Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

PIONIC HYDROGEN

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PSI 2010, Paul Scherrer Institut, October 11-14, 2010

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 & R.06.03

X-ray spectroscopy of exotic atoms

pionic and muonic hydrogen

pionic deuterium

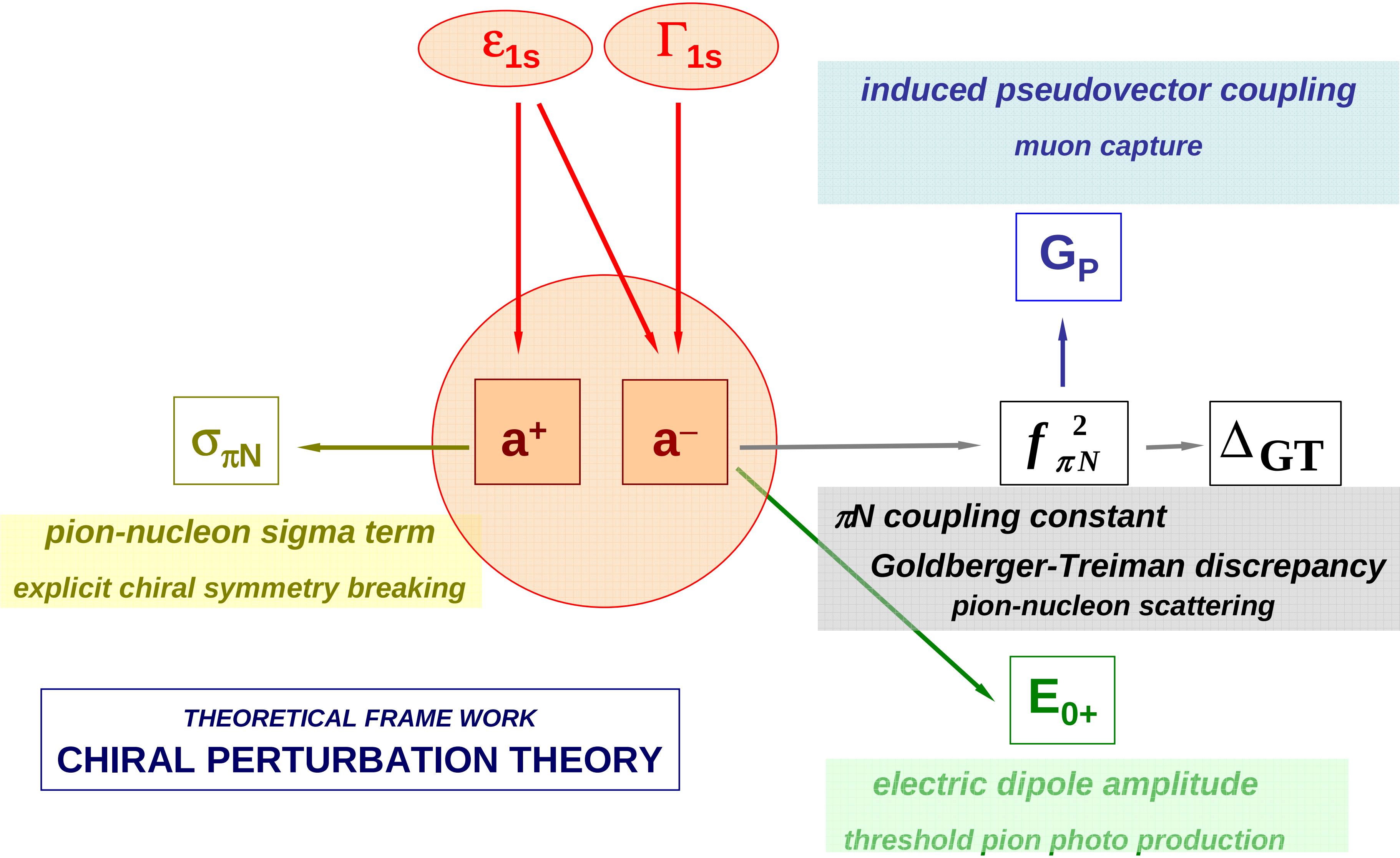
goal - strong-interaction effects to ≈ 1%

PION-NUCLEON

SCATTERING LENGTHS

$\mathbf{a}^{\pm}$

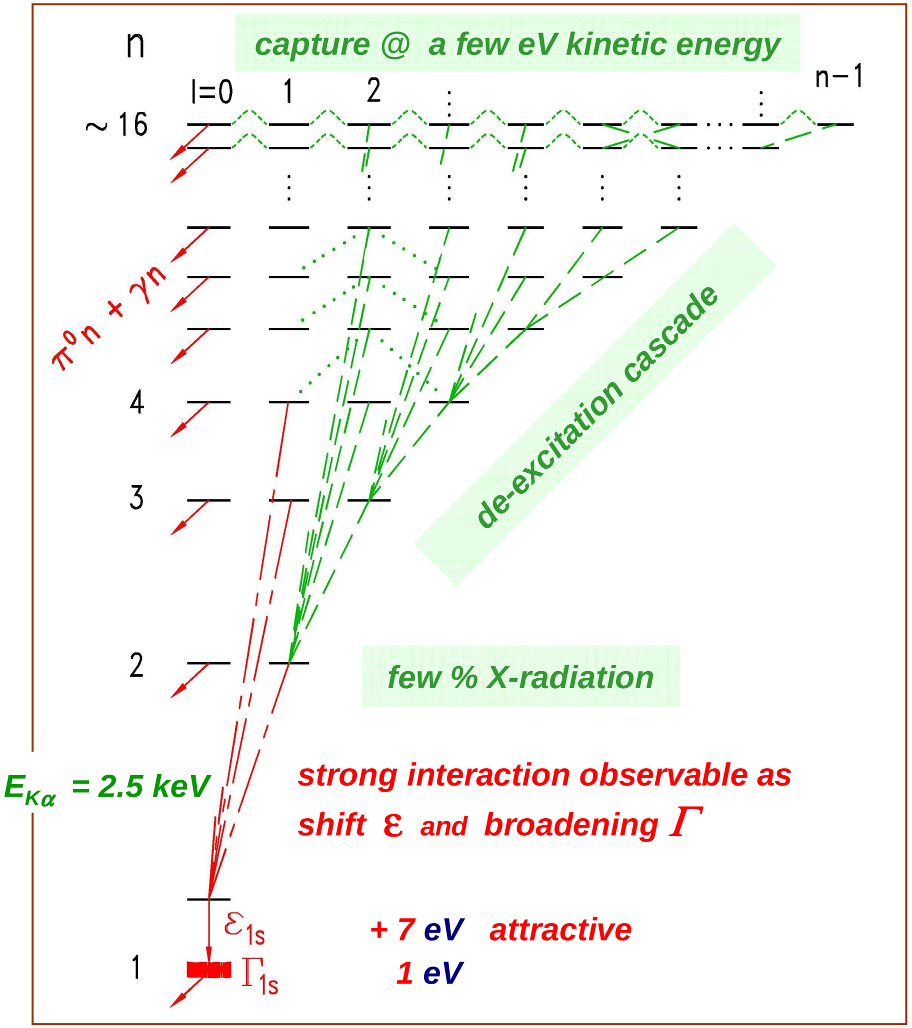
PION-NUCLEON SCATTERING LENGTHS related quantities



THEORETICAL FRAME WORK

CHIRAL PERTURBATION THEORY

PIONIC HYDROGEN - πN scattering at „rest“



which scattering length where?

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

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

$\pi D\ \varepsilon_{1s} \propto a_{\pi^- p\to\pi^- p} + a_{\pi^- n\to\pi^- n} \propto 2\cdot a^+ + \dots$

$a^\pm$ = isospin even/odd scattering length

isospin 1 ⊗ 1/2 ⇒ 1/2 ⊕ 3/2

THEORY

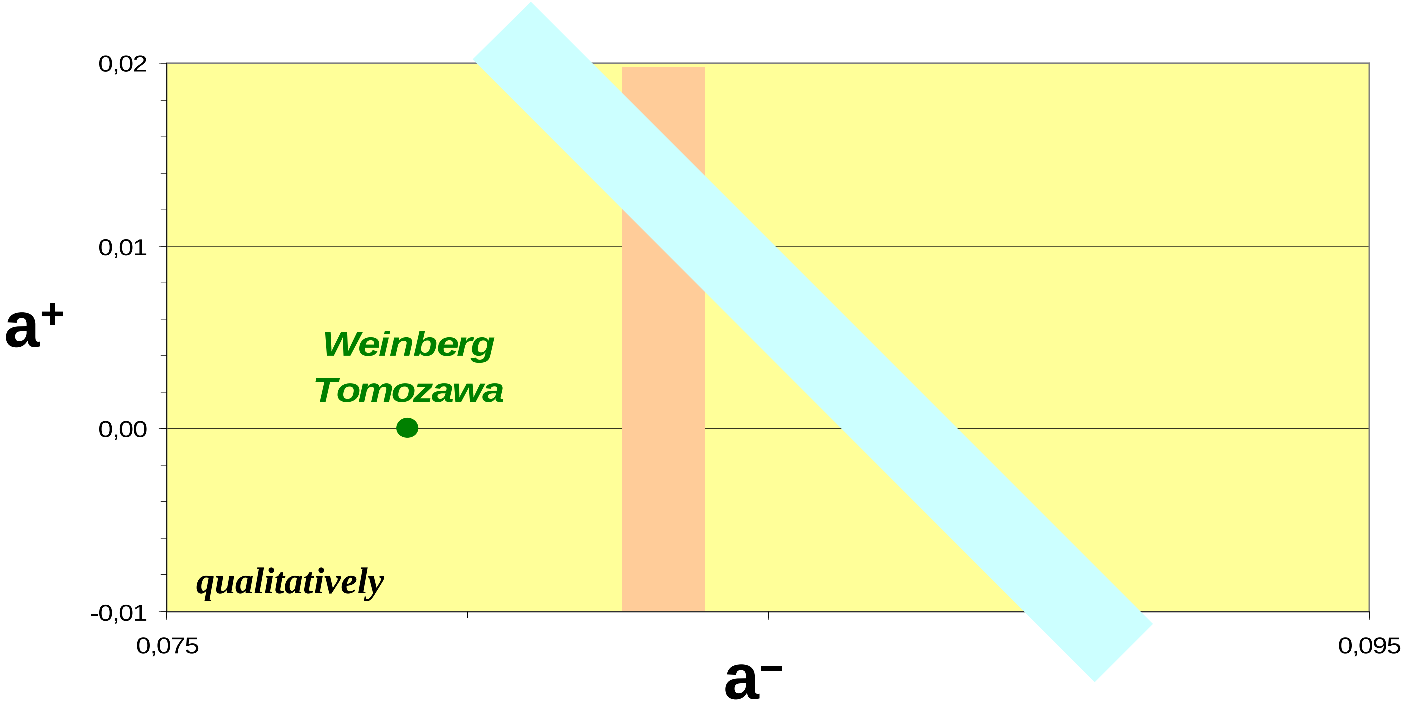
isospin breaking corrections
few-body effects etc,
under control !!!

