HADRONIC ATOMS

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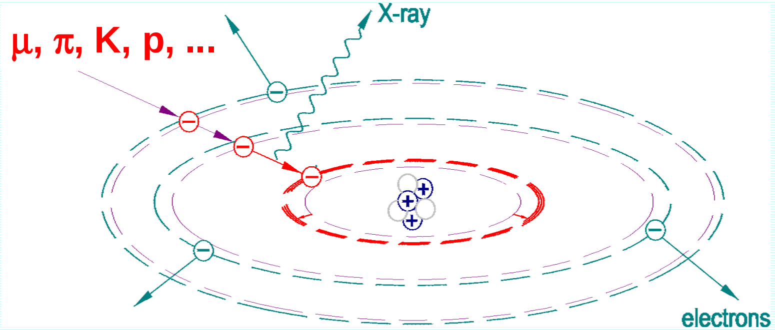
capture of a

negatively charged particle

in the Coulomb field of nuclei



EXOTIC ATOM

principal method

X-ray spectrocopy

in addition

recoil nuclei

daughter nuclei

Auger electrons

particle-nucleus interaction

particle properties

nuclear properties

atomic physics - QED

1. Caucasian-German School and Workshop on Hadron Physics
Tbilisi, 30.8.-2.9.2004

ORDERS OF MAGNITUDE

$$V_{Coulomb} = -Ze^2 / r$$

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

radii $a_n = (hc / m_{red} c^2 \alpha) \cdot (n^2/Z)$

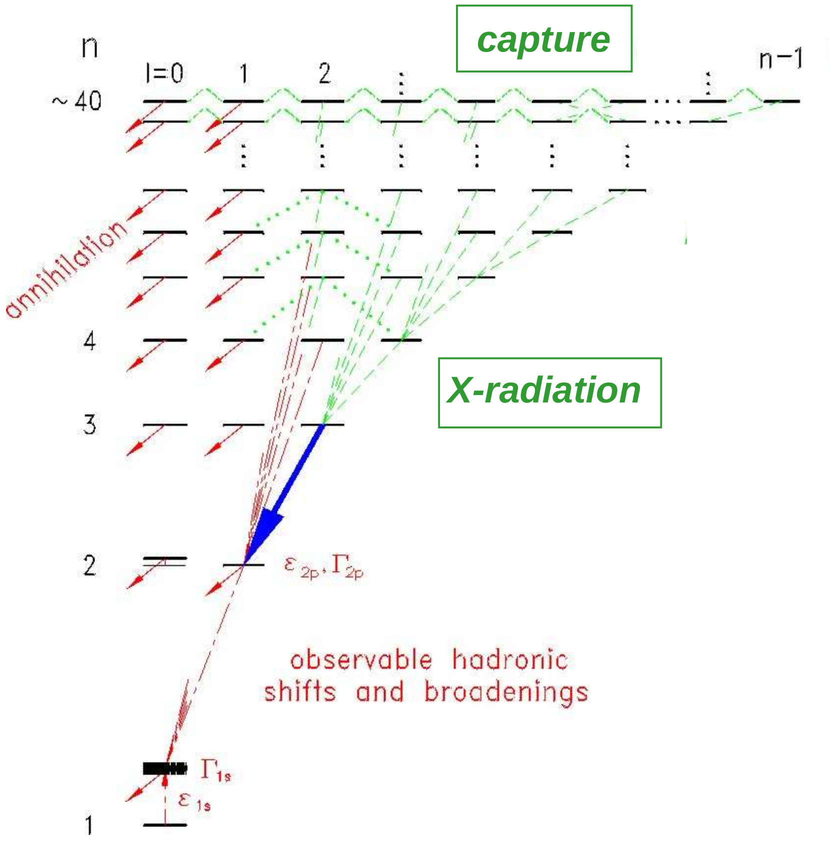
		m / MeV/c^2	$B_{n=1}$ / keV	"Bohr" radius / fm	
atomic	ep	0.511	0.0136	$0.5 \cdot 10^5$	capture
	μp	105	2.5	279	
↓	πp	140	3.2	216	atomic ↓ cascade
	$\bar{p}p$	938	12.5	58	
"nuclear" dimensions	$< r_p >$			0.8	hadronic interaction

particle-nucleus scattering at "rest"

elastic and inelastic

ATOMIC CASCADE

isolated ***antiprotonic hydrogen***



OBSERVABLES

- X-ray energies

- line intensities

GOAL

scattering length

$$a \propto \varepsilon - i\,\Gamma/2$$

$\Gamma \cdot \Delta t \cong \hbar$

ε > 0 (<0) ≡ *attractive (repulsive) interaction*

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

EXOTIC HYDROGEN

elementary reactions $\pi^- p$, $K^- p$, $\bar{p}p$

EXOTIC DEUTERIUM

$d \approx p + n$ *particle - neutron interaction*

isospin

A ≤ 4

particle - nucleon → *particle - nucleus interaction*

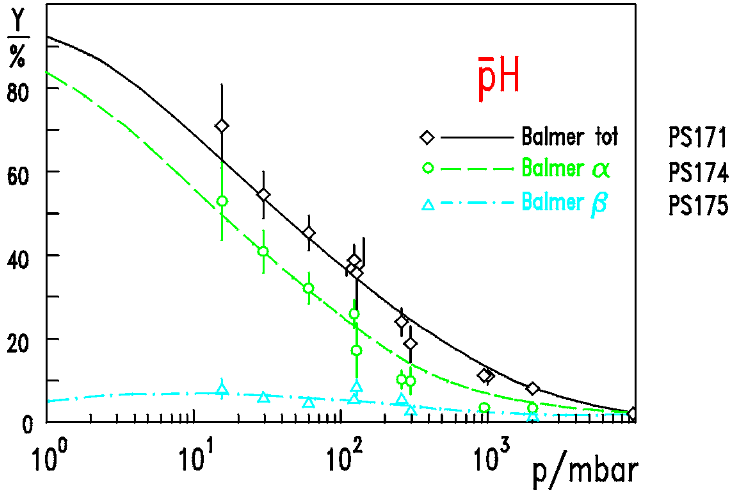
A >> 1

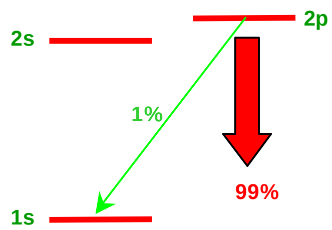
in-medium effects *chiral restoration*

nuclear structure *neutron halo, isospin*

EXOTIC HYDROGEN

pressure dependence of line yields





Stark-mixing ⇒ ***small line yields Y***

strong annihilation ⇒ $Y_{2p\text{-}1s} \approx Y_{3d\text{-}2p} / 100$

≈ 2 GeV/c² per annihilation ⇒ ***high background***

$\bar{p}p \rightarrow n\,\pi^{+} + n\,\pi^{-} + m\,\pi^{0}$

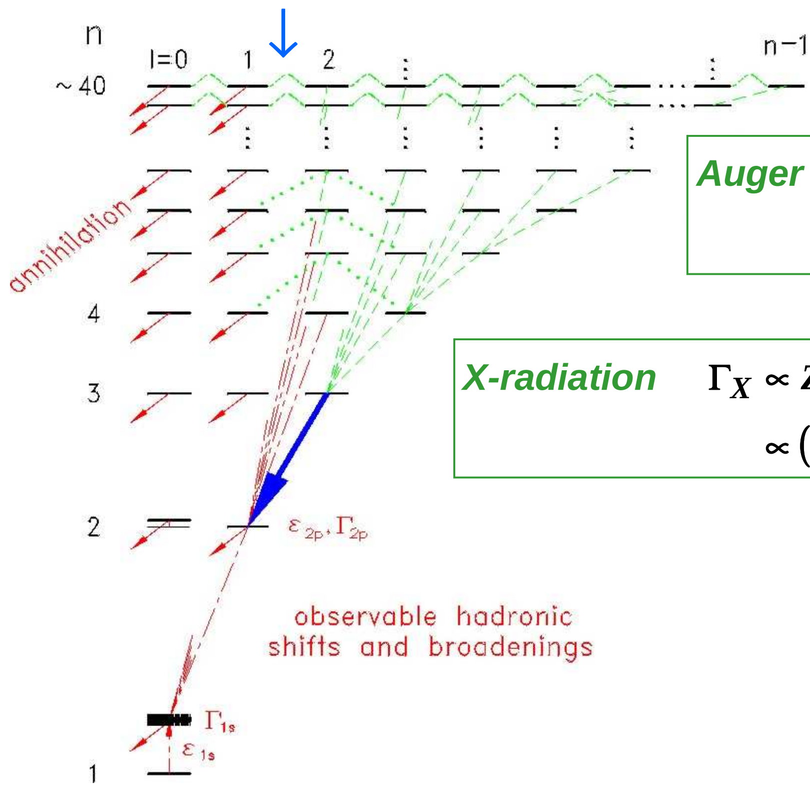
↘ 2 γ

ATOMIC CASCADE

exotic hydrogen <u>not</u> an isolated system !

Stark mixing $\langle n,l|E1|n,l\pm1\rangle \propto n\sqrt{n^2-l^2}$

collisions with H_2



Auger emission $\Gamma_A \propto Z^2$

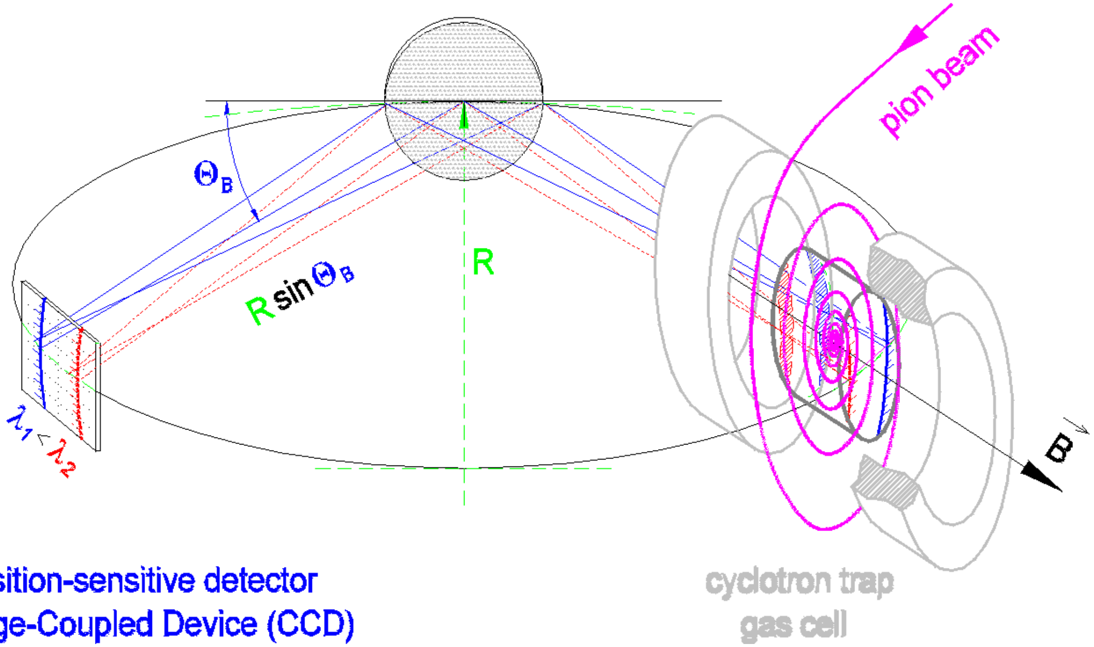
$\propto (\Delta E)^{-1/2}$

X-radiation $\Gamma_X \propto Z^4$

$\propto (\Delta E)^3$

PRINCIPLE of SET-UP

ultimate <u>energy resolution</u>



<u>position & energy resolution</u>

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

high <u>stop density</u>

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

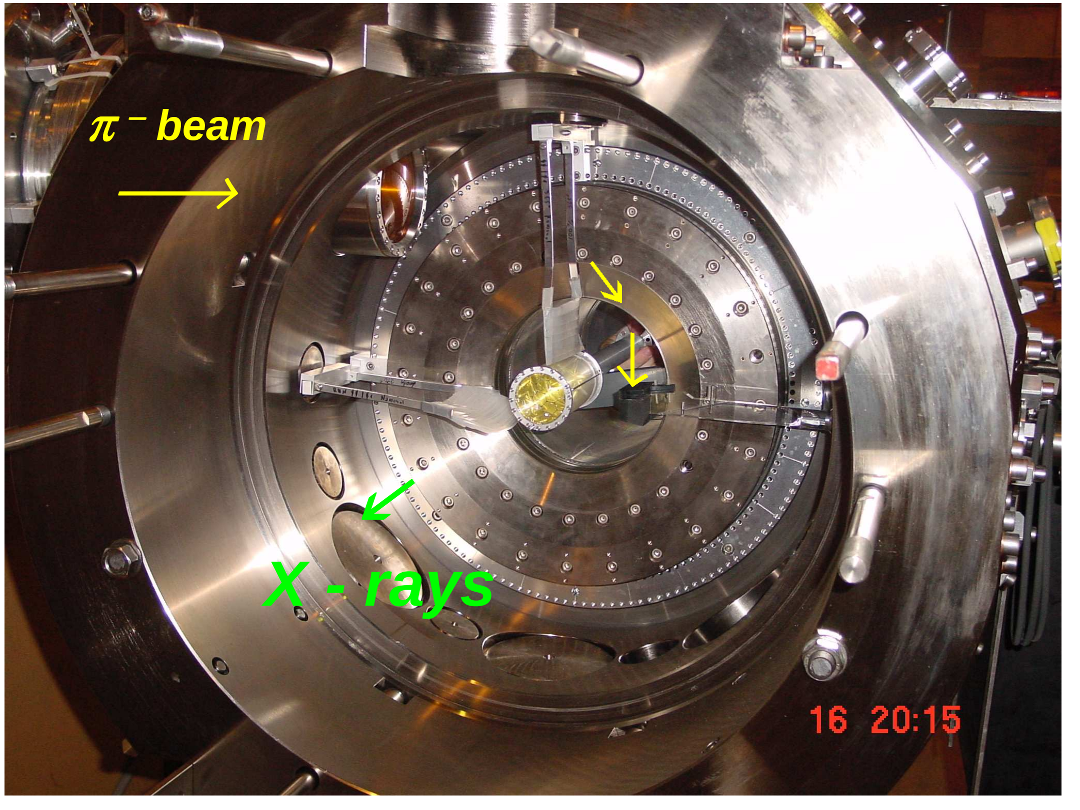
L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253

