LIGHT ANTIPROTONIC ATOMS

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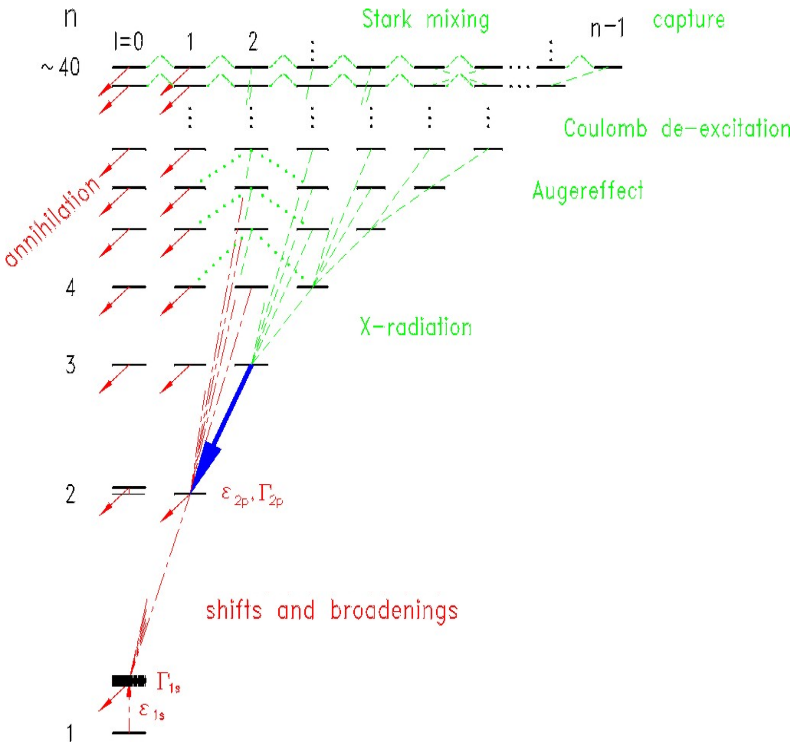
atomic cascade in hydrogen



X-ray intensities - density dependence

de-excitation of atomic cascade

X-ray energy - bound state QED

strong interaction

hadronic shift ε

hadronic width Γ

NUCLEON-ANTINUCLEON potential

scattering lengths $a \propto \varepsilon - i\Gamma/2$

STRONG INTERACTION

goals

$A \leq 4$ nuclei

hadronic effects in s, p, and d waves

• $\bar{p}p$	***s*-wave**	*spin-spin interaction*
• $\bar{p}d$	$\bar{p}n$	*isospin*
• $\bar{p}p$, $\bar{p}d$	***p*-wave**	*spin-orbit interaction* *bound states*
• $\bar{p}A(N,Z)$		*annihilation strength* *baryon-antibaryon asymmetry*

THEORETICAL DESCRIPTION

$$V_{\mathrm{Coulomb}} + U_{\mathrm{hadronic}}$$

U_{hadronic} = meson exchange + annihilation

scattering: $\bar{p}p \leftrightarrow \bar{p}p$

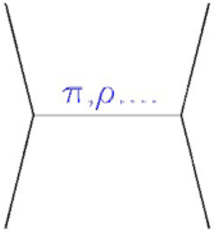
$\bar{p}p \leftrightarrow \bar{n}n$

$\bar{p}p \rightarrow$ mesons

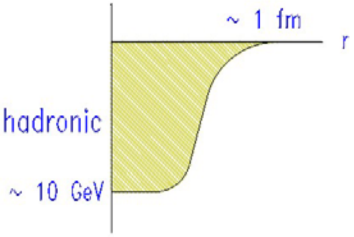
$NN \xrightarrow{\text{G-parity}} \bar{N}N$