different

!!! $\pi D\ \Gamma_{1s} \propto \Im\, a_{\pi^- d\to nn+nn\gamma}$

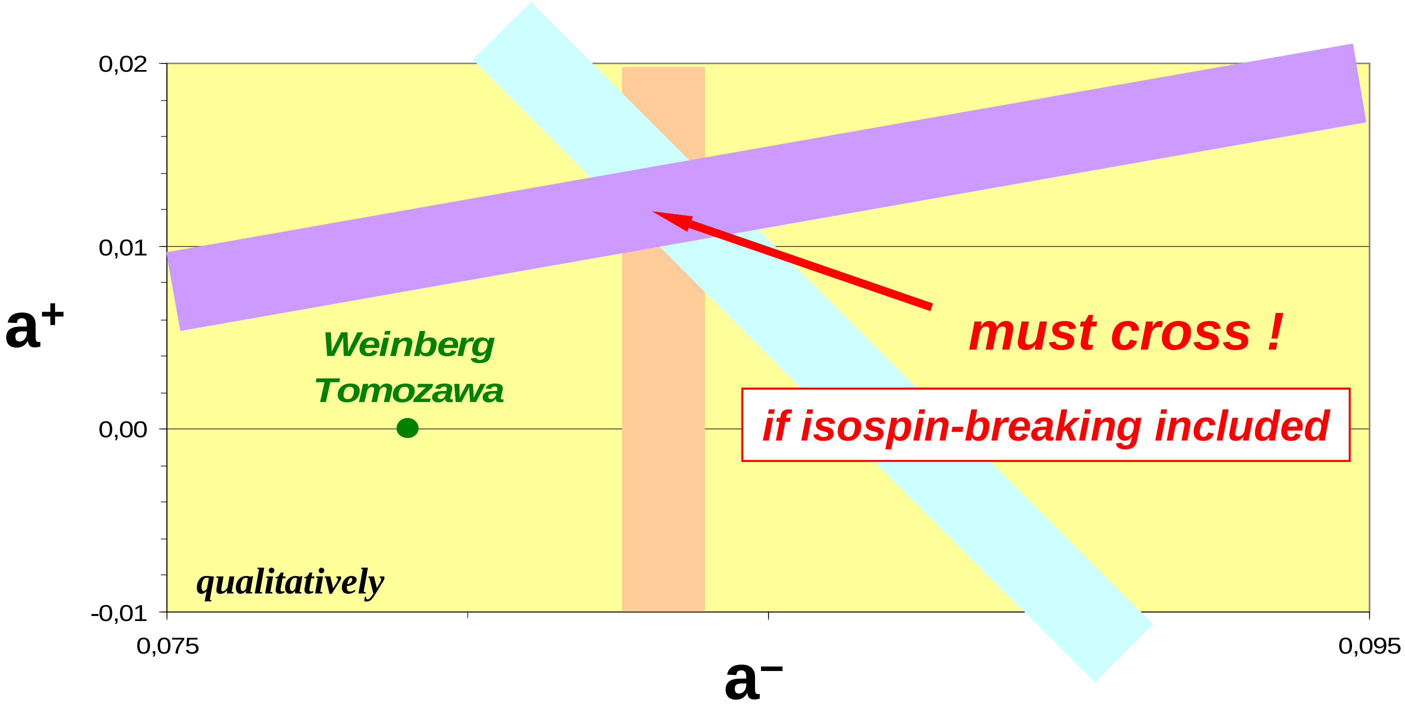
constraints for $a^{\pm}$ from πH

πH	ε_{1s}	$\propto f(a^+, a^-, LEC(c_1, f_1, f_2))$
πH	Γ_{1s}	$\propto [f(a^-, LEC(c_1, f_2))]^2$



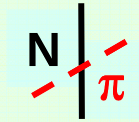
constraints for $a^{\pm}$ from πH and πD

πH	ε_{1s}	$\propto f(a^+, a^-, LEC(c_1, f_1, f_2))$
πH	Γ_{1s}	$\propto [f(a^-, LEC(c_1, f_2))]^2$
πD	ε_{1s}	$\propto f(a^+, a^-, LEC(c_1, f_1, f_2))$



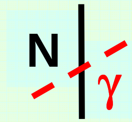
HYDROGEN & DEUTERIUM - ORIGIN OF Γ_{1s}

CEX scattering



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

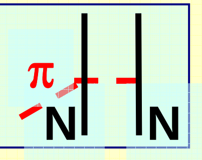
radiative capture



BR are well known from experiment

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

„true" absorption



NN ⇔ NNπ

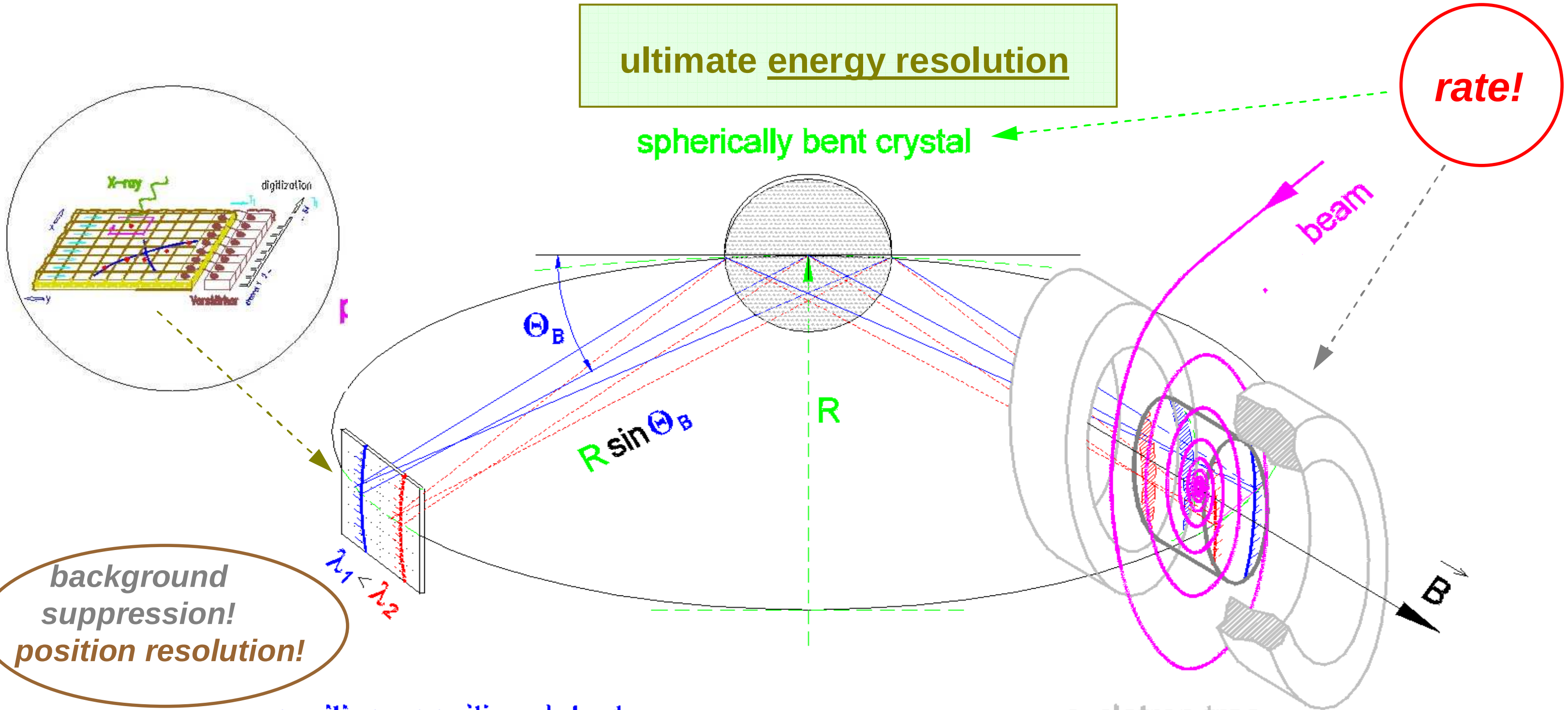
s-wave pion production/absorption

EXPERIMENT

- ***How to produce a suitable <u>X-ray source</u>?***
- ***What about <u>background</u>?***
- ***<u>Resolution</u> of the crystal spectrometer ?***

Johann-type SET-UP

ultimate energy resolution



background suppression!
position resolution!

position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

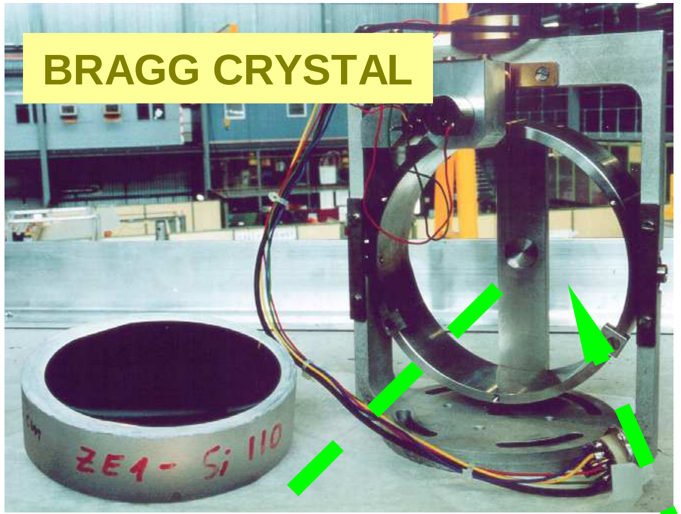
position & energy resolution

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

high stop density

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

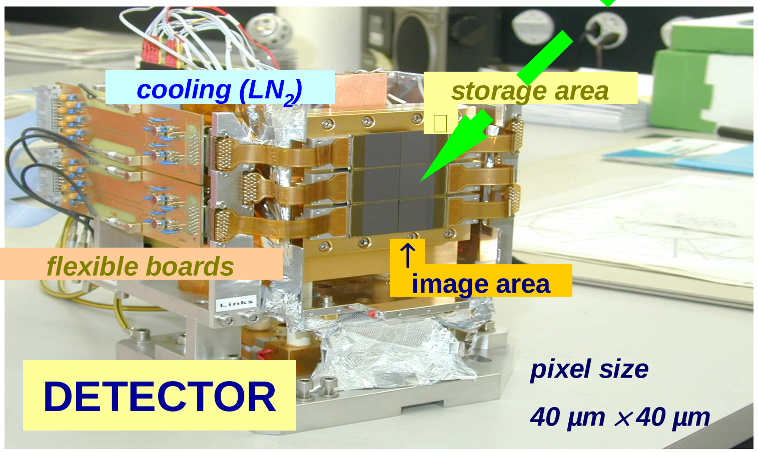
L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253



