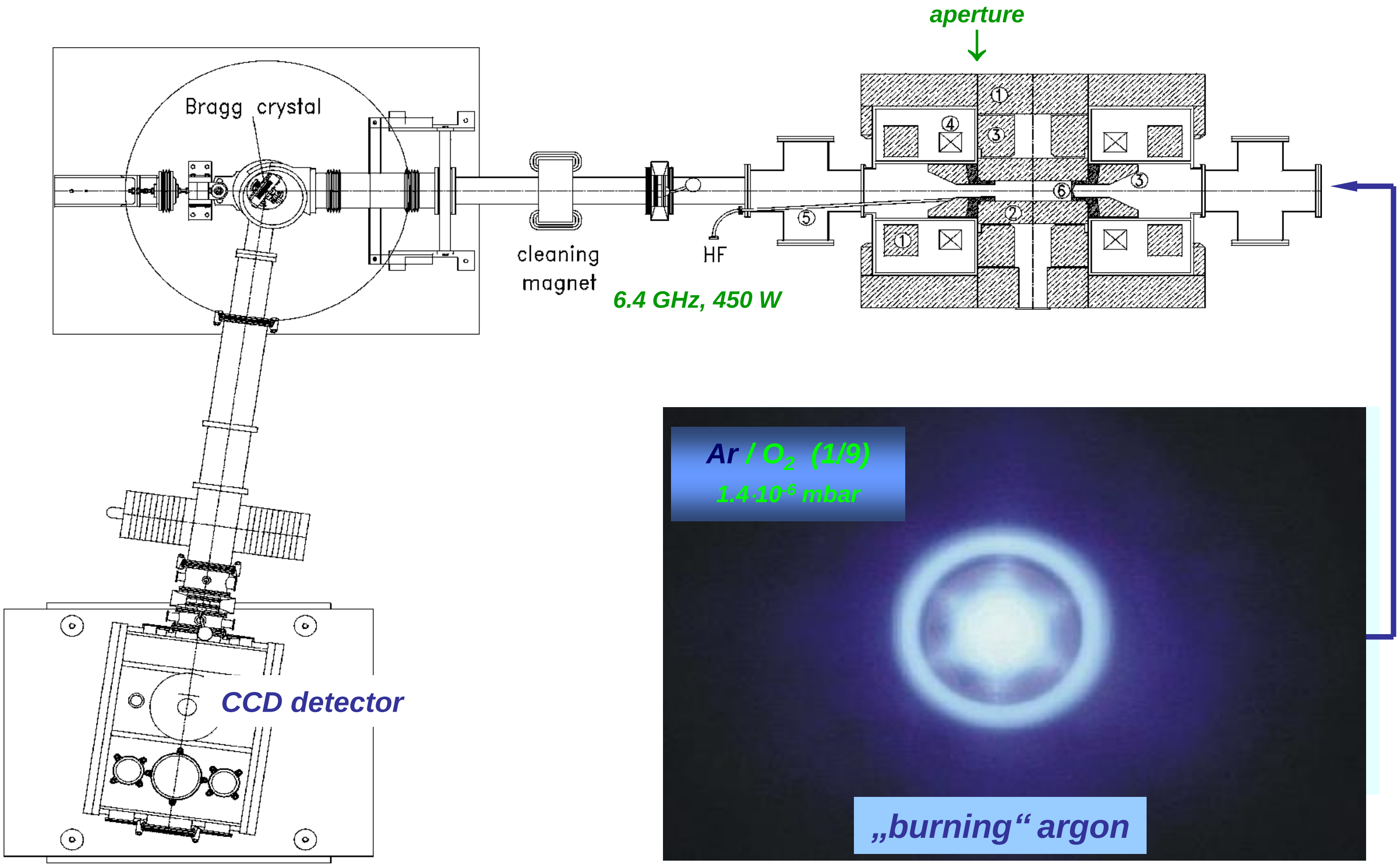
He-like electronic atoms

$\Rightarrow$ <u>narrow</u> X-ray transitions

Γ_X = 10 - 40 meV

CRYSTAL SPECTROMETER and PSI ECRIT

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



6.4 GHz, 450 W

CCD detector

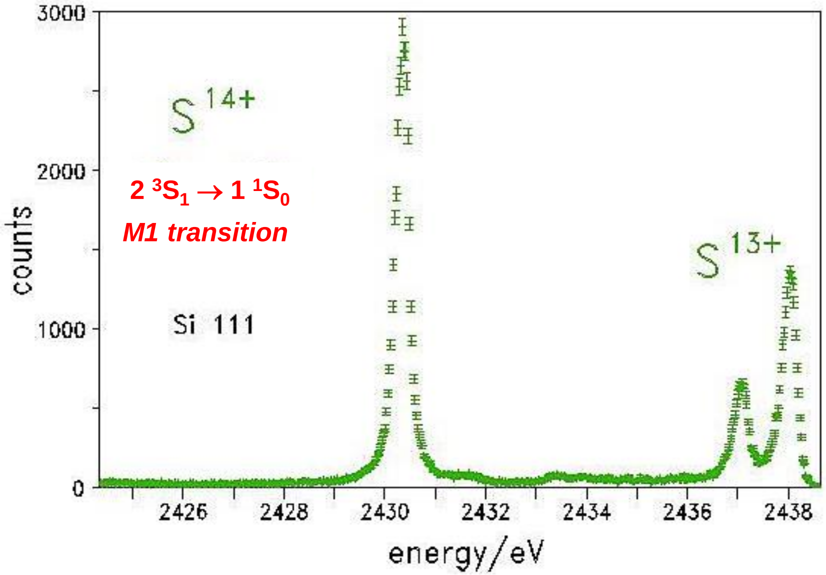
Ar / O_2 (1/9)

