PIONIC HYDROGEN

QED $\rightarrow$ low-energy QCD

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for the PIONIC HYDROGEN collaboration

Debrecen – Coimbra – Ioannina – Jülich – Paris – PSI – Vienna

PSI experiments R-98.01 and R-06.03

D. F. Anagnostopoulos, S. Biri, D. D. S. Covita, H. Gorke, D. Gotta, A. Gruber, M. Hennebach,
A. Hirtl, P. Indelicato,, T, Ishiwatari, Th. Jensen, E.-O. Le Bigot, J. Marton, M. Nekipelov,
J. M. F. dos Santos, S. Schlesser, Ph. Schmid, L. M. Simons, M. Trassinelli, J. F. C. A. Veloso, J. Zmeskal

PSAS 2006,Venice,16.6..2006

- **INTRODUCTION**

- **πN interaction and πH atoms**

- **EXPERIMENT**

- **OUTLOOK**

Approach to low-energy QCD

Lagrangian $\mathcal{L}_{QCD} = \sum_{\substack{f=u,d,s,\\ c,b,t}} \bar{\Psi}_f \left[i\gamma^{\mu}(\partial_{\mu} - ig \sum_{a=1}^{8} A_{\mu,a}) - m_f \right] \Psi_f - \frac{1}{4} \mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}$

color $SU(3): q_f = \begin{pmatrix} red \\ green \\ blue \end{pmatrix}$

light quarks u,d flavor SU(2)

or u,d,s " SU(3)

$\mathcal{G}_{\mu\nu,a} = \partial_{\mu}\mathcal{A}_{\nu,a} - \partial_{\nu}\mathcal{A}_{\mu,a} + gf_{abc}\mathcal{A}_{\mu,b}\mathcal{A}_{\nu,c}$

8 gauge fields $A_{\mu,a}$

self interacting gluon fields

$\alpha_{strong} \approx 1$: no perturbative solution

$\langle 0 | \partial A^{\mu} | \pi \rangle = f_{\pi} m_{\pi}^2 \neq 0$

axial vector <u>almost</u> conserved $(m_{\pi}/m_p)^2 = 0.02$

<u>partially</u> conserved axial current (PCAC)

conserved in the chiral limit $m_{\pi} \to 0$

f_{π} = 93 MeV $\neq 0$ pion decay constant

Chiral symmetry

$m_\pi \approx m_N / 7 \approx 0$ — at hadronic scale = 1 GeV/c^2

$\pi \to \mu\nu / e\nu$ — BR $\approx 1/10^{-4}$ — $m_q \approx 0$ fermions, (V-A) helicity suppression

no pion decay — $m_q = 0$ cannot change handedness (chirality)

left $\Leftarrow$ right $\Rightarrow$

N — acts as source for 0^- field quanta („π“)

QCD with „massless“ quarks: chiral symmetry

chiral limit $m_f = 0$

$\Rightarrow$ $\mathcal{L}$ chirally invariant left $\leftrightarrow$ right

$\Rightarrow$ „equal“ mass parity doublets of hadron states

expected	experiment
$\mathcal{M}(0^-) \approx \mathcal{M}(0^+)$	$\mathcal{M}(\pi, \mathcal{K} \eta) \ll \mathcal{M}(0^+)$
$\mathcal{M}(1^-) \approx \mathcal{M}(1^+)$	$\mathcal{M}(\rho, \omega, \mathcal{K}^*, \phi) \ll \mathcal{M}(1^+)$

<u>Explicit</u> (flavor) symmetry breaking

by finite (current) quark mass

$$\mathcal{L}_{\mathcal{M}} = -\overline{\Psi}\mathcal{M}\Psi = -\overline{\Psi}\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}\Psi$$

microscopic understanding of

PCAC

$$\partial_\mu A_a^\mu = i\,\overline{\Psi}_u\left\{\mathcal{M}, \frac{\lambda_a}{2}\right\}\gamma_5\Psi_d \quad \neq \quad 0$$

$$\partial_\mu(A_1^\mu + iA_2^\mu) = (m_u + m_d)\overline{\Psi}_u i\gamma_5\Psi_d$$

$m_u \approx m_d \approx 1\%\ m_\pi$

$m_s \approx m_\pi$

symmetry re-established for m $\longrightarrow$ 0

perturbative treatment

does <u>not</u> produce $\mathcal{M}(0^-)$, $\mathcal{M}(1^-)$ << $\mathcal{M}(0^+)$, $\mathcal{M}(1^+)$

Hadron masses ?

How to get the quarks dressed ?

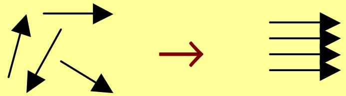
Spontaneous symmetry breaking

Back to chiral limit $m_{quark} = 0$

Spontaneously broken (hidden) symmetry: no 0^+ „ground“ state

Symmetry of $\mathcal{L}$ does not appear for ground state

example: Ferromagnetism



$\Rightarrow$ ***QCD vacuum populated by scalar $q\bar{q}$ pairs***

chiral condensate $\langle \bar{q}_f q_f \rangle \neq 0$

$\Rightarrow$ ***Quarks acquire dynamical (momentum dependent) mass***

non-perturbative (traditionally: constituent quarks)

$$m_\pi^2 = \frac{1}{2 f_\pi^2}(m_u + m_d)\langle u\bar{u} + d\bar{d}\rangle + higher\ orders, \quad m_K^2 = \ldots, \quad m_\eta^2 = \ldots$$

Gell-Mann-Oakes-Renner relations

$\Rightarrow$ ***SU(n=3): $\exists$ (n^2-1) (massless) Goldstone bosons***

identified with 0^- meson octet (finite mass from explicit symmetry breaking $m_q \neq 0$)

Chiral perturbation theory

Effective field theory

- *replace quark by Goldstone boson fields* — *SU(2): 3 pion fields π*
- $\mathcal{L}_{quark\text{-}gluon} \to \mathcal{L}_{eff}(\pi, \partial\pi, \partial^2\pi, \ldots)$ — *Weinberg 1979, Leutwyler, ...*
- $\mathcal{L}_{eff} = \mathcal{L}^0_{eff} + \mathcal{L}^1_{eff} + \mathcal{L}^2_{eff} + \ldots$ — *low-energy expansion in orders of*
- *parameters*
  - *quark mass differences* — $(m_d - m_u), (m_s - m_u), \ldots$
  - *momenta* — q
  - *fine structure constant* — α
- *short range behavior* $\to$ low-energy constants (LECs) *from experiment*

$\Rightarrow$ ***Low energy theorems*** *leading order of current algebra*

- $\pi\pi$ scattering $\xrightarrow{m_q \to 0}$ 0 — *(Goldstone-)Boson - (Goldstone-)Boson interaction*
- πN scattering

$$f^2_{\pi N} = \frac{m_\pi}{4}\frac{g_A^2}{f_\pi^2}$$

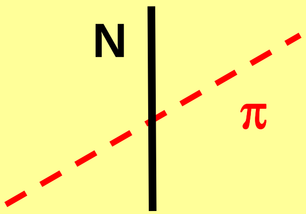
LO ChiPT: Goldberger-Treiman relation

relates strong πN coupling
nuclear β-decay (g_A)
weak pion decay

Low-energy πN *INTERACTION*

πN scattering lengths a

isospin $1 \otimes 1/2 = 1/2 \oplus 3/2$



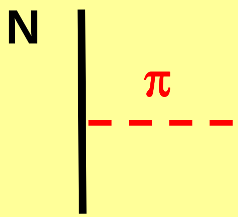
at threshold — ***2 real numbers, e.g.*** $a^{\pm}$ ***(combinations of*** $a_{1/2}$ ***&*** $a_{3/2}$***)***

chiral limit $a^{+} \equiv 0$

$$a^{-} = m_\pi / 2f_\pi = -0.079 / m_\pi$$

πN coupling constant

$$a^{-} \Leftrightarrow f^{2}_{\pi N}$$



Goldberger- Miyazawa-Oehme (GMO) sum rule

πN sigma term

$$a^{+} \Leftrightarrow \sigma_N = \frac{m_u + m_d}{4M} \langle p | \bar{u}u + \bar{d}d | p \rangle$$