DEGRADERS and CRYOGENIC TARGET

inside

CYCLOTRON TRAP II

super-conducting split coil magnet



Set-up PS207

LEAR

$\bar{p}$ ***p = 16 mbar***

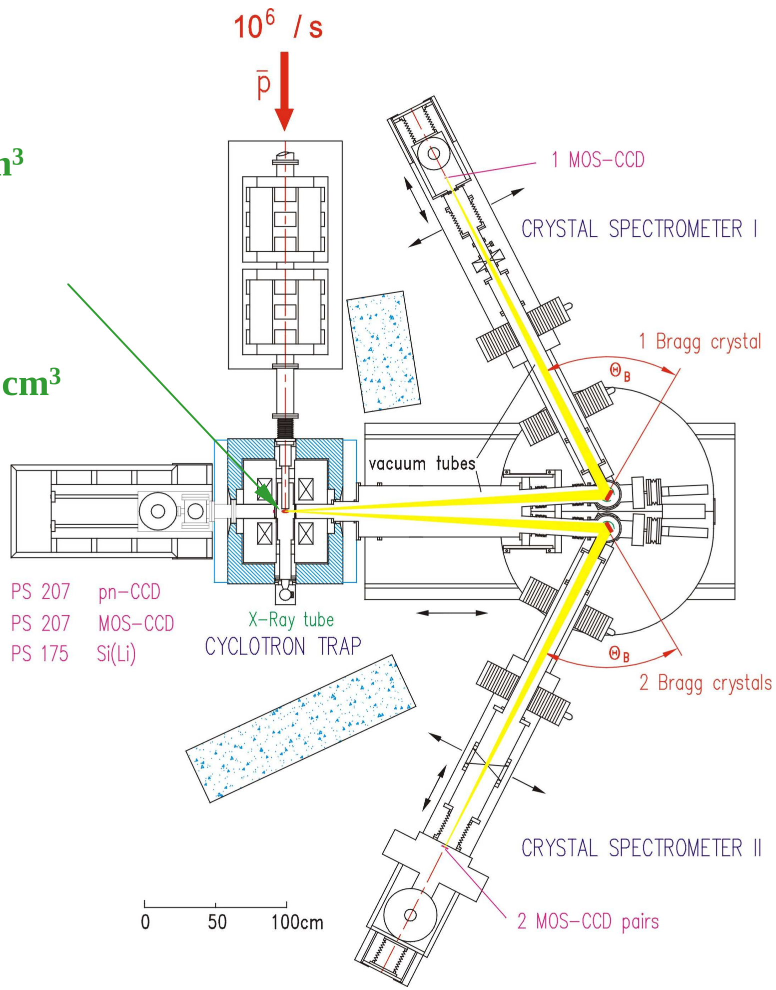
stop volume ≈ 5 cm³

90%

π ***p = 1 bar***

stop volume ≈ 100 cm³

1%

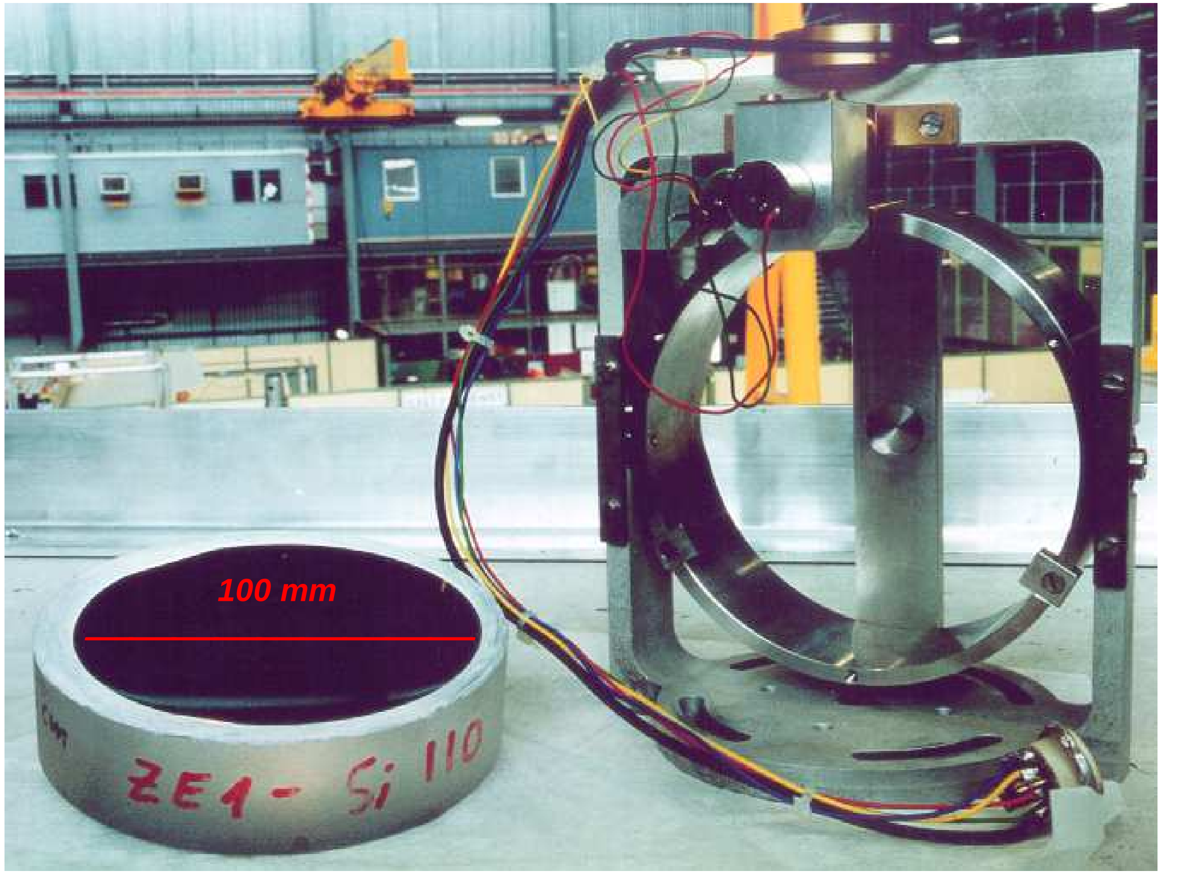


$\Delta E_X / E_X$ few 10^{-6}

resolution few 10^{-4}

Spherically curved Bragg crystal

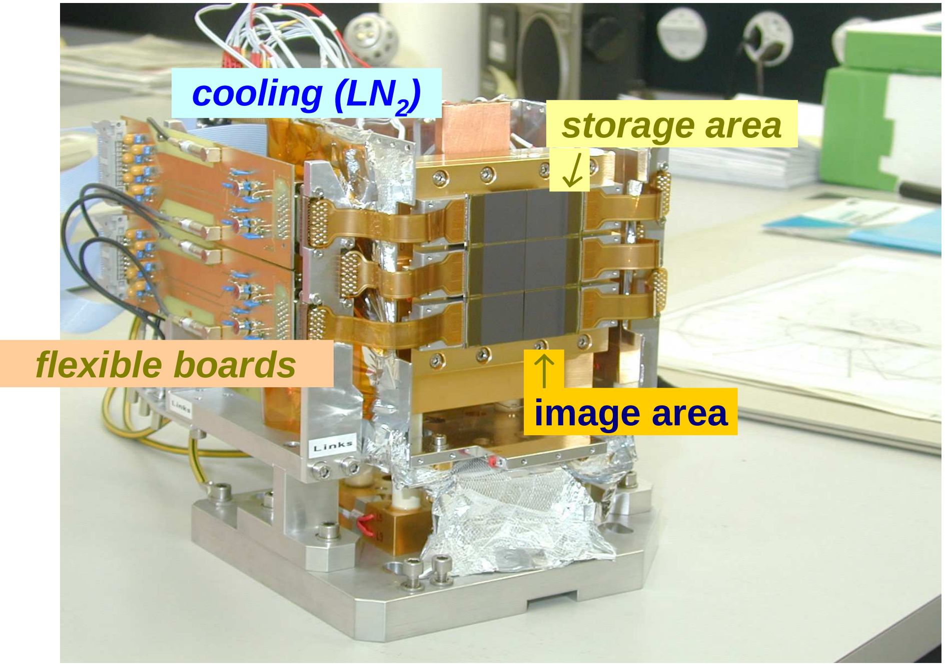
radius of curvature 2985.4 mm



Large - Area Focal Plane Detector

PSI experiment R-98.01 (PIONIC HYDROGEN)

2 × 3 CCD 22 array** with **frame buffer



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

pixel size 40 μm × 40 μm

600 × 600 pixels per chip

frame transfer ≈ 10 ms

data processing 2.4 s

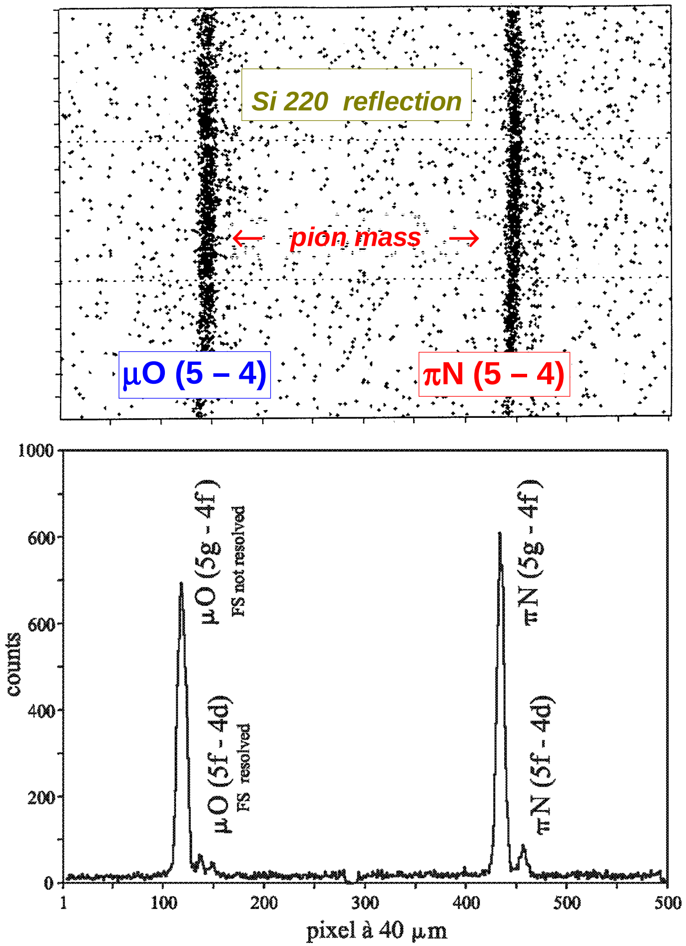
operates at – 100℃

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

$\varepsilon_X \approx$ 90%

PION MASS

PSI experiment R-97.02



mixture O_2 / N_2 90% / 10%

1.4 bar

15 counts per hour per line

Peak / background ≈ 50

statistics accumulated≈ 10000 per line

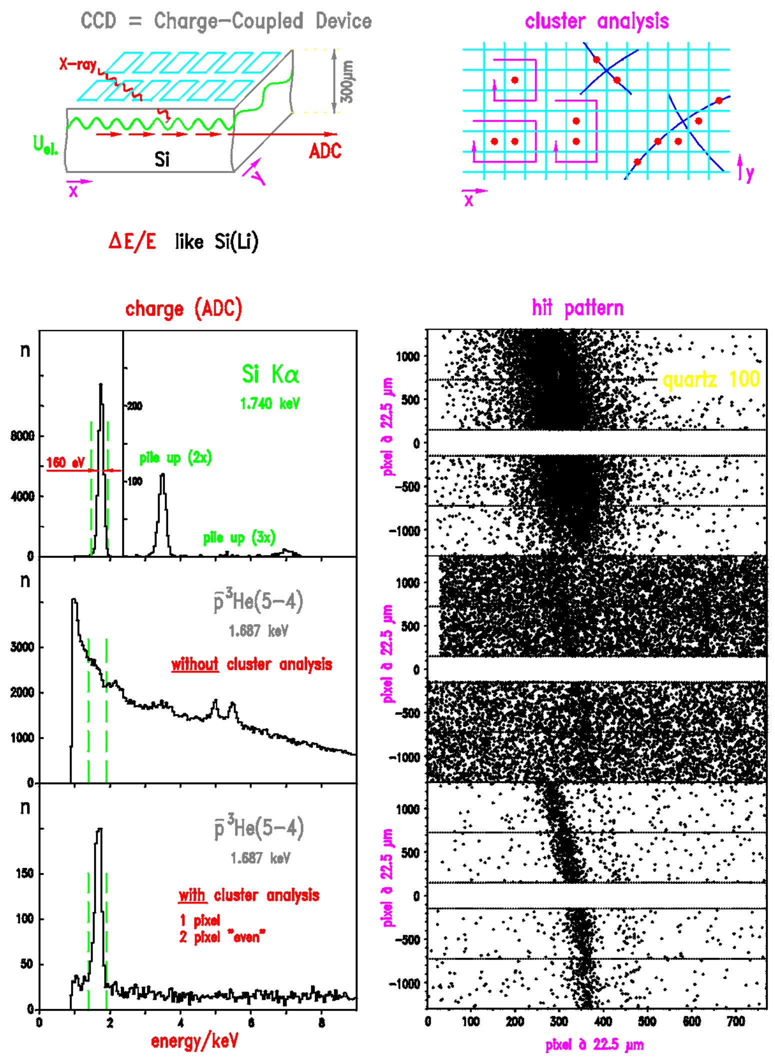
excpected **Δm / m < 2ppm**

final analysis presently going on

BACKGROUND suppression

using

CCDs



ANTIPROTONS

antinucleon - nucleon interaction

meson exchange

annihilation

THEORETICAL DESCRIPTION

$V_{Coulomb} + U_{hadronic}$

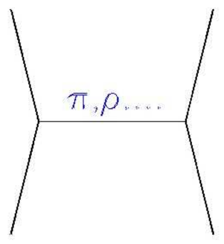
$U_{hadronic}$ = meson exchange + annihilation