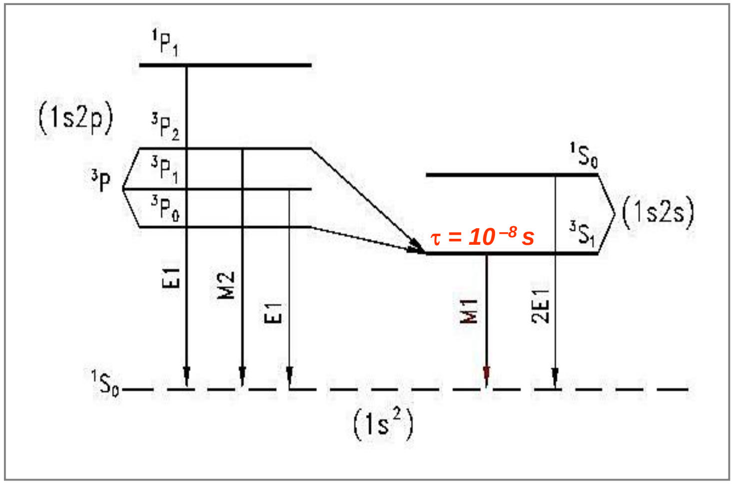
$1.4 \cdot 10^{-6}$ mbar

„burning“ argon

SPECTROMETER RESPONSE at πH Lyman ENERGIES

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





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

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

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

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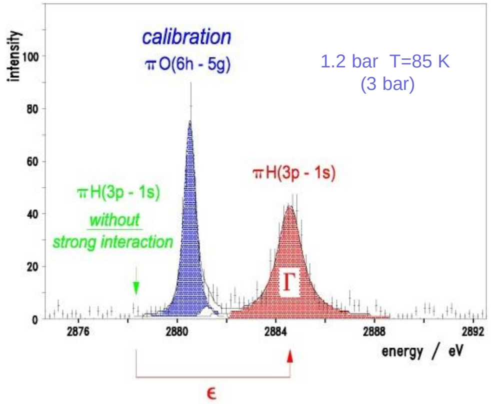
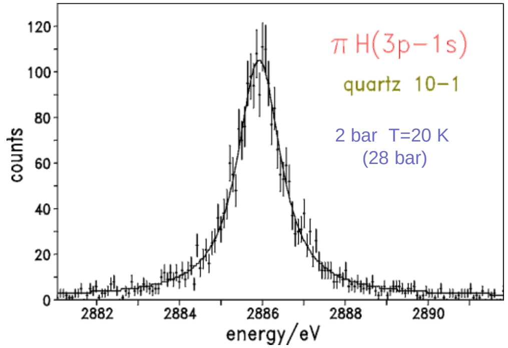
DETERMINATION OF ε_{1s}

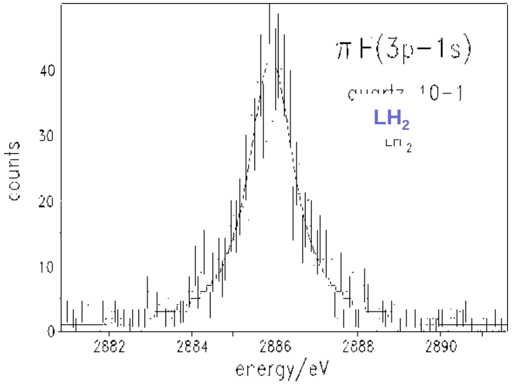
=

find angle difference to reference line

πH(3p - 1s)







energy calibration

πH / πO *mixture*

mixture H_2 / O_2 (98% / 2%)

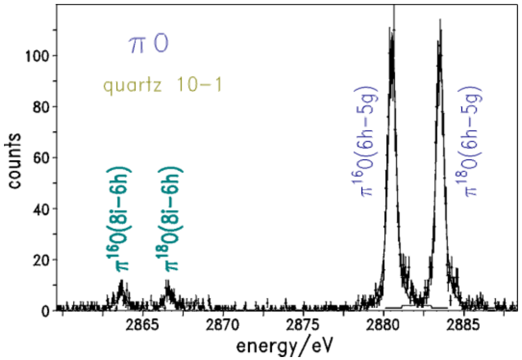
1.2 bar @ T = 85K

energy calibration simultanuously

πH / πO *alternating*

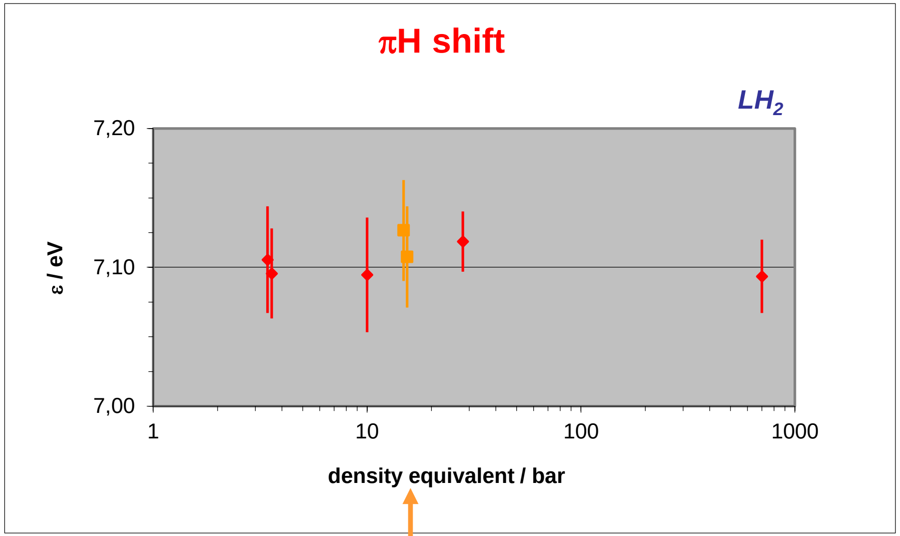
mixture ^{4}He / $^{16}O_2$ / $^{18}O_2$ (≈ 80% / 10% / 10%)

2 bar @ T = 86K



πH(3p - 1s) ε_{1s}

no density dependence identified ⇒ "no" X-ray transitions from molecular states



previous experiment – Ar Kα

ETHZ-PSI H.-Ch.Schröder et al. Eur.Phys.J.C 1(2001)473

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

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

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

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

most recent value for mπ ± 1.3ppm
M. Trassinelli et al, Phys. Lett. B 759 (2016) 583

$\Rightarrow \Delta\varepsilon_{m_\pi} = \pm\, 0.8$ meV !

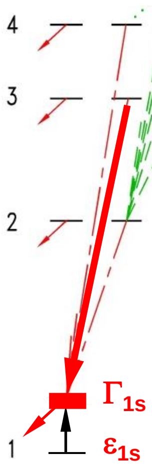
new QED value $\Delta\varepsilon_{QED} = \pm\, 1.4$ meV
S. Schlesser et al. Phys. Rev. C 84 (2011) 015211

⇒ *- 22 meV* !

