Precision Spectroscopy at High Fields: The case for antiprotonic ions

- *Formation of antiprotonic atoms in dilute gases leads to highly-charged ions*
- *Antiproton ends up in high-n maximum l orbits (weak strong interaction effects)*
- *Very interesting information can be learnt for atomic structure*

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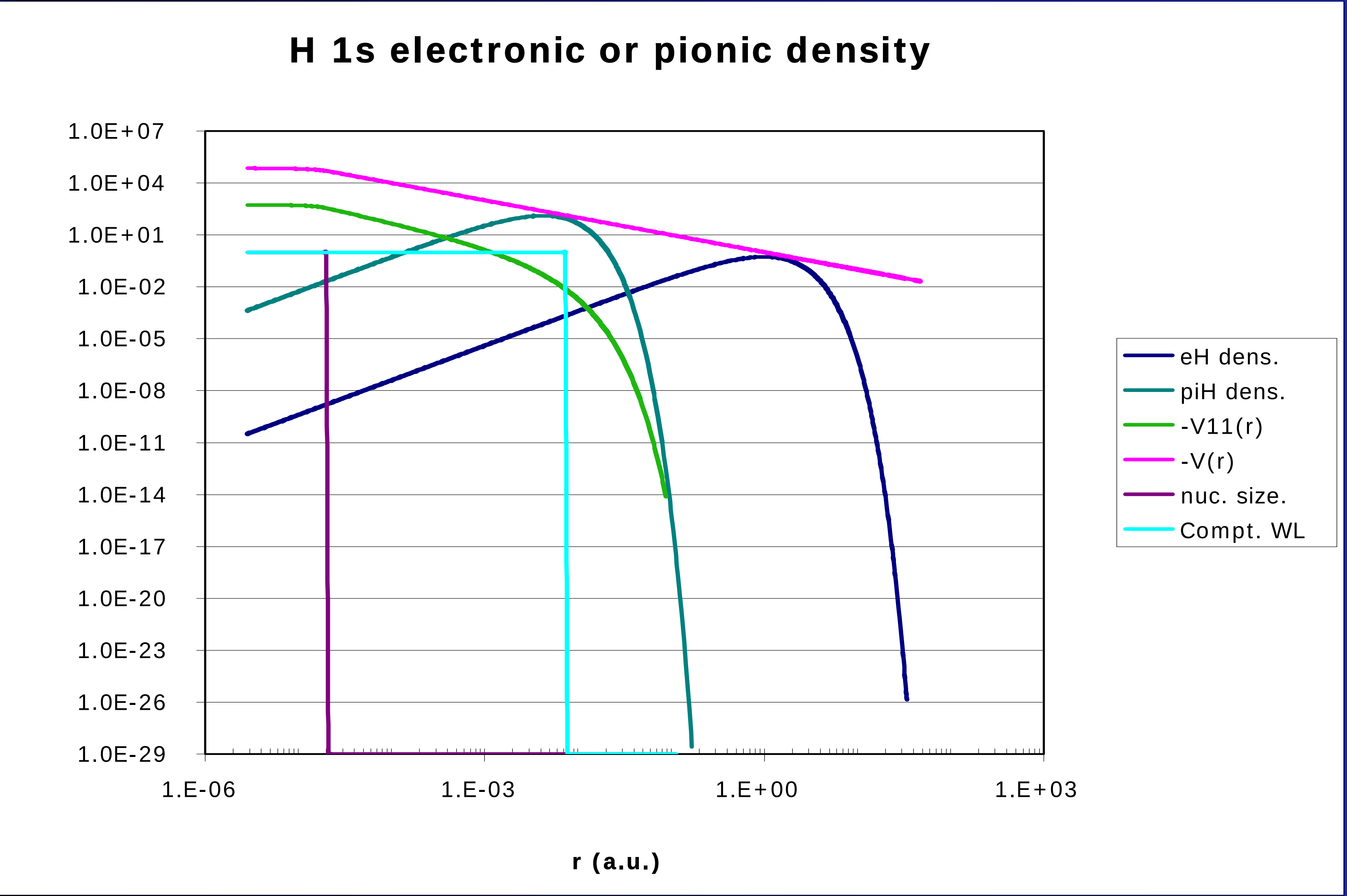
A Few Facts for BSQED in Antiprotonic Atoms

- Vacuum Polarization dominates QED effects for antiprotonic transitions
- Not much is known for two-body corrections (recoil+QED corrections, Hyperfine structure) in non-leptonic atoms
- Hyperfine and fine structure as well as corrections due to anomalous magnetic moment of the antiproton are of the same order of magnitude and must be accounted for to same accuracy
- At some level it becomes difficult to separate from strong-interaction and hadronic effects