spherically curved

R = 3 m
Φ = 10 cm

Large - Area Focal Plane Detector

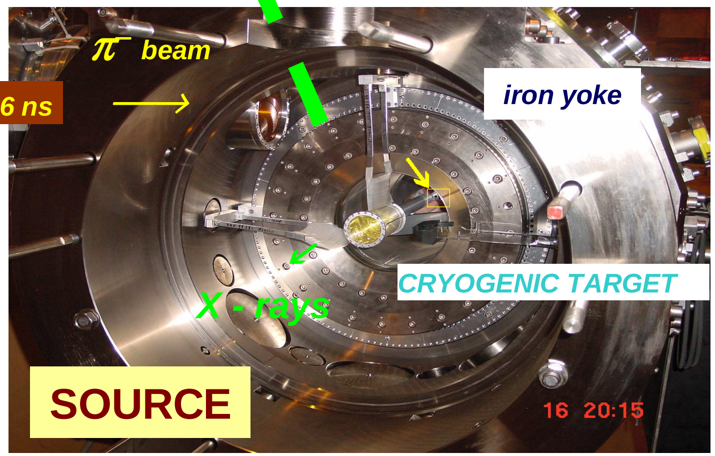


CYCLOTRON TRAP

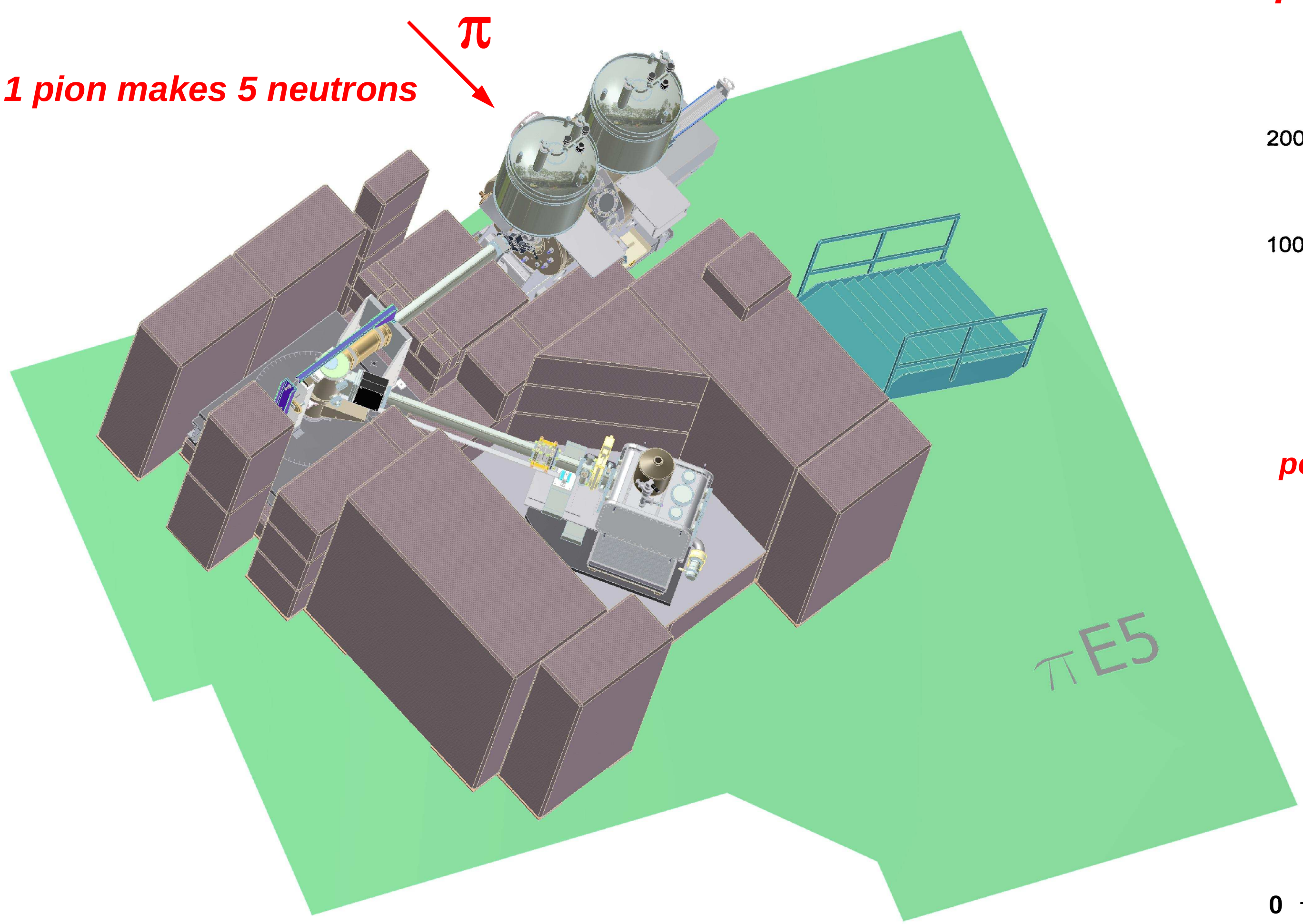
one coil removed

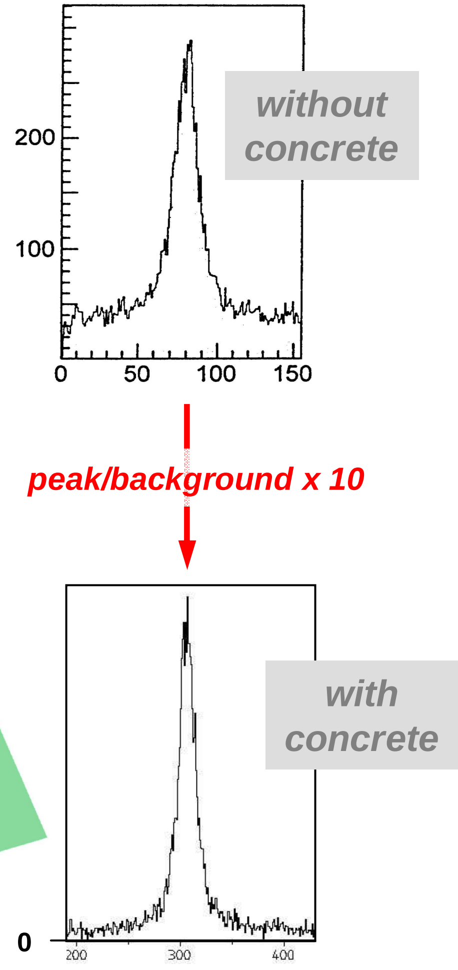
10^9 π/s

$\tau_{\pi\pm}$ = 26 ns



TYPICAL SET-UP at PSI

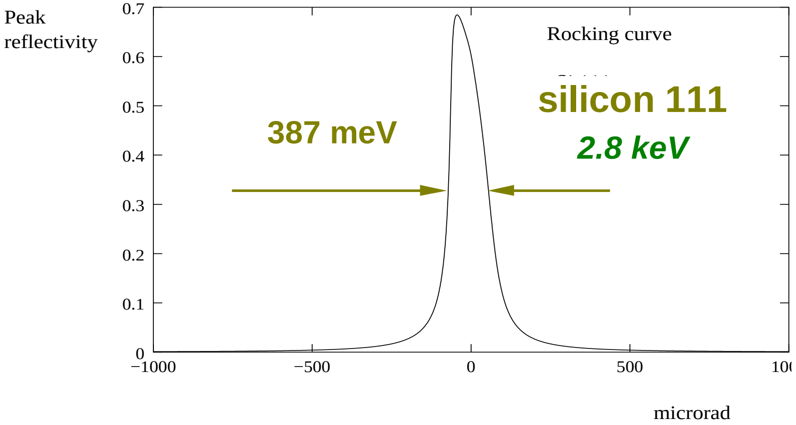




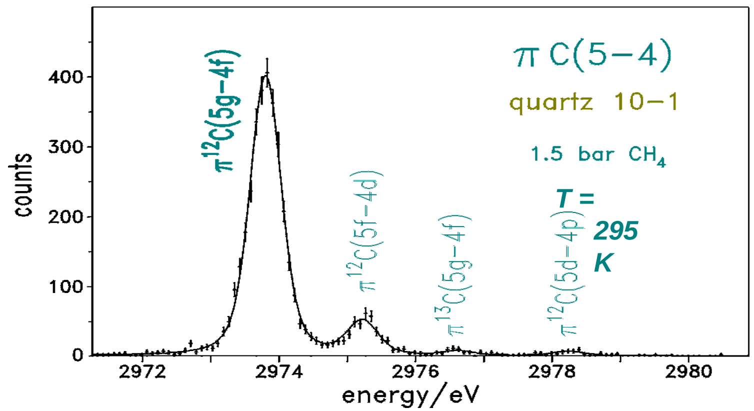
CRYSTAL RESOLUTION

dynamical theory of diffraction

XOP2 code
plane crystal
Sanchez, del Rio, 1995



exotic atom - pionic carbon



closest to energy of □H(4p-1s)

for real crystal mounting?
⇔
measurement indispensible!

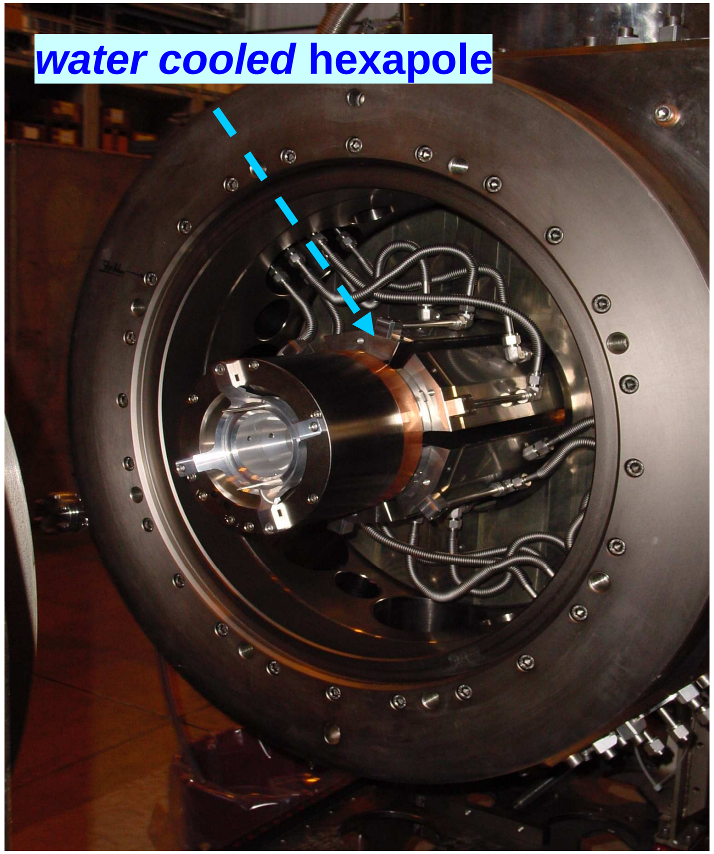
3500 events in 70 h - needed 10 x more

no narrow few keV γ lines available

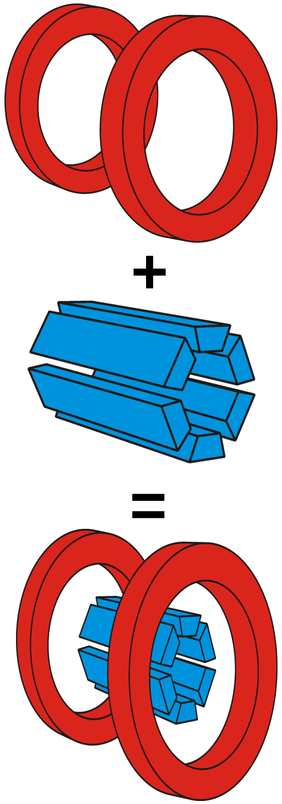
accuracy limited by rate !

ECRIT = Electron Cyclotron Resonance Ion Trap

"misuse" ion source as X-ray source



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



Superconducting coils

- *cyclotron trap*

permanent hexapole

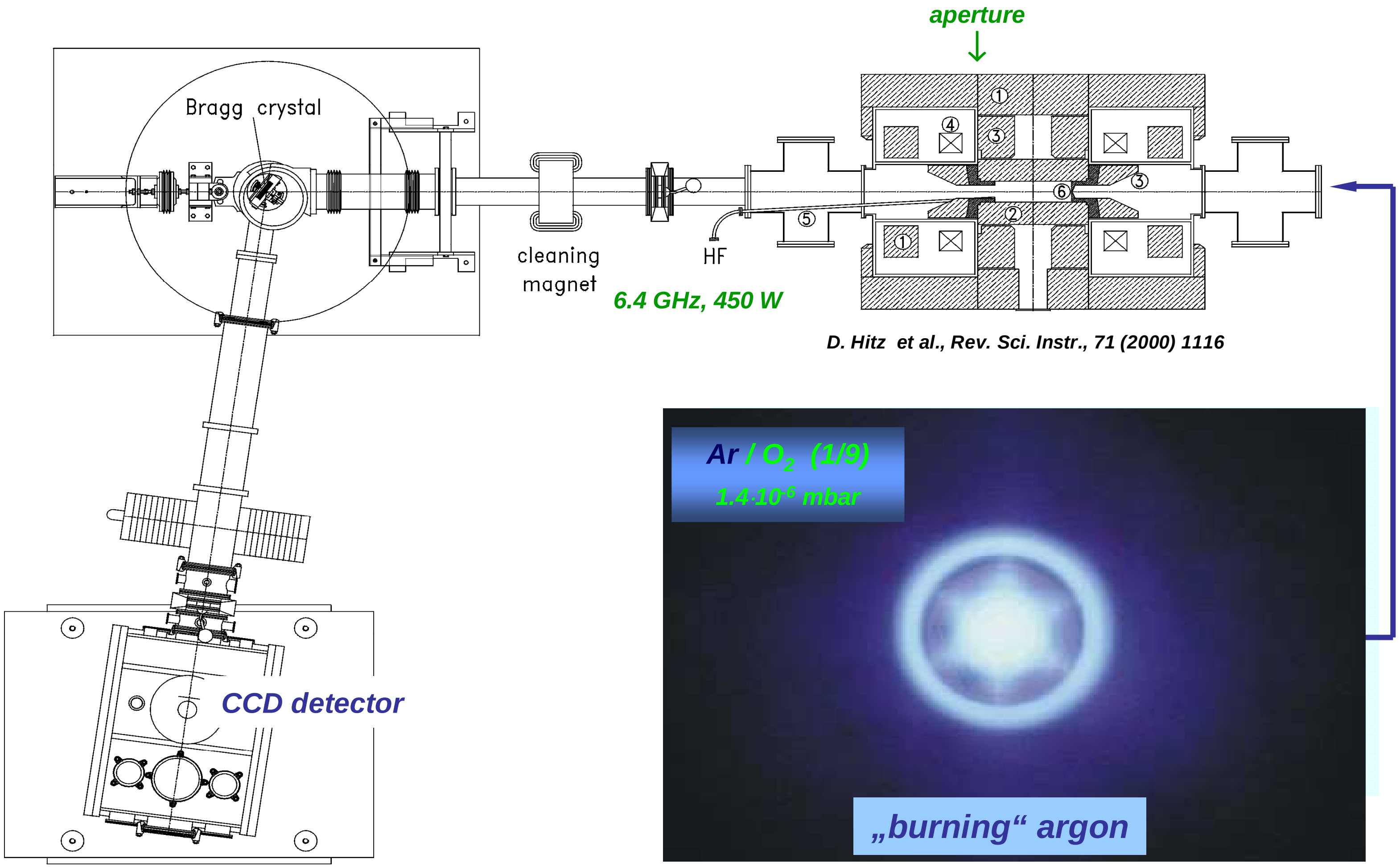
- *AECR-U type*
- *1 Tesla at the hexapole wall*
- *open structure*

large mirror ratio = 4.3

B_{max} / B_{min} !