measures — ***explicit chiral symmetry breaking***

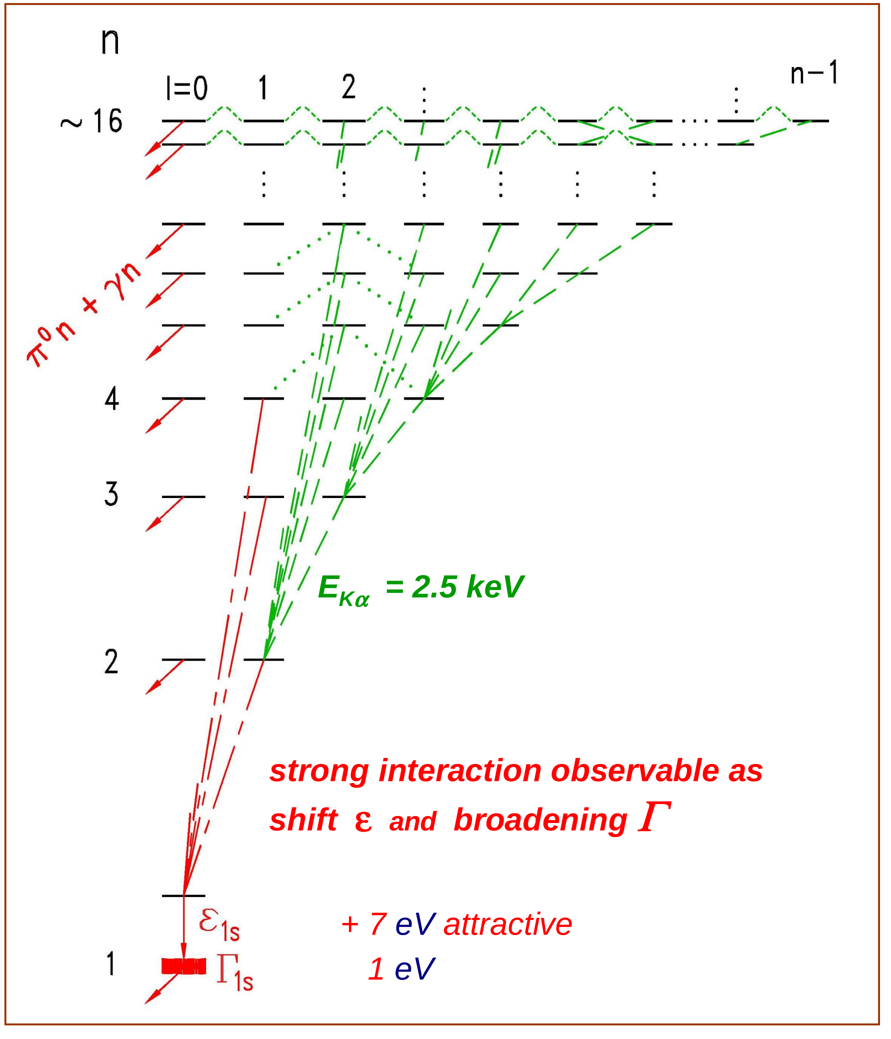
$\langle p | \bar{s}s | p \rangle$ ***contribution to the nucleon mass***

χPT THEORY

LABORATORY

πN interaction and πH atoms

PIONIC HYDROGEN - πN scattering at „rest“



2 isospin scattering length

$a^{\pm} = a_{\pi^- p\to\pi^- p} \pm a_{\pi^+ p\to\pi^+ p}$

isospin invariance: $m_u = m_d$

$a_{\pi^- p\to\pi^- p} + a_{\pi^+ p\to\pi^+ p} = -\sqrt{2}\; a_{\pi^- p\to\pi^0 n}$

THEORY

$\varepsilon_{1s} \propto a_{\pi^- p\to\pi^- p}$

$\propto (a^{+} + a^{-})\cdot(1+\delta_{\varepsilon})$

$\Gamma_{1s} \propto (1+1/P)\cdot(a_{\pi^- p\to\pi^0 n})^2$

$\propto (1+1/P)\cdot(a^{-}(1+\delta_{\Gamma}))^2$

PANOFSKY ratio P

$\pi^- p\to\pi^0 n / \pi^- p\to\gamma n = 1.546 \pm 0.009$

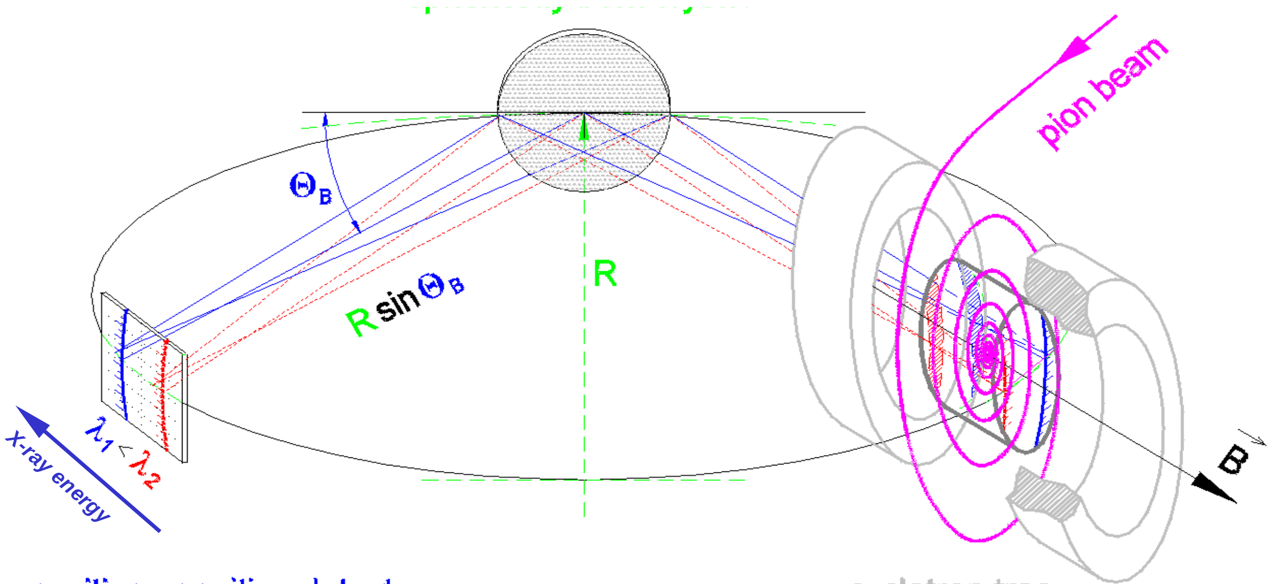
J. Spuller et al., Phys. Lett. 67 B (1977) 479

EXPERIMENT

Principle Set-up

ultimate energy resolution

spherically bent Bragg crystal



position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

position & energy resolution

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

high stop density

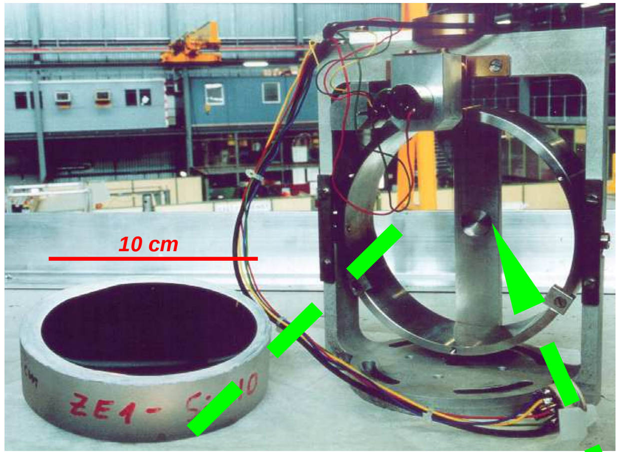
⇒ **high X - ray line yields**

⇒ **bright X - ray source**

Spherically curved Bragg crystal

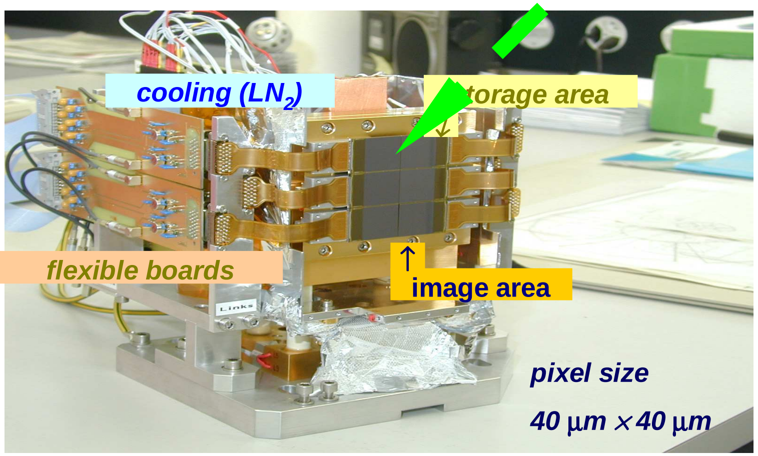
silicon 111
or
quartz 10-1

R = 3 m



Large - Area Focal Plane Detector

2×3 array of 24 mm $\times$ 24 mm devices



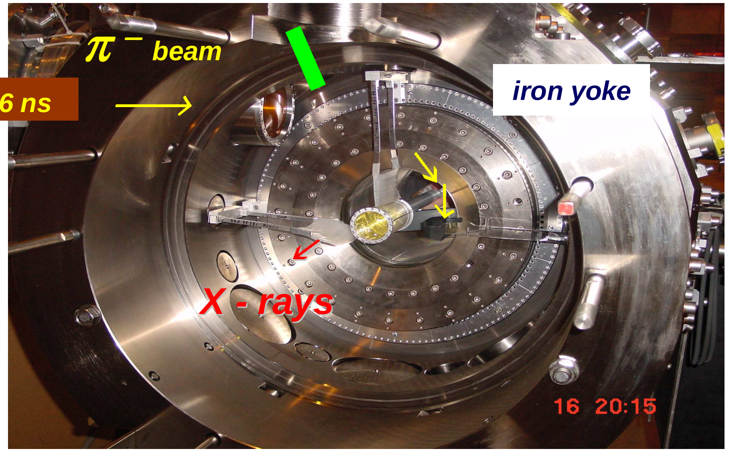
N. Nelms et al., Nucl. Instr. Meth 484 (2002) 419