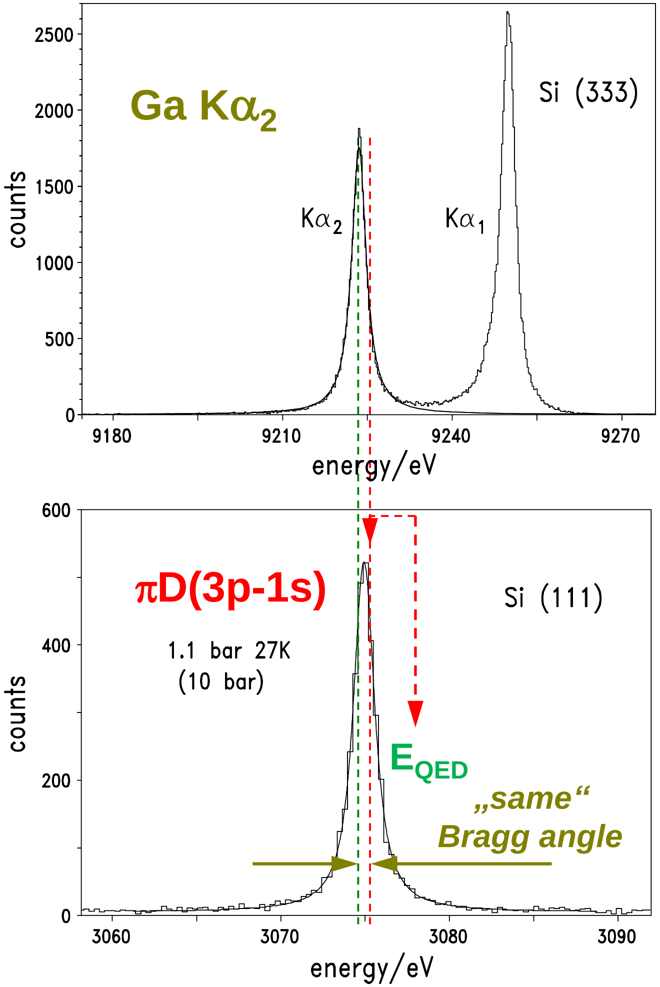
$\pi D(3p - 1s)$ ε_{1s}

energy calibration

strong interaction



repulsive



3 bar
10 bar
22 bar
} *no molecule formation seen*

error budget

± 27 meV	*Ga Kα$_2$*
± 10 meV	*statistics*
± 8 meV	*pion mass*
± 5 meV	*systematics*
± 2 meV	*QED*

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

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

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

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

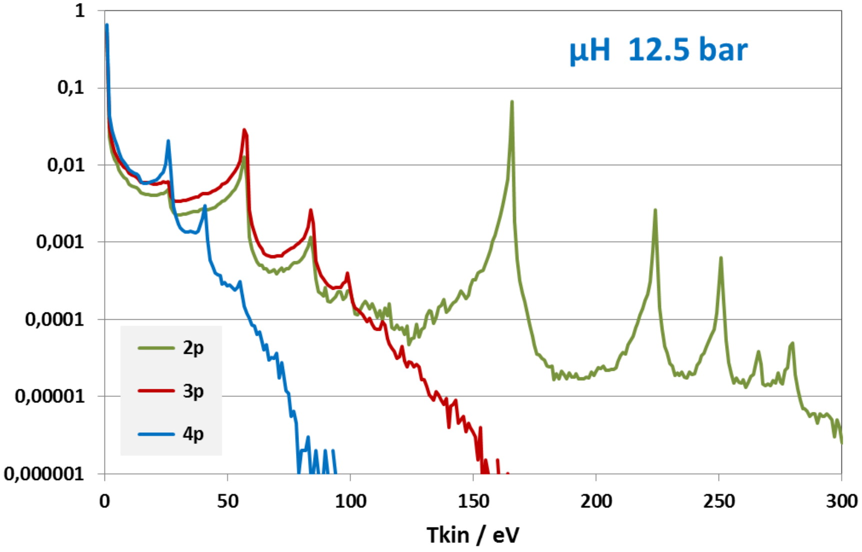
EXTRACTION OF Γ_{1s}

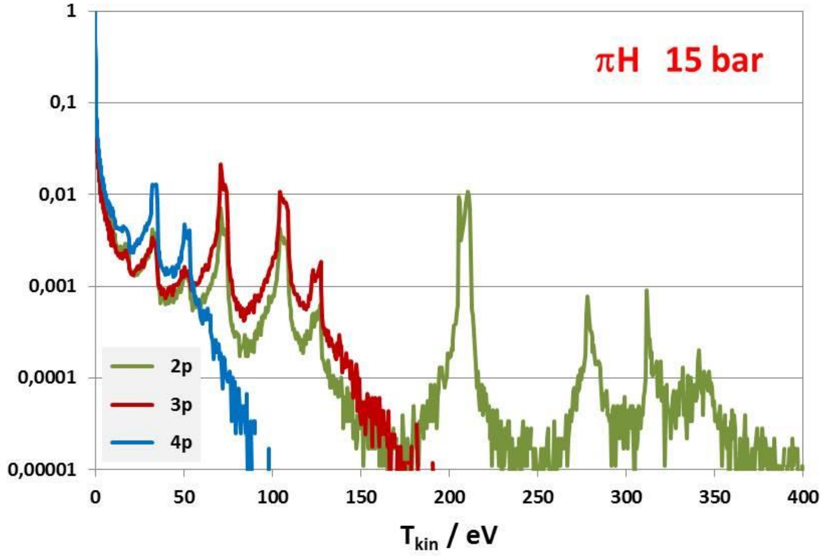
=

find model for Coulomb de-excitation

Prediction from cascade theory

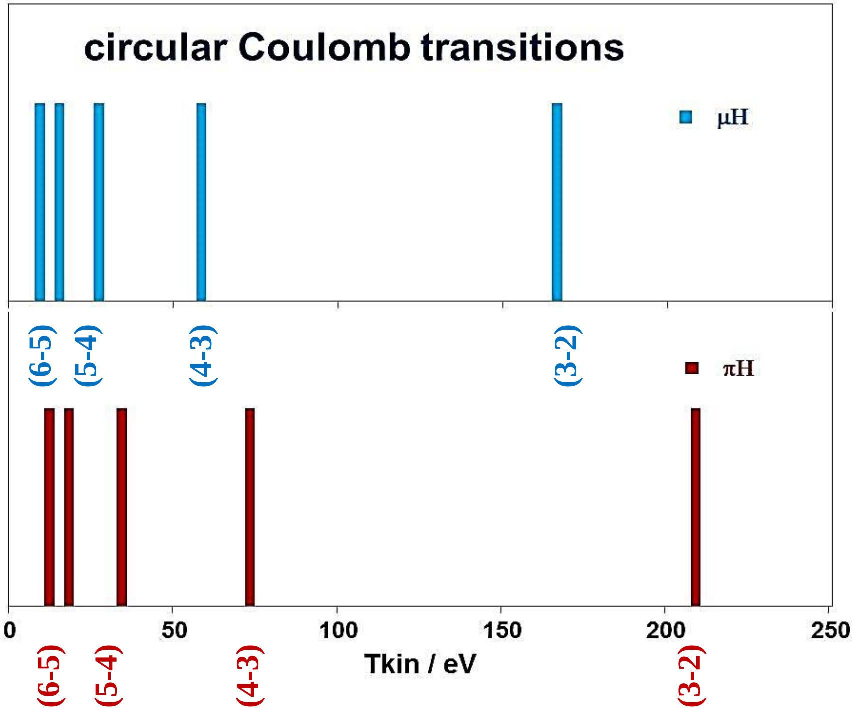
***ESCM** (extended standard cascade model) model follows development of kinetic energy*