$U \propto a\,\rho(r)$

Re U_{hadronic}



Im U_{hadronic}



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

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

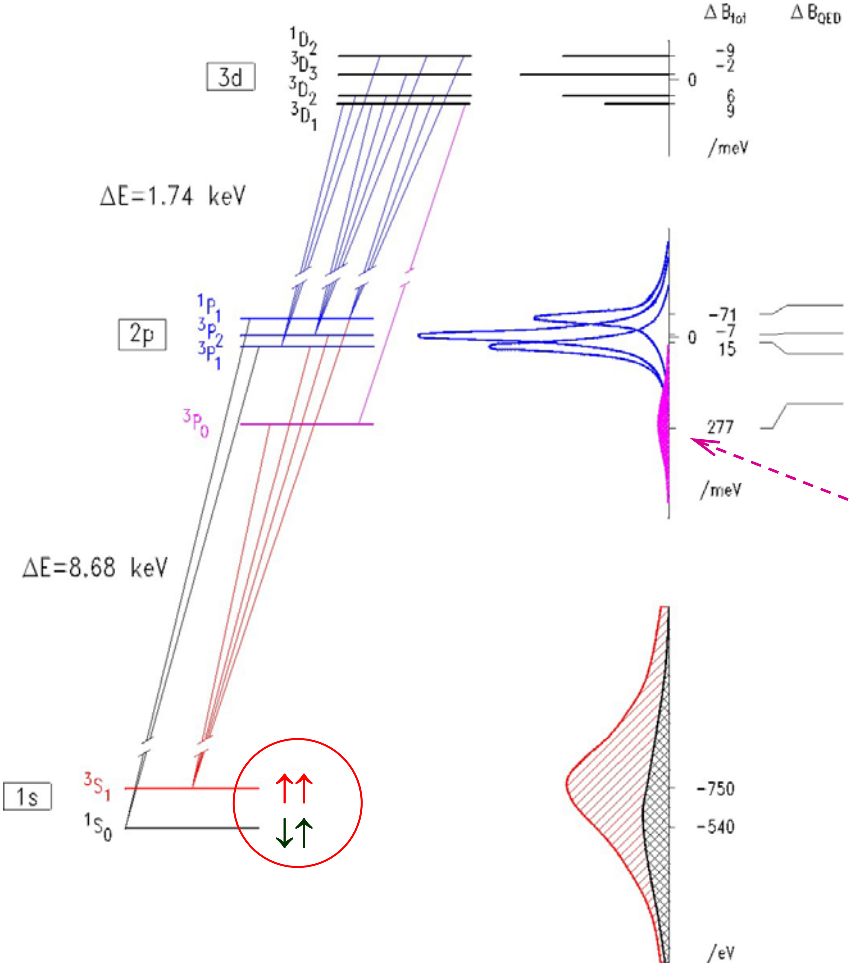
spin-spin "deuteron"
spin-orbit effects

no microscopic theory

☞ ***check spin dependence !***

PROTONIUM - hyperfine states

s- and p-state strong interaction effects



d state

strong interaction negligible

p state

spin-orbit interaction

meson exchange:
strongly attractive
isoscalar tensor interaction

Richard, Sainio, Phys. Lett. B (1982)349

s state

spin-spin interaction

$\varepsilon > 0$ (<0) ≡ attractive (repulsive) interaction

HISTORY

strong-interaction effects in A ≤ 4

pre - *LEAR experiments* *1974 – 1980*

targets

Si(Li), Ge ^{4}He

LEAR experiments *1983 – 1996*

1983 - 1988

- **PS171** *XDC* H_2
- **PS174** *Si(Li), GSPC* H_2 D_2 ^{4}He

- **PS175** *cyclotron trap* H_2 D_2 ^{3}He ^{4}He
  Si(Li), Ge, XDC

1984 - 1996

- **PS207** *cyclotron trap* H_2 D_2