CYCLOTRON TRAP second coil removed

π^- stop efficiency 1% / bar

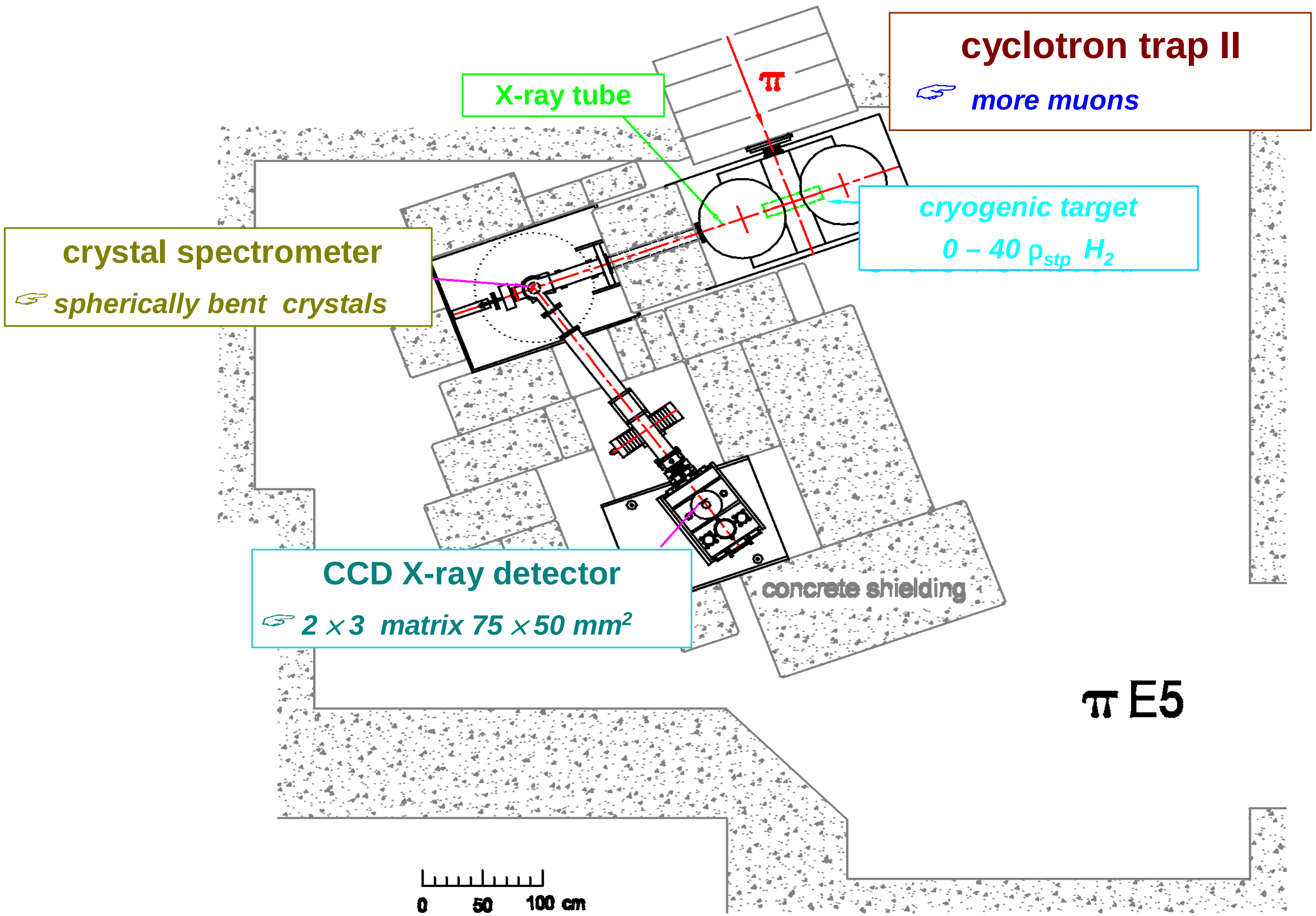
10^9 π/s

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



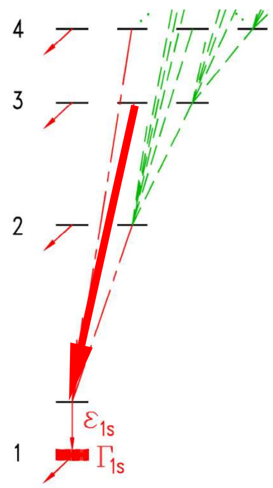
L. M. Simons, Hyperfine Interactions 81 (1993) 253

SET-UP with concrete shielding at PSI



ε_{1s}

$\pi H(3p - 1s)$ *transition energy*



density dependence ?

MOLECULAR FORMATION

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

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

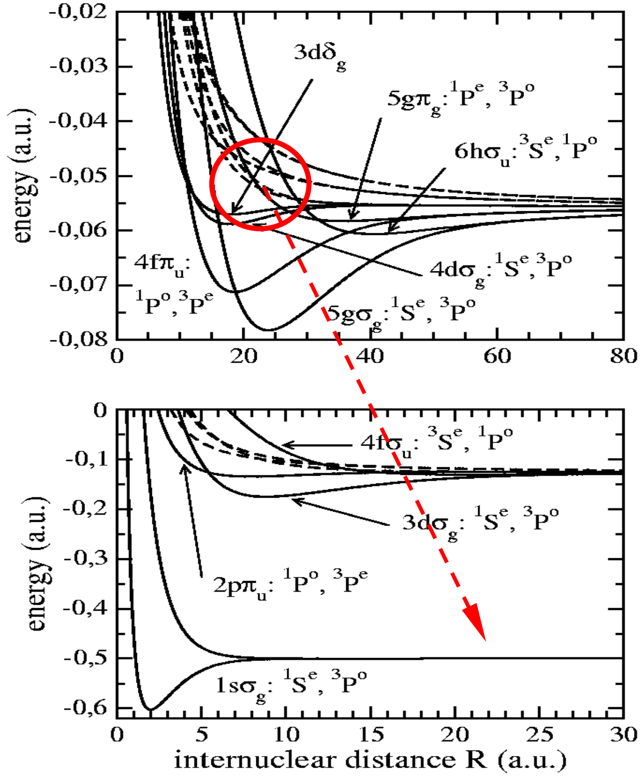
decay usually by Auger process

X-ray transitions from molecular states ?

rate $\leftrightarrow$ collision probability (density) !

N=3

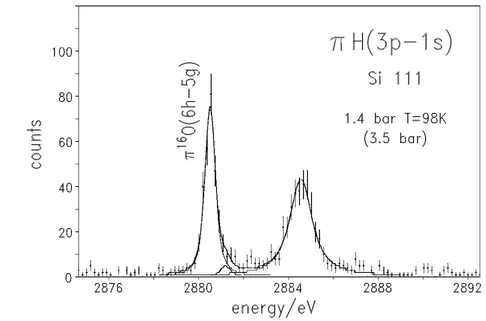
N=1, 2



DENSITY VARIATION 3.5 -700 bar

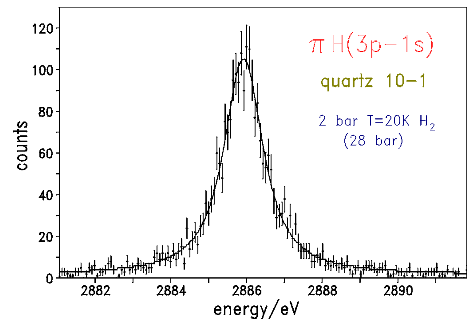
energy calibration πO(6h-5g)

$$E_{QED} = 2880.506 \pm 0.001 \text{ eV}$$



πH / πO

simultaneously

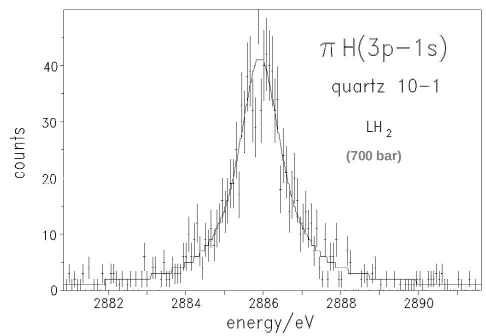


alternately πH / πO

mixture ^4He / $^{16}O_2$ / $^{18}O_2$

(≈ 80%/10%/10%)

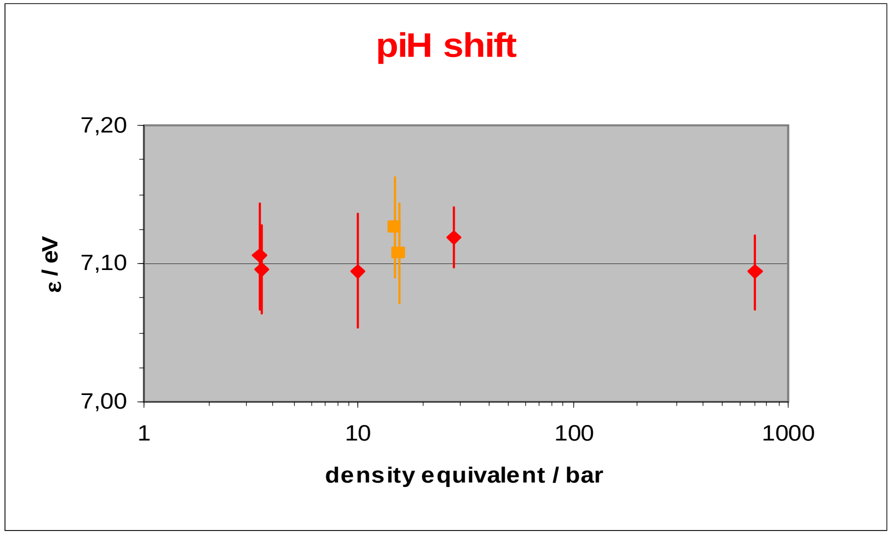
2 bar @ T = 86K



πH(3p-1s) energy

no ***density dependence identified***

$\Rightarrow$ "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 $\pm$ 0.008 $\pm$ 0.009 eV