***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



neglected here: possible Δn=2 Coulomb transitions

maximal Doppler broadening of X-ray line

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

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

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

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

ANALYSIS METHODS

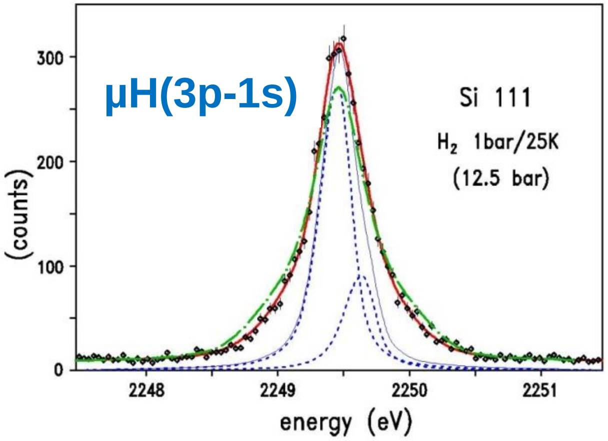
I **MAXIMUM LIKELIHOOD „FIT“**

„MINUIT“ χ^2 analysis

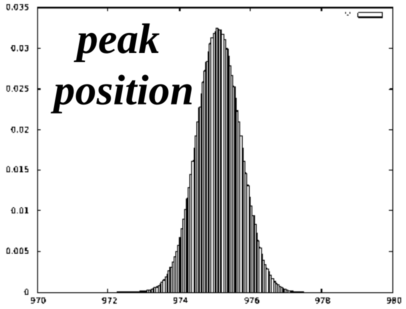
„bias“ problem

II **BAYESIAN APPROACH**

ANALYSIS - μH(3p - 1s)

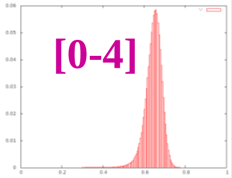


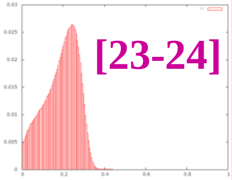
„obvious“ parameters
look like Gaussian

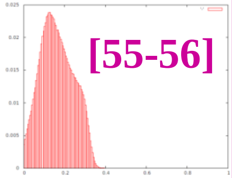


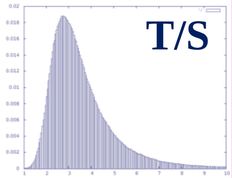
comparison: 3-component model

χ^2 analysis		Bayesian approach	
[0-2]	61±2	[0-4]	65^{+3}_{-4}
[24-27]	25±3	[23-25]	24^{+4}_{-10}
[57-58]	14±4	[55-57]	16^{+10}_{-4}
HFS free	211±19		212^{+23}_{-21}
T/S	3.6±0.6		$3.2^{+1.6}_{-0.7}$
HFS fixed			
T/S	2.9±0.2		$2.5^{+1.1}_{-0.5}$









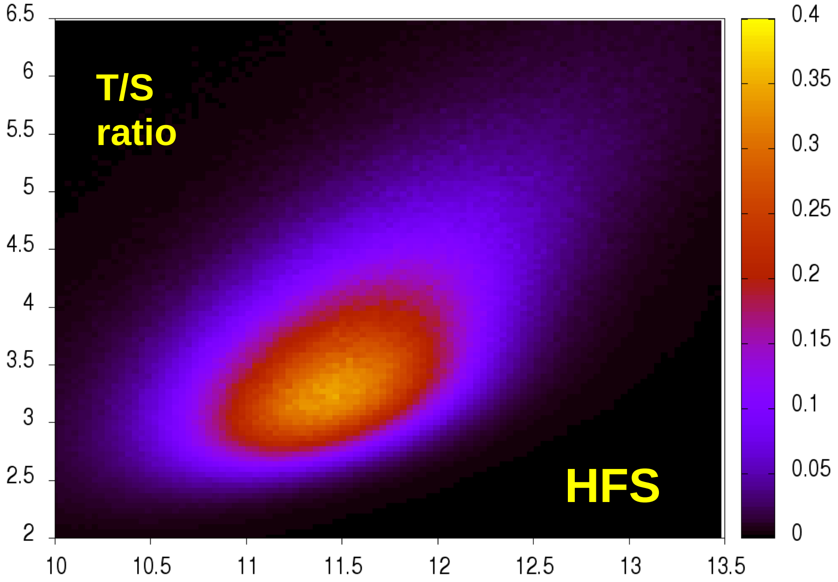
ANALYSIS - μH(3p - 1s)

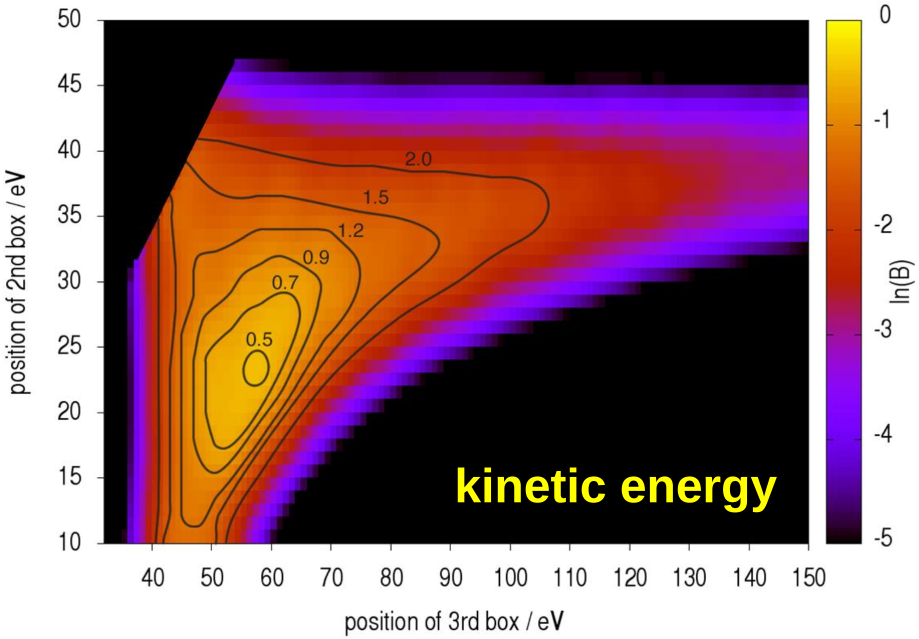
Bayesian approach: two-dimensional posterior probability