CRYSTAL SPECTROMETER and PSI ECRIT

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

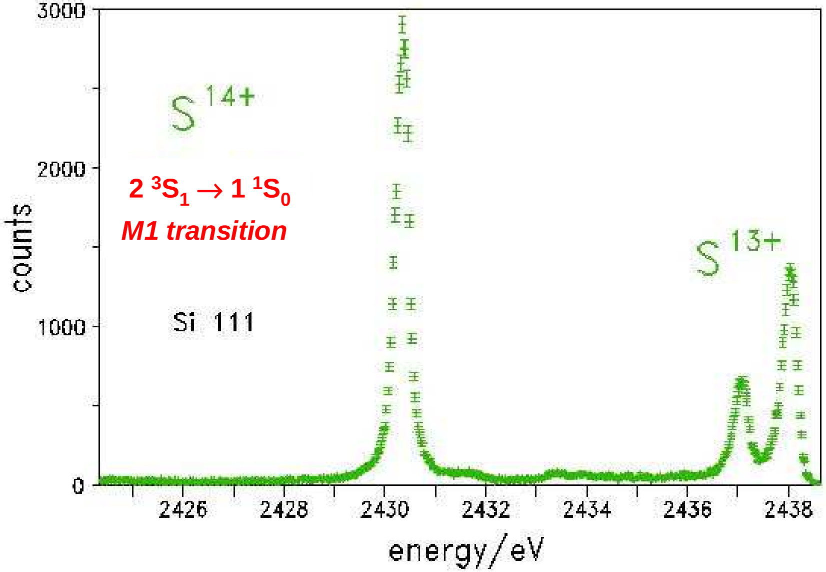


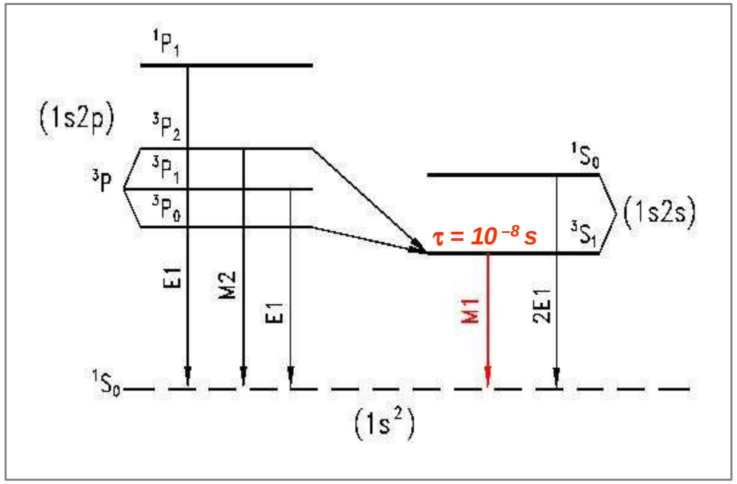
D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116

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

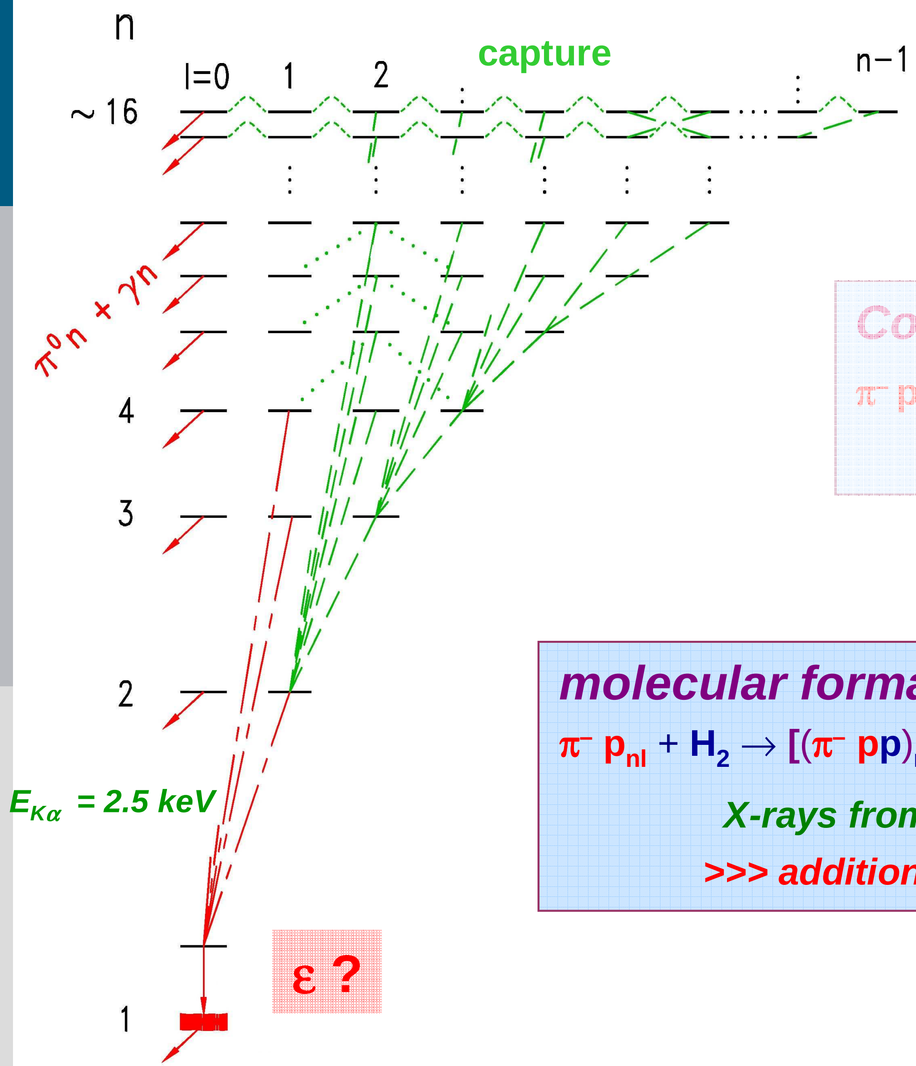
to be compared with Monte-Carlo ray tracing folded with plane crystal response

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

OBSTACLES

- ***Molecular formation***
- ***Coulomb de-exciatation***

πH - ATOMIC CASCADE I



density dependent

Coulomb de-excitation

$\pi^- p_{nl}$ + H=H → $\pi^- p_{n'l'}$ + H+H + *kinetic energy*

>>> Doppler broadening ! <<<

molecular formation

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

X-rays from molecular states ?

>>> additional energy shift ? <<<

MOLECULAR POTENTIALS

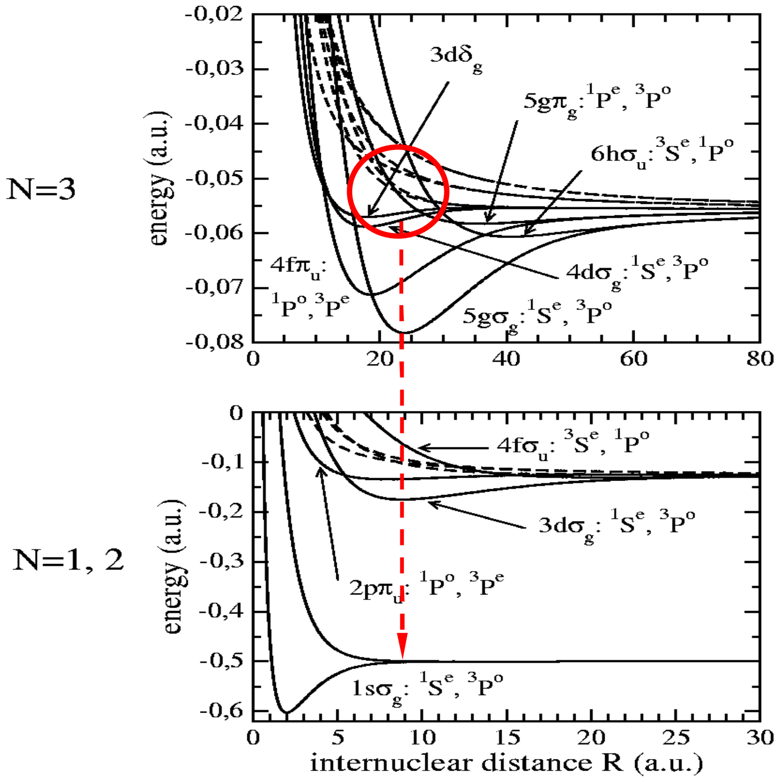
***known to exist from** muon-catalysed fusion, μH*

$$\pi p_{nl} + H_2 \rightarrow [(\pi pp)_{njv} \cdot p]\, ee_{Kv}$$

decay usually by Auger process

X-ray transitions from molecular states ?

rate ↔ collision probability (density) !



μH experiment

quenching of** μp_{2s} **via** [(μpp)p]ee **formation

R. Pohl et al., Hyp. Int. 138 (2001) 35

consequences for πH (np → 1s) transitions

$$E_X \rightarrow E_X - \Delta E \ ?$$

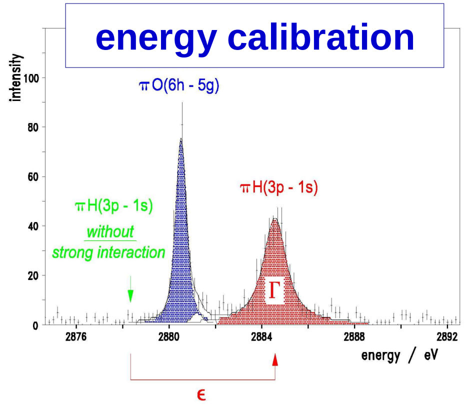
(how many) bound states below
dissociation limit of 4.5 eV ?