Hydrogen Scales



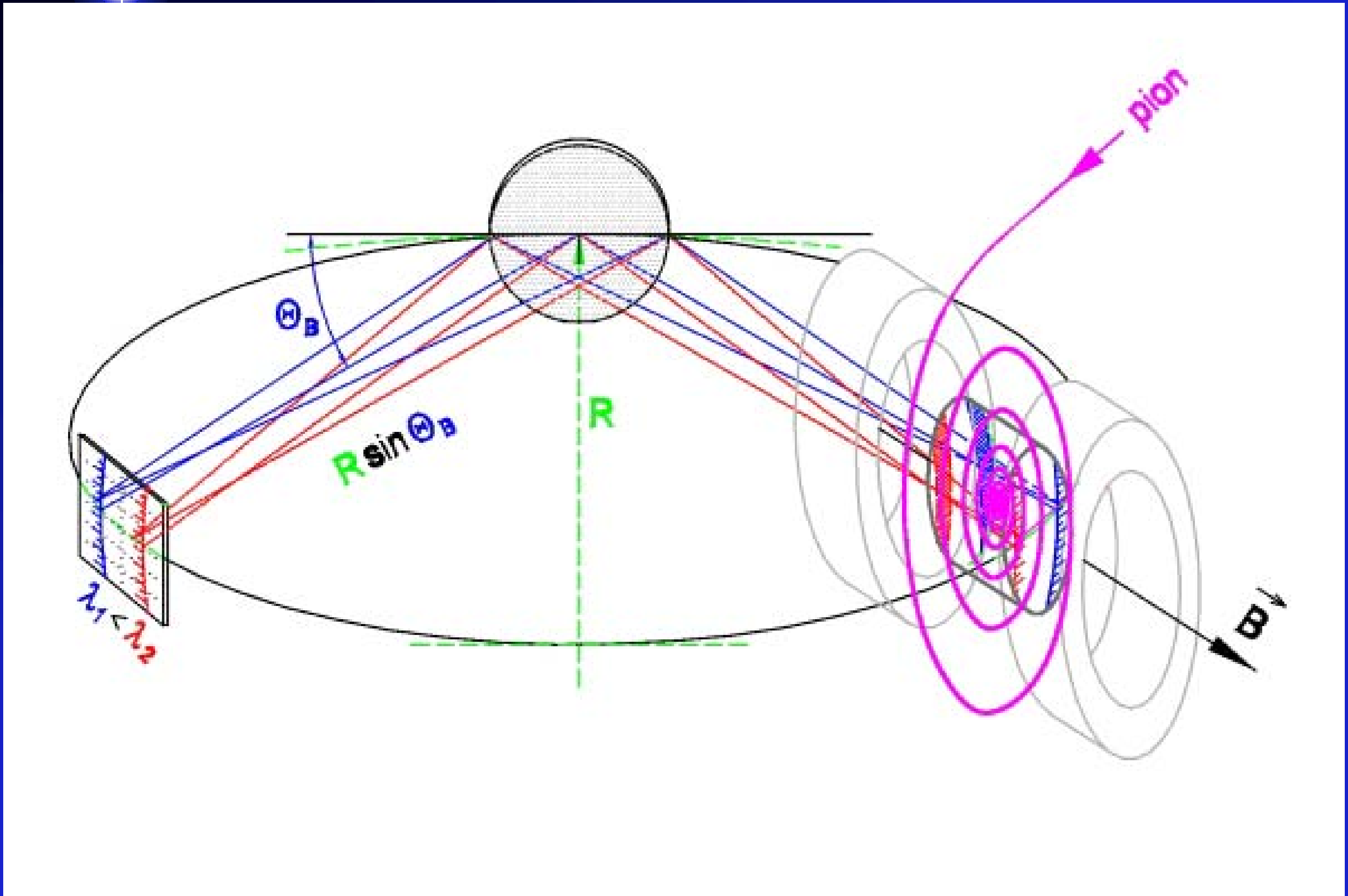
An mostly unexplored world

- If one except the metastable states of the $He^{++}\ e^{-}\ p^{-}$ system (the so-called atomcule) which has been studied in detail by laser spectroscopy (ASACUSA experiment) very little is known
- Only a few spectra at low resolution from capture on light gases and Ne, Ar, Kr and Xe have been performed
- A few cases have been studied by high resolution crystal spectroscopy at CERN LEAR, just before it closed.
- Those experiments required about 5×10^{8} antiproton/hour, about 1.5 order of magnitude more than available at the AD and slow extraction

Principle of the experiment

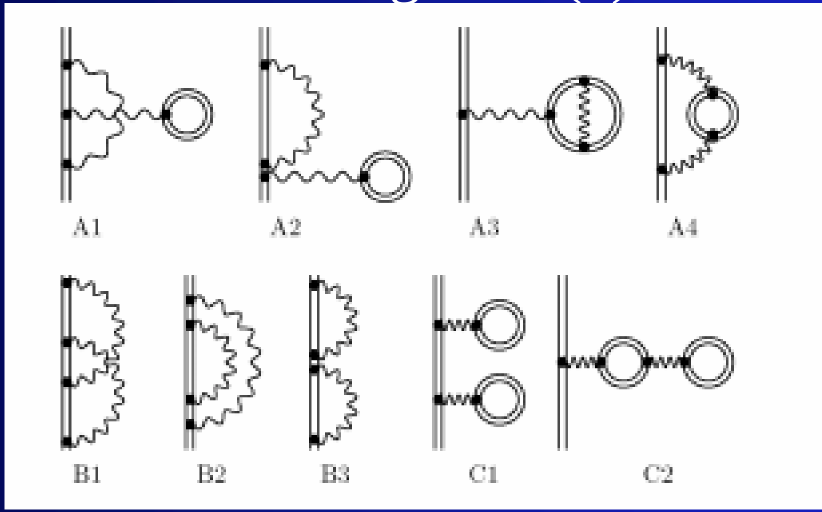
- Uses Anticyclotronic Trap II
- Capture on dilute gaz
- High efficiency, High Resolution Bragg Spectrometer
- Slow extraction required
- Incoming beam momentum ~105 MeV/c
- 96% of incoming antiprotons stopped at the center of the trap (antiprotons are STABLE)
- Could be extracted if necessary

Schematic of the experiment



QED Contributions to 3d-2p transitions in antiprotonic hydrogen

- Vacuum polarization of order ($Z\alpha$) 1.8 eV on 1.7 keV
- Vacuum polarization of order α ($Z\alpha$) 15 meV (Kàllén & Sabry A3+C2)+2.2 meV (Loop after Loop C1 to all orders)
- Self-energy and mixed diagrams (?)