  crystal spectrometer
  CCDs

EXPERIMENT

general considerations

stopped antiprotons

PRESSURE DEPENDENCE

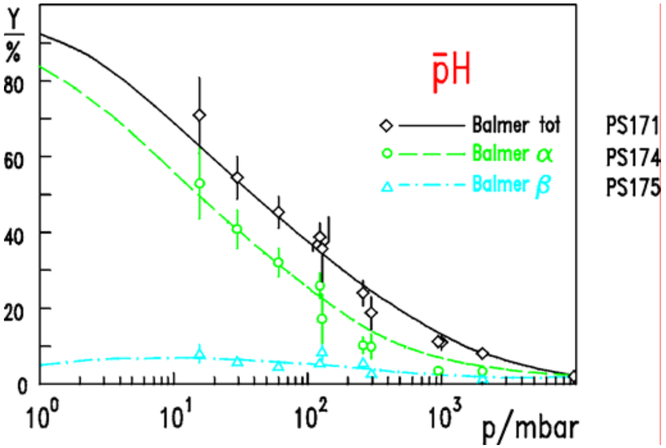
of atomic cascade

- **collisions** → ***Stark-mixing***

  low X-ray yields

- **2p state** $\Gamma_{X\text{-ray}} << \Gamma_{annihilation}$

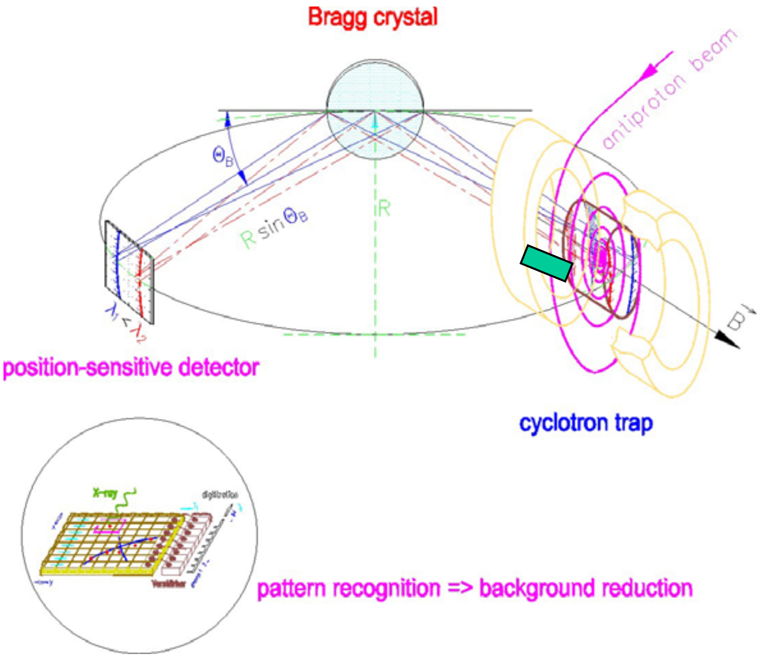
  $K\alpha$ X-ray yield < 1%



DEMANDS

for precision experiments

- ***high yield X-ray yields***
- ***ultimate energy resolution***



high annihilation induced background

PS207 - LEAR

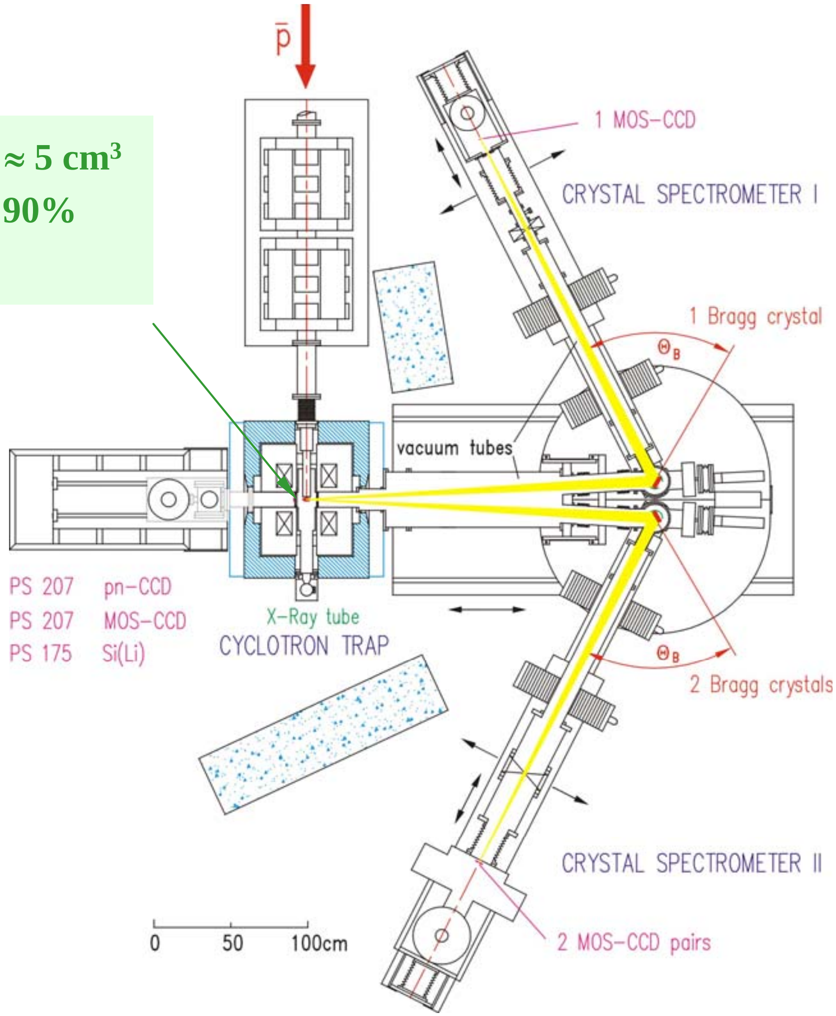
105 MeV/c

10^6 / s

stop volume ≈ 5 cm^3

stop efficiency 90%

at $p = 16$ mbar



energy determination	*energy resolution*
few 10^{-6}	*few 10^{-4}*

STRONG INTERACTION

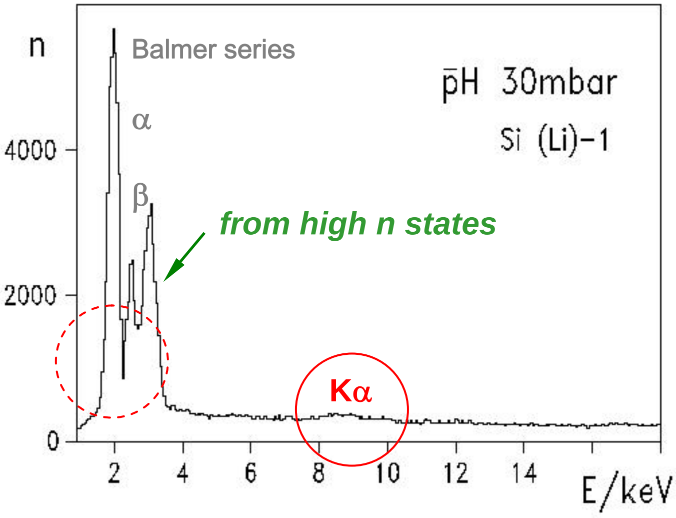
results

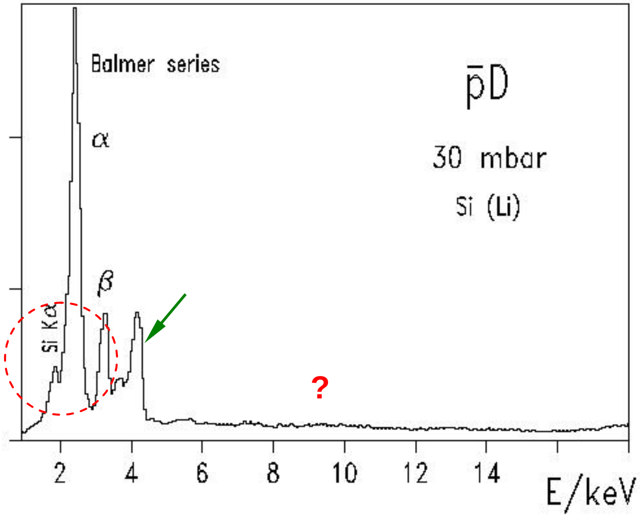
ANTIPROTONIC HYDROGEN

two different energy ranges

crystal spectrometer

direct measurement





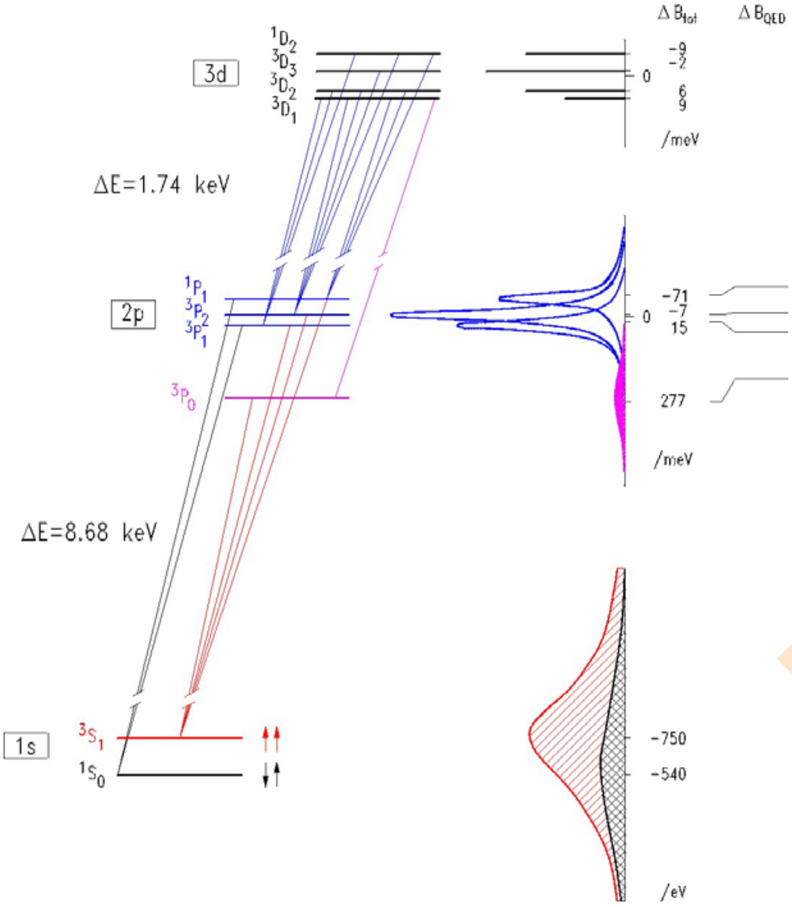
PS175: K. Heitlinger et al., Z. Phys. A 342 (1992) 359