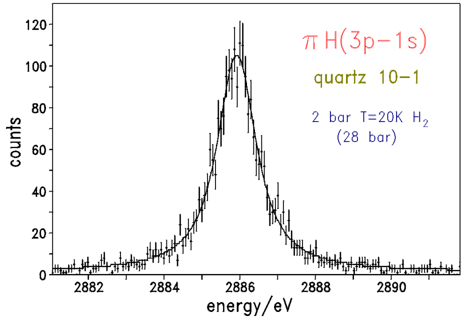
Jonsell, Froelich and Wallenius for n=1,2,3
Phys. Rev A 59 (1999) 3440

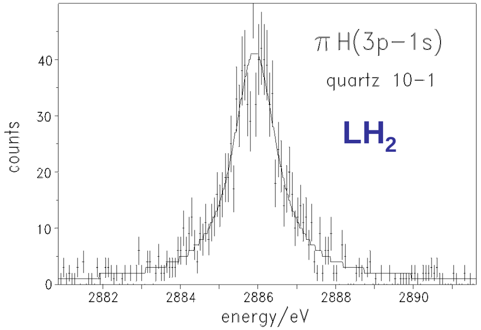
calculation	*ppμ*	*ddμ*
$\Gamma_{X\text{-}ray} / \Gamma_{total}$	≈ **0.03**	≈ **1**

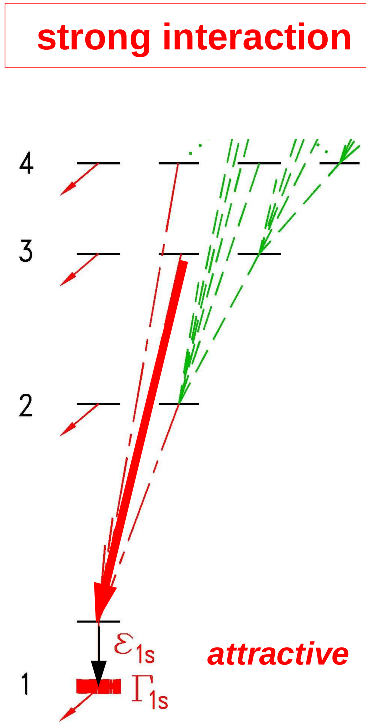
Lindroth, Wallenius and Jonsell
Phys. Rev A 68 (2003) 032502
Kilic, Karr and Hilico
Phys. Rev. A70 (2004) 042506

πH(3p-1s) energy density dependence - measurement









πH / πO mixture

(98%/2%)
1.2 bar @ T = 85K

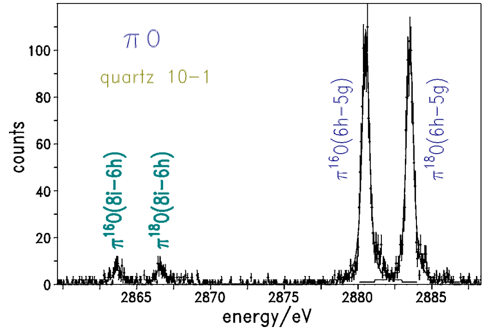
energy calibration simultanuously

πO

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

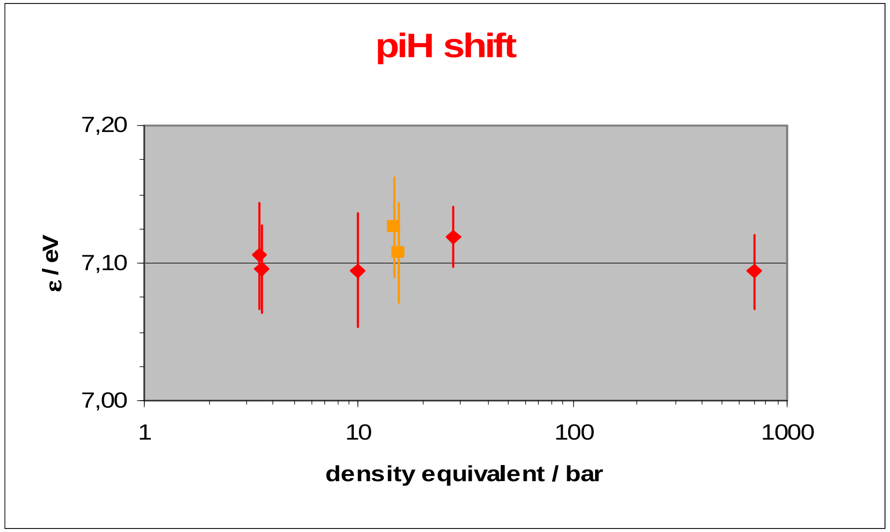
2 bar @ T = 86K

energy calibration/measurement alternating



πH(3p-1s) energy density dependence - result

***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

R-98.01

***Maik Hennebach,** thesis Cologne 2003*

ε_{1s} **= + 7.120 ± 0.008 ± 0.009 eV**

↓

mainly pion mass	ΔE_{QED} = ± 0.006 eV **!**
new calculation πH ⇒	ΔE_{QED} = ± 0.001 eV **!**
P. Indelicato, priv. comm.	

there is another final QED value since 2010!

not yet used here

ε_{1s} **= + 7.120 ± 0.008 ± 0.006 eV (± 0.2%)**

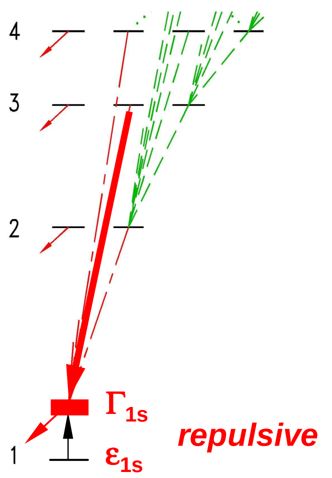
↑

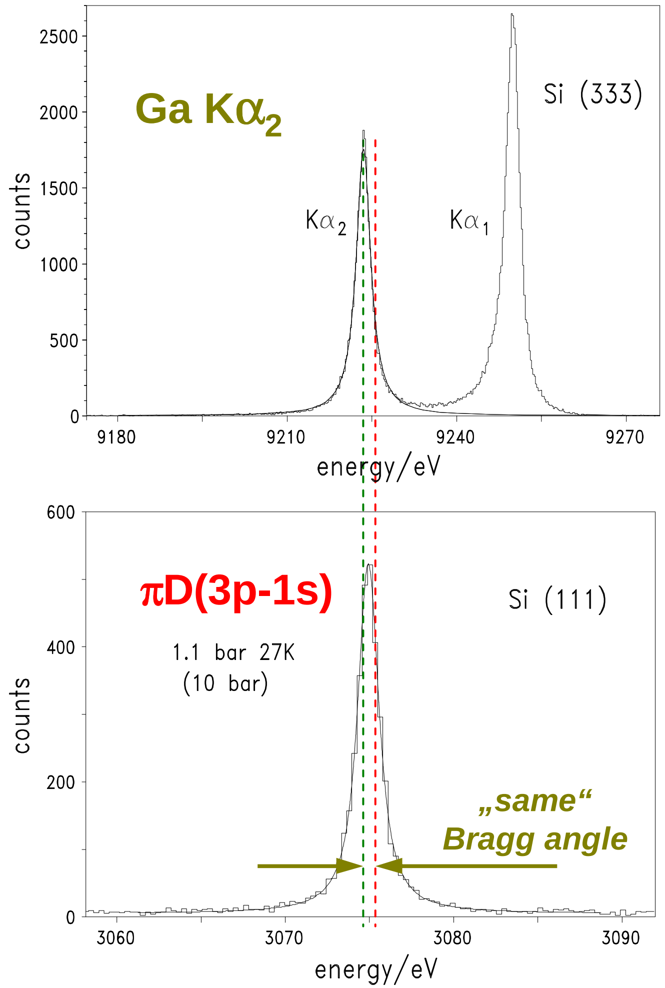
preliminary

PIONIC DEUTERIUM

energy calibration

strong interaction





T.Strauch, PhD thesis 2009 Univ. Cologne
T. Strauch et al., to be published

target material: GaAs

by chance: tabulated energy
<u>also</u> from GaAs
⇒ no chemical shift

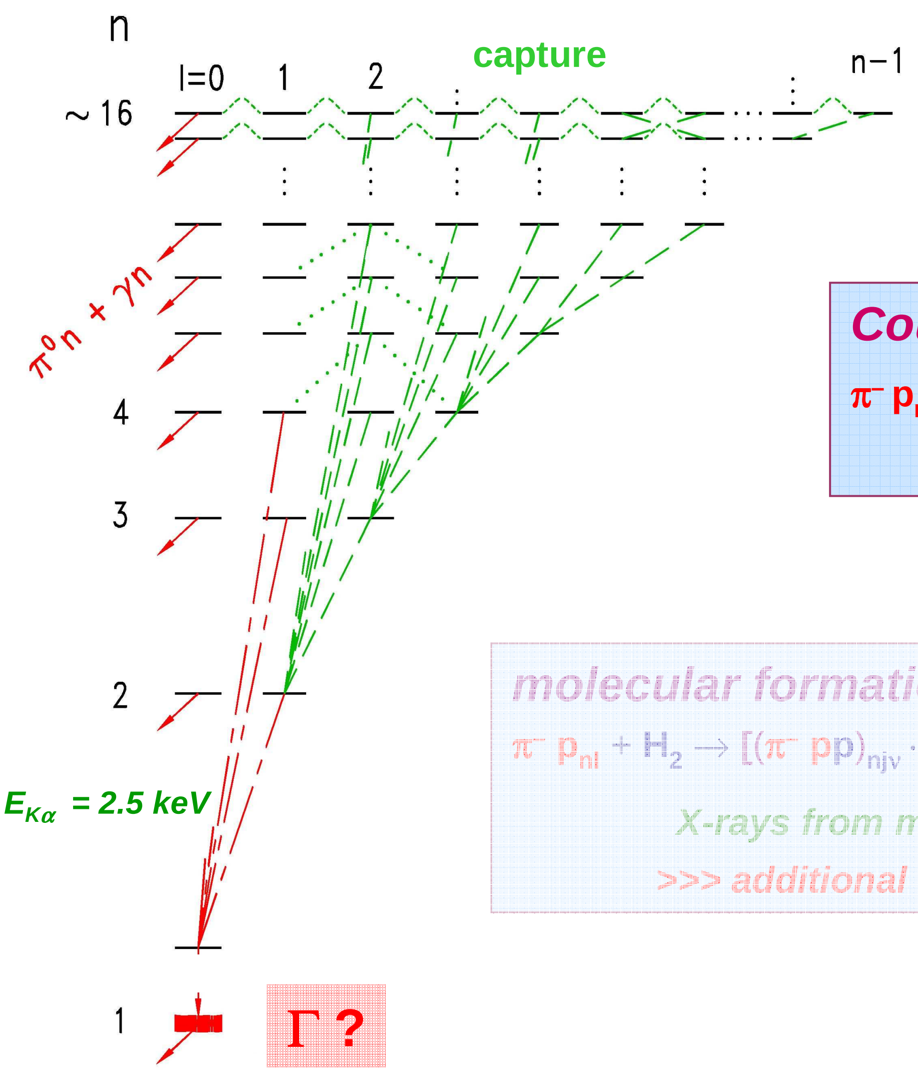
3 bar
10 bar
22 bar
} *no molecule formation seen*

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

uncertainties

- *27 meV Ga Kα_2*
- *10 meV statistics*
- *8 meV pion mass*
- *5 meV systematics*
- *2 meV QED*

πH - ATOMIC CASCADE II



density dependent

Coulomb de-excitation

$\pi^- p_{nl}$ + H=H → $\pi^- p_{n'l'}$ + H+H + ***kinetic energy***

>>> Doppler broadening ! <<<

molecular formation

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

X-rays from molecular states ?