HFS free 212^{+23}_{-21}

T/S $3.2^{+1.6}_{-0.7}$

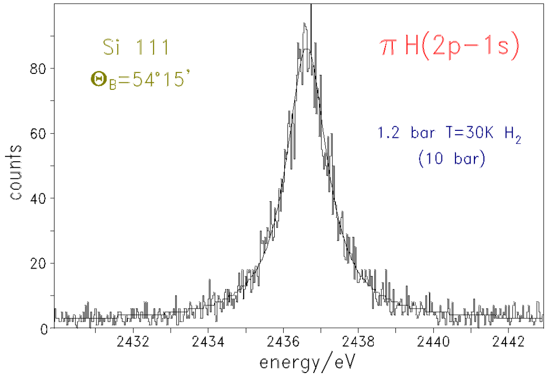
2 high-energy components

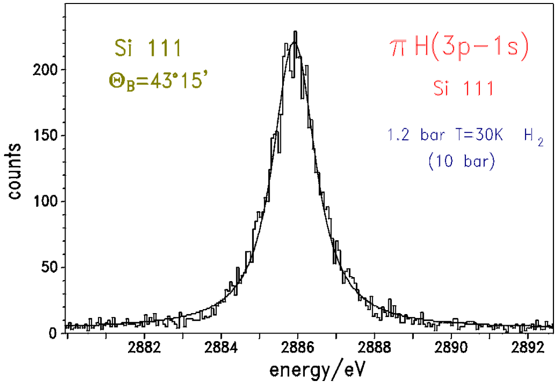


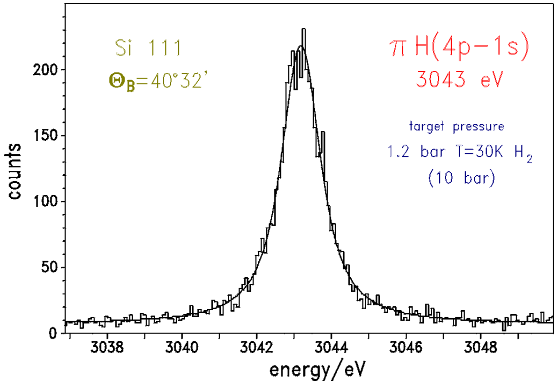


D.S. Covita, PhD thesis Coimbra 2008
D.S. Covita et al., Phys. Rev. Lett. 102, 023401 (2009)
M.Theisen, Diploma thesis FZJ 2013
D.S. Covita et al., Eur. Phys. J. D 72, 72 (2018)

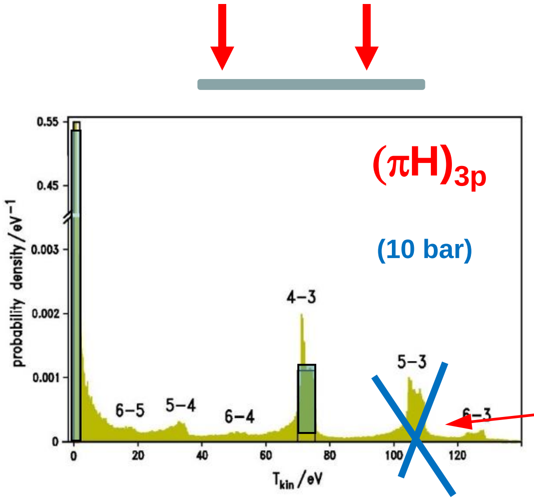
***ANALYSIS* - πH(np - 1s) Γ_{1s}**







alternative HE components



?