main problems

Hydrogen

PROTONIUM - 1s ground state

cyclotron trap + MOS CCD

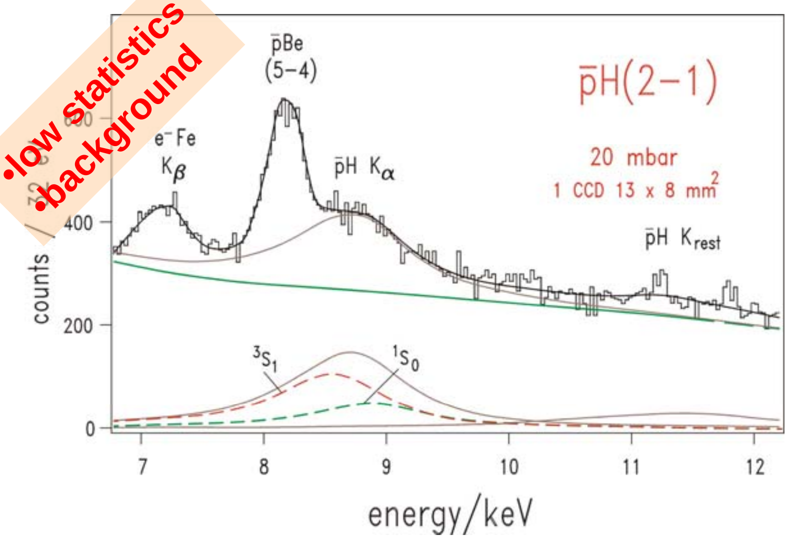


LEAR experiment PS207

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

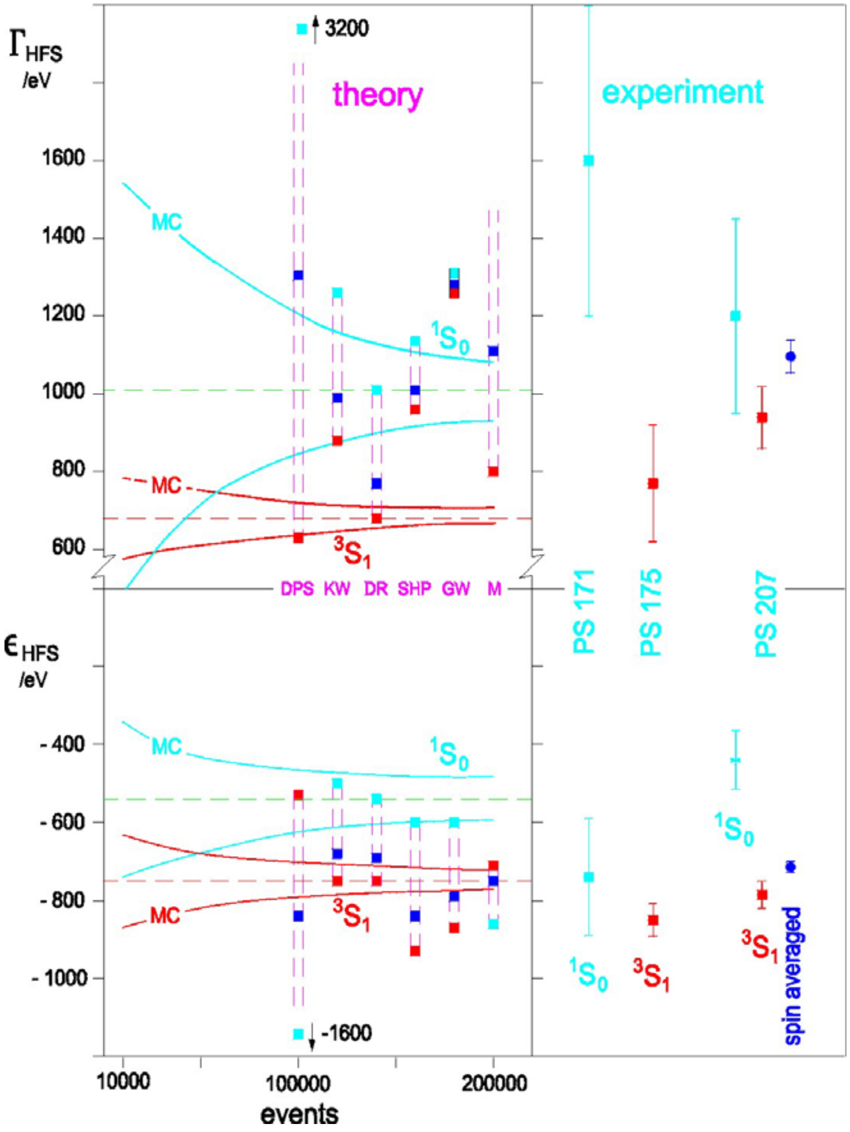
	ε / eV	Γ / eV
spin average	- 714 ± 14	1097 ± 42
$^1S_0$	- 440 ± 75	1200 ± 250 *
$^3S_1$	- 785 ± 35	940 ± 80 *

* fixed $^1S_0$ / $^3S_1$ ratio
background from pD



- low statistics
- background

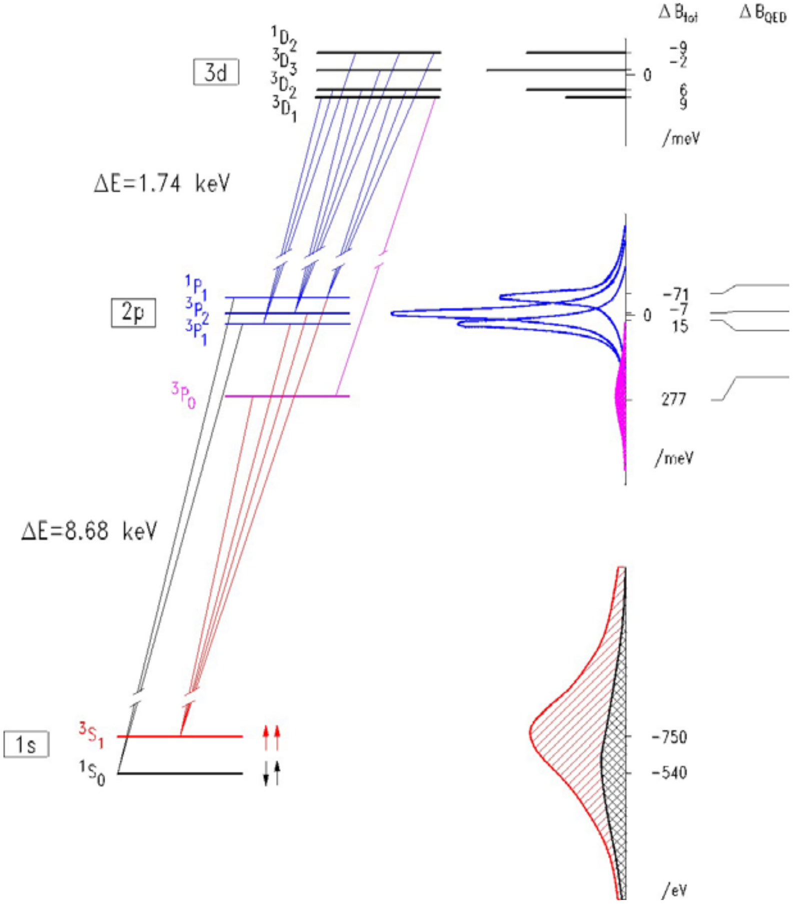
comparison theory - experiment



How well known is the splitting ?

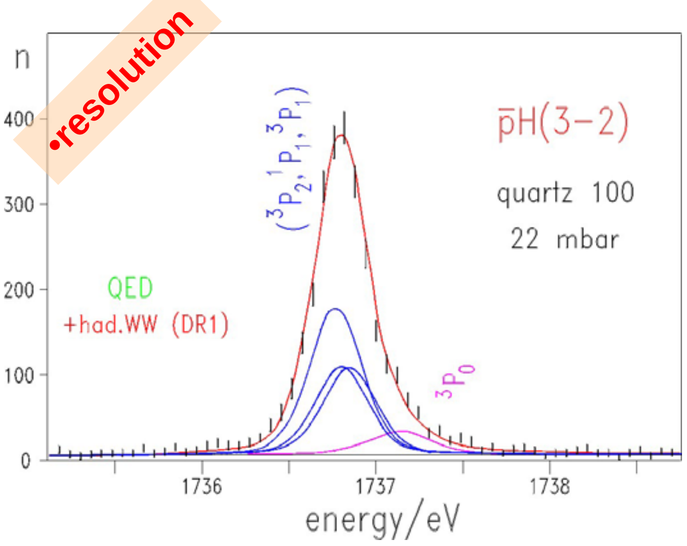
PROTONIUM - 2p state

cyclotron trap + crystal spectrometer



LEAR experiment PS207

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



•resolution

	ε / meV	Γ / meV
spin average	+ 15 ± 20	38.0 ± 2.8
$^3P_0$	+ 139 ± 38	120 ± 25

bound states ?