ΔE_{QED} = ± 0.006 eV **!**

new calculation πH $\Rightarrow$ ΔE_{QED} = ± 0.001 eV **!**

P. Indelicato, priv. comm.

ε_{1s} = + 7.120 $\pm$ 0.008 $\pm$ 0.006 eV ($\pm$ 0.2%)

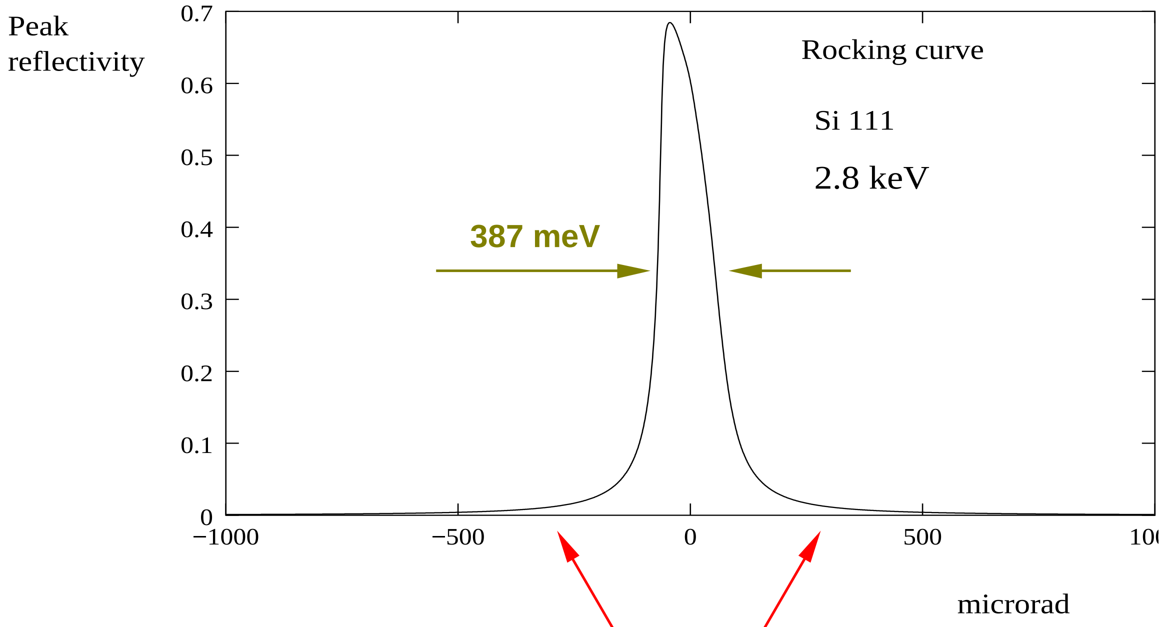
Γ_{1s}

LINE SHAPE = **R** $\otimes$ **L** $\otimes$ **Σ D**

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

How to extract ?

CRYSTAL RESOLUTION



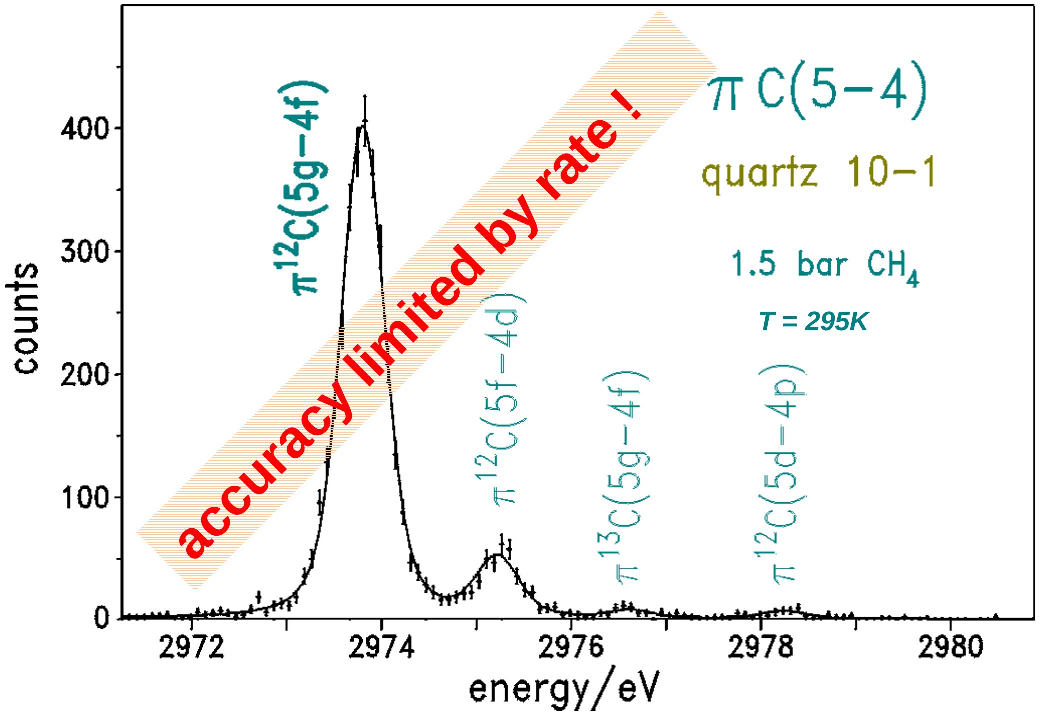
diffraction theory

XOP2 code
plane crystal

similar to a Lorentzian in the tails

no narrow lines in the few keV range from radioactive sources

Pionic carbon

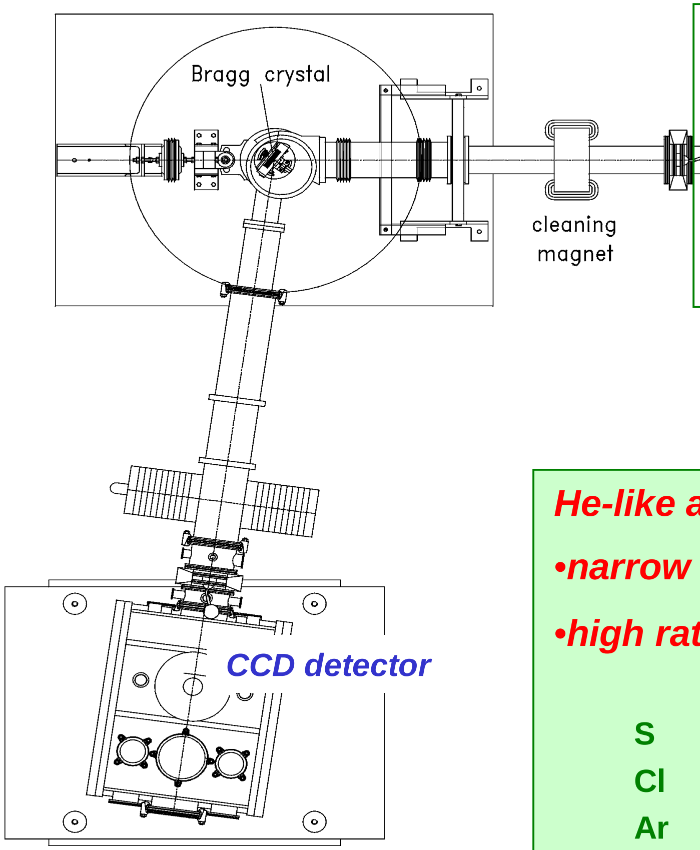


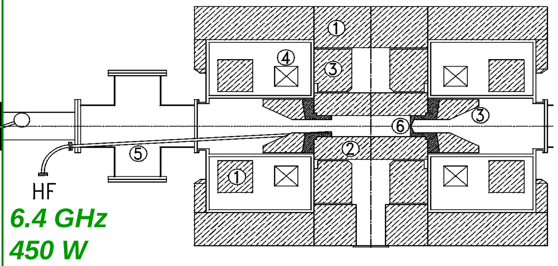
3500 events

70 h

closest to energy of πH(4p-1s)

new approach **Electron Cyclotron Resonance Ion Trap (ECRIT)**





ECRIT

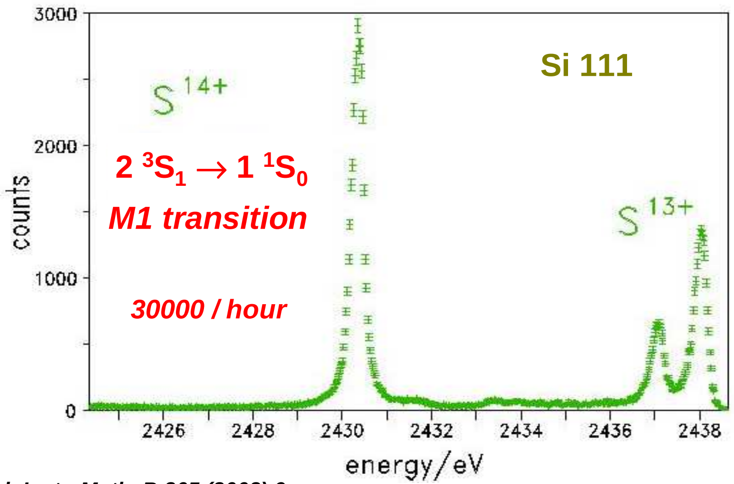
- ***= cyclotron trap (4)***
- ***+ hexapole magnet (2)***
- ***+ high frquency (5)***