- Relativistic and QED Recoil corrections beyond usual ones need to be investigated

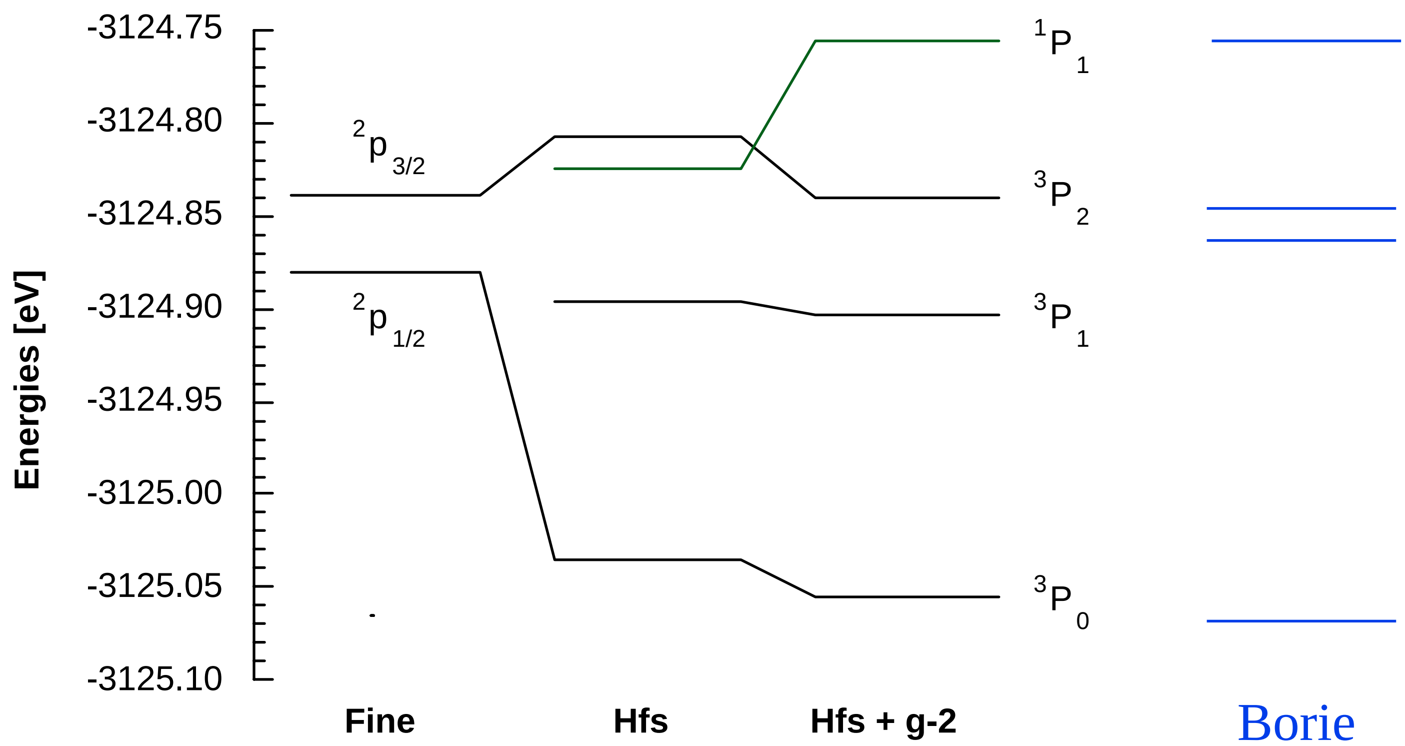
Mixed QED/structure Contributions to 3d-2p transitions in antiprotonic hydrogen

- Hyperfine structure (interaction of the antiproton spin and orbital magnetic moment with proton magnetic moment) Antiproton considered as a Dirac Particle
- Bohr Weisskopf effect (magnetic moment distribution in the proton)
- g - 2 for the antiproton (g = 5.58, not 2!)

$$\frac{a \hbar q}{2 m} \beta \left(i \frac{\boldsymbol{\alpha} \cdot \mathbf{E}}{c} - \boldsymbol{\Sigma} \cdot \mathbf{B} \right)$$

