Precision X-ray Spectroscopy with Exotic Atoms to Probe QED and Nuclear Structure

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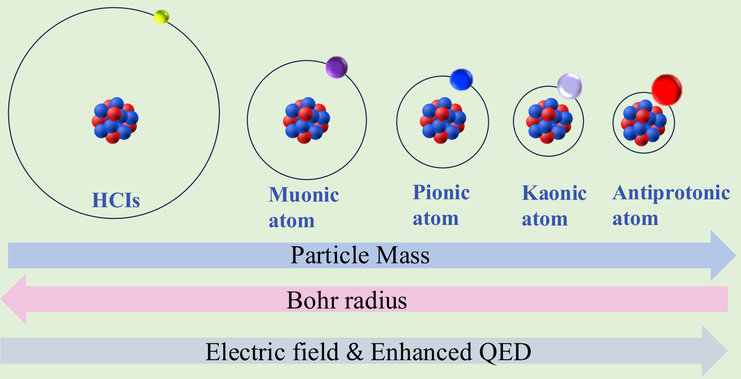
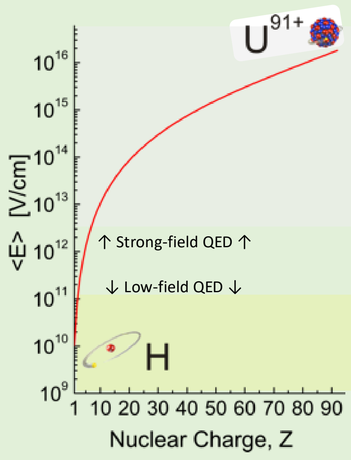
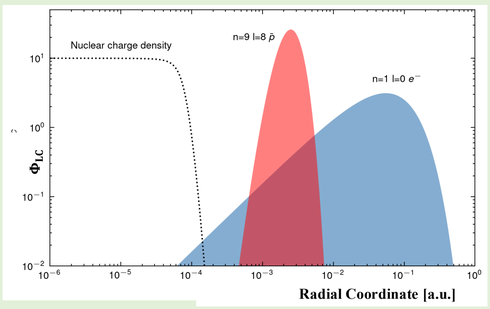
INTRODUCTION





- QED theory no longer perturbative in $Z\alpha$
- Strong-field QED transitions in the ~keV regime, no direct laser spectroscopy
- Direct spectroscopic QED measurements are limited by Doppler shifts and poorly known nuclear properties

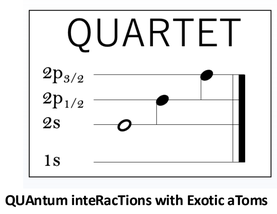
✓ High precision comparison between theory and experiment possible for low-Z systems (H, He, D)



Circular Rydberg levels with negligible overlap with the nucleus

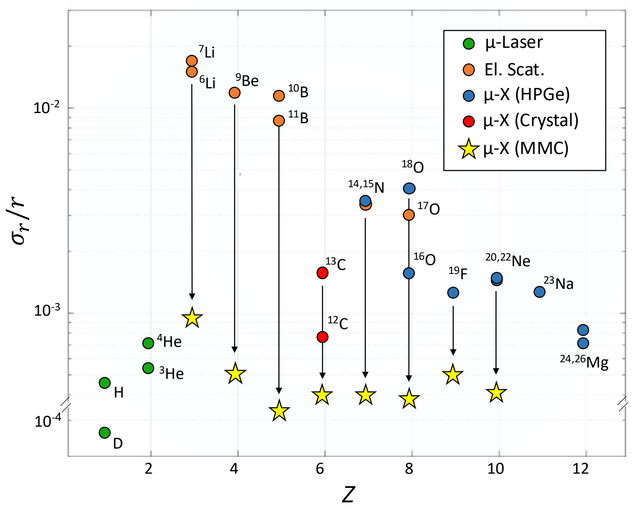
✓Exotic atoms as excellent probe for testing bound strong filed QED and nuclear structure

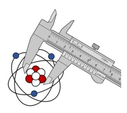
OUR GOAL



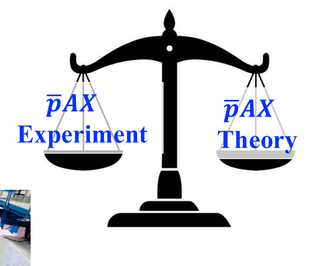
QUAntum inteRacTions with Exotic aToms

- Determine nuclear root mean square charge radii for $3 \le Z \le 10$ imporved by factor 3-10.
- Measure $2p \rightarrow 1s$ for $3 \le Z \le 10$ to ppm accuracy, i.e. 0.2-1 eV at PSI with muonic x ray spectroscopy via Magnetic microcalorimeters .