scattering: $\bar{p}p \leftrightarrow \bar{p}p$ — $\bar{p}p \rightarrow$ mesons

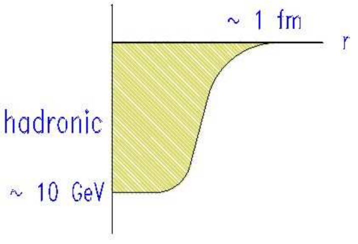
$\bar{p}p \leftrightarrow \bar{n}n$

$NN \xrightarrow{\text{G-parity}} \bar{N}N$ — $U \propto a\,\rho(r)$

Re $U_{hadronic}$



Im $U_{hadronic}$



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

Buck, Dover, Richard, Ann. Phys. (NY) 121 (1979) 47

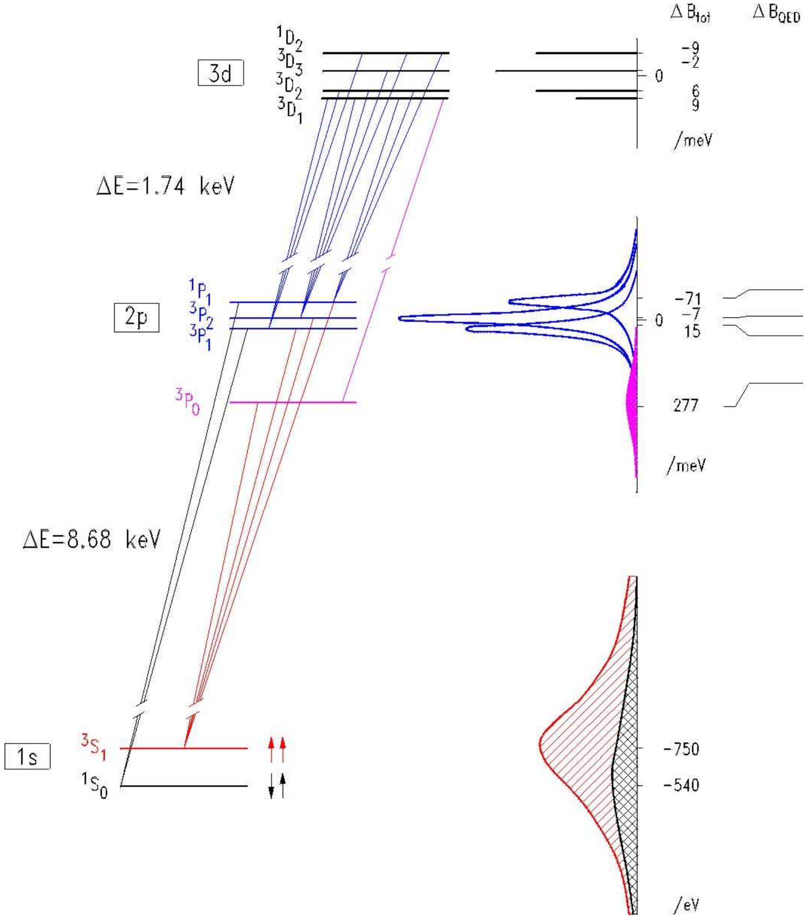
spin-spin "deuteron" — ***no microscopic theory***

spin-orbit effects

☞ ***check spin dependence !***

PROTONIUM

predicted hyperfine splitting



strong-interaction effects

J. Carbonell, G. Ihle, J.-M. Richard, Z. Phys. A 334 (1989) 329

d state

strong interaction negligible

p state

spin-orbit interaction

s state

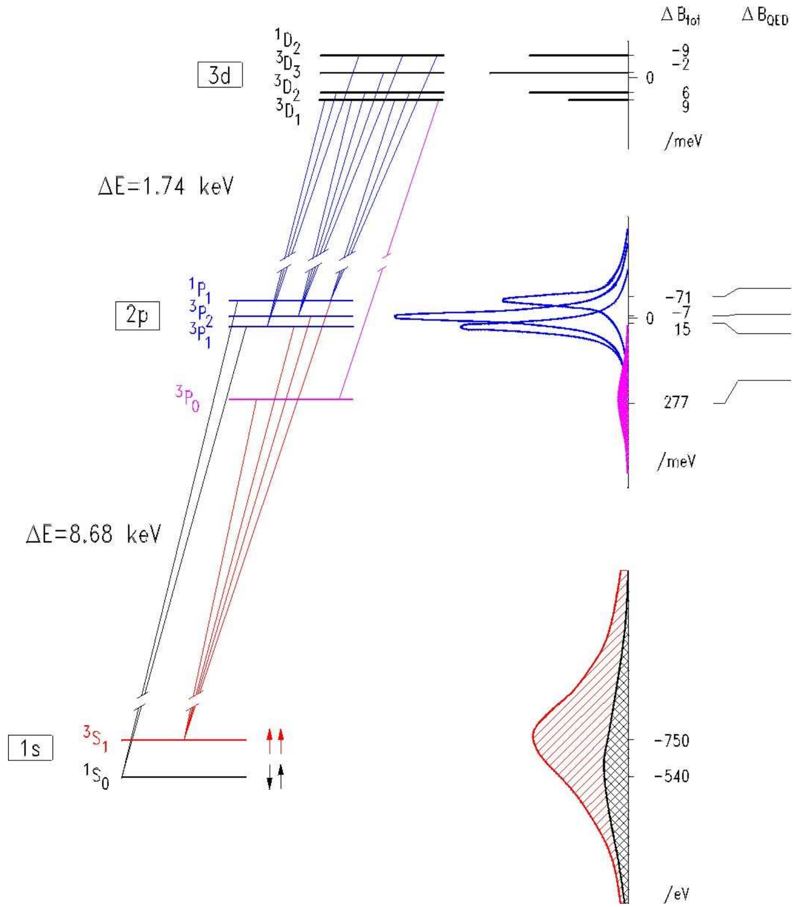
spin-spin interaction

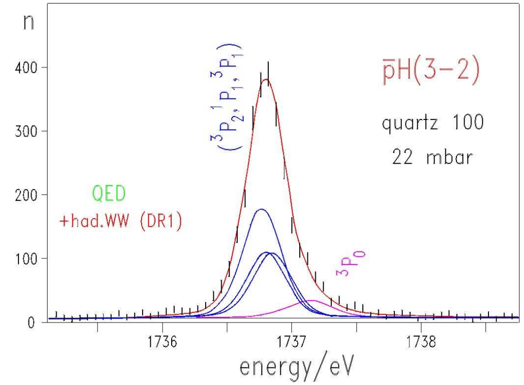
$\bar{p}$ meanfree pathlength in nuclear matter ≈ 1.2 fm

PROTONIUM

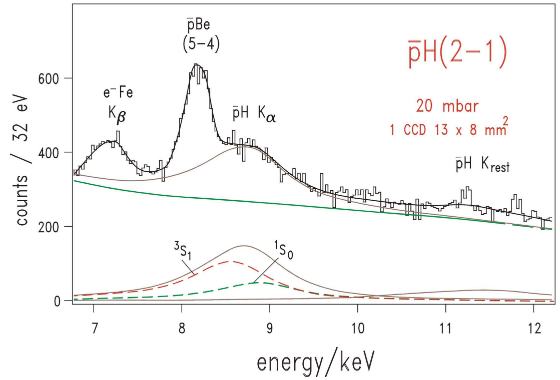
s- and p-state strong interaction effects

LEAR experiment PS207





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

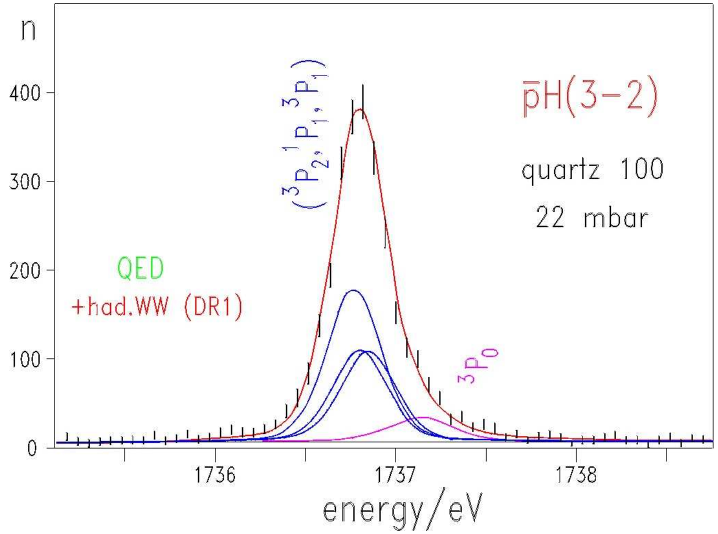


M. Augsburger et al., Nucl. Phys. A 658 (1999) 149

PROTONIUM

2p state

LEAR experiment PS207



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

- **Hadronic width**

  2p ***spin average*** $\Gamma = 38.0 \pm 2.8$ *meV*

  $^3P_0$ $\Gamma = 120 \pm 25$ *meV*

  ↑

  meson exchange

- **Hadronic shift**

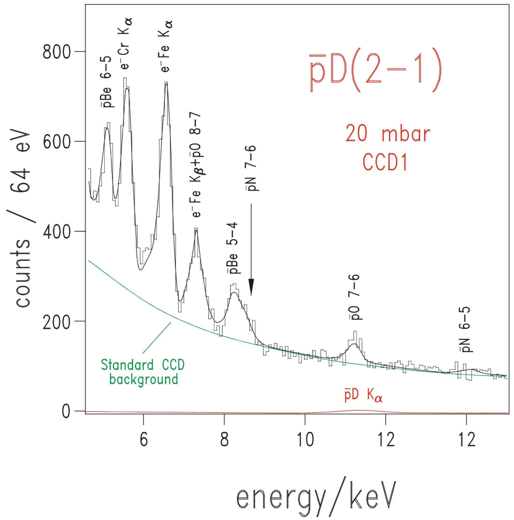
  2p ***spin average*** $\varepsilon = +15 \pm 20$ *meV*

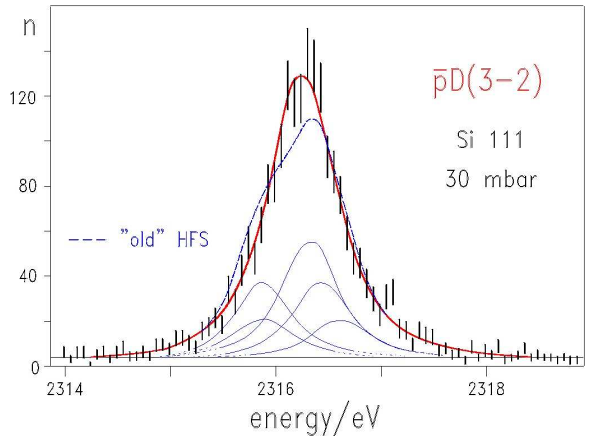
  $^3P_0$ $\varepsilon = +139 \pm 38$ *meV*