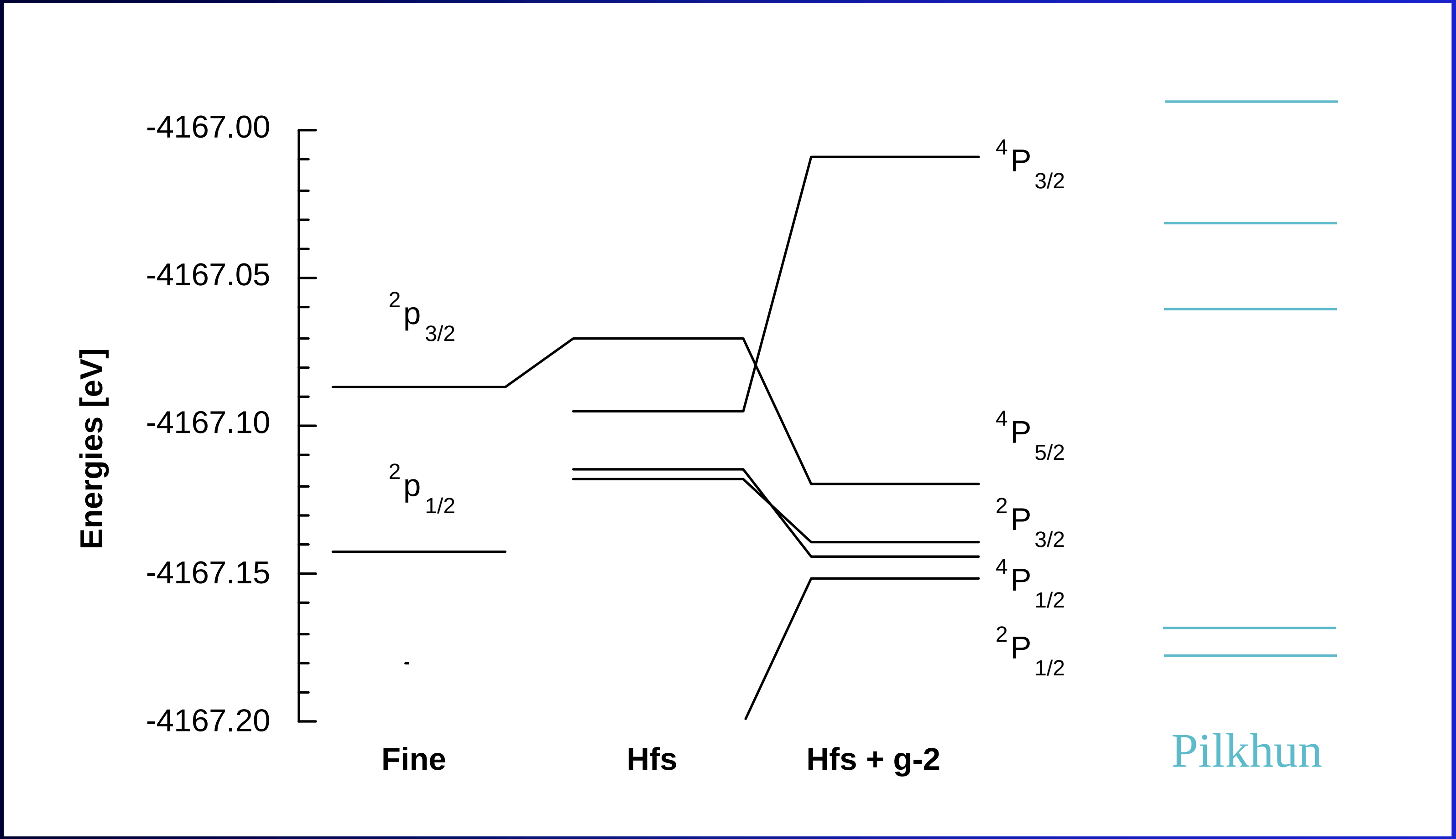
- As fine and hyperfine structure and g - 2 corrections are of the same order of magnitude we must diagonalize the full hamiltonian to include those effects non-perturbatively
- Antiproton and proton size corrections (0.02 meV)