J. Carbonell, Nucl. Phys. A 692 (2001) 11

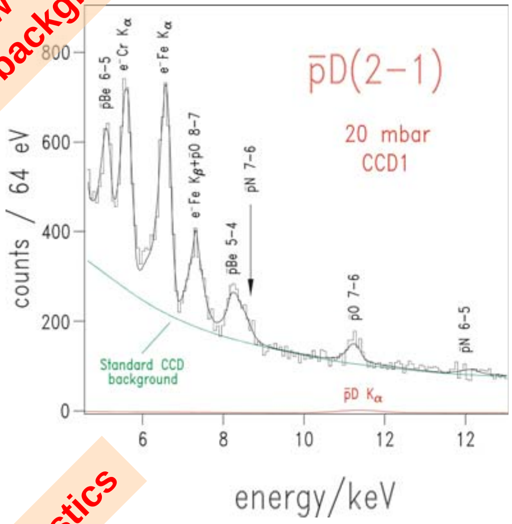
Deuterium

Antiprotonic DEUTERIUM

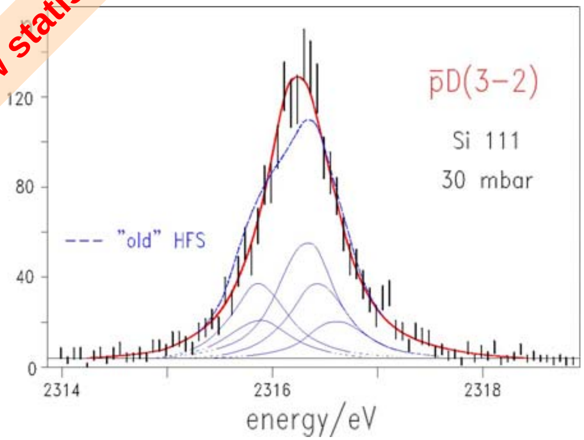
s- and p-state strong-interaction effects

LEAR experiment PS207

•low statistics
•background



•low statistics



- ***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

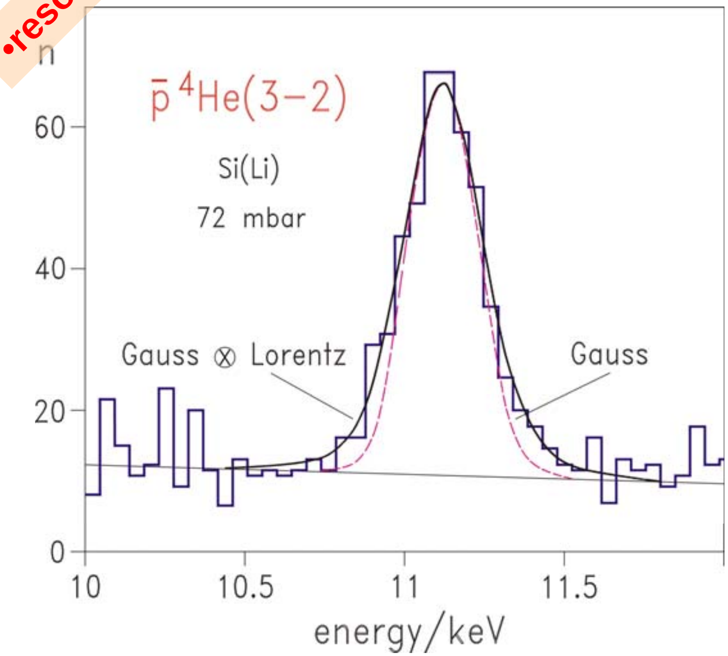
Helium

Antiprotonic HELIUM

isotope effects

•resolution

LEAR experiment PS175



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

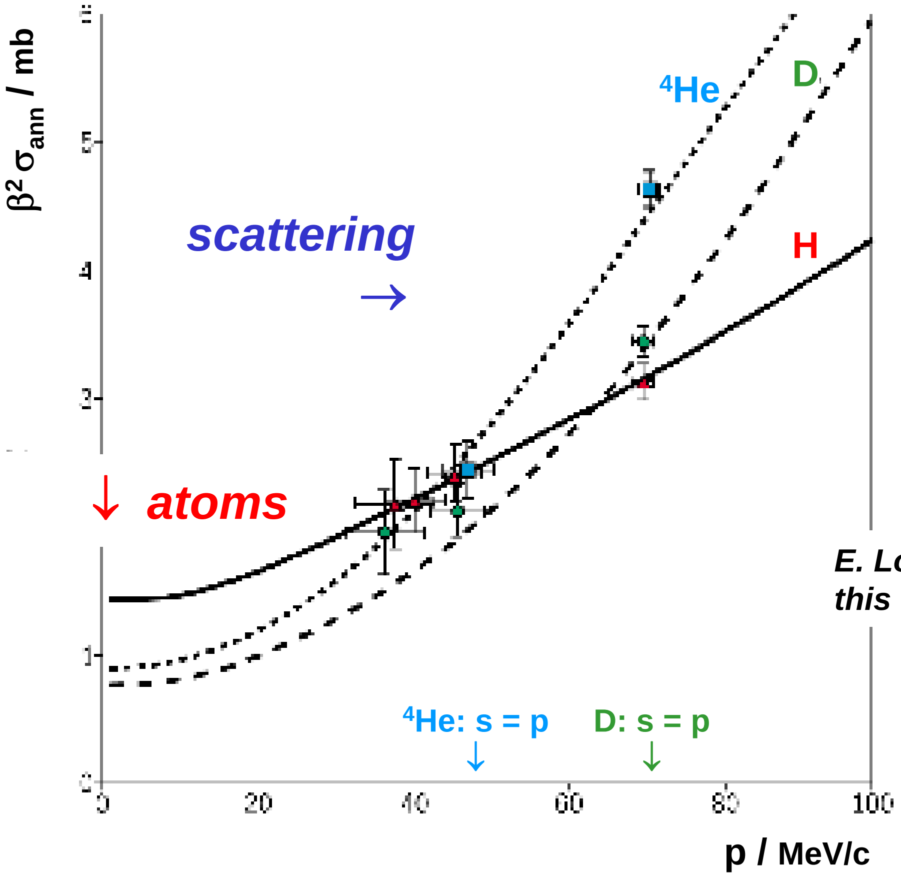
spin average		ε	Γ	
$\bar{p}\,^{3}$He	2p	-17 ± 5	25 ± 9	eV
	3d*		2.14 ± 0.18	meV
$\bar{p}\,^{4}$He	2p	-18 ± 2	45 ± 5	eV
	3d*		2.36 ± 0.10	meV

* *from intensity balance*

single - nucleon annihilation ?