„FIT“ →

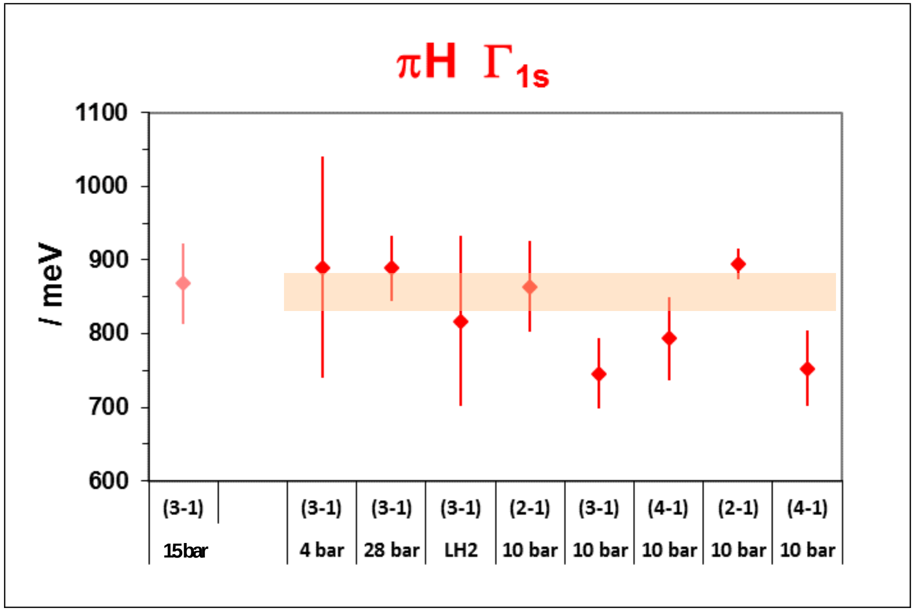
Coulomb transition

low-energy	*≈50%*
5-4	*---*
6-4	*---*
4-3	*≈50%*
3-2	*?*

low-energy	*≈55%*
5-4	*---*
6-4	*---*
4-3	*≈45%*
5-3	*---*

low-energy	*≈50%*
6-5	*---*
5-4	*≈50%*
6-4	*---*

πH(np - 1s) Γ_{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

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

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

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

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

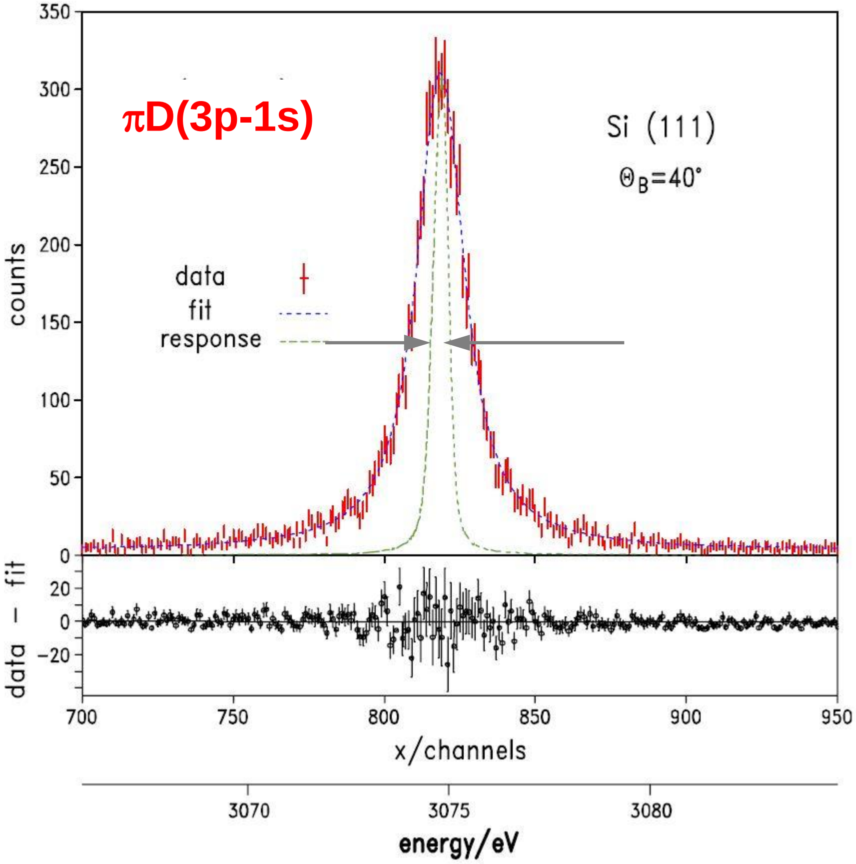
	Γ_{1s} / meV
„FIT“ bias corrected	*852 ± 22*
Bayesian approach	*856 ± 27*

Kln. energy distribution from cascade theory

Γ_{1s} = *781 – 963 ± (7 – 20) meV*

no solution!

πD(3p - 1s) Γ_{1s}



$$\Gamma_{1s} = \left(1.171\,^{+0.023}_{-0.049}\right)\,eV \quad \left(\,^{+2\%}_{-4\%}\right)$$

$$\Im\, a_{\pi^- d} = \left(6.22\,^{+0.12}_{-0.26}\right) \cdot 10^{-3}\, m_\pi^{-1}$$

error budget

± 23 meV statistics

± 43 meV Coulomb de-excitation (≤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 LENTGHS

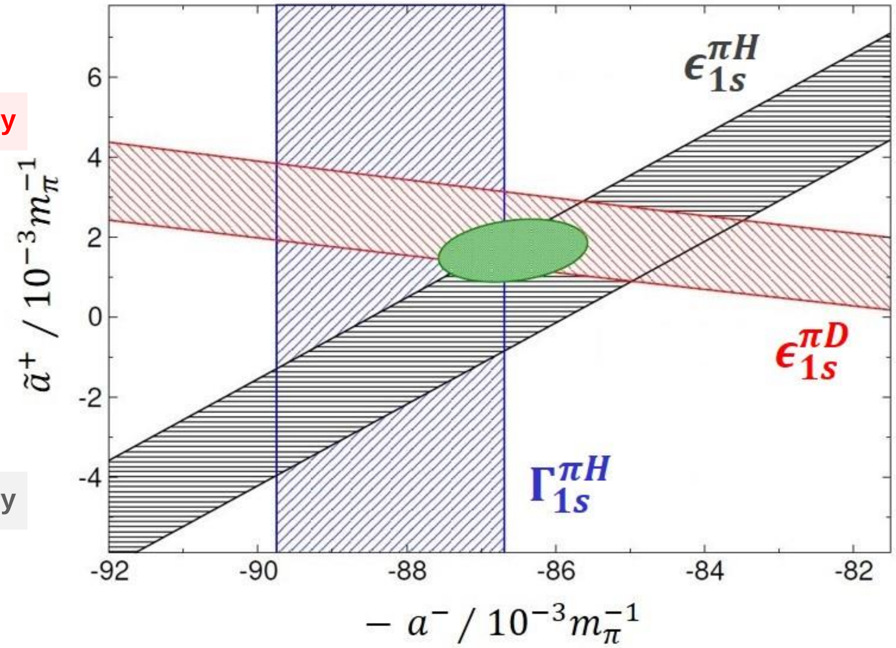
$\pi N \Leftrightarrow \pi N$

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

Δ exp (*Coulomb de-excitation*) ≈ 2 × Δ theory

Δ exp << Δ theory

Δ exp << Δ theory



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

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 : 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

$NN \Leftrightarrow \pi NN$

NN ⇔ πNN threshold parameter α

charge symmetry   *detailed balance (T invariance)*

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

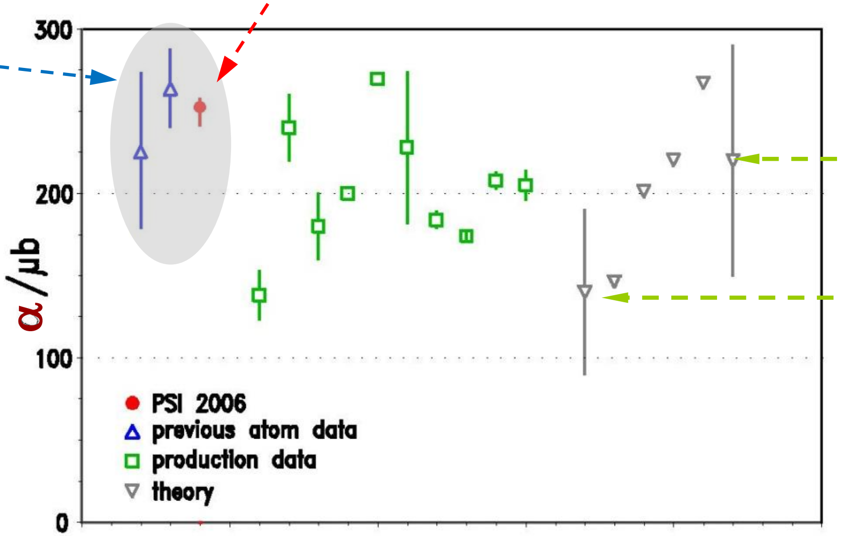
$NN \quad {}^3S_1(I=0)\to {}^3P_1(I=1)$

$$\Gamma_{1s} \propto \Im\, a_{\pi^- d} \propto \ \alpha(pp\to\pi^+ d) = (\,251\ {}^{+\ 5}_{-11}\,)\ \mu b \quad ({}^{+2}_{-4}\%)$$

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



χPT NLO

χPT LO

χPT

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

→ few % !?