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

He-like atoms

- ***narrow few keV X-rays***
- ***high rate***

S	↔	πH(2p-1s)
Cl	↔	πH(3p-1s)
Ar	↔	πH(4p-1s)



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

COULOMB DE-EXCITATION

LINE SHAPE = $R \otimes \cancel{L} \otimes \Sigma D$

crystal	~~Lorentzian~~	Doppler broadening
resolution	$\cancel{\Gamma_{1s}}$	*Coulomb de-excitation*

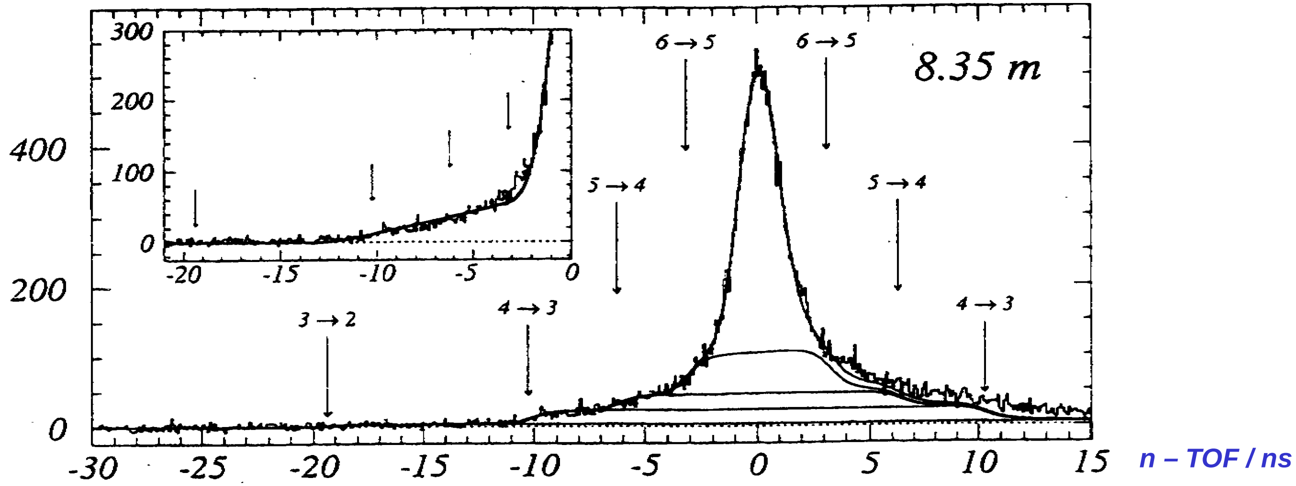
MUONIC HYDROGEN

COULOMB DE-EXCITATION *NEUTRON - TOF*

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

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

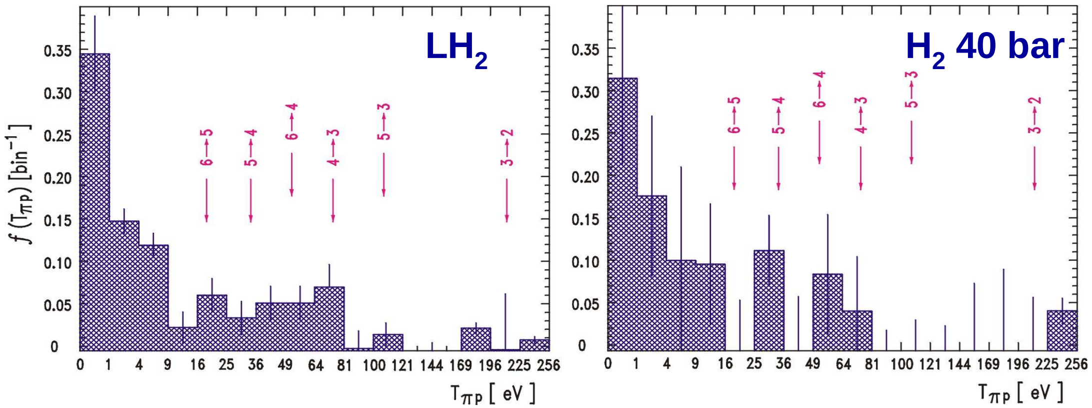
moving neutron source



non-radiative transitions

$\Downarrow$

quasi-discrete velocity profile



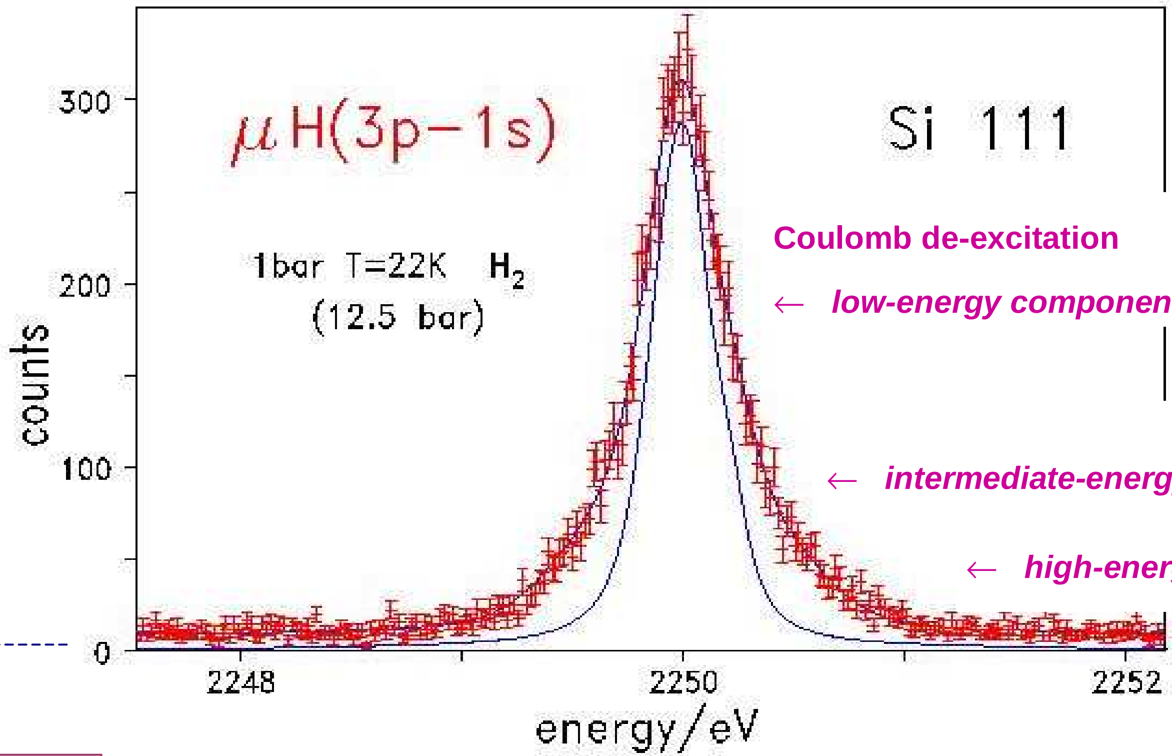
A. Badertscher et al., Eur. Phys. Lett. 54 (2001) 313