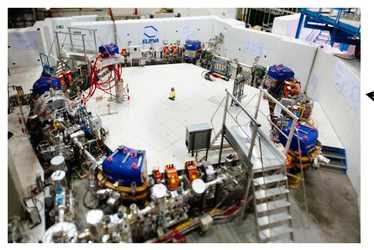




Antiprotonic x-ray spectroscopy



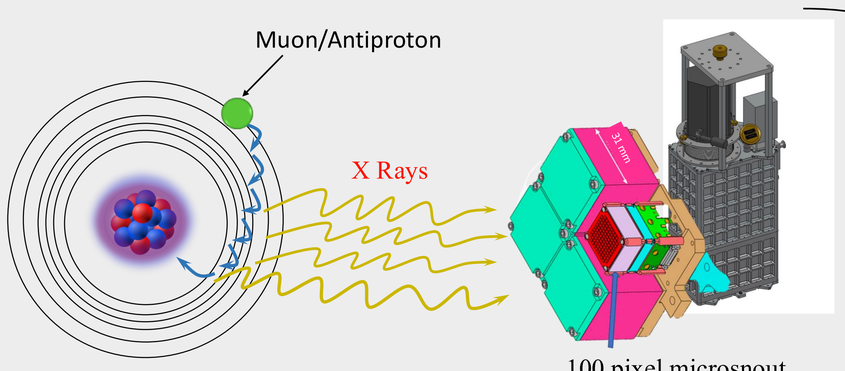
Higher order QED Test via antiprotonic x ray spectroscopy with transition edge sensors



ELENA ring at the Antimatter Factory (AD) @CERN

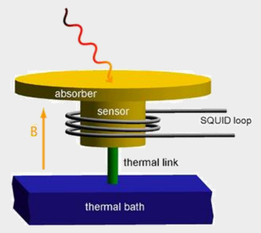
Only place in the world where low energy antiprotons are available

OUR CONCEPT

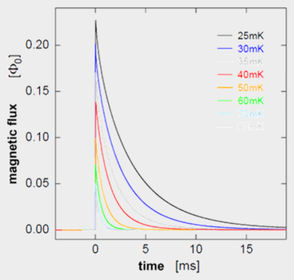


- ✓ High quantum efficiency
- ✓ Broadband (important for calibration)
- ✓ **Superb resolution** $\left(\frac{E}{\Gamma_E} > 10^3\right)$
- ✓ Fast rise time (important for background suppression)

Working Principle of a Metallic Magnetic Calorimeters



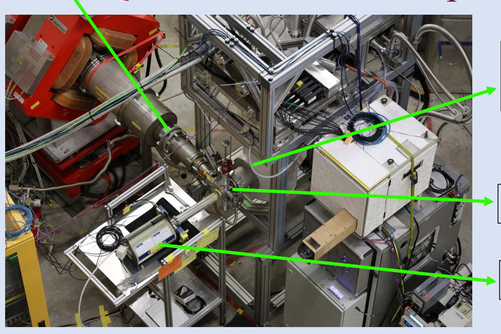
* Absorber thickness determines efficiency at given energy



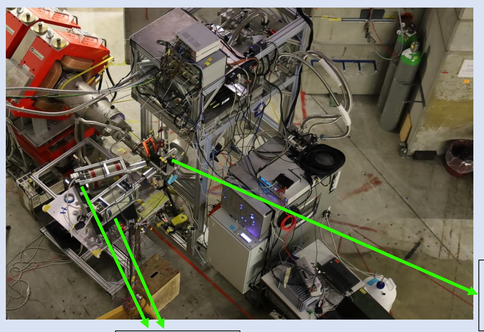
δE (Absorption of energy) ⇨ $\delta T = \frac{\delta E}{C}$ (Increase of temperature) ⇨ $\delta M = \frac{\partial M}{\partial T}\frac{\delta E}{C}$ (Change of magnetisation) ⇨ $\delta\Phi \sim \delta M \sim \delta T \sim \delta E$ (Change of magnetic flux)