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

annihilation cross section



E. Lodi-Rizzini, this workshop

	Trueman formula	*fit*
Im a_s	- 0.69±0.3	- 0.69±0.04 fm
Im a_p	- 0.77±0.6	- 0.75±0.07 fm^3

striking agreement

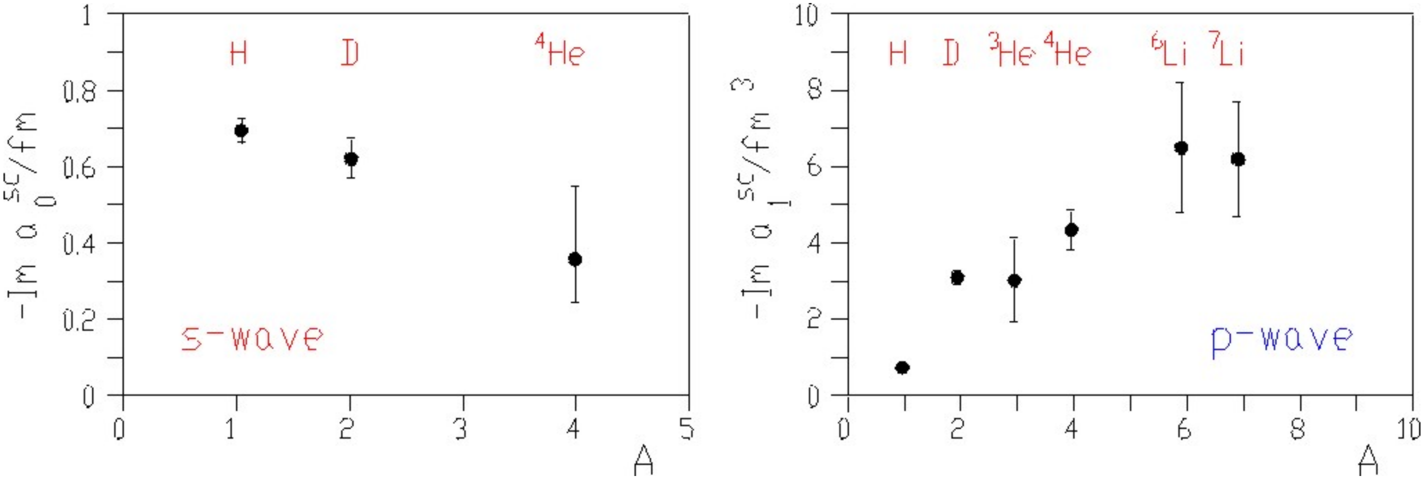
discussion and references: K. Protasov et al., Eur. Phys. J. A 7 (2001) 429

ANNIHILATION STRENGTH

vs.

atomic weight

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



S. Wycech,
this workshop

saturation ?

seen also in optical potential analyses

$$U_{opt} \propto a \cdot \rho(r)$$

A. Gal, E. Friedman and C.J. Batty, Phys. Lett. B491 (2000) 219

qualitatively – strong annihilation suppresses wave function inside matter

e. g. $\varepsilon_{1s} < 0$ **for** $\bar{p}p$

Relative annihilation on p,n - isospin I = 0,1

$$R^{\text{free}}_{s-\text{wave}} = \frac{\bar{p}n}{\bar{p}p} = \frac{a_{I=1}}{\tfrac{1}{2}\left(a_{I=0} + a_{I=1}\right)} = 1.14 \pm 0.13$$

$\bar{p}H$ & $\sigma_{\bar{n}p}$

$$R^{\text{bound}} = 0.78 \pm 0.03$$

$\bar{p}D$ streamer chamber

?

$$R^{\text{bound}} = 0.45 \pm 0.04$$

$\bar{p}\,{}^{3,4}\text{He}$ streamer chamber

Balestra et al.
Nucl. Phys. A 491 (1989) 541 and ref. therein

$$\frac{{}^{3}\text{He}}{{}^{4}\text{He}} = 0.84 \pm 0.02$$

single-nucleon annihilation dominates

$$\frac{\Gamma({}^{3}\text{He})}{\Gamma({}^{4}\text{He})} = 0.83 \pm 0.12$$

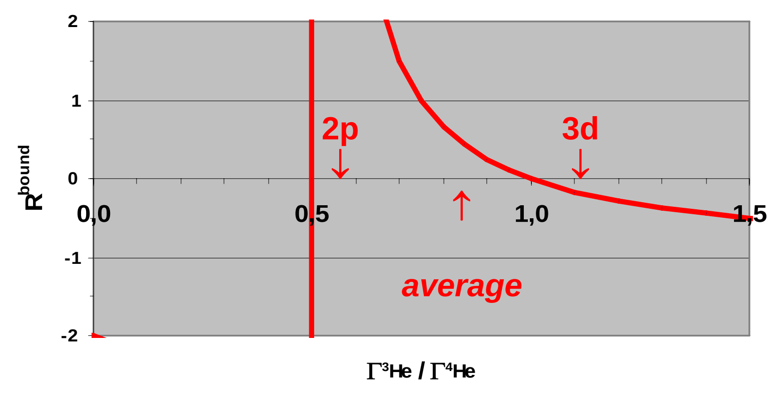
average 2p + 3d

atomic state: 50% p- + 50% d-wave

cascade calculation – G. Reifenröther et al., Th. Jensen

$$\frac{\tilde{\Gamma}({}^{3}\text{He})}{\tilde{\Gamma}({}^{4}\text{He})} = \frac{2 + R^{\text{bound}}}{2 + 2R^{\text{bound}}}$$

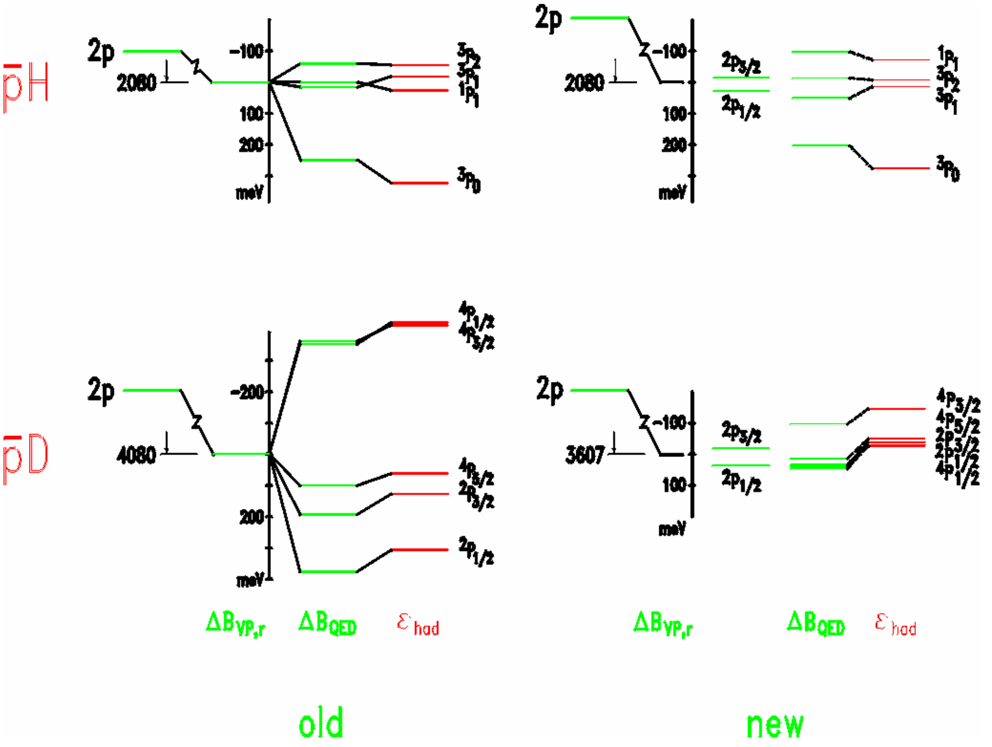
$$\tilde{\Gamma} = \Gamma \quad \textit{corrected for different overlap}$$