COULOMB DE-EXCITATION X - RAYS

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

↑

moving X-ray source



Coulomb de-excitation

← *low-energy component*

← *intermediate-energy component*

← *high-energy component*

no satellites from molecular formation identified

↑

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

Lindroth, Wallenius and Jonsell
Phys. Rev A 68 (2003) 032502

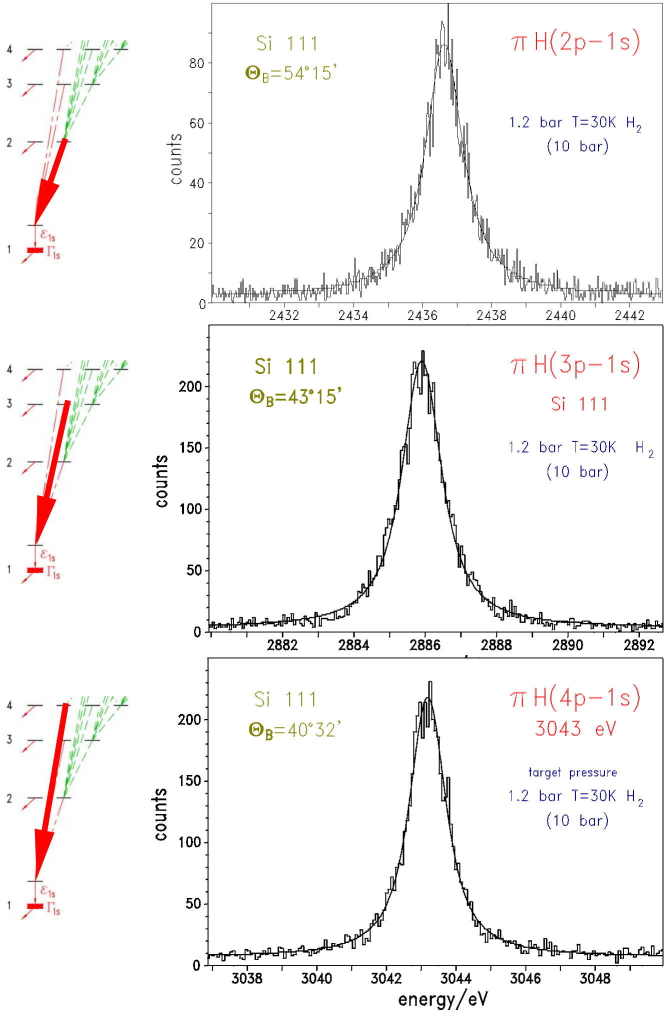
Kilic, Karr and Hilico
Phys. Rev A 70 (2004) 042506