>>> additional energy shift ? <<<

COULOMB DE-EXCITATION NEUTRON - TOF

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

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

↑

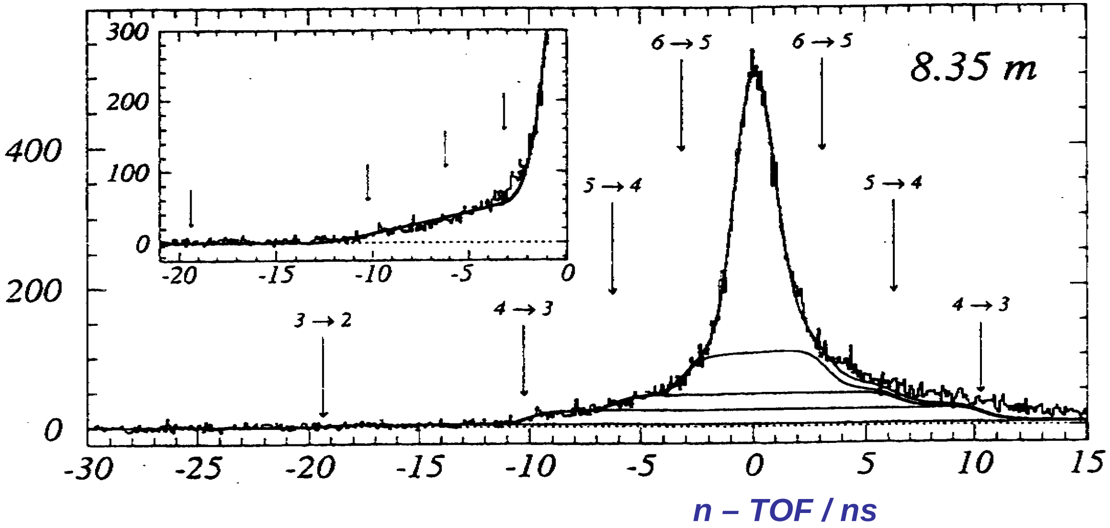
moving neutron source

analogue

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

↑

moving X-ray source

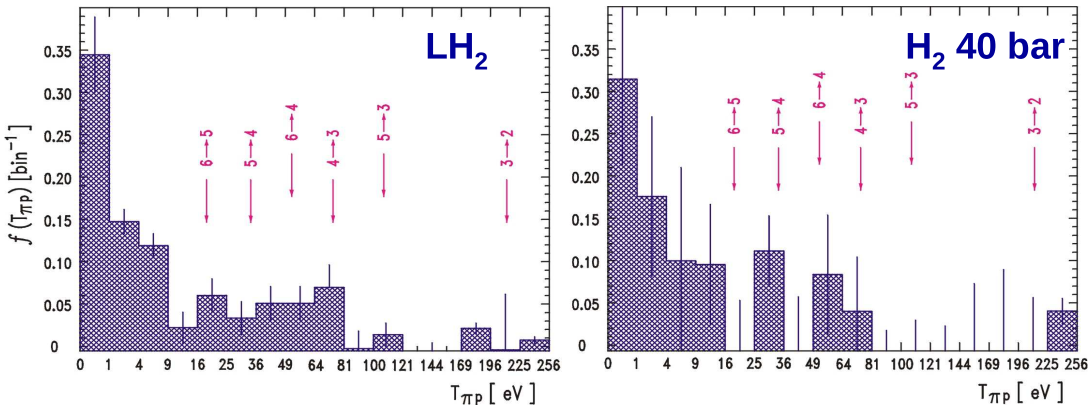


non-radiative transitions

⇓

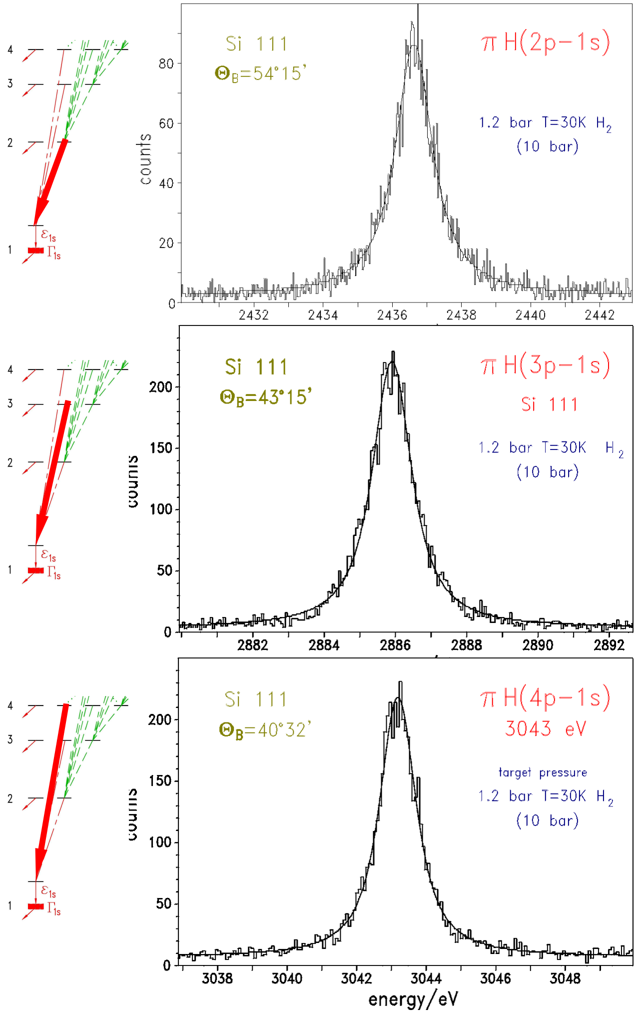
quasi-discrete velocity profile

Doppler broadening



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

LINE WIDTH and INITIAL STATE



***not* corrected**

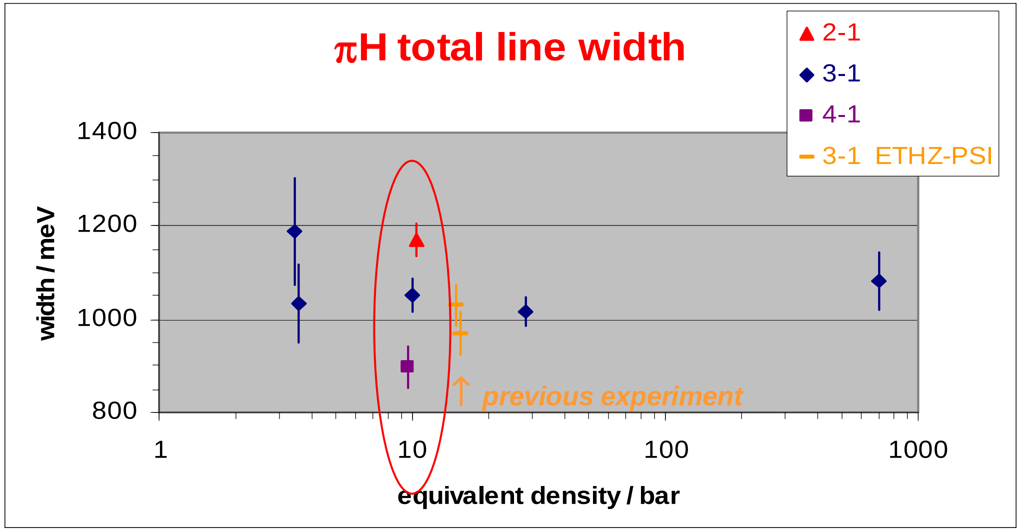
for

Coulomb de-excitation

crystal resolution

from πC / ECRIT

subtracted



remove Γ_{1s}

LINE SHAPE = R ⊗ ~~L~~ ⊗ Σ D

crystal *response*

~~Lorentzian Γ_{1s}~~

Doppler broadening *Coulomb de-excitation*

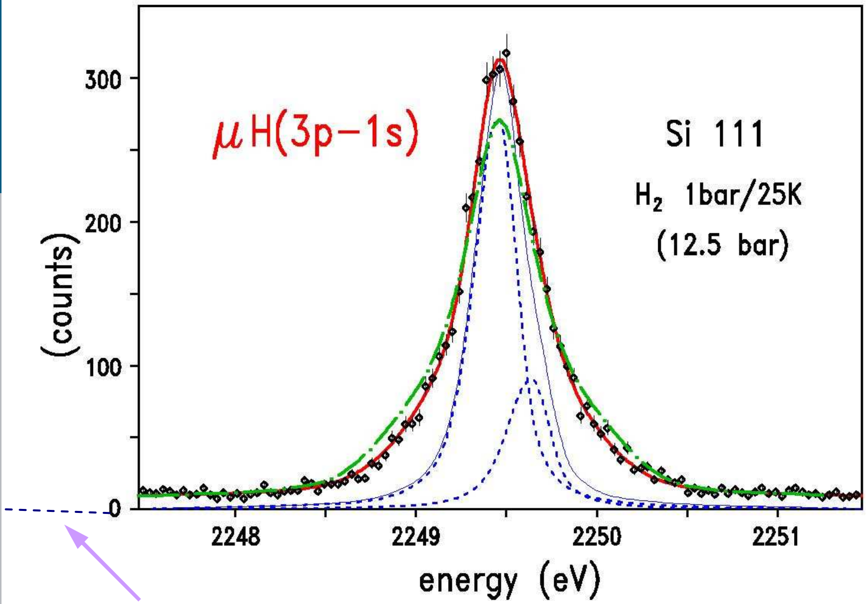
depends on initial state

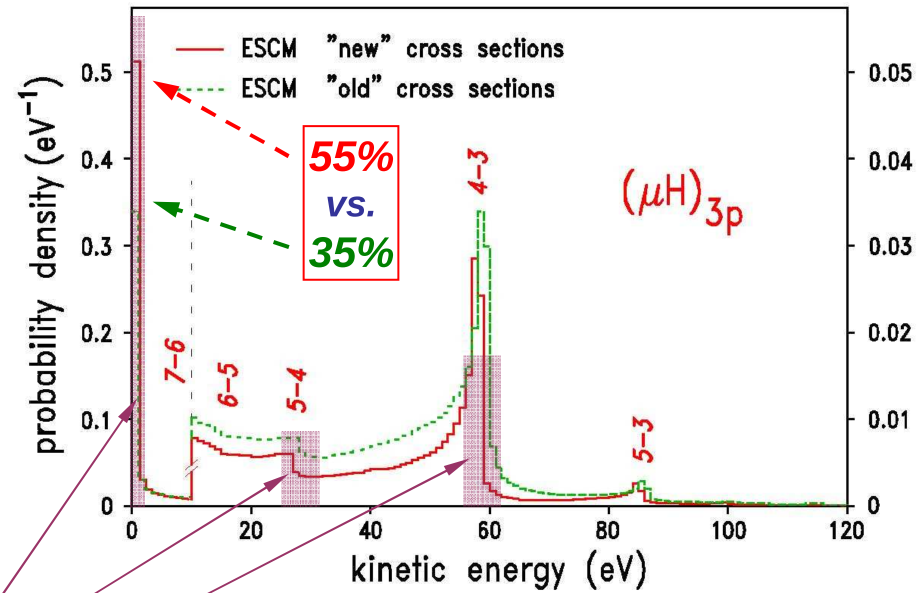
ECRIT

MUONIC HYDROGEN

CONSTRAINT from CASCADE CALCULATION ?

MUONIC HYDROGEN





no satellites from molecular formation identified

low-Tkin:	61 ± 2 %
medium-Tkin	25 ± 3 %
high-Tkin	14 ± 4 %

box fits = model free fit

triplet / singlet = 3.0 ± 0.3

ΔE= 183 meV (theory)

recalculation of cross sections

thesis: D. Civita, (Coimbra)
D.S. Covita et al., Phys. Rev. Lett. 102 (2009) 023401

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)
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 130, 341 (2006)
V.P. Popov and V.N. Pomerantsev, arXiv:0712.3111v1[nucl-th] (2007)

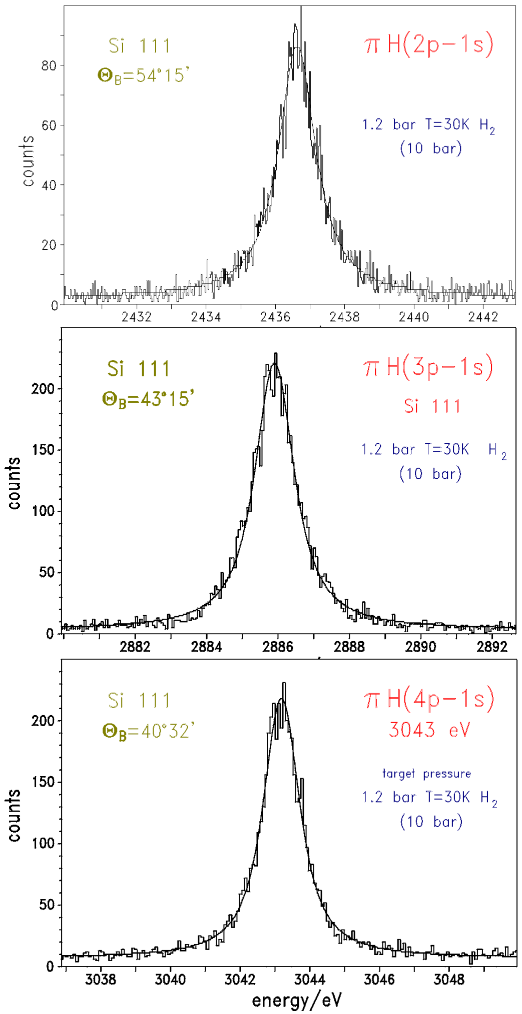
Γ_{1s}

LINE SHAPE = **R** ⊗ **L** ⊗ **Σ D**

crystal	**Lorentzian**	**Doppler broadening**
response	Γ_{1s}	***Coulomb de-excitation***
	↑	***depends on initial state***