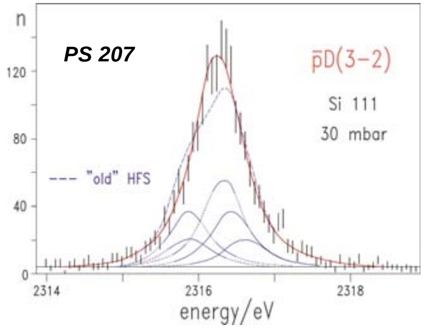


BOUND STATE QED

example ***antiprotonic Hydrogen***

2p hyperfine splitting





S. Boucard and P. Indelicato, to be published
Veitia, Pachucki, Phys. Rev A 69 (2004) 042501

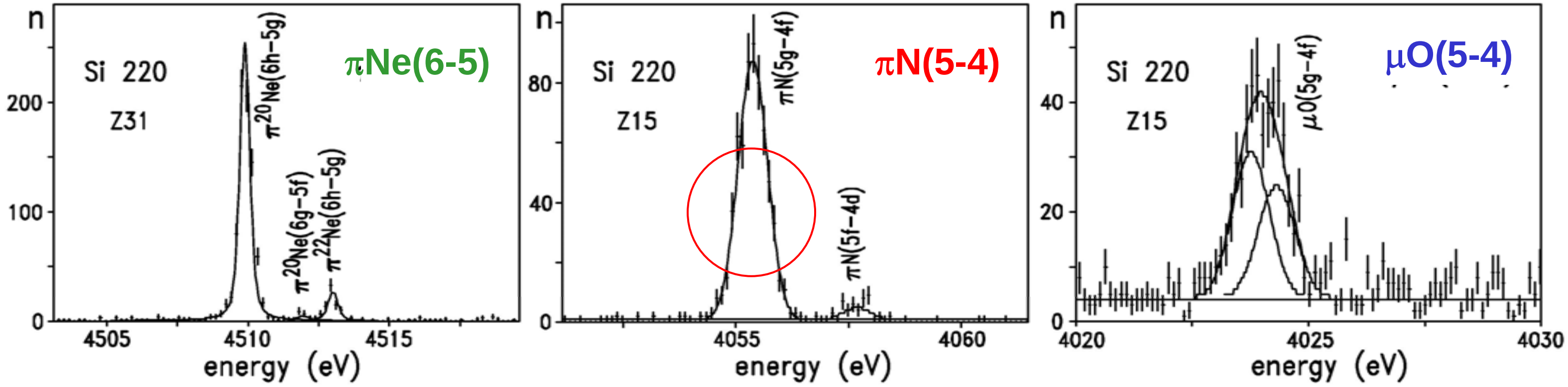
discussion see D. Gotta, Prog.Part.Nucl.Phys. 52 (2004) 133

CAPTURE & CASCADE

COULOMB EXPLOSION

atoms and molecules

response function
ΔE = 520 meV



$\Delta E_{Doppler} \approx$ 800 ± 100 meV
$\Rightarrow q_1 \cdot q_2 \approx 9 \pm 2$

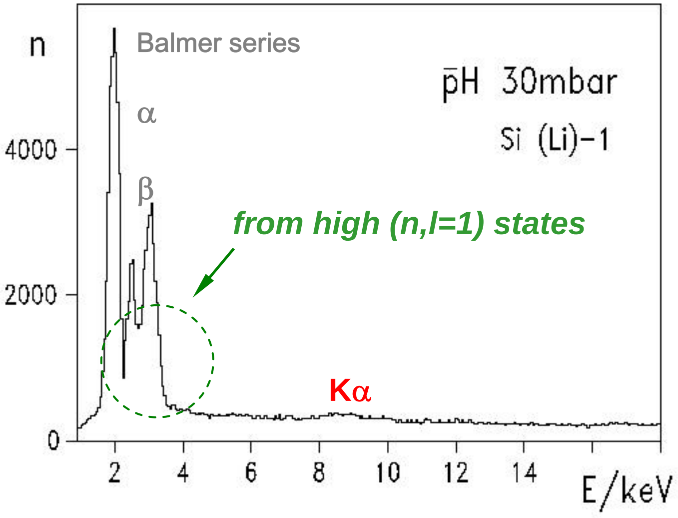
$\approx$ 900 ± 300 meV
$\Rightarrow q_1 \cdot q_2 \approx 19 \pm 10$

T. Siems et al., Phys. Rev. Lett. 84 (2000) 4573

- ***symmetric molecules N_2, O_2***
- ***compounds CO_2, C_2H_2, C_2H_2***

ANTIPROTONIC HYDROGEN - series limit

high np states populated in contrast to μH, πH



from high (n,l=1) states

$$n_{max} \approx \sqrt[3]{2n_f^2 \Big/ \left(\Delta E / E_{\infty - n_f}\right)}$$

$n_{max} \approx 40$ for $\Delta E = 300$ meV

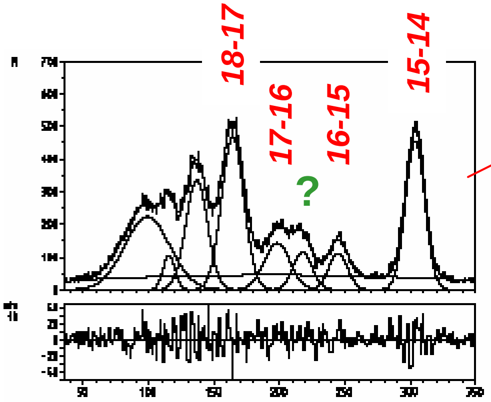
n_{max} : resolvable state
n_f : final state

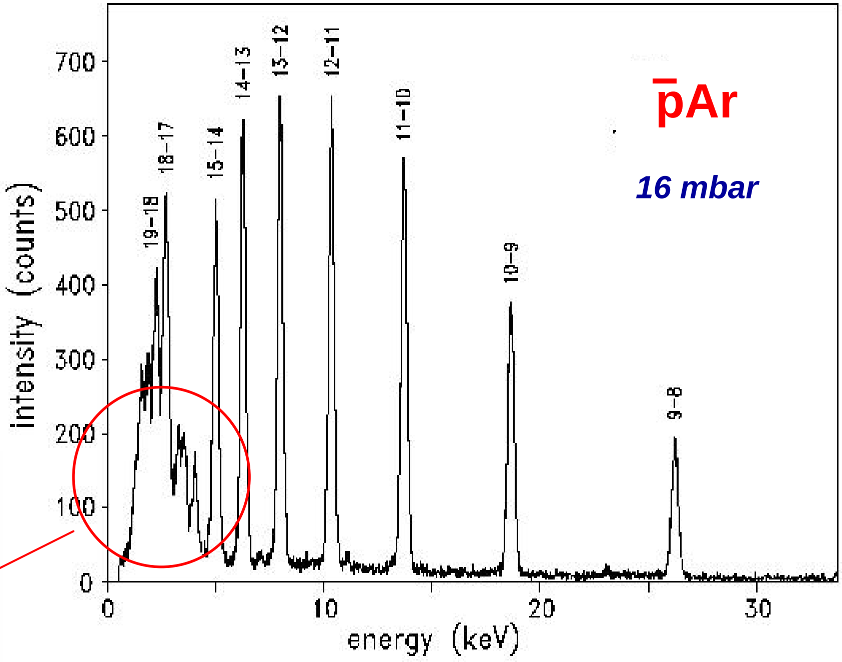
ΔE : energy resolution
$E_{\infty - n_f}$: transition energy from series limit