Antiprotonic Hydrogen

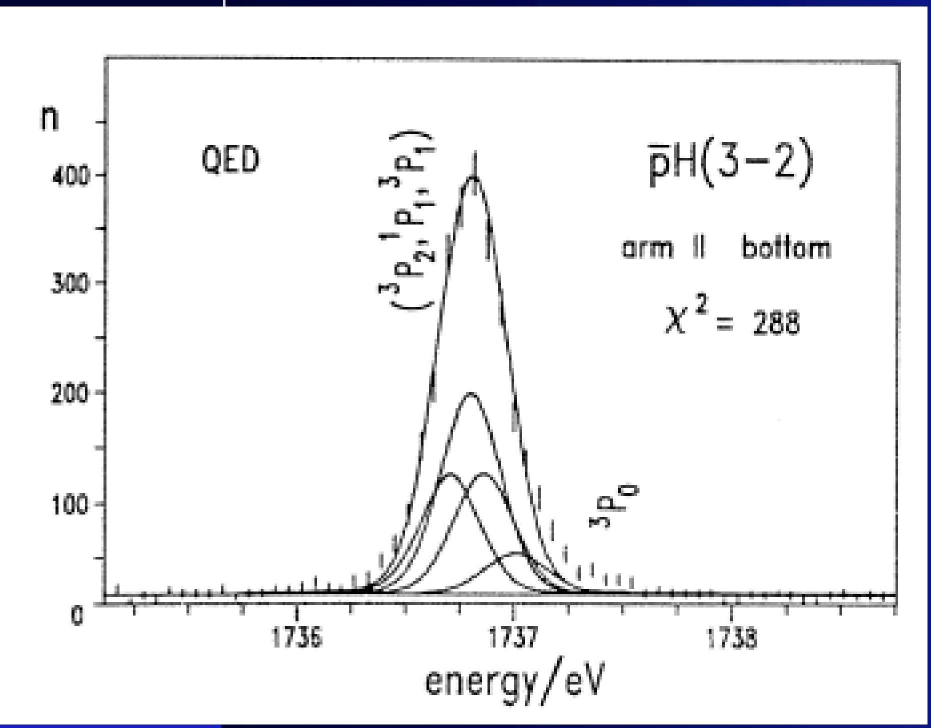


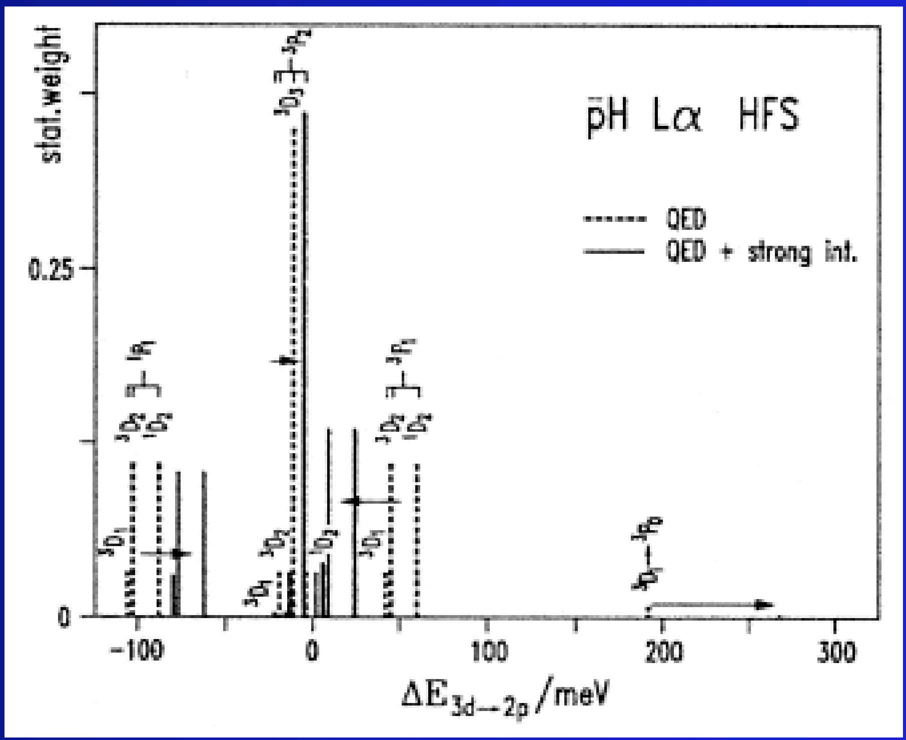
Proton radius 0.811⇒0.871fm 0.5 eV on 1s, 0.2 meV on $2p_{1/2}$. S. Boucard and P. Indelicato

Antiprotonic Deuterium



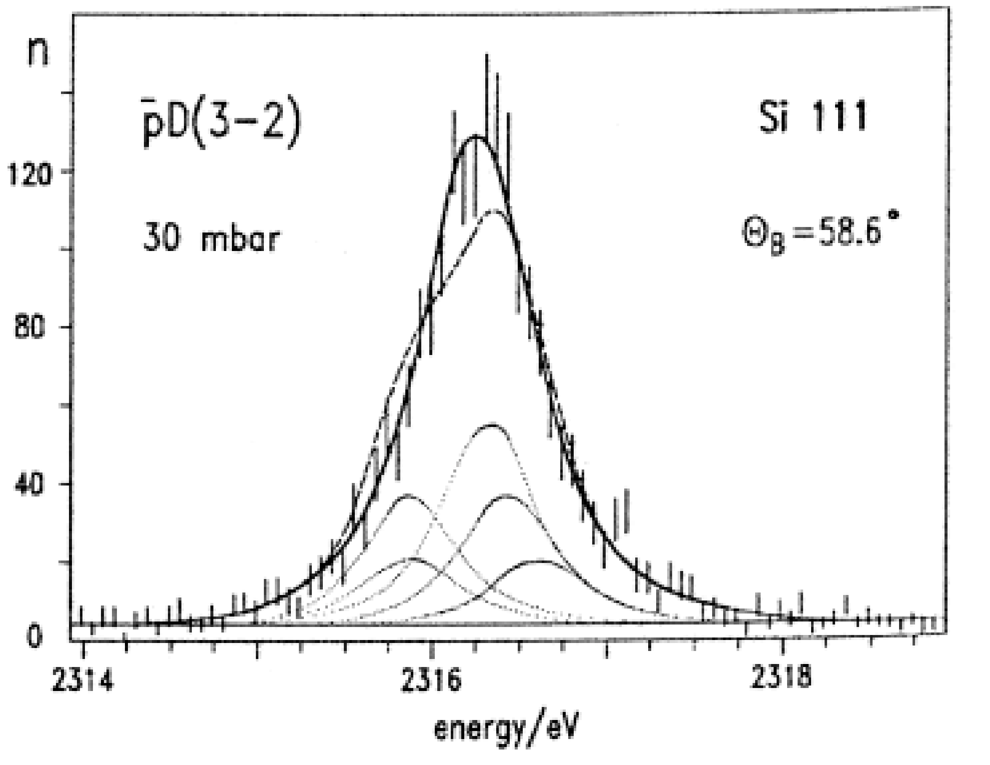
Comparison with Experiment (antiprotonic H)