Antiprotonic DEUTERIUM

s- and p-state strong interaction effects

LEAR experiment PS207





- ***ground state*** **weak signal**

spin average ε_{1s} = - 1050 ± 250 eV

Γ_{1s} = 1100 ± 750 eV

M. Augsburger et al., Phys. Lett. B 461 (1999) 417

- ***2p state*** ***HFS not resolvable***

spin average ε_{2p} = - 243 ± 26 meV

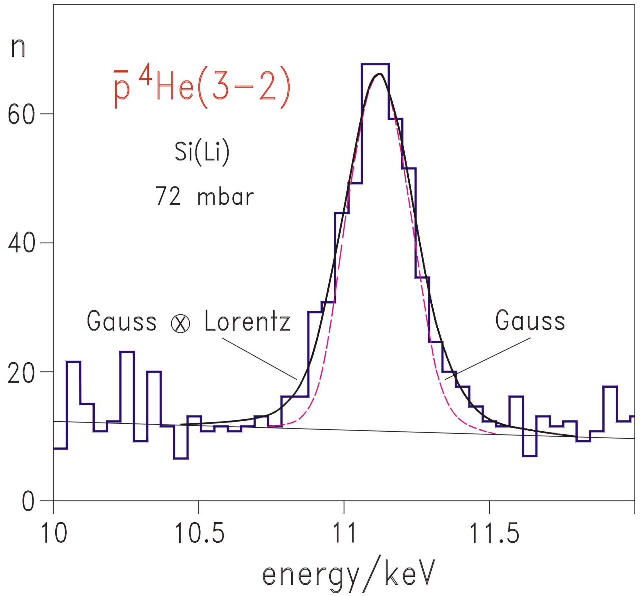
Γ_{2p} = 489 ± 308 meV

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

Antiprotonic HELIUM

isotope effects

LEAR experiment PS175



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

	spin average	ε */ eV*	Γ */ eV*
•	$\bar{p}\,^3$He 2p	*– 17 ± 5*	*25 ± 9*
•	$\bar{p}\,^4$He 2p	*– 18 ± 2*	*45 ± 5*

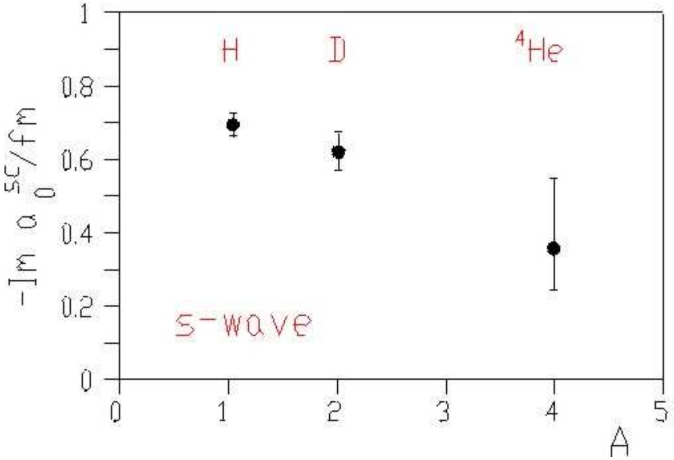
single - nucleon annihilation ?

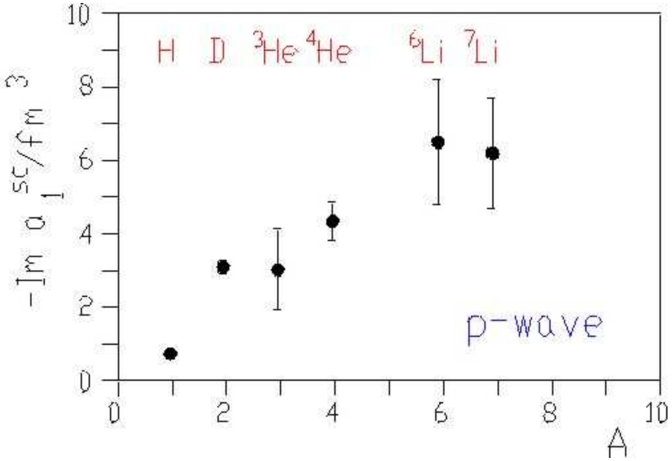
$$\Gamma_{A(Z,N)} \propto Z \cdot \Gamma_{\bar{p}\,n} + N \cdot \Gamma_{\bar{p}\,p}$$

ANNIHILATION STRENGTH

vs.

atomic weight





saturation ?

K. Protasov et al., Eur. Phys. J. A 7 (2001) 429

PIONS

pion - nucleon interaction

low-energy approach of QCD

=

χ***PT chiral perturbation theory*** "ideal" world $m_u = m_d$ (= m_s) = 0 CHIRAL SYMMETRY (S = ½)

$\Rightarrow$ m ($\pi^- = |d\bar{u}>$ = 0

$F_\pi = 0$ no π decay

real world $m_\pi > 0$ but small $m_\pi \approx m_p / 7$

χPT expansion at chiral limit $m_{quark} \rightarrow 0$

order parameters momenta

quark mass difference $m_u - m_d$, ...

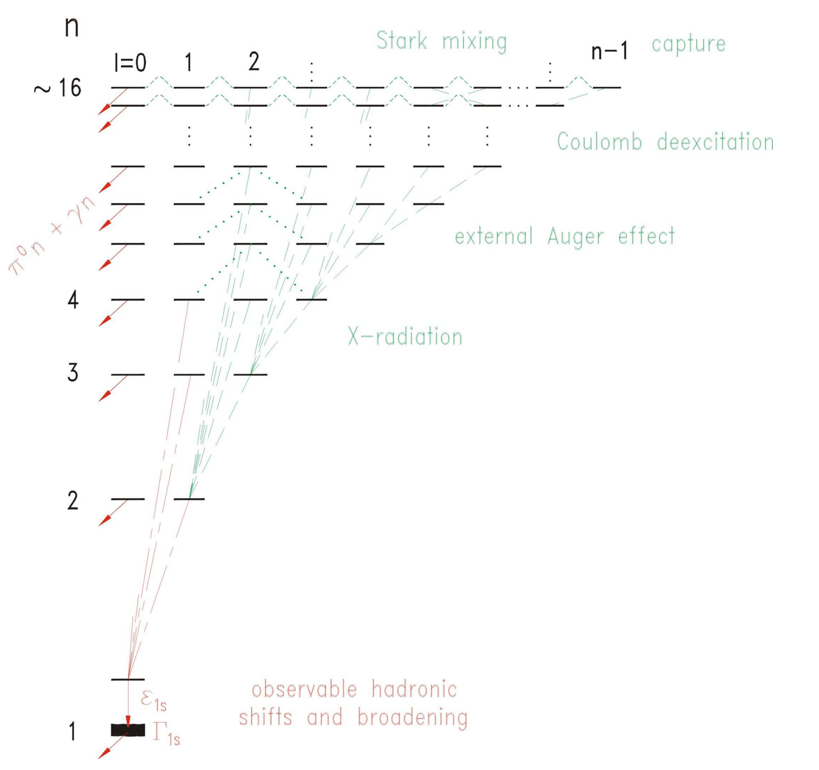
and $\alpha_{el.-mag.}$

system	theory	experiment		
ππ	best	DIRAC	CERN	difficult - % accuracy ?
πN	2 nd best	PIONIC HYDROGEN	PSI	$\lesssim$ % !
KN	$m_s >> m_u , m_d$	DEAR	DAΦNE	started

low-energy theorems $\leftrightarrow$ scattering length a

πN Heavy-Baryon χPT

PIONIC HYDROGEN



		$\pi^- H$	$\pi^- D$
	3p - 1s	2.88	3.08 keV
ε_{1s}		+ 7 attractive	- 2 eV repulsive
Γ_{1s}		1	1 eV

πN scattering at „rest“

2 isospin amplitudes

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

isospin invariance: $m_u = m_d$

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

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

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

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

LOW-ENERGY πN INTERACTION

Gell-Mann-Oakes-Renner relation

PS meson mass

$$m_\pi^2 = \frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d \rangle / F_\pi^2 + O(m_{u,d}^2)$$

quark condensate

Goldberger-Treiman relation

πN coupling constant $f_{\pi N}$

$$f_{\pi N}^2 = \frac{m_\pi^2}{4}\frac{g_A^2}{F_\pi^2} = 0.072 \qquad (+\text{higher orders} \leftrightarrow \chi\text{PT})$$

low-energy theorems ↔ scattering length *a*

Goldberger- Miyazawa-Oehme (GMO) sum rule

$$(1+\frac{m_\pi}{M})\frac{a^-}{m_\pi} = \frac{2 f_{\pi N}^2}{m_\pi^2 - (m_\pi^2/2M)^2} + \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma_{\pi^- p}^{tot}(k_\pi) - \sigma_{\pi^+ p}^{tot}(k_\pi)}{2\omega(k_\pi)} dk_\pi$$

$\Delta\int \approx 1\%$

πN sigma-term σ_N

$$(1+\frac{m_\pi}{M})a^+ = \frac{m_\pi^2}{4\pi f_\pi^2}\left(\frac{\sigma_N}{m_\pi^2} + d - \frac{g_A^2}{4M_N}\right)$$

F_π pion decay constant

GOAL

precise determination of

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

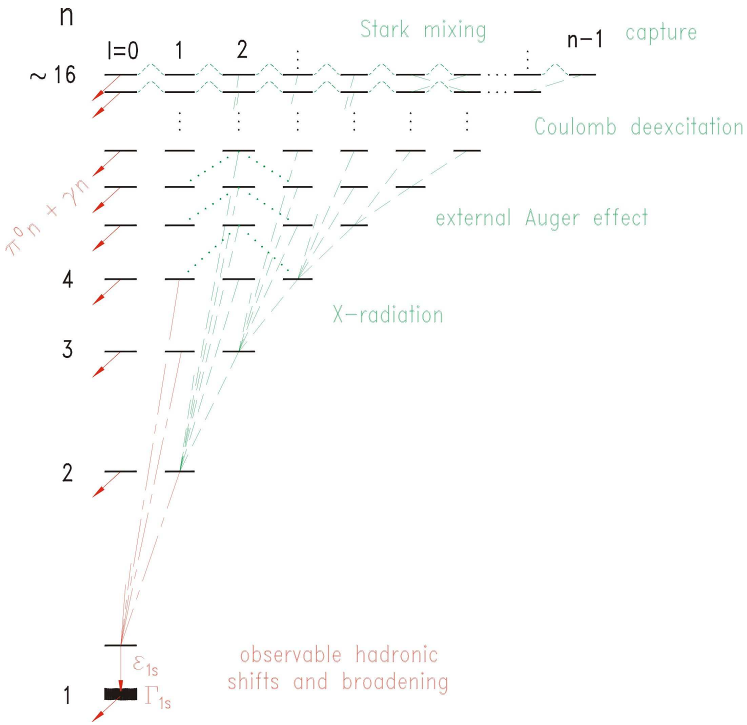
πN coupling constant $f_{\pi N}^{2}$

measurement $\Delta\varepsilon_{1s} / \varepsilon_{1s} \ll 1\%$

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

πp ***<u>not</u> an isolated system !***

CASCADE - COLLISIONAL PROCESSES $\pi p + H_2$



1. **Stark mixing**

"dangerous" processes

2. **[(πpp)p]ee – molecule formation („DH“) ?**

significant radiative decay modes ?

☛ ε_{had}

MOLECULAR POTENTIALS

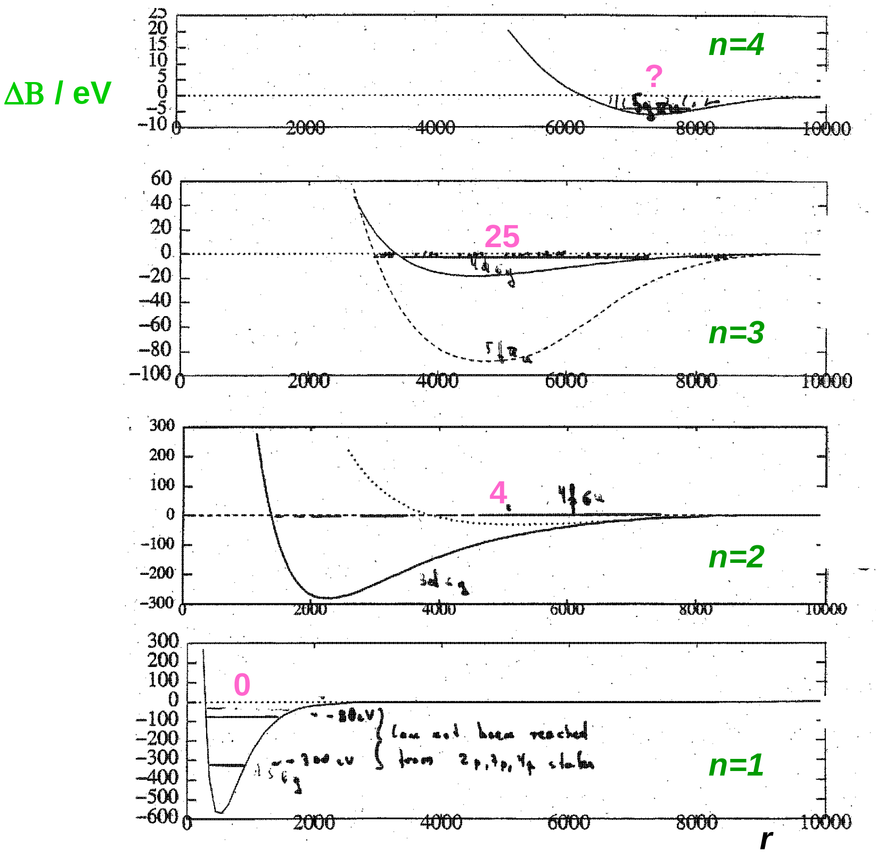
"Vesman" mechanism for excited states: $\pi p_{nl} + H_2 \rightarrow [(\pi pp)_{nj\nu} \cdot p]\, ee_{K\nu}$

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

quenching of μp_{2s} ***via*** $[(\mu pp)p]ee$ ***formation***

theory

S.Hara et al.
I.Shinamura
V.I.Korobov, …



potential curves scaled from Sharp, Atomic data 2 (1971)119

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

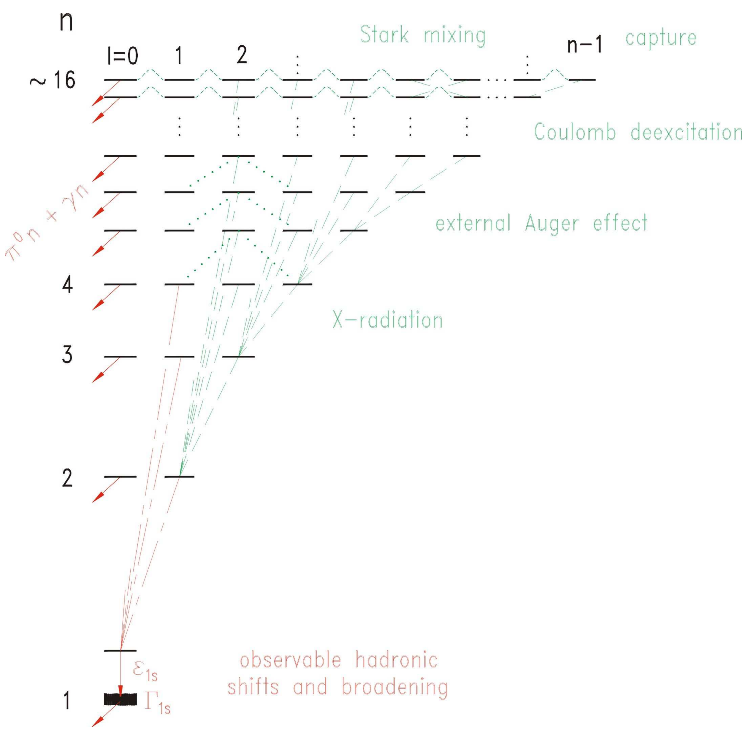
	$pp\mu$	$dd\mu$
$\Gamma_{X\text{-ray}} / \Gamma_{total}$	≈ 0.03	≈ 1

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

Kilic, Karr and Hilico
to be published

πp *not* an isolated system !