----- *crystal response ECRIT 2004*

triplet / singlet = 3.0 ± 0.2

ΔE= 182 meV

LINE WIDTH and INITIAL STATE



__not__ corrected

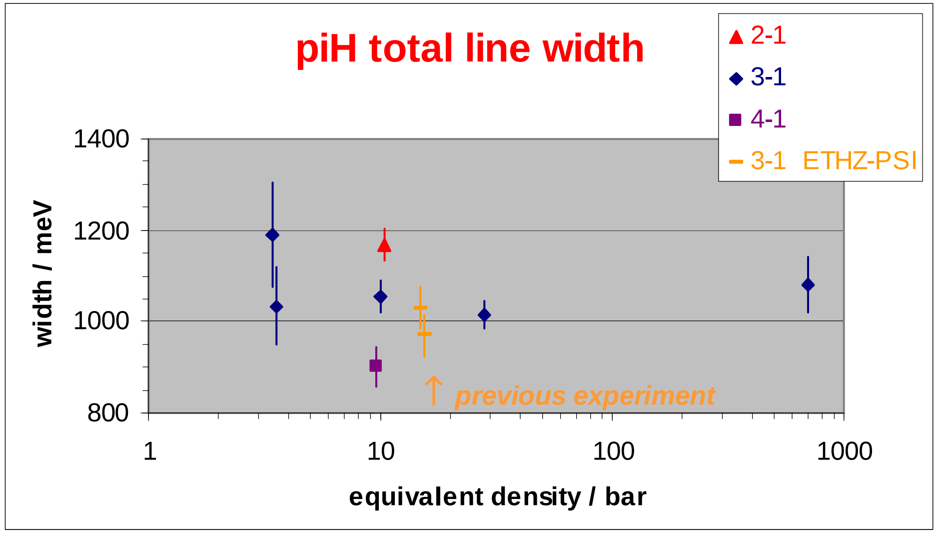
for

Coulomb de-excitation

crystal resolution

from πC / ECRIT

subtracted



Γ_{1s} < 850 meV

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

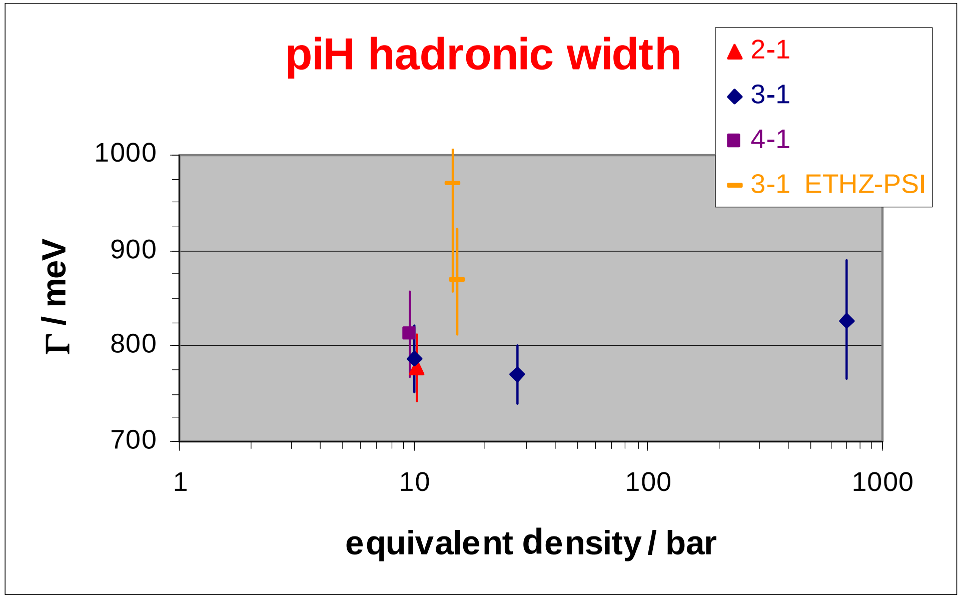
2001 and 2002 πH data + *ECRIT*

previous experiment

$\Gamma_{1s} \approx$ **865 ± 69 meV (8%)**

→

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



Fit to boxes from Coulomb de-excitation

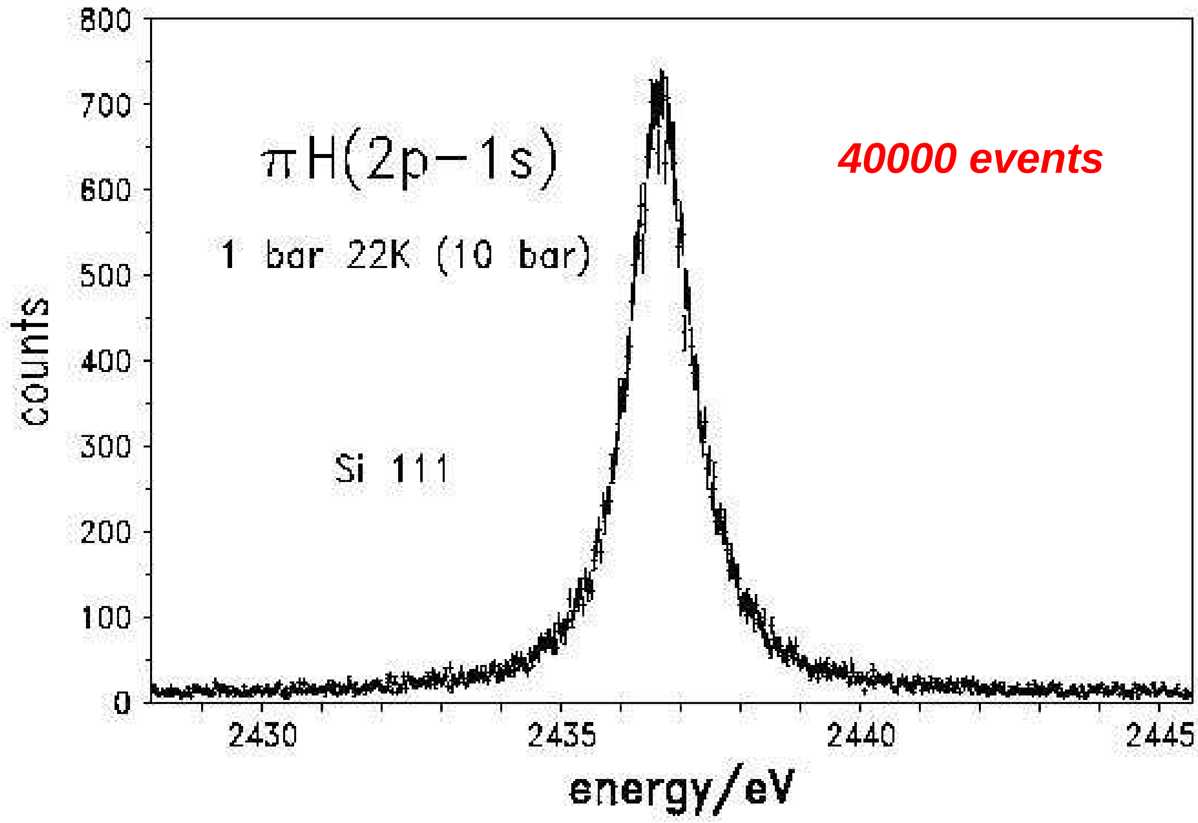
and

ECRIT 2002 crystal resolution subtracted

R-98.01 $\Gamma_{1s} \approx$ **823 ± 19 meV *(3.5%)*** *preliminary*

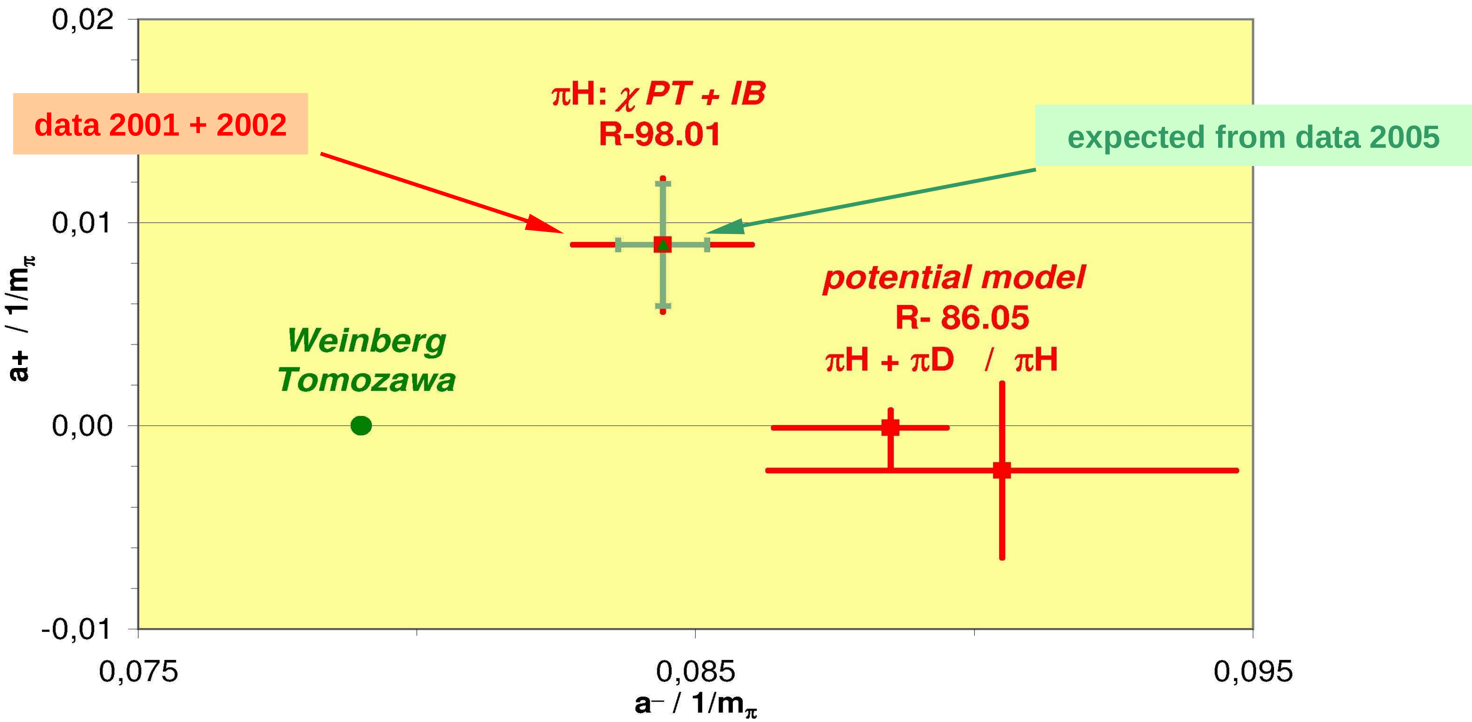
High Statistics Measurement - analysis still going on

September-October 2005



expected $\Delta\Gamma_{1s} / \Gamma_{1s} \approx 1.5\%$

πN scattering lengths $a^{\pm}(\pi H)$



$\varepsilon_{1s} \quad \propto \; [\, a^{+} + a^{-}]\,(1 + \delta_{\varepsilon})$ $\qquad \delta_{\varepsilon} = -7.2 \pm 2.9\,\%$ *J. Gasser et al., Eur. Phys. J. C 26 (2003) 13*

$\pm 1.9\,\%$ *from LEC f_1*

$\Gamma_{1s} \quad \propto \; [\, a^{-}\,(1 + \delta_{\Gamma})\,]^{2}$ $\qquad \delta_{\Gamma} = +0.6 \pm 0.2\,\%$ *P. Zemp, thesis University of Bern 2004*

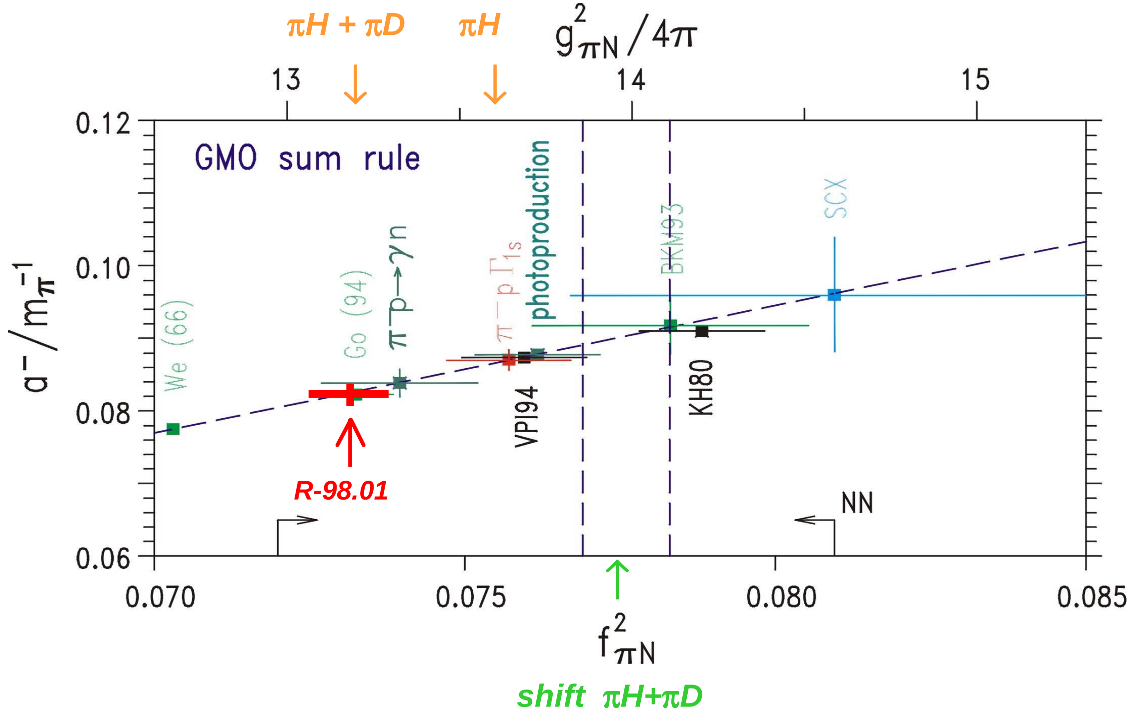
χPT 3rd order $\qquad$ *LECs c_1, f_1, f_2 (2nd order)*

πN coupling constant $f^2_{\pi N}$

Goldberger- Miyazawa-Oehme
(GMO)
sum rule

$$\left(1+\frac{m_\pi}{M}\right)\frac{a^-}{m_\pi} = \frac{2f^2_{\pi N}}{m^2_\pi-(m^2_\pi/2M)^2} + \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma^{tot}_{\pi^- p}(k_\pi)-\sigma^{tot}_{\pi^+ p}(k_\pi)}{2\omega(k_\pi)}dk_\pi$$

$\Delta\int \approx 1\%$



↓ previous experiment

H.-Ch. Schröder et al.,
Eur. Phys. J. C 21 (2001) 473

ε_{1s} π^-H $a_{\pi^-p\to\pi^-p}$

ε_{1s} π^-D a^+ $= a_{\pi^-p\to\pi^-p} + a_{\pi^+p\to\pi^+p}$

$\equiv a_{\pi^-p\to\pi^-p} + a_{\pi^-n\to\pi^-n}$

charge symmetry

↑ Ericson, Loiseau & Thomas

Phys. Rev. C 66, 014005 (2002)

OUTLOOK

PIONIC DEUTERIUM

ε_{1s} *better constraints for*

πN *isospin scattering lengths* a^{+} & a^{-}

LEC f_1

NEW !

Γ_{1s} *pion production/absorption at threshold* $\pi NN \leftrightarrow NN$

Deser formula

$$\epsilon_{1s} + i\,\Gamma_{1s}/2 = -\,(2\alpha^3 m_{red}^2 c^4/\hbar c)\cdot a_{\pi d}$$ + Coulomb corrections

$$\Re\, a_{\pi D} = a_{\pi^- p} + a_{\pi^- n} + \text{corrections}$$
$$= a^+ + \text{corrections}$$