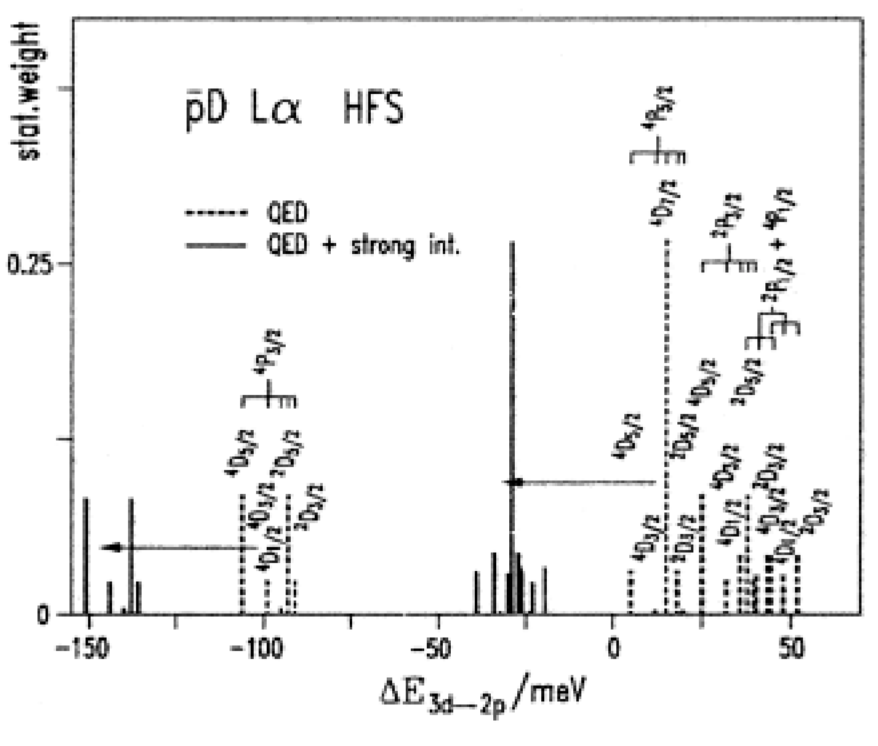




D. Gotta, D.F. Anagnostopoulos, M. Augsburger, G. Borchert, C. Castelli, D. Chatellard, J.P. Egger, P. El-Khoury, H. Gorke, P. Hauser, P. Indelicato, K. Kirch, S. Lenz, T. Siems et L.M. Simons. *Nuclear Physics A*. **660**, p. 283-321, (1999). "*Balmer α transitions in antiprotonic hydrogen and deuterium*".

Comparison with Experiment (antiprotonic D)





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Proposal for High precision QED tests in pionic atoms: should be done for antiprotons too!

Element	^{14}N *3d-4f*	^{40}Ar *7i-6h*	Diff.
Klein-Gordon (fin. nucl.)	8759.815	8839.070	-79.255
Uehling	8.223	3.665	4.558
Wichman and Kroll	-0.003	-0.013	0.010
Kallën and Sabry	0.066	0.034	0.031
Loop after loop Uehling	0.010	0.003	0.007
Relat. recoil	0.011	0.008	0.003
Total	8768.122	8842.766	-74.645

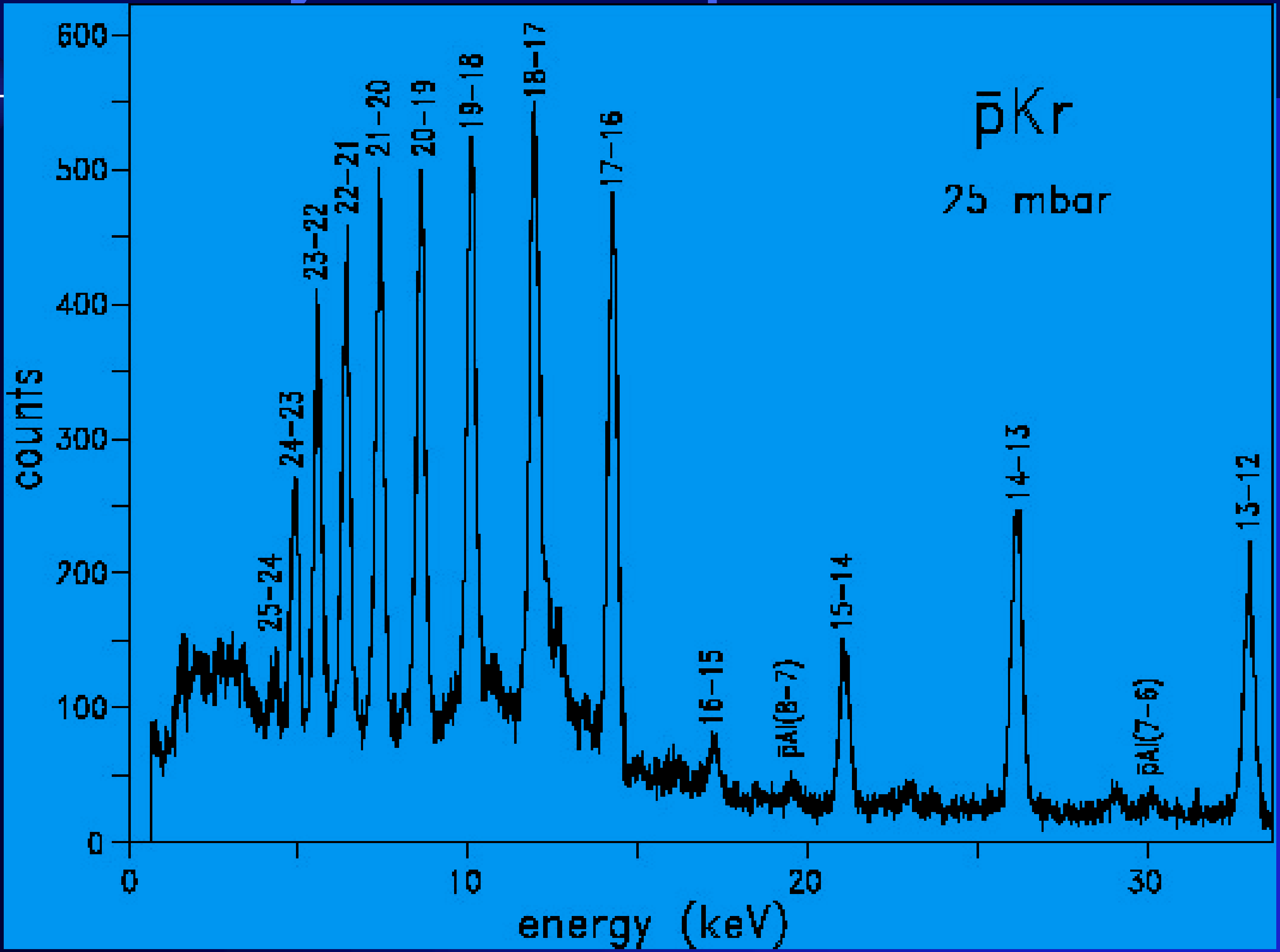
Accidental coincidence provide ways of very accurate test (~8 meV) of QED calculations in pionic atoms