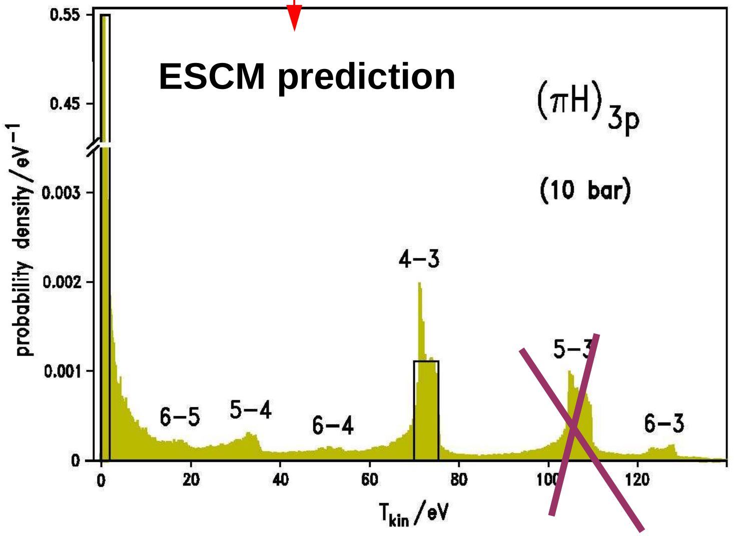
model free approach

"BOX" FITS



inconsistent

$\Gamma = \Gamma(np)$



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	*---*

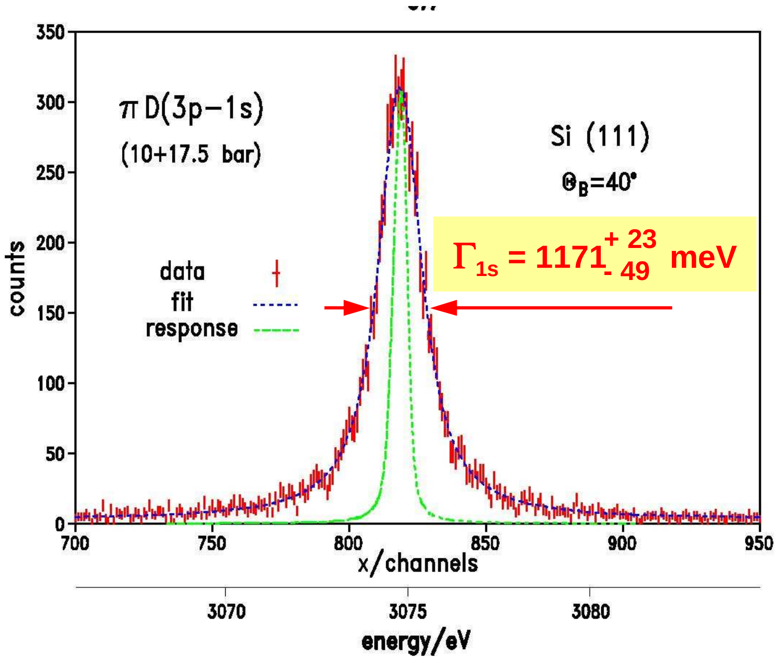
upper limit from 4p-1s

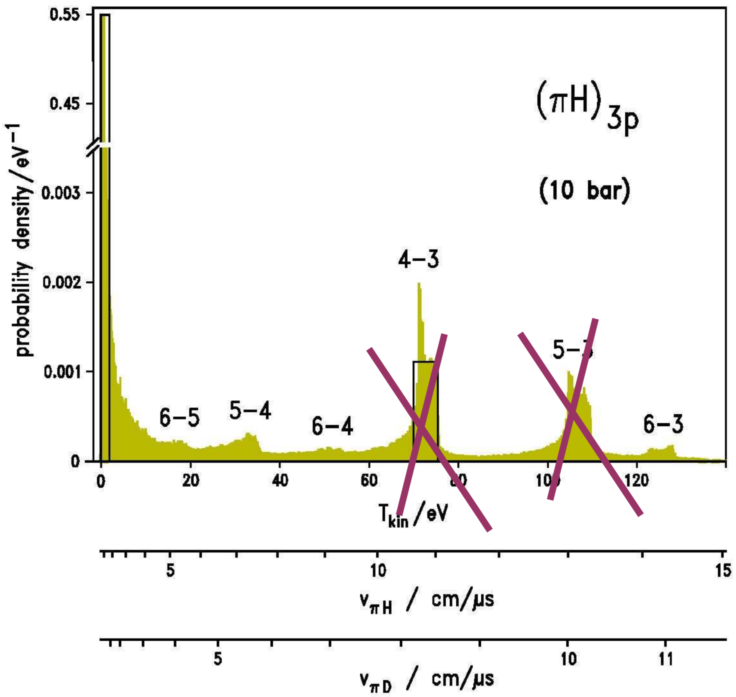
$\Gamma_{1s} \approx 800 \pm 40$ meV *(5%)*

limit without cascade theory

so far weighted average R-98.01 $\Gamma_{1s} \approx 823 \pm \approx 19$ meV *(≈2.3%)* *preliminary*

$\pi D \quad \Gamma_{1s}$





< 10%

High-energy components ?

SUMMARY

πN scattering lengths a^+ and $\tilde{a}$

Δ exp>>Δ theory - no f_1

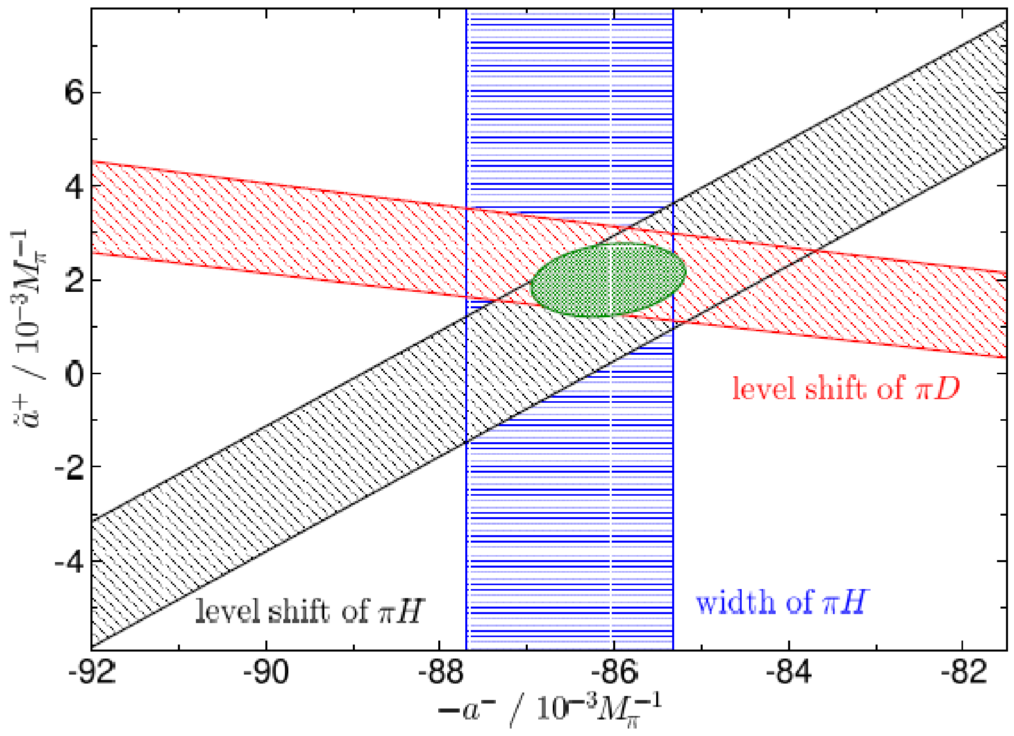


FIG. 2: Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energy shift of πH, as well as the πD energy shift.

Δ exp <<Δ theory - LEC f_1

Δ exp << Δ theory - LEC f_1

experimental input

πH	ε_{1s}, Γ_{1s}
πD	ε_{1s}

cPT: V. Baru, C. Hanhart, M. Hoferichter, B. Kubis, A. Nogga, and D. R. Phillips, to be published

data: R-98.01 (preliminary) and R-06.03 (final)

NN ⇔ πNN threshold parameter α

charge symmetry *detailed balance*

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

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

πD

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

direct from G

π production experiments

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

(the term $\beta\, C_1^2\, \eta^3$ is crossed out)

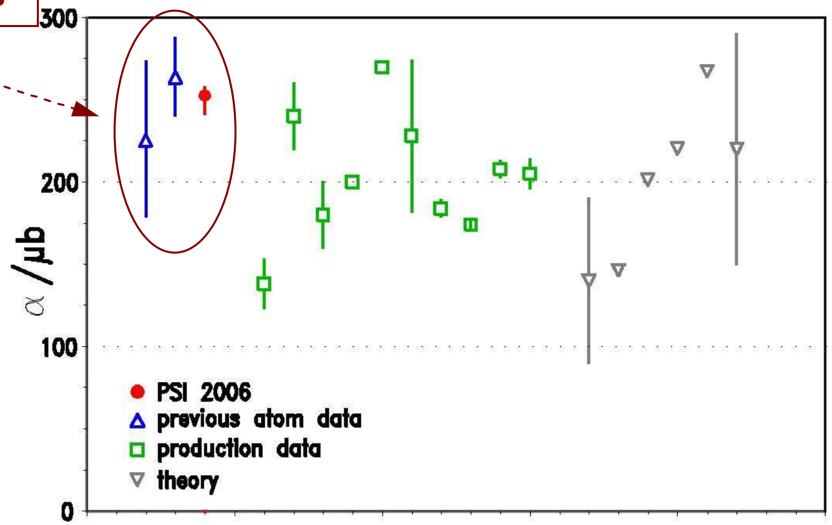
extrapolation to threshold

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

exotic-atom results

πD
Th. Strauch,
PhD thesis, Cologne 2009

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



χPT NLO

χPT LO

χPT

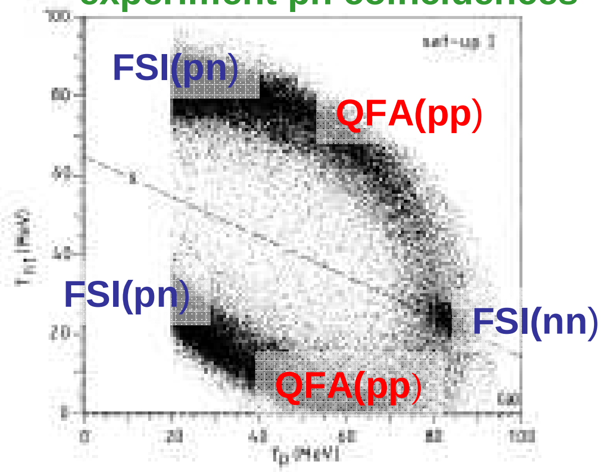
at present
Δα/α ≈ 30%

→ few %

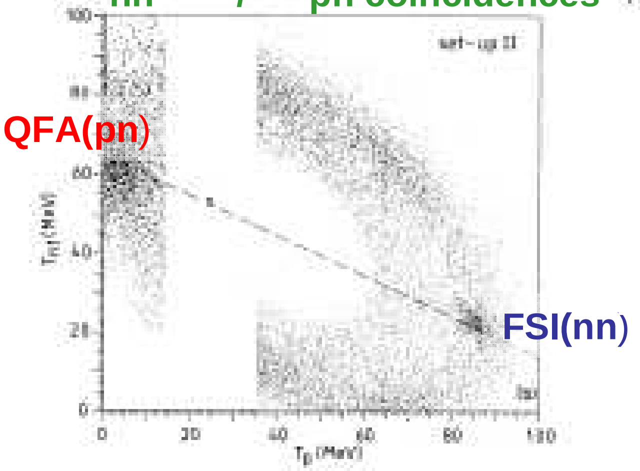
V. Lensky et al.,
Eur. Phys. J. A 27 (2006) 37