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

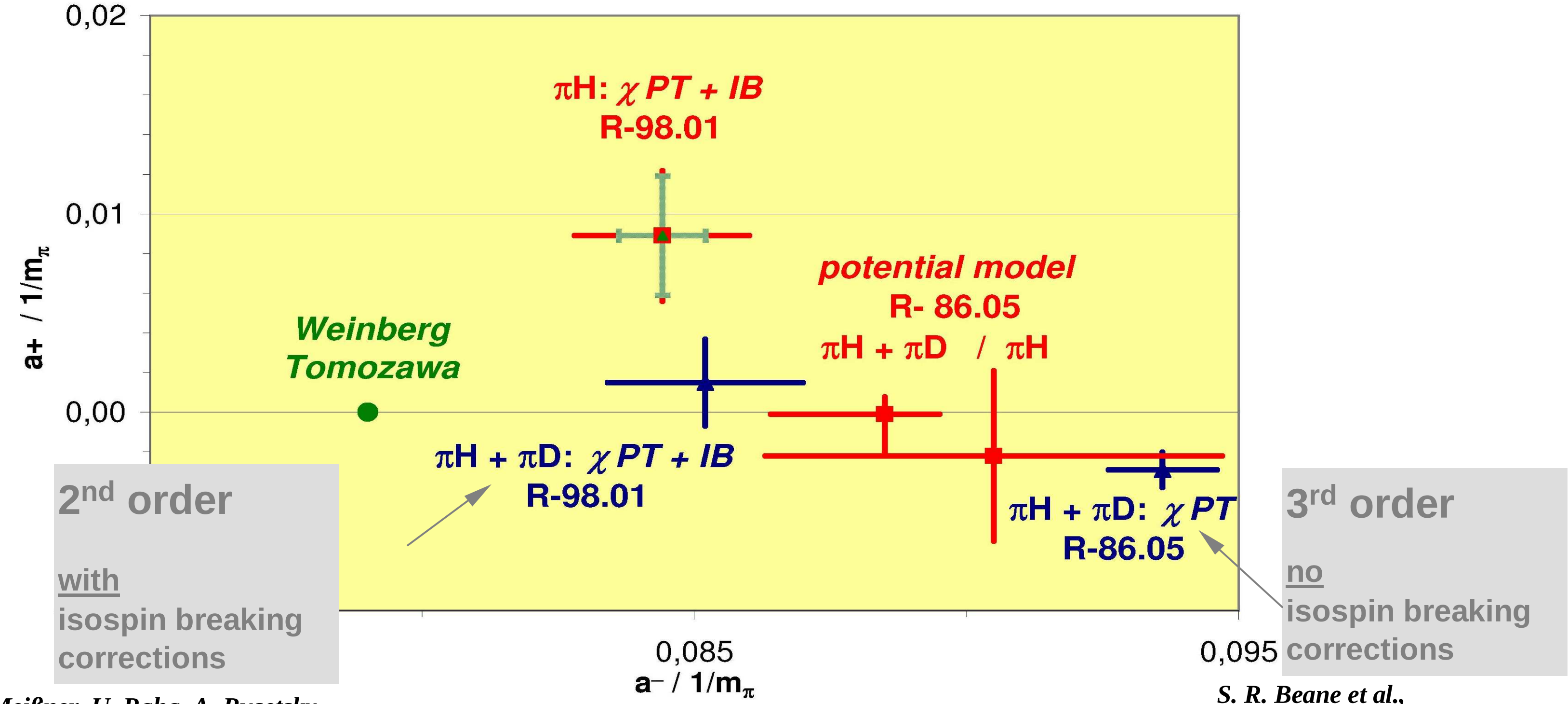
corrections are large

single + multiple scattering
absorption

constraint für $a^{\pm}$

access to $\pi NN_{I=0} \leftrightarrow NN_{I=1}$ reaction

πN scattering lengths $a^{\pm}$ ($\pi H + \pi D$)



U.-G. Meißner, U. Raha, A. Rusetsky
arXiv:nucl-th/0512035

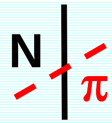
S. R. Beane et al.,
Nucl. Phys. A 720 (2003) 399

1. $a^{\pm}$ from πH (ε_{1s}, Γ_{1s}) and πD (ε_{1s}) <u>must</u> fit !

2. correlated fit (a^+, a^-, f_1) *constraint for f_1*

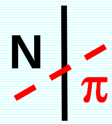
origin of Γ_{1s}

CEX scattering



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

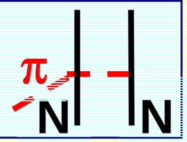
radiative capture



BR are well known

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

„true“ absorption



πNN threshold parameter α

charge symmetry *detailled balance*

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

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

πD atom

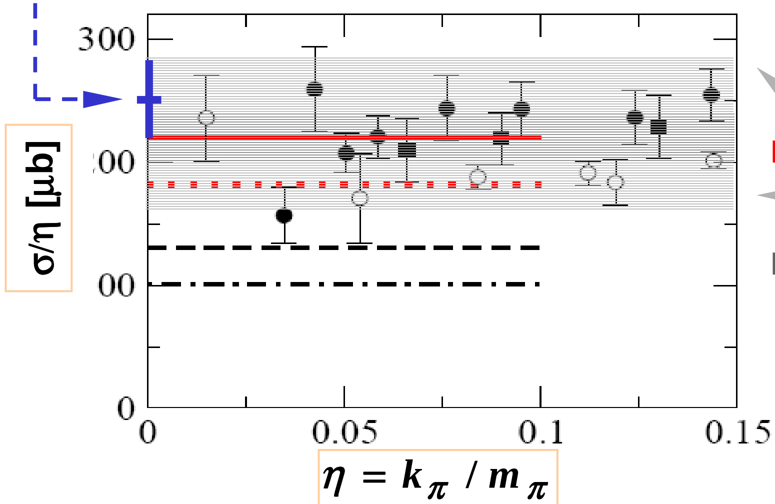
$$\Im\, a_{\pi D} \propto \Gamma_{\pi^- d \to nn} + \Gamma_{\pi^- d \to nn\gamma} = \frac{1}{6\pi} m_p \cdot \alpha$$

J. Hüfner, Phys. Rep. 21 (1975) 1

π production

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

extrapolation to threshold



NLO

LO

χPT

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

V. Lensky et al., nucl-th/0511054,2005

$\to$ few %

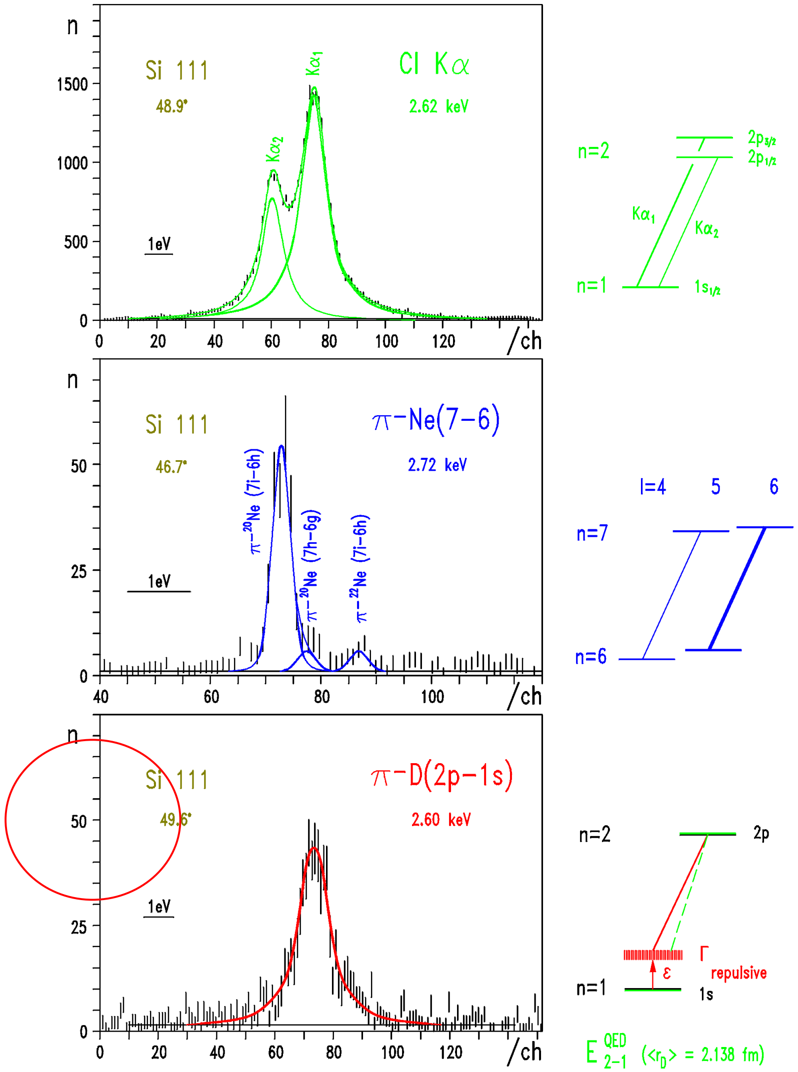
energy calibration I

response function I

strong interaction

$\varepsilon_{1s} = -\,2.469 \pm 0.055$ eV
$\Gamma_{1s} = \;\; 1.093 \pm 0.129$ eV

P. Hauser et al., PR C 58 (1998)R1869



Cl Kα
2.62 keV
15 min

πNe(7-6)
2.72 keV
12 h

πD(2p-1s)
2.60 keV
15 h

SUMMARY

PIONIC ATOMS - A = 1,2

		$\Delta\varepsilon_{1s}/\varepsilon_{1s}$	$\Delta\Gamma_{1s}/\Gamma_{1s}$	
πH	R-98.01	0.2%	4% $\rightarrow$ < 2%	✓ 2005
πD	R-06.03	3% $\rightarrow$ < 1%	12% $\rightarrow$ < 4%	NEXT
	again:	density dependence ?	<u>new</u> category: true absorption	
	aim:	better constraints for	threshold pion production	
		a^+, a^- <u>and</u> LEC f_1	$\pi NN \leftrightarrow NN$	

PIONIC HYDROGEN - HISTORY

almost 40 years