CASCADE - COLLISIONAL PROCESSES $\pi p + H_2$



1. **Stark mixing**

2. **[(πpp)p]ee – molecule formation („DH“) ?**

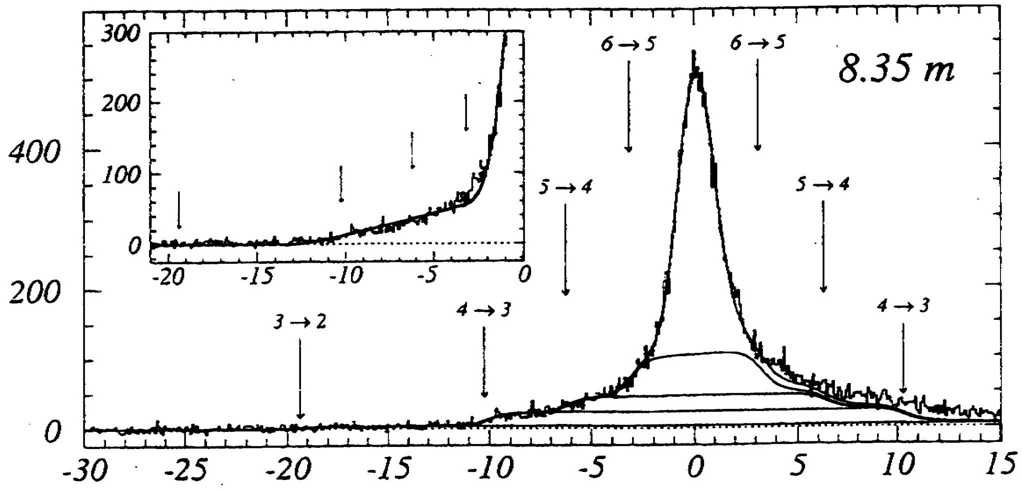
3. **Coulomb - de-excitation !**

 non radiative process $n_i \rightarrow n_f$ ***+ kinetic energy***

 Doppler broadening

 ☛ Γ_{had}

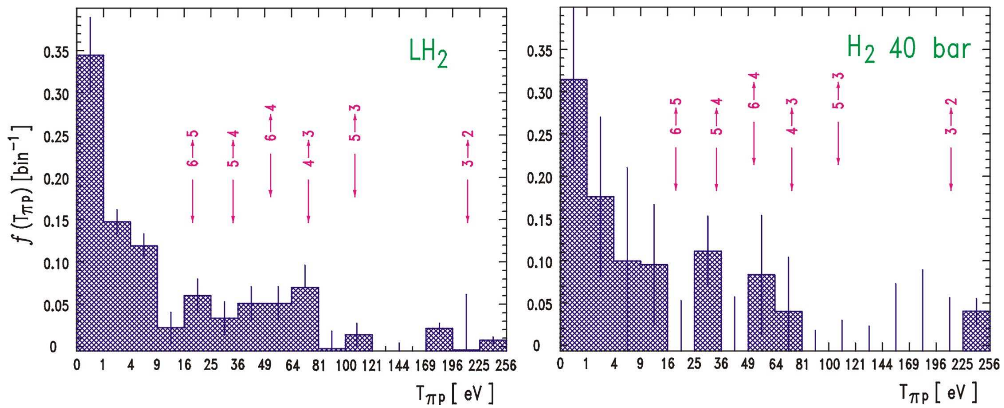
NEUTRON - TOF $(\pi^- p)_{ns} \rightarrow \pi^0 n$



Coulomb de-excitation $(\pi^- H)_n$ + H=H $\rightarrow$ $(\pi^- H)_{n-1}$ + H + H + ***kinetic energy***

⇓

quasi-discrete velocity profile



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

"environment independent"

determination

of

HADRONIC EFFECTS

STRATEGY

study of the atomic cascade $\leftrightarrow$ ***collisional effects vary with density !***

I.

ENERGY

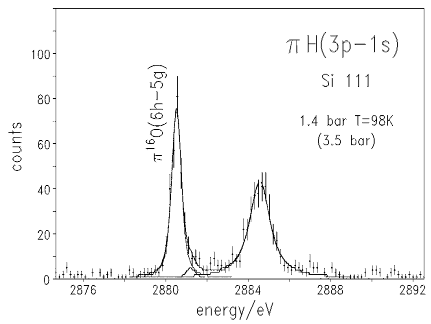
☛ ε_{had}

novel calibration method

hydrogen-like πA

πH(3p-1s) - density dependence

PSI experiment R-98.01 (PIONIC HYDROGEN)



mixture H_2 / $^{16}O_2$

(98%/2%)

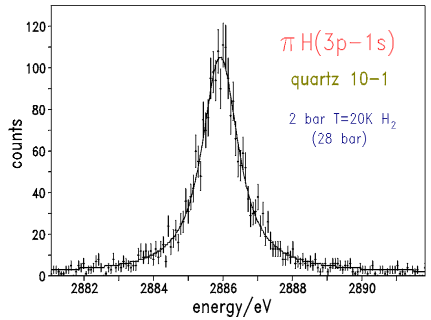
1.2 bar @ T = 85K

≈ 4 bar equivalent density

πH / πO

energy calibration

simultanuously



H_2

2 bar @ T = 20K

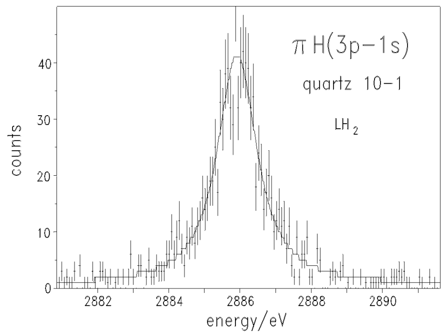
≈ 28.5 bar equivalent density

πO

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

(≈80%/10%/10%)

2 bar @ T = 86K

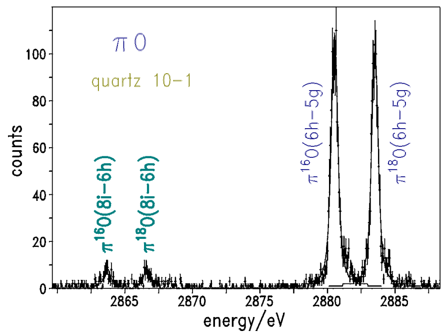


H_2

1 bar @ T = 17K

LH_2

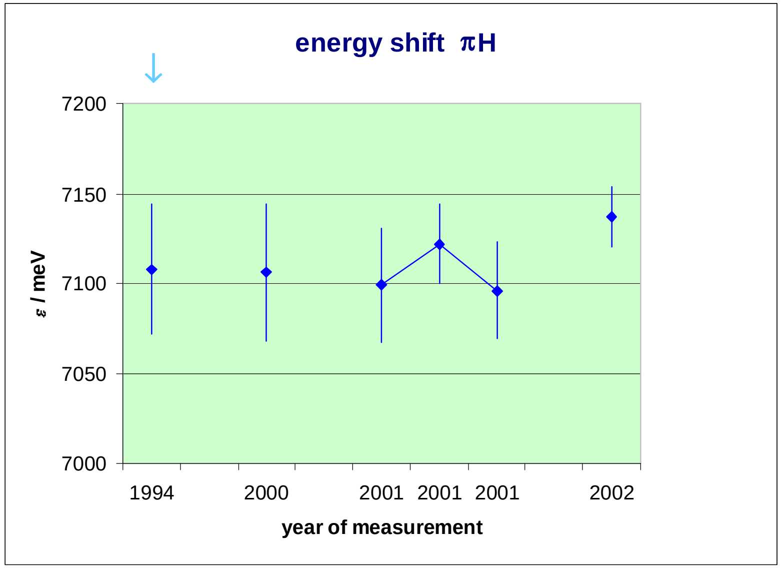
first time



πH(3p-1s) ***no* density dependence identified**

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

ε_{1s} *in agreement with previous experiment*



R-98.01

Maik Hennebach, *thesis Cologne 2003*

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

ΔE_{QED} **= ± 0.006 eV !**
P. Indelicato, priv. comm.

! πD prediction *radiative decay from molecule increases*

! πT " " " " " *dominates*

II.

LINE WIDTH

☛ $\Gamma_{\mathbf{had}}$

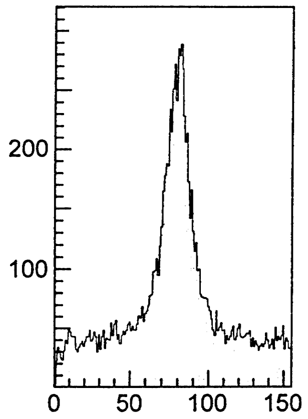
II a

PEAK / BACKGROUND !

Peak-to-background *and* fit interval

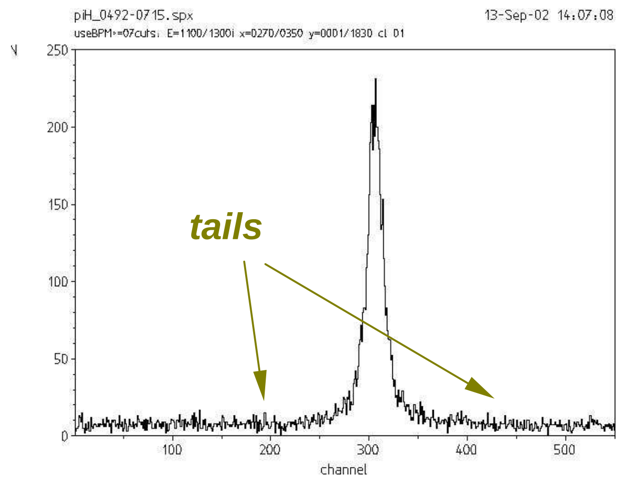
1 m concrete shielding!