Dalitzplot $\pi^{-}\,{}^{3}He \rightarrow pnn$ *PSI R-73.07*

experiment pn coincidences



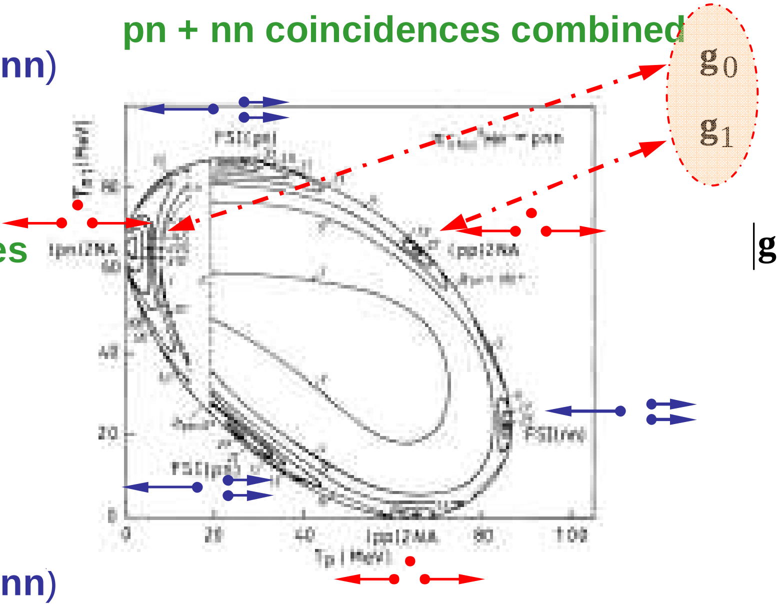
nn / pn coincidences



QFA quasi free reaction

FSI final state interaction

pn + nn coincidences combined



nn transitions

$$^{3}\mathbf{S}_1(\mathbf{I}=0) \rightarrow {}^{3}\mathbf{P}_1(\mathbf{I}=1)$$

$$^{1}\mathbf{S}_0(\mathbf{I}=1) \rightarrow {}^{3}\mathbf{P}_0(\mathbf{I}=1)$$

$$|\mathbf{g}_0/\mathbf{g}_1| = 2.48 \pm 0.24$$

$$\mathbf{g_0} \Leftrightarrow \alpha$$
$$\downarrow$$
$$\mathbf{g}_1$$

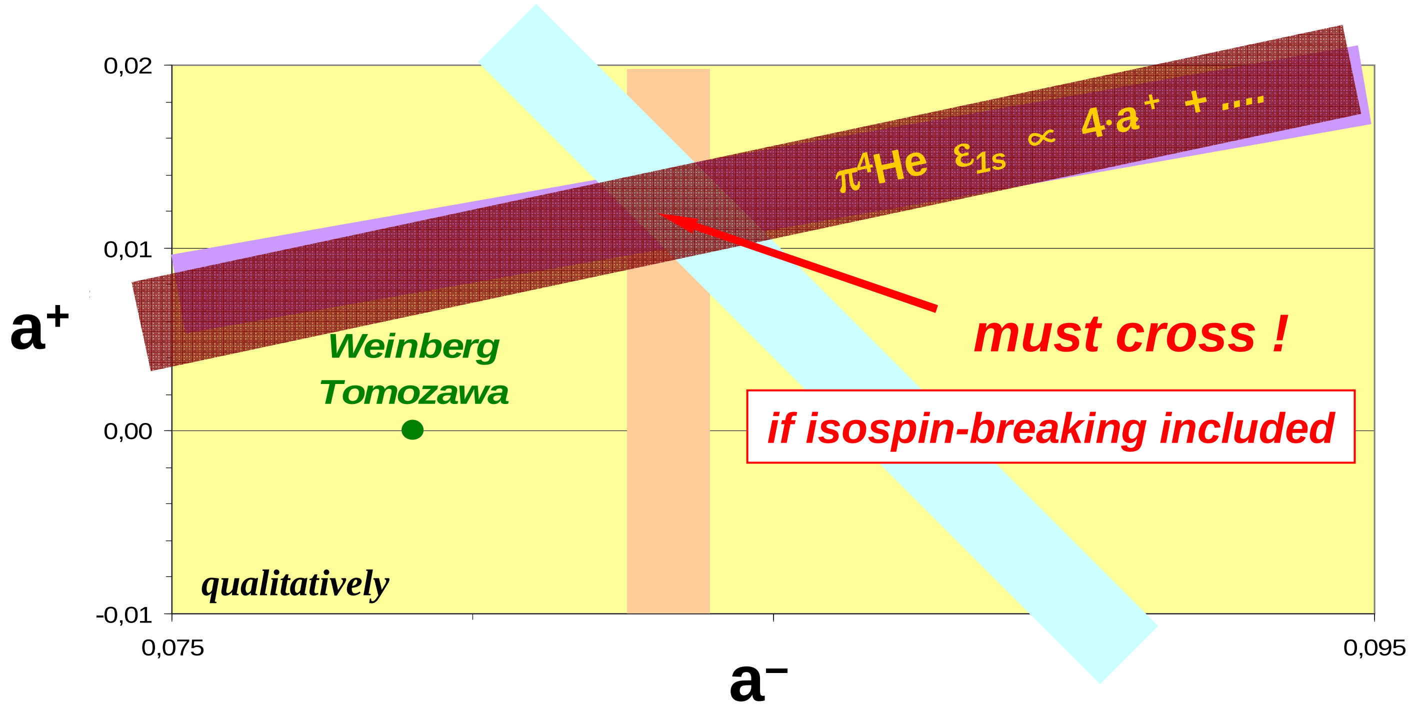
χPT?!

D.Gotta et al., Phys. Lett. 112B (1982) 129
D. Gotta et al., Phys. Rev. C 51 (1995) 469
E. Daum et al., Nucl. Phys. A 539 (1995) 553

PERSPECTIVES

NEW QUESTIONS

πA INTERACTION + ADDITIONAL ACCESS TO $a^{\pm}$

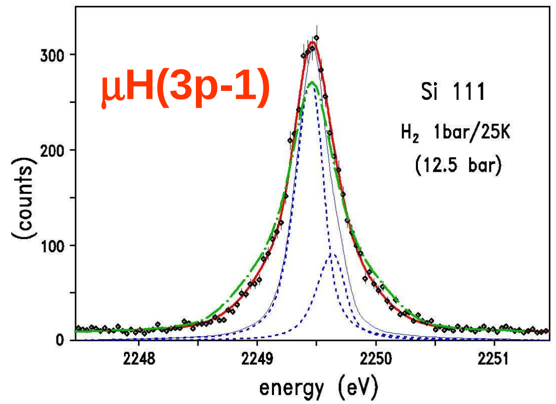


comparison I=1/2 nuclei ^{3}He / T

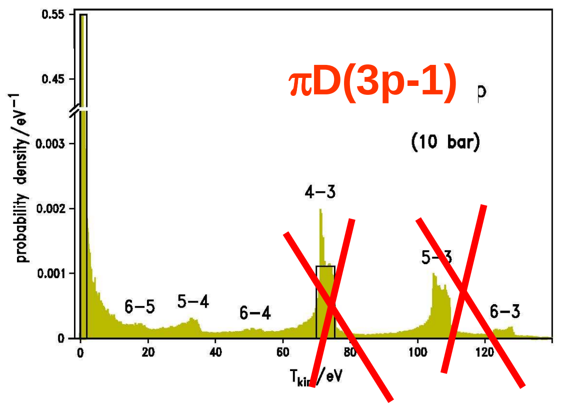
Theory — *C.Werntz and H. S.Valk, Phys. Rev. C 37, 724 (1988). G(pT) predicted from radiative capture pT□□nnn*
Baru, Haidenbauer, Hanhart, Niskanen, Eur. Phys. J. A 16 (2003) 437, T/3He comparison:
.... more coming

CASCADE or IS SOMETHING MISSING ?

? *X-ray satellites from molecular formation*



? *high-energy components*

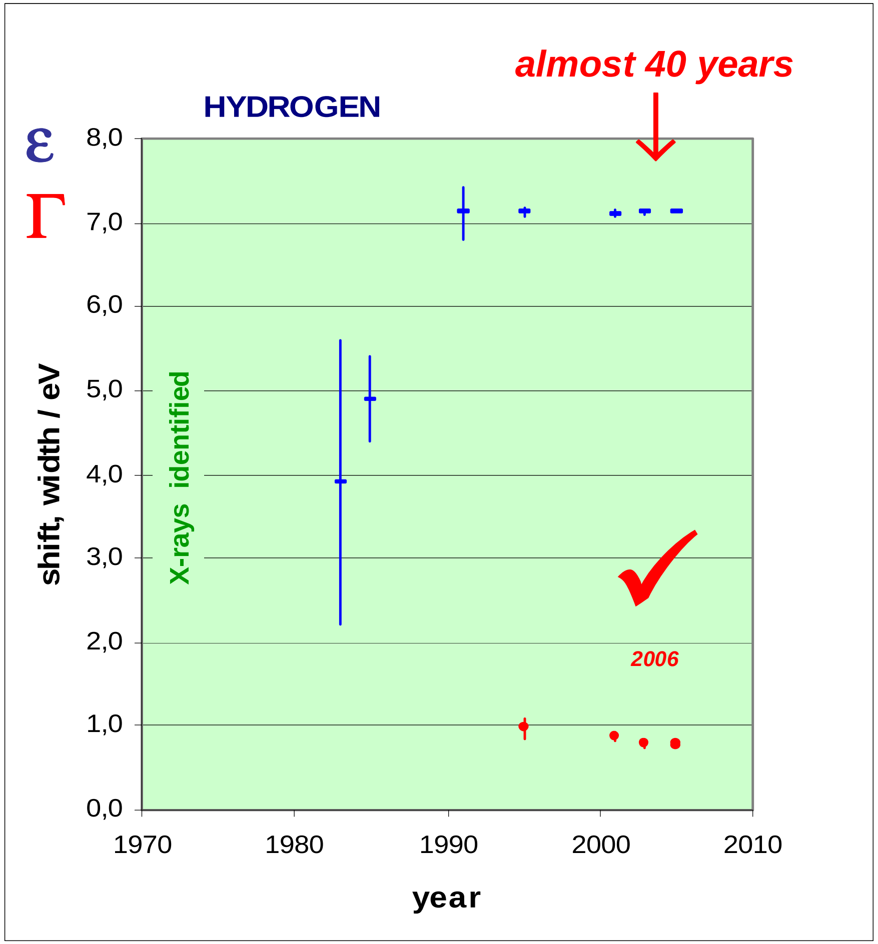


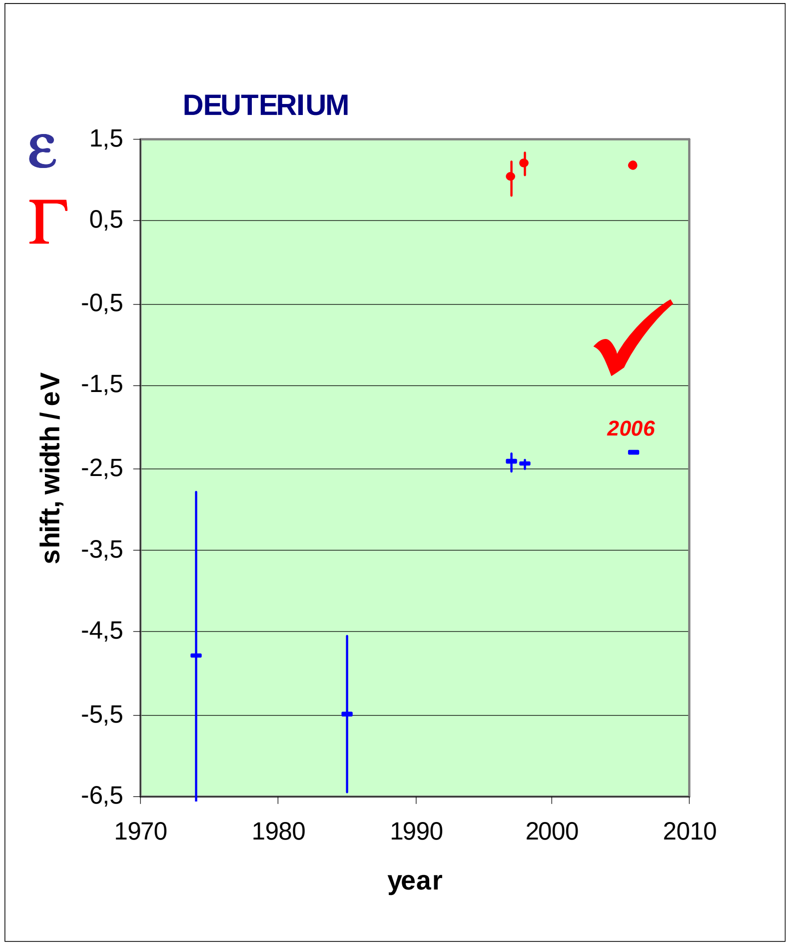
μD

? *does cascade theory improve for πH as for μH - if yes: $\Delta\Gamma \rightarrow \Delta\Gamma/2$*

cross sections

PIONIC HYDROGEN STORY





THANK YOU

PIONIC HYDROGEN collaboration

PSI experiments R-98.01 and R-06.03

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Cascade theory

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$\rightarrow$ ***Diploma and PhD thesis*** $\leftarrow$