more "microscopic" cascade theory
Jensen
Markushin

ELECTRONIC X-RAYS - ARGON

**Auger
vs.
radiative
de-ecxcitation**

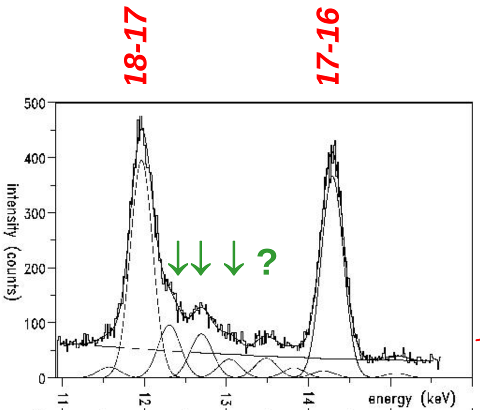




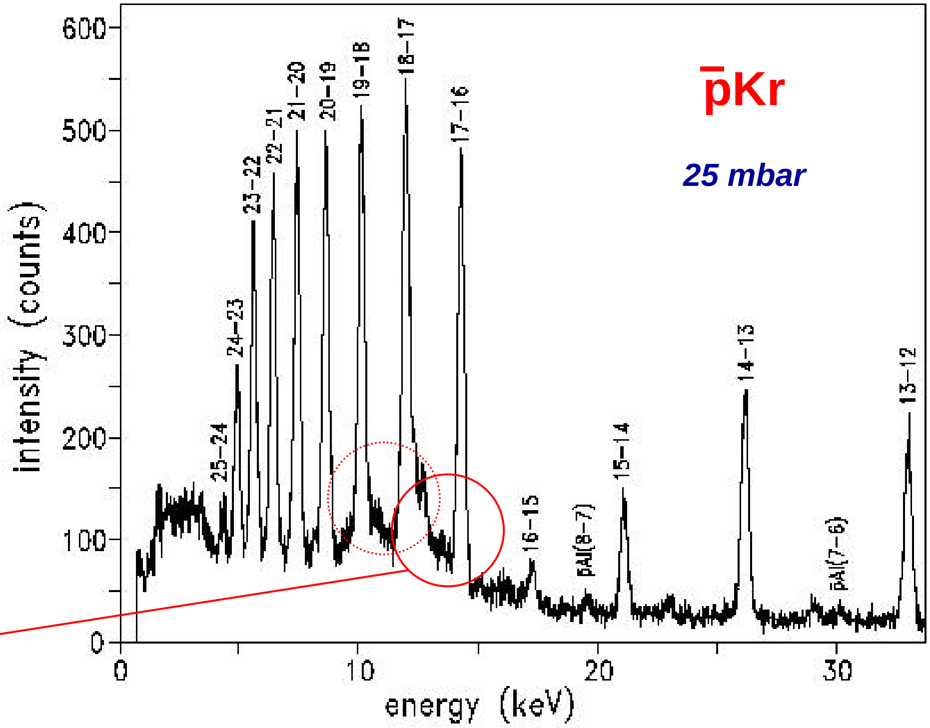
data: PS175
analysis Rashid et al.

ELECTRONIC X-RAYS - KRYPTON

**de-ecxcitation
of
remaining
electron shell**

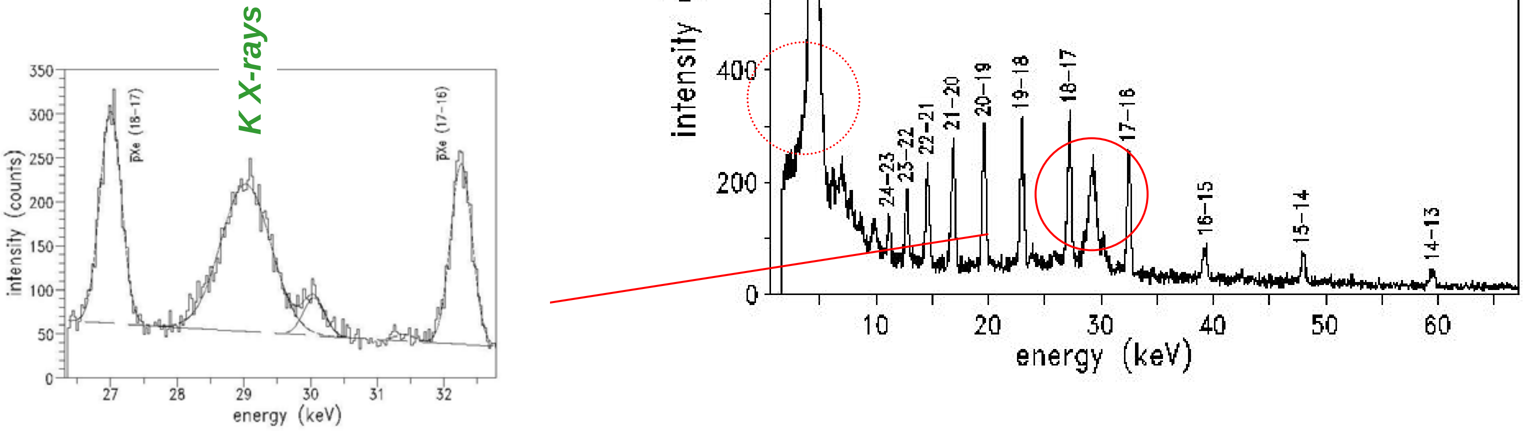


many unresolved lines ?



ELECTRONIC X-RAYS - XENON

**de-ecxcitation
of
remaining
electron shell**



TOOL KIT

antiproton „beams“

AD ***MUSASHI*** — *antiproton trap → DC extraction → gas cell*

direct measurements

FLAIR — *high intensity DC beams*

direct measurements + crystal spectrometer

future option — *traps and gas jets*

X-ray detector *direct measurement* — *fast CCDs*

A. Ackens et al., IEEE vol. 46 (1999) 1995 → *pixel size 75 μm*

H. Gorke, this workshop → *600 frames / s*

crystal spectrometer

2 – 3 keV *ultimate resolution* — ΔE = 300* → 200 meV

asymmetric cut crystals

10 keV *„bad“ resolution* — 300* → „1 eV“

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* *PS 207 and PSI ECRIT (D. Anagnostopoulos et al., to be pub in NIM A)*

SUMMARY

- *$\bar{p}p$ $^1S_0$ / $^3S_1$*
- *$\bar{p}d$ ground state*
- *$\bar{p}p$, $\bar{p}d$ p-states*
- *$\bar{p}A(N,Z)$*
- *bound-state QED*
- *capture and cascade*

AD

+ ***FLAIR***

↑
crystal spectrometer