large-area X-ray detector



↑

previous experiment



↑

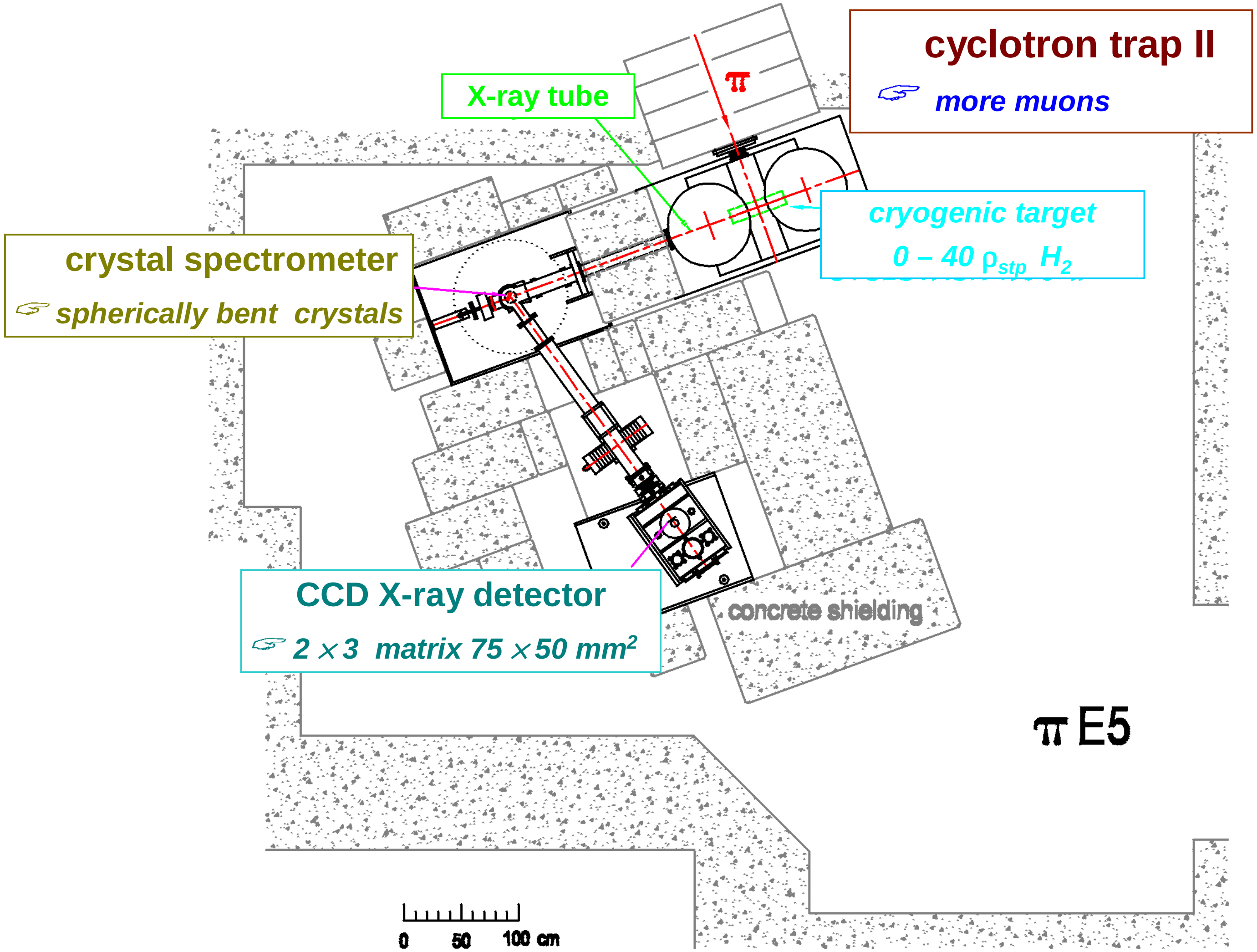
new experiment

concrete *good peak-to-background*

detector *coverage of tails*

SET-UP at PSI

R-98.01 (PIONIC HYDROGEN)



II b

MEASURED LINE SHAPE	**=**	**R**	$\otimes$	**L**	$\otimes$	Σ **D**
		crystal		Γ_{1s}		**Doppler broadening**
		resolution		↑		***Coulomb de-excitation***
		ECRIT		**πH**		***muonic hydrogen***

RESOLUTION FUNCTION

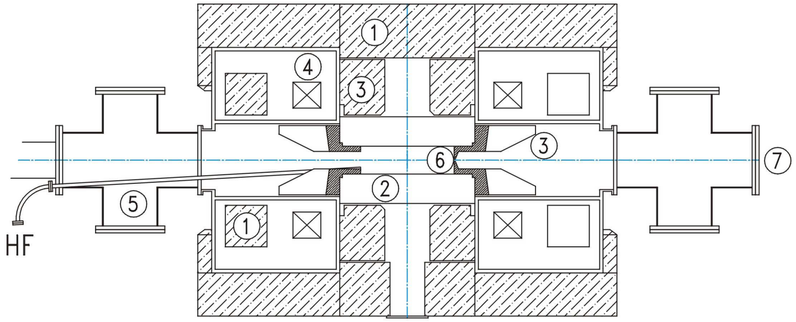
novel method

helium-like electronic atoms

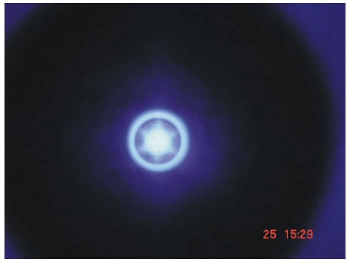
RESPONSE FUNCTION II

Electron Cyclotron Resonance Ion Trap **cyclotron trap + hexapole magnet**

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



FIRST PLASMA



"burning" argon

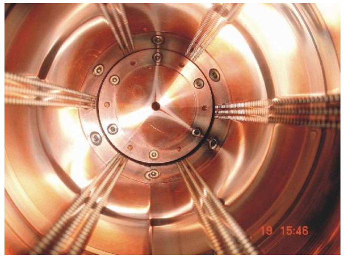
H- and He-like electronic atoms

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

⇒ narrow X-ray transitions

Γ_X = 10 - 40 meV

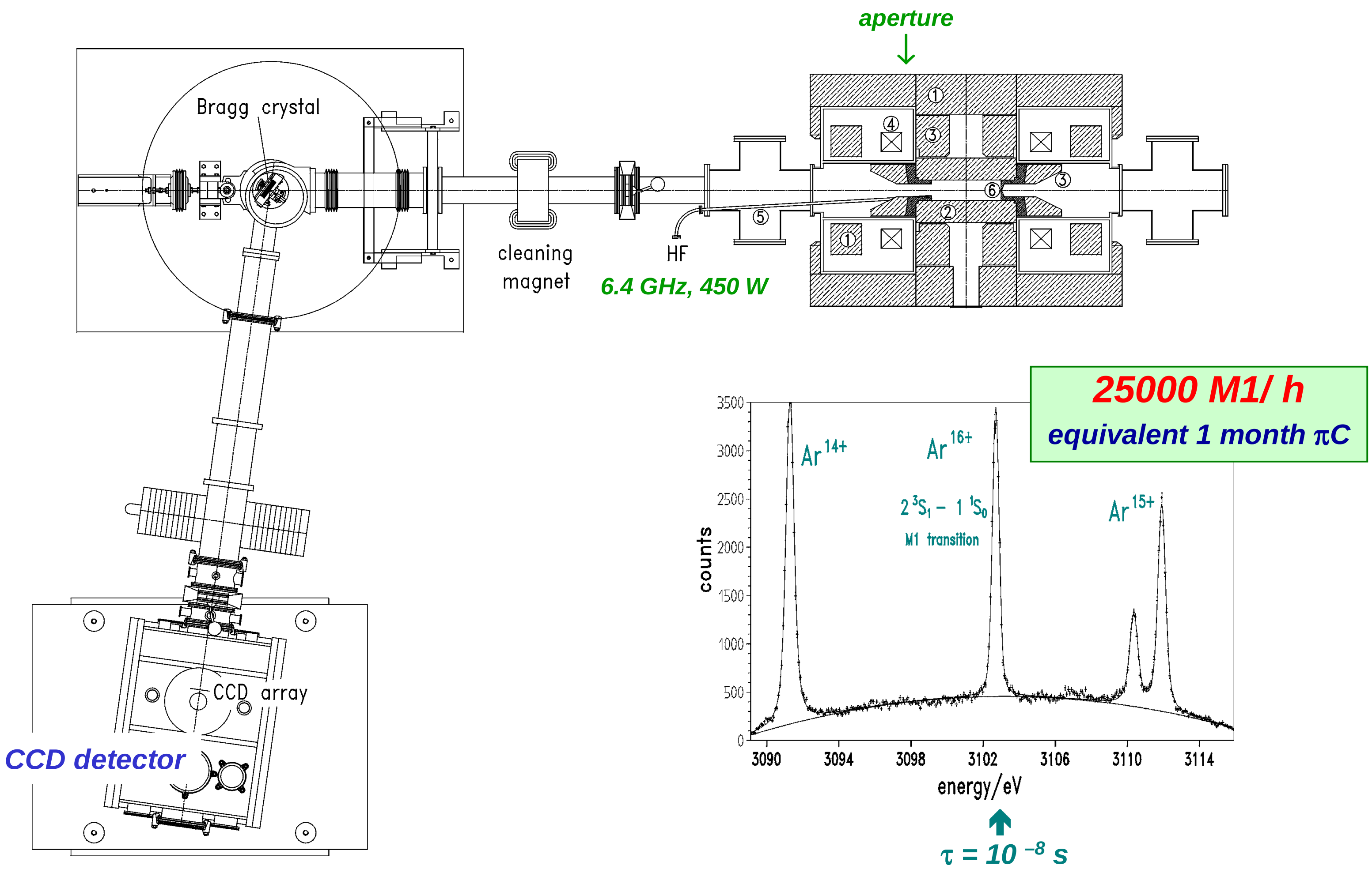
INSIDE HEXAPOLE



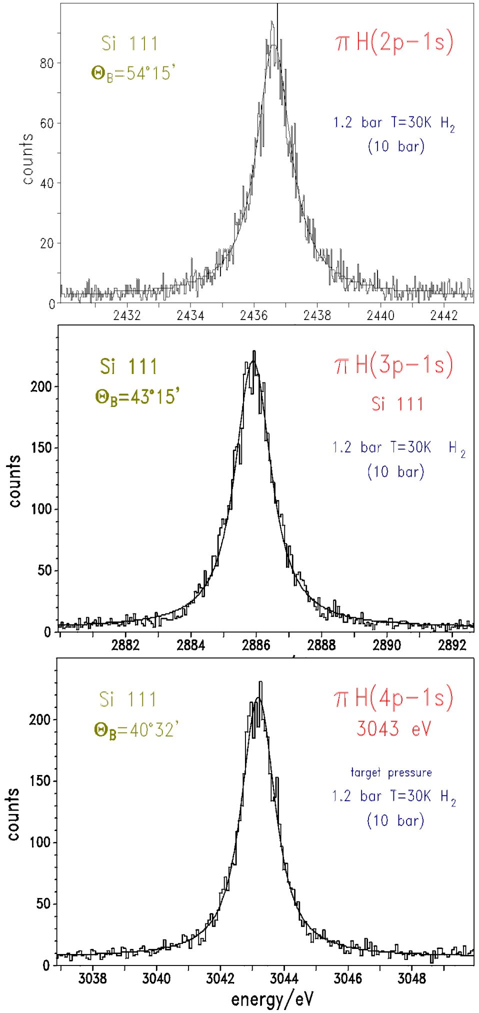
Cu end flange

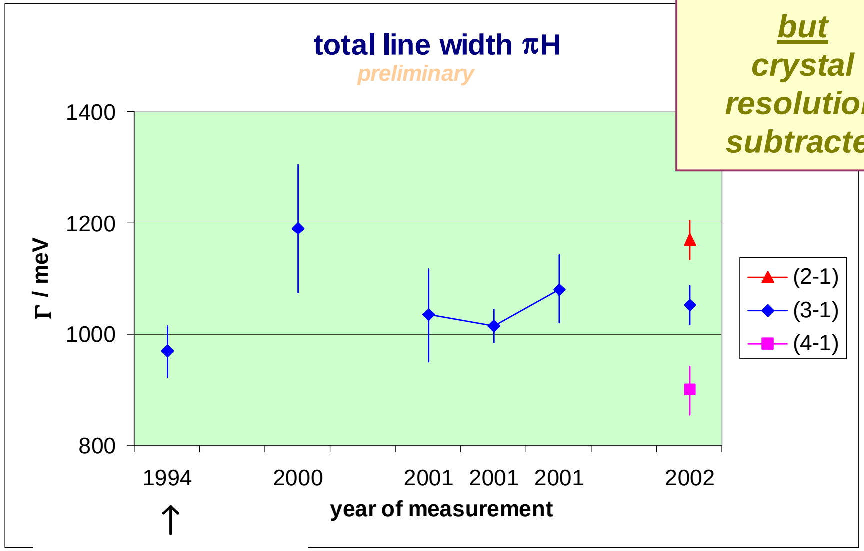
PSI ECRIT and CRYSTAL SPECTROMETER

D.F.Anagnostopoulos et al., Nucl. Instr. Meth. B 205 (2003) 9; subm. to Nucl. Instr. Meth. B 8/2004



LINE WIDTH and INITIAL STATE





not
corrected for Coulomb de-excitation

but
crystal resolution subtracted

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

Γ_{1s} < 850 meV

Maik Hennebach, *thesis Cologne 2003*

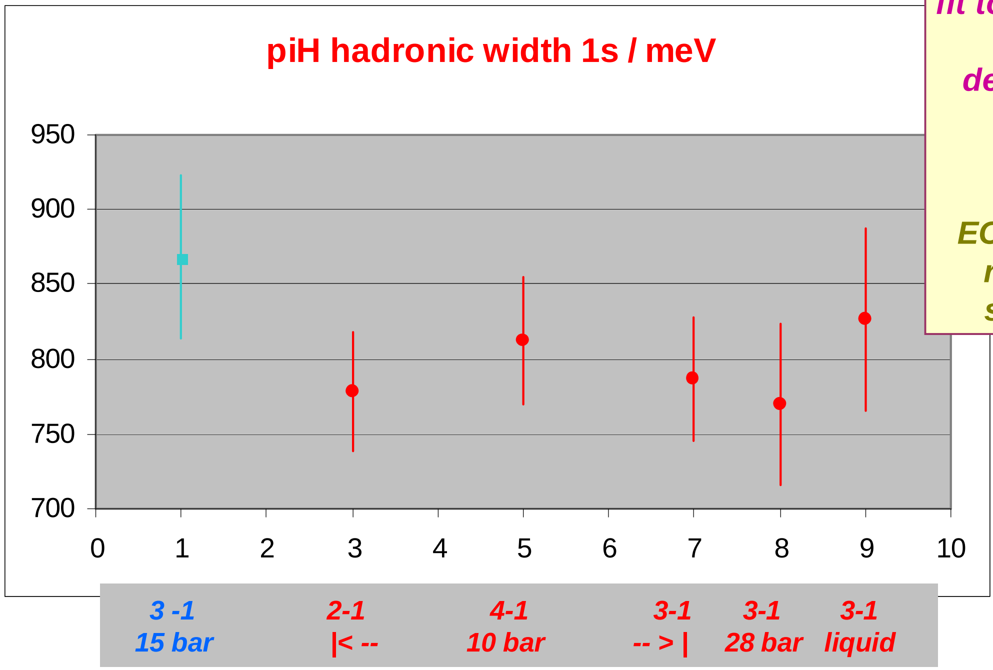
PEAK-TO-BACKGROUND ratio improved by one order of magnitude !