Crystal spectroscopy and exotic atoms, P. Indelicato et L.M. Simons, Quantum Electrodynamics and Physics of the Vacuum, G. Cantatore ed., AIP Conference proceedings, **Vol. 564**, American Institute of Physics (Melville, New York) pp 152-157, (2001).

Formation of antiprotonic atoms

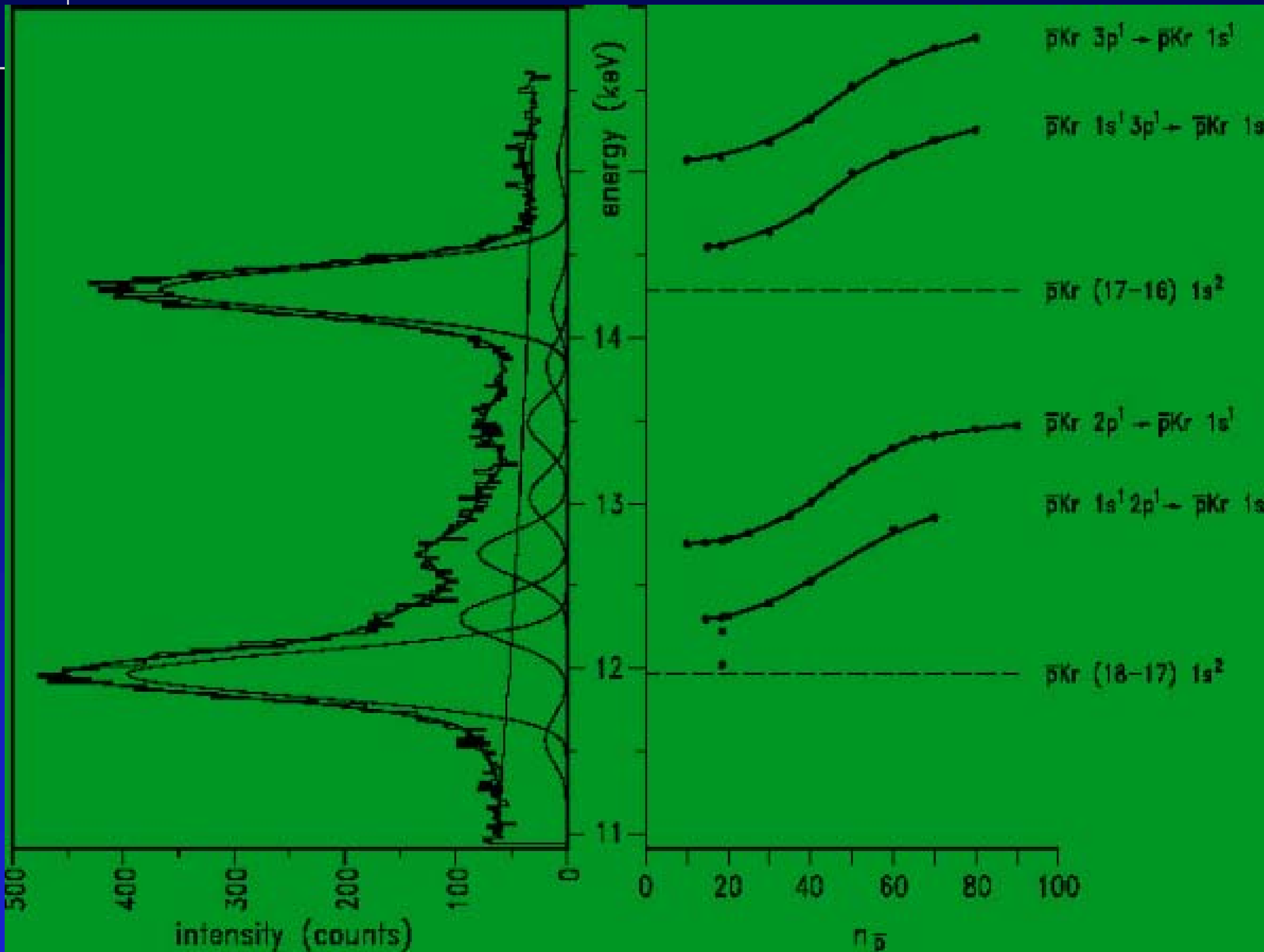
- Antiproton are captured in high-n levels because of their mass
- Stark-mixing and annihilation lead to an Irast decay (transition between n,l=n-1 to n-1,l=n-2) between circular states
- Energy of antiprotonic transitions is so large it can ionize many electrons (auger effect, similar to internal conversion in nuclei) may be up to bare Xe.
- This can lead to very exotic electron shell structure
- For Xe, very broad electronic structure have been observed, very similar to those found in exploding Xe clusters with lasers