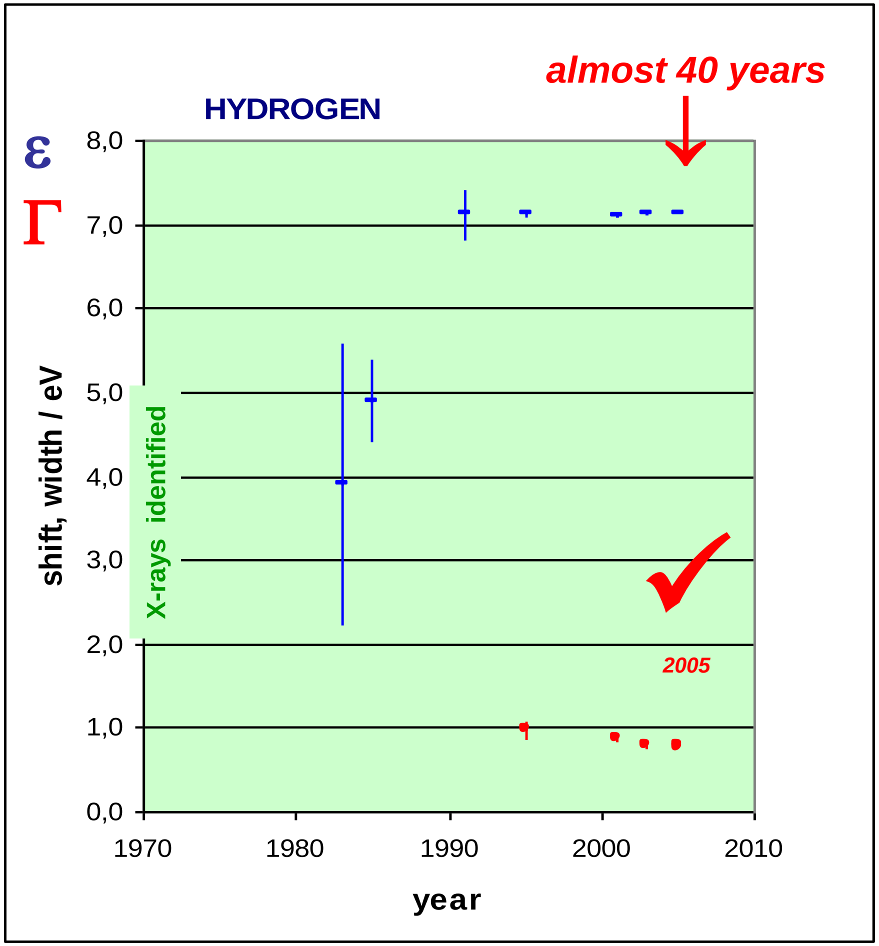
V. Lensky et al.,
Eur. Phys. J. A 27 (2006) 37

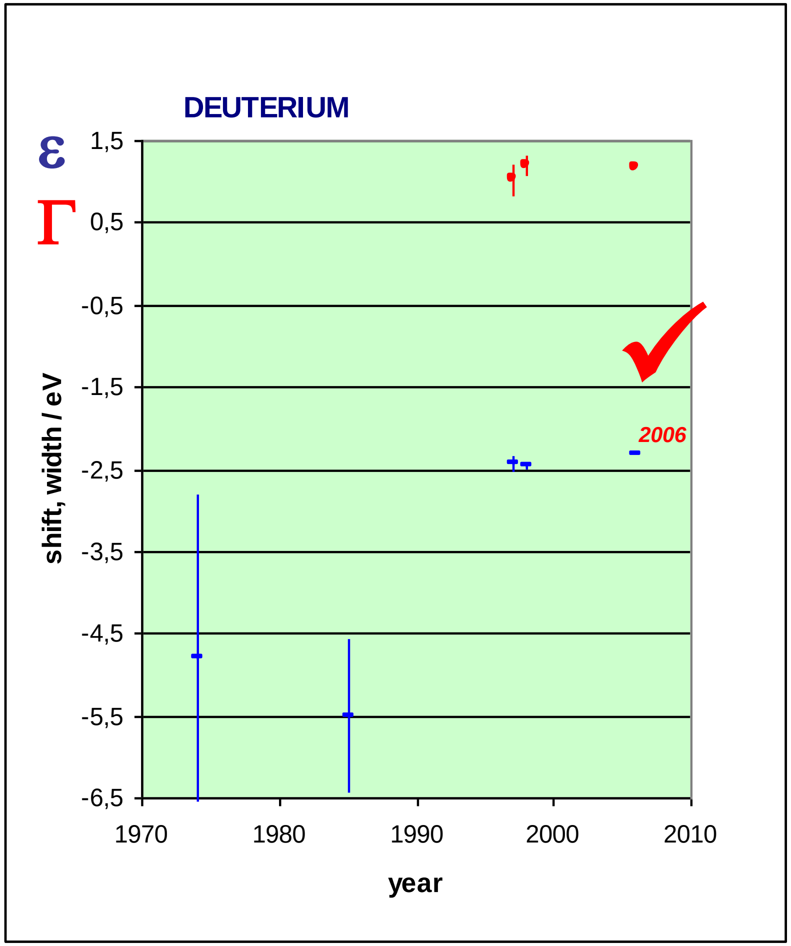
Outlook experiment
$\Delta\Gamma/\Gamma$ → 1%