FIRST (2002) ECRIT RESULTS ***and*** ***HADRONIC WIDTH***

$\Gamma_{1s} \approx$ **865 ±69 meV (7%)** →

previous experiment

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



fit to boxes from Coulomb de-excitation

and

ECRIT crystal resolution subtracted

R-98.01 $\Gamma_{1s} \approx$ **800±30 meV** ***(3-4%)*** ***preliminary***

with forthcoming ECRIT measurements ***(→ 2.5% - 3%)***

πN SCATTERING LENGTHS

πH - hadronic shift ϵ_{1s}
&
πN s-wave isospin scattering lengths

Deser formula → incl. Coulomb - strong-int. interference

$$\epsilon_{1s} = -2\alpha^3 \mu_c^2 \mathcal{A}(1 - 2\alpha\mu_c (\ln\alpha - 1)\mathcal{A}) + \cdots$$

2nd order χPT

$$\mathcal{A} = a_{0+}^{+} + a_{0+}^{-} + \epsilon$$
$$= \frac{1}{8\pi(m_p + M_{\pi^+})F_\pi^2} \times \left\{ m_p M_{\pi^+} - \frac{g_A^2 m_p M_{\pi^+}^2}{m_n + m_p + M_{\pi^+}} + m_p(-8c_1 M_{\pi^0}^2 + 4(c_2 + c_3)M_{\pi^+}^2 - 4e^2 f_1 - e^2 f_2) \right\},$$

O(δ^2) in δ = q,
α =1/137,
(m_d-m_u)

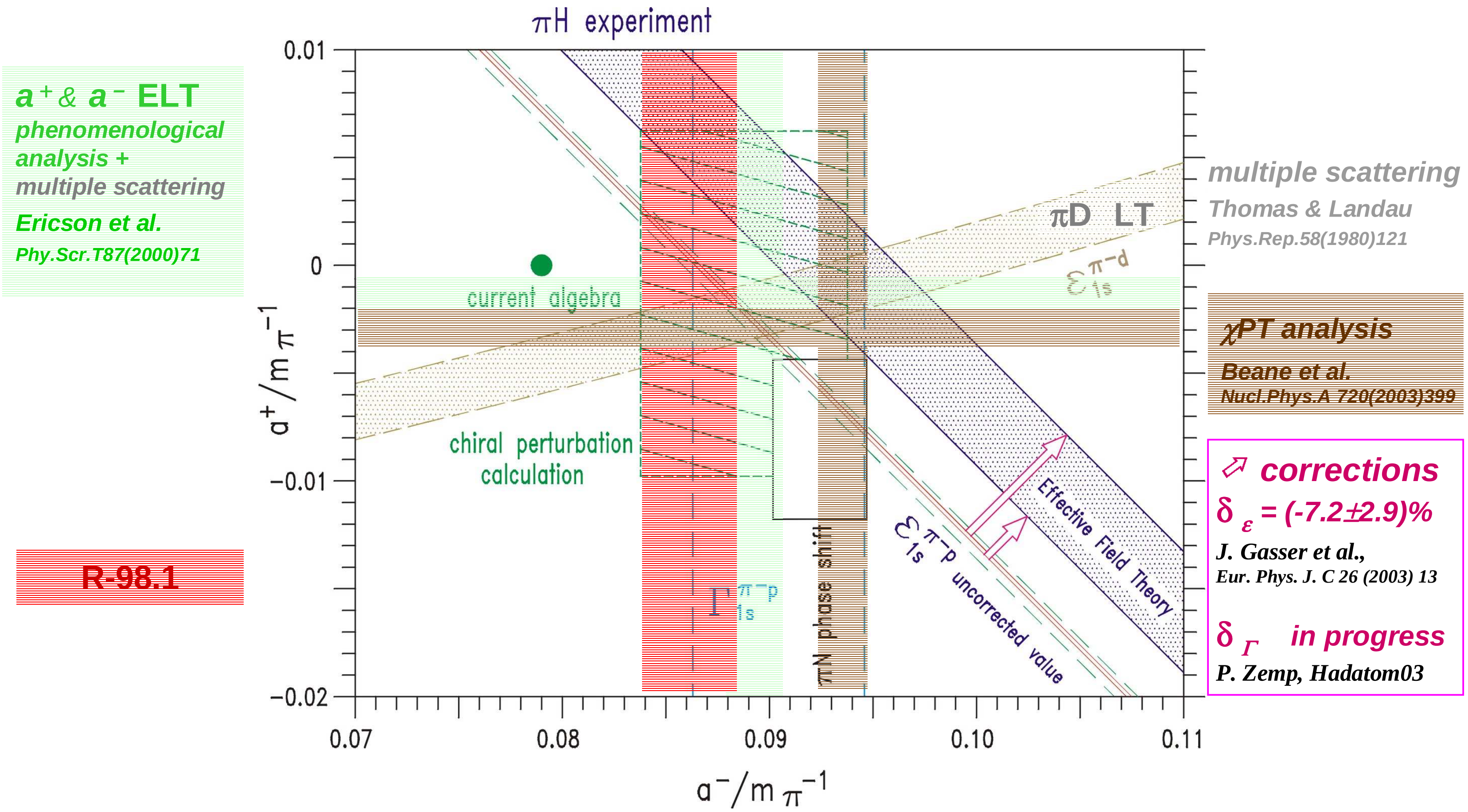
LECs f_1, f_2, c_1 contribute to isospin breaking in O(δ^2)

accuracy of prediction O(10%)

V.E. Lyubovitskij & A. Rusetsky, Phys. Lett. B 494(2000)9

V.E. Lyubovitskij et al., Phys. Lett. B 520(2001)204

πN scattering lengths $a^{\pm}$



● *current algebra* *Weinberg, Tomozawa '66* **π*N phase shift*** ***KH 1980***

- - HBχPT 3rd order *Fettes, Meissner, Steininger NP A640(1998)199*

πN coupling constant $f^2_{\pi N}$

Goldberger- Miyazawa-Oehme (GMO) sum rule

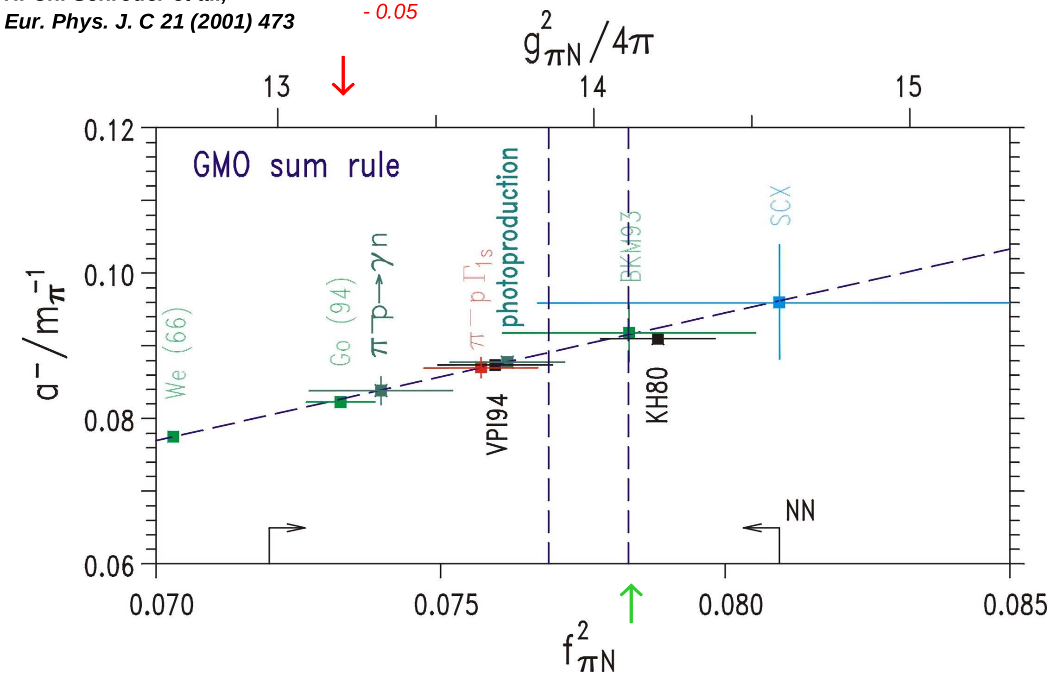
$$\left(1+\frac{m_\pi}{M}\right)\frac{a^-}{m_\pi}=\frac{2 f^2_{\pi N}}{m^2_\pi-(m^2_\pi/2M)^2}+\frac{1}{2\pi^2}\int_0^\infty\frac{\sigma^{tot}_{\pi^- p}(k_\pi)-\sigma^{tot}_{\pi^+ p}(k_\pi)}{2\omega(k_\pi)}dk_\pi$$

$\Delta\int\approx 1\%$

previous πH exp.

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

$13.21^{+0.11}_{-0.05}$



ε_{1s} $\pi^- H$ $a_{\pi^- p\to\pi^- p}$

ε_{1s} $\pi^- D$ 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

$13.89^{+0.23}_{-0.11}$ 14.11±0.20 **Ericson, Loiseau & Thomas**

Phys. Rev. C 66 (2002) 014005

πD - hadronic shift ε_{1s}
&
πN s-wave isospin scattering lengths

d ≈ *p* + *n* *corrections!*

$a_{\pi^- p} + a_{\pi^- n} = (a_{1/2} + 2a_{3/2})/3$
$= 2a^+$ *isoscalar scatt. length*

$$\frac{\varepsilon_{1s}}{B_{1s}} = -\frac{4}{r_B}\Re a^{had}_{\pi^- d}$$ *Deser formula*

$$\Re a^{had}_{\pi^- d} = 4\frac{M+m_\pi}{2M+m_\pi}a^+ + SS + DS + HC + AB$$

SS single scattering
DS double scattering (≈ 60%)
HC higher orders
AB absorptive corrections

↓

$\Re\, a_{\pi d} = -0.0261 \pm 0.0005 / m_\pi$

↓

$\Re\, a_{\pi d} \leftrightarrow a^{\pm}$

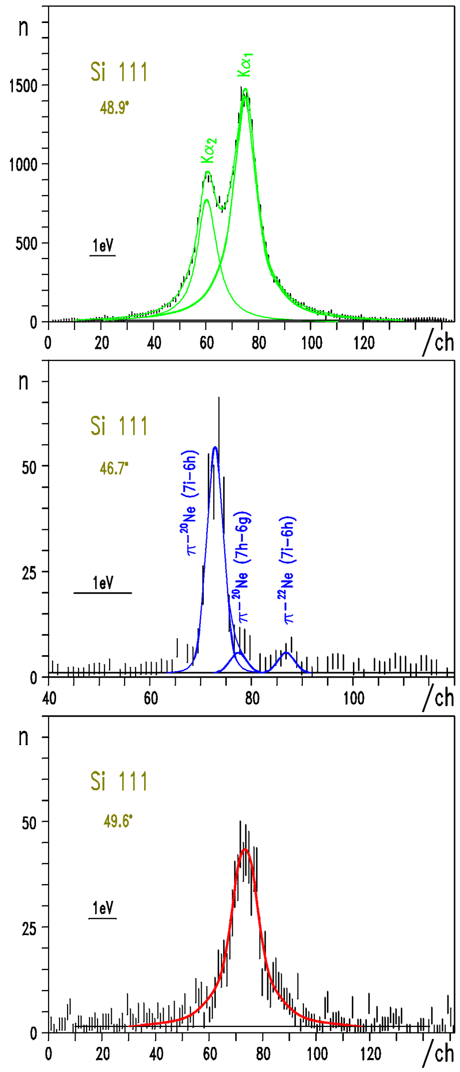
experiments

D. Chatellard et al., NPA 625(1997)855
P. Hauser et al., PRC 58(1998)R1869

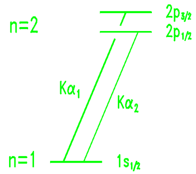
calculations

Beane, Bernard, Lee, Meissner, PR 57 (1998) 424
Ericson, Loiseau & Thomas, PR C 66, 014005 (2002)
Beane, Bernard, Epelbaum, Meissner, Phillips NPA 720 (2003)399
Rusetski et al., in progress
...