Internal dynamic of antiprotonic atoms



Rashid, Gotta, Simons, Indelicato, Fricke

Detail near the Kr Kα line



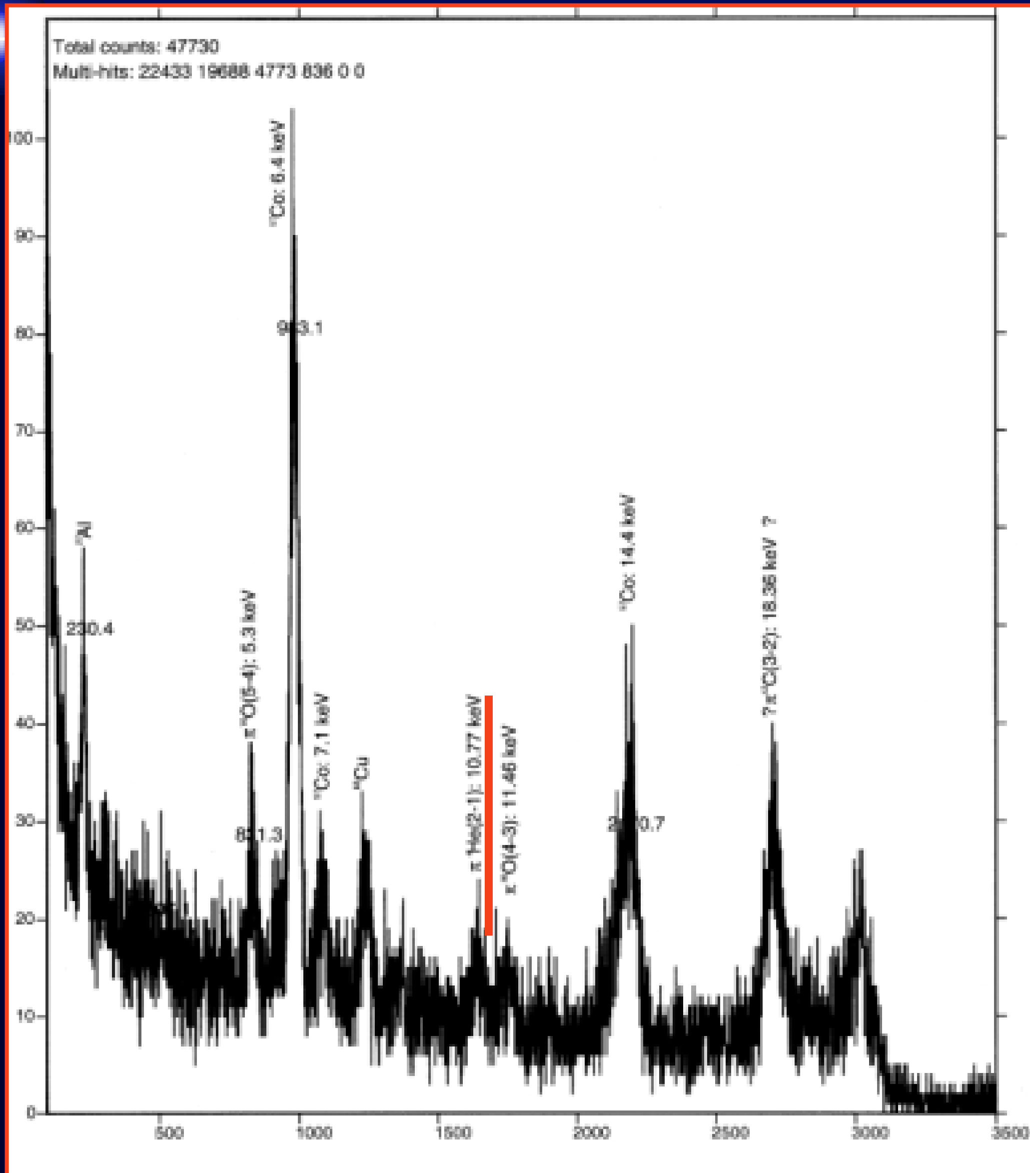
New ultra-fast CCD detector for low-energy exotic atom physics

- The pn CCD detector developped at Jülich with the technology from Münich (XMM) can read 600 frames/s and recognise charged particules tracks

- It is ideal for transition for which the Strong-Interaction broadening is large (e.g., for transition to level with strong presence probability in the nucleus)

- It can reduce background by orders of magnitude compared to Si(*Li*) or Ge(*i*) detectors.

First spectrum on pionic ^{4}He



^{4}He 1 bar

ΔE = 250 eV

pn-CCD:300 000 frames = 7.5 min
MOS CCD: 30s for 1 readout

Gorke, Gotta, Simons

Detector is looking directly at the source

Conclusions and perspectives

- Many ways of studiing antiprotonic atoms can be proposed for both strong-interaction and hadronic physics and for the study of the electron-shell/antiproton internal dynamics, cascade and energy
- This is a very little explored world that could be full of interesting surprises
- High-intensity, low energy, slow-extraction needed