theoretical progress needed

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

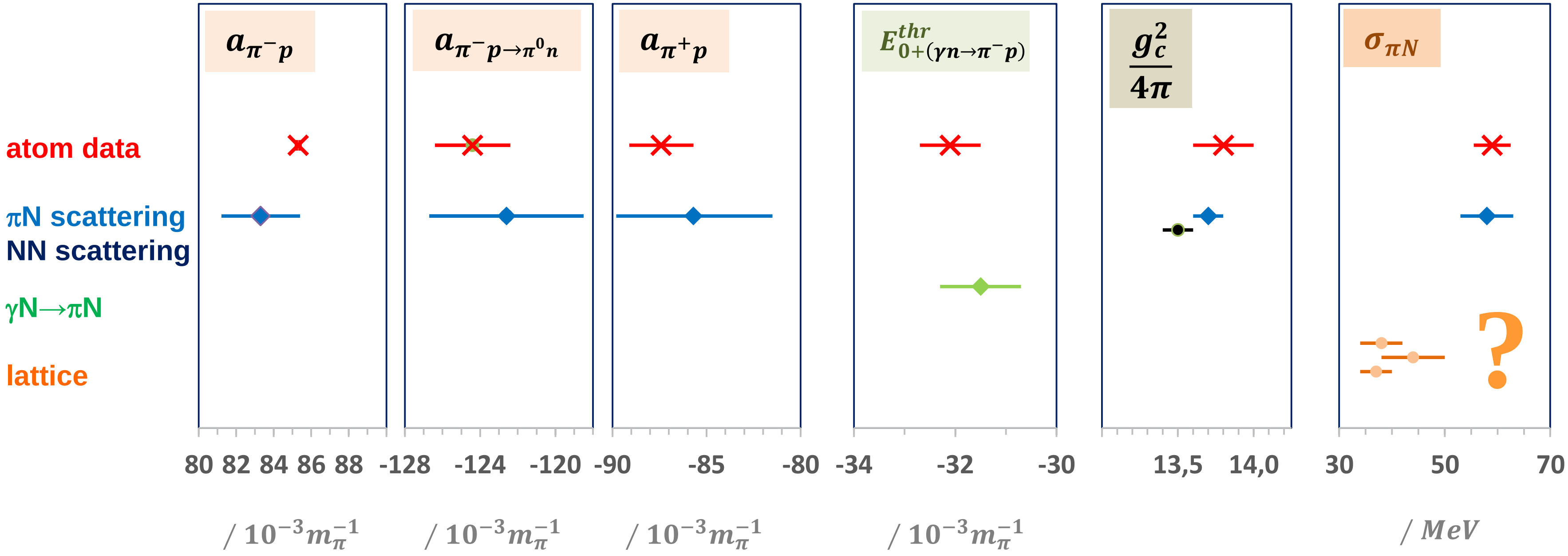
PIONIC HYDROGEN STORY





- **πN scattering length: bands cross**
- **s - wave π - production strength**
- **μH – singlet / triplet**
  - **ΔE_{HFS}**
  - **cascade theory ≈ line shape**
- **atomic & πN scattering data etc. highly consistent**

Comparison of various inputs



analyses involve input from χPT

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

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

$\sigma_{\pi N}$ ⇔ *WIMP – nucleon scattering*

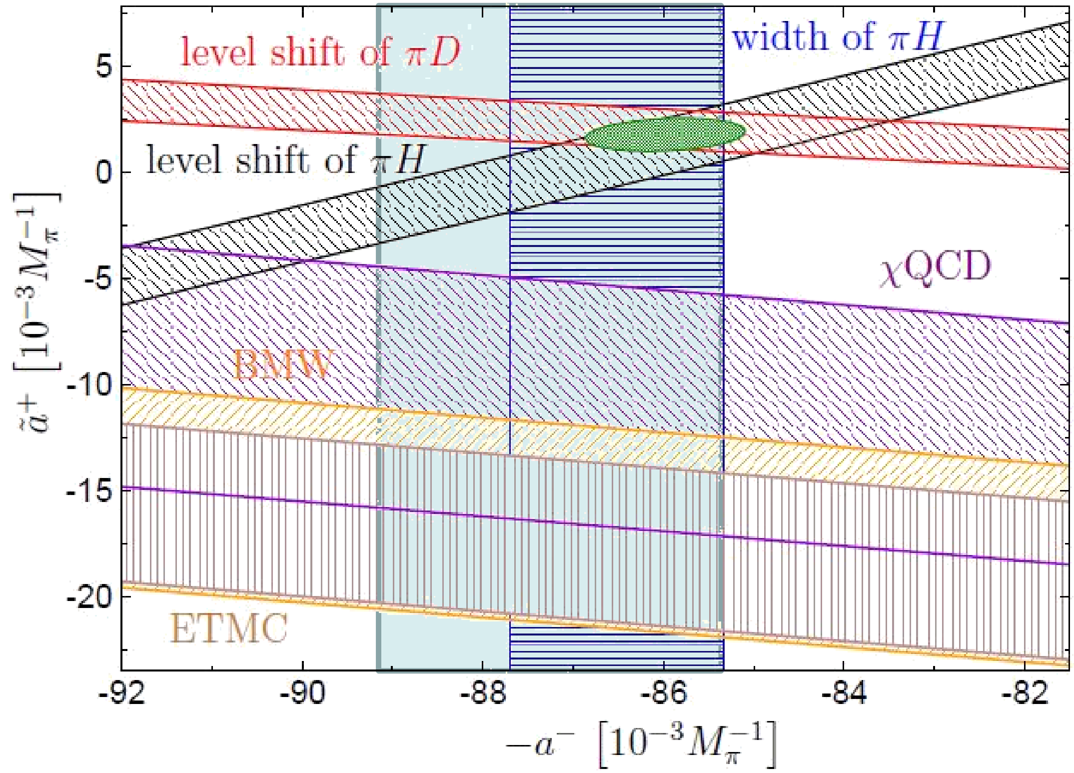


Figure 1: Constraints on the πN scattering lengths from pionic atoms (black: level shift in πH, blue: width of πH ground state, red: level shift in πD) and from lattice σ-terms (orange: BMW [20], violet: χQCD [21], brown: ETMC [22]).

← pionic atoms analysis

?

← lattice

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** **πH(4p-1s)**

πH(5p-1s) ?

set-up **increase resolution** **quartz 10-2**

exploit higher pion fluxes at PSI

cascade **understand even better** **µH, µD**

kinetic energy distribution

T_{kin}-distribution as input possible?

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 and R-06.03

Debrecen , Inst. of Nucl. Research
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F. D. Amaro, D. S. Covita, J. M. F. dos Santos, J. F. C. A. Veloso,

Ioannina, Dept. of Material Science
D. F. Anagnostopoulos

Jülich, FZJ IKP2, ZEA-2
A. Blechmann, H. Gorke, D.Gotta, M. Hennebach, M. Nekipelov, Th. Strauch, M. Theisen

Paris, Lab. Kastler-Brossel UPMC ENS CNRS
E.-O. Le Bigot, P. Indelicato, S. Schlesser, M. Trassinelli

PSI, Lab. for Part. Physics
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Vienna, SMI
P. Bühler, H. Fuhrmann, A. Gruber, A. Hirtl, T. Ishiwatari, J. Marton, Ph. Schmid, J. Zmeskal

Cascade theory

V. E. Markushin (PSI), Th. Jensen (ETHZ,PSI,LKB,FZJ,SMI), V. Pomerantsev, V. Popov (MSU)

→ Diploma and PhD thesis ←

THANK YOU