PIONIC DEUTERIUM



energy calibration I

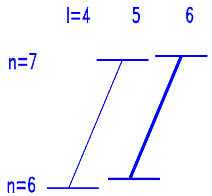


Cl Kα

2.62 keV

15 min

response function I

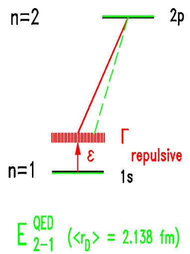


πNe(7-6)

2.72 keV

12 h

strong interaction



πD(2p-1s)

2.60 keV

15 h

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

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

final approach to

COULOMB DE-EXCITATION

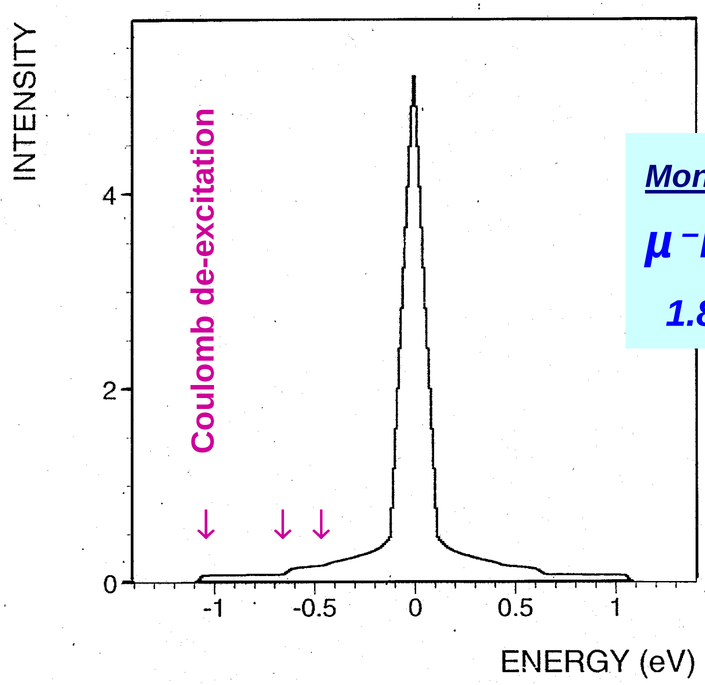
muonic hydrogen

MEASURED LINE SHAPE	**=**	**R**	$\otimes$	~~**L**~~	$\otimes$	Σ **D**
		crystal		Γ_{1s}		**Doppler broadening**
		resolution		↑		***Coulomb de-excitation***

MUONIC HYDROGEN

to quantify Coulomb de-excitation

Line shape of X-ray transitions



Monte-Carlo simulation

μ^-H (2p-1s) @ 15 bar

1.89 keV

cascade model calculation (V.E. Markushin – PSI)

KAONS

kaon - nucleon interaction

low-energy approach of QCD - χPT

including the "heavy" light s quark

no dedicated kaon facility in the world

KEK experiment   PS-E-228

first unambiguous observation of K⁻ H X-rays

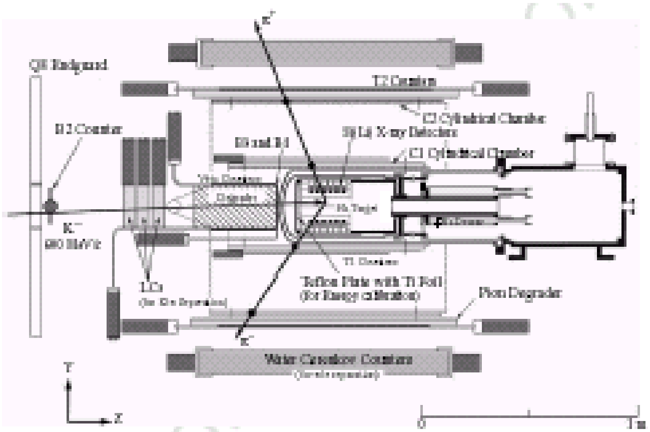
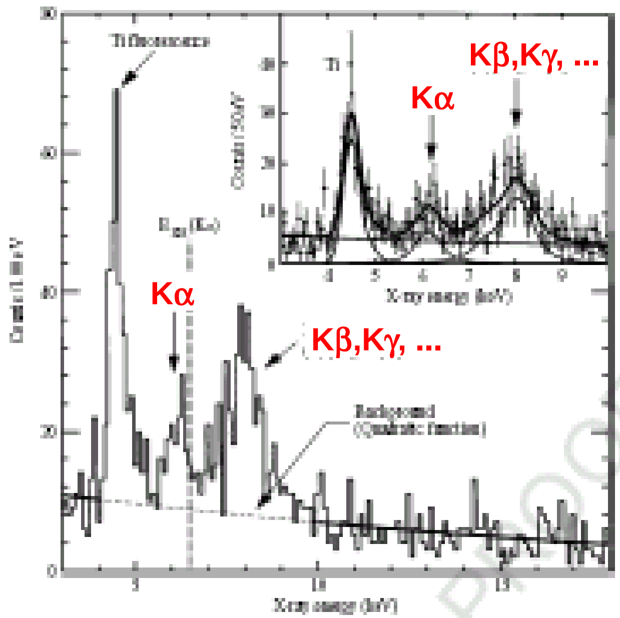


Fig. 8. The set-up of the kaonic hydrogen experiment at KEK (from [210]). Kaons are stopped in hydrogen gas cooled to 100 K at a pressure of 4 bar.

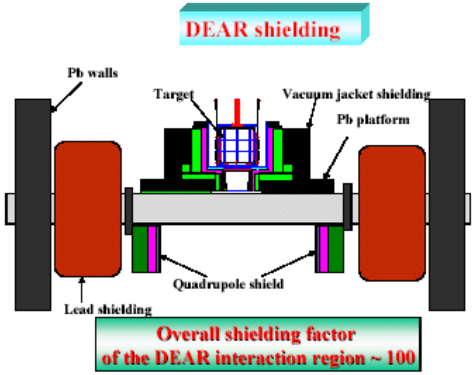


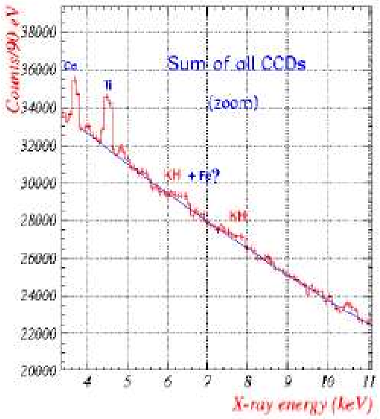
π/ K= 90

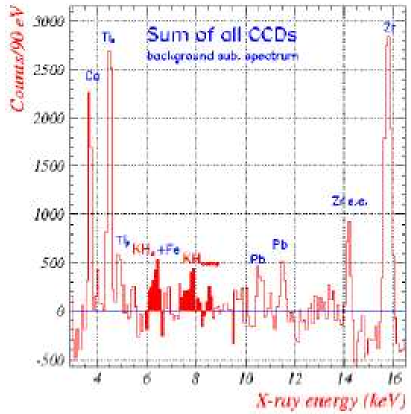
trigger on decay products necessary

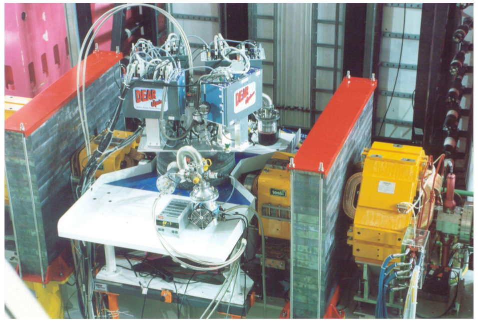
M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067
T. M. Ito et al., Phys. Rev. C 58 (1998) 2366

DEAR collaboration @ $e^+ e^-$ collider DAΦNE







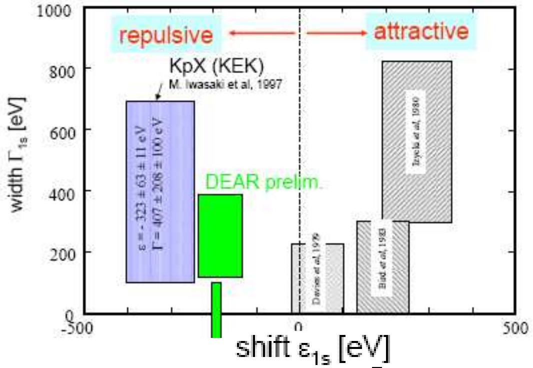


K_α = 3100 +/- 1300 ev.

$K_{complex}$ = 6800 +/- 2400

ε = (162 +/- 40) eV

Γ = ~(200+/- 80) eV



next step - triggerable X-ray detctors *again* **KH**

→ *silicon drift detectors* SIDDHARTA *for the first time* **KD**

SUMMARY

LIGHT PIONIC ATOMS

		$\Delta\varepsilon_{1s}/\varepsilon_{1s}$	$\Delta\Gamma_{1s}/\Gamma_{1s}$
πH	D. R-98.01	0.2%	1% (2005)
πD	D. Chatellard et al. (1994) P. Hauser et al. (1998)	2%	12%
π^3He	I.Schwanner et al. (1979) NP A 412 (1984) 253	10%	25%
πT		---	---

χPT

a^+, a^-, $f_{\pi N}$

$\pi^- p \leftrightarrow \pi^- n$

isospin breaking (1-2%)

$\pi^3He \pm \pi T$

$\Rightarrow a^+, a^-$

LIGHT KAONIC ATOMS

		$\Delta\varepsilon_{1s}/\varepsilon_{1s}$	$\Delta\Gamma_{1s}/\Gamma_{1s}$	
KH	*DEAR*	**25%**	**40%**	a_{Kp}
				χPT including s quarks
	SIDDHARTA	**few %** *≥2006*		
KD	*SIDDHARTA*	**few %** *planned*		a_{Kn}
				isospin amplitudes a_0, a_1
K^4He		**25%**	**60%** *no plans*	*puzzling !!!*

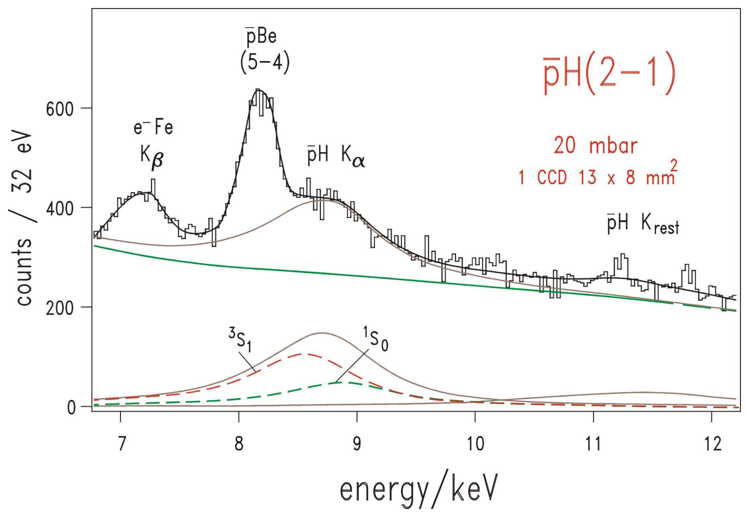
~~KAON / EHF~~ → NOAK

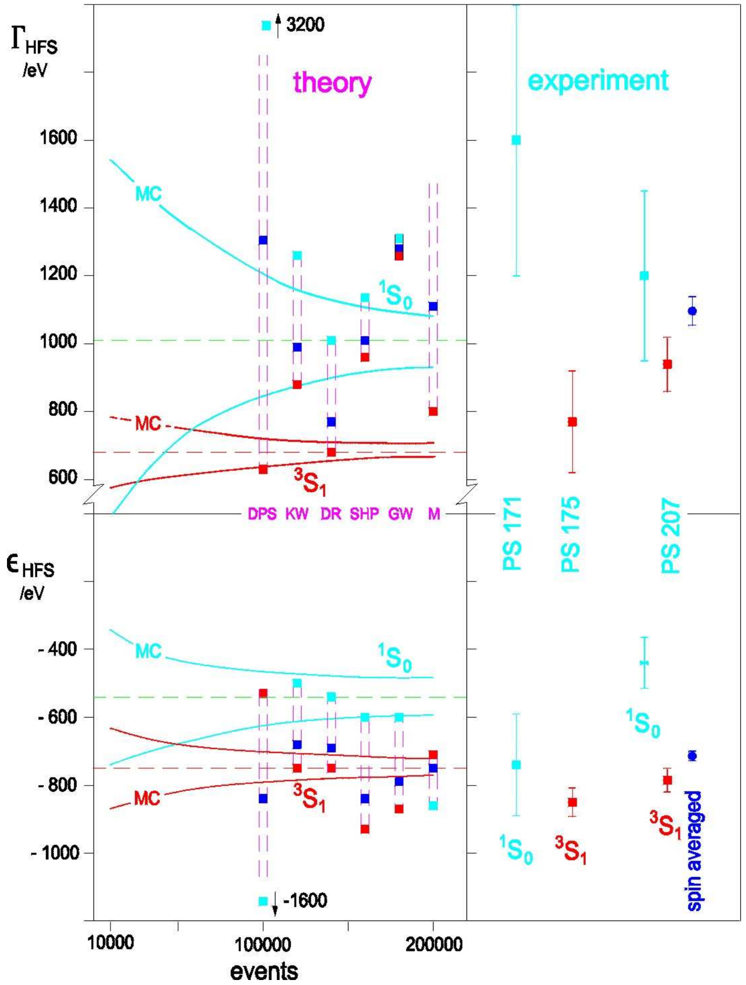
LIGHT ANTIPROTONIC ATOMS

$\bar{p}p$ $\bar{p}d$	**s- and p-wave**	$^1S_0$ / $^3S_1$ ground state	spin-spin interaction
light $\bar{p}$ atoms		$\bar{p}p$ and $\bar{p}n$	annihilation strength (A)

AD / FLAIR GSI ?

PROTONIUM ground state





	ε / eV	Γ / eV
Spin average	- 714 ± 14	1097 ± 42
$^1S_0$	- 440 ± 75	1200 ± 250 *
$^3S_1$	- 785 ± 35	940 ± 80 *

* fixed $^1S_0$ / $^3S_1$ ratio
background from $\bar{p}D$

M. Augsburger et al., NP A 658 (1999) 149

fight (for survival) at PSI

prepare for FLAIR