EXPERIMENTAL SETUP

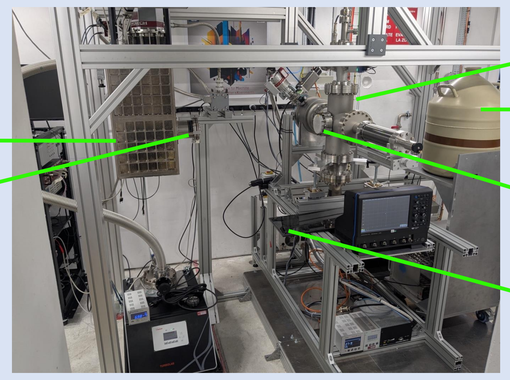
QUARTET 2024 Setup



QUARTET 2025 Setup



PAX TEST BEAMTIME 2025 Setup

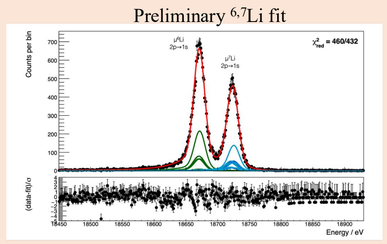


RESULTS

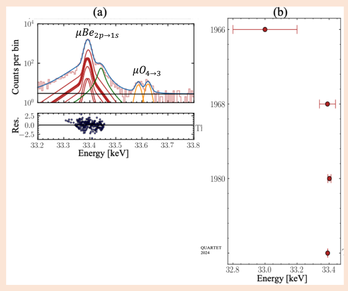
Analysis Status @2024 QUARTET Beamtime

maXs-30 detector

Preliminary ^{6,7}Li fit



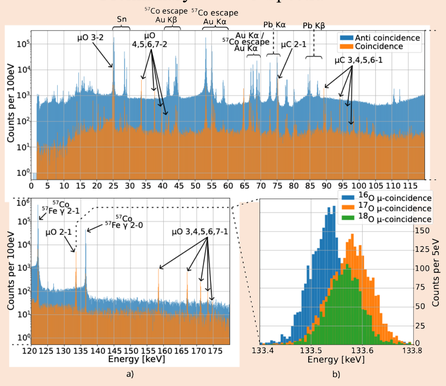
Concluded ^{9}Be analysis



- Fitted with FS-HFS
- Constrained by relative energy splitting and intensities from theory.

Analysis Status @2025 QUARTET Beamtime

Preliminary ^{16,17,18}O Spectra



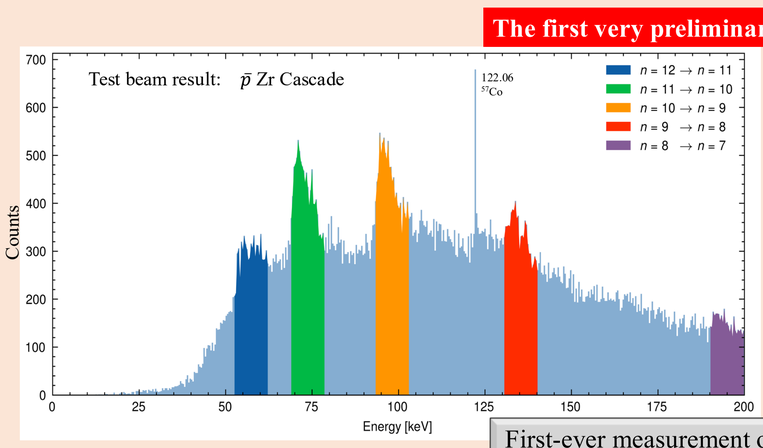
maXs-100 detector

PAX TEST BEAM Status @2025

Successful proof of principle

The first very preliminary results of the test beam

Just 17 hrs of data



First-ever measurement of antiprotonic atom cascade x rays using a microcalorimeter