Fundamental Interactions and Beyond with X-ray Spectroscopy of Exotic Atoms

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Bound state QED—a rich landscape
Self-energy
Vacuum polarization
Bound state QED—a rich landscape
Strong field Bound State QED (BSQED)

- High precision comparison between theory and experiment possible for low-Z systems (H, He, D)
- Strong-field QED transitions in the ~keV regime, no direct laser spectroscopy

Hydrogen-like Uranium

\[ \Delta E_{\text{QED}} \approx 10^{-5} \text{eV} \]

\[ \Delta E_{\text{QED}} \approx 500 \text{eV} \]

Hydrogen – Laser spectroscopy (\( \Delta E \sim 10\text{eV} \))

\[ \Delta E_{\text{QED}} \approx 10^{-5} \text{eV} \]

\[ a_0/100 \]

\[ X, \gamma \text{ ray detectors (} \Delta E \sim 100 \text{ keV)} \]

\[ \uparrow \text{Strong-field QED} \]

\[ \downarrow \text{Low-field QED} \]
Strong field Bound State QED (BSQED)

- QED effects become relatively more important
- QED theory non-perturbative ($Z\alpha$)
- Theory exists but experiments difficult to test higher-order QED contributions

Frontier via complementary methods
Ex. g-factors, high-intensity lasers, …
Strong field Bound State QED (BSQED)

Hydrogen-like Uranium

Stellar plasmas
Dark matter
Beyond Standard Model searches

Hydrogen

Laser spectroscopy ($\Delta E \sim 10\text{eV}$)

$\Delta E_{\text{QED}} \approx 10^{-5}\text{eV}$

Stellar plasmas
Dark matter
Beyond Standard Model searches

Highly-charged S emission:
Strong field Bound State QED (BSQED)

Problem: Missing precision measurements!

Hydrogen-like Uranium

\[ \Delta E_{QED} \approx 10^{-5} \text{eV} \]

Laser spectroscopy (\( \Delta E \approx 10 \text{eV} \))

\[ \Delta E_{QED} \approx 10^{-5} \text{eV} \]

Hydrogen

\[ a_0/100 \]

**Problem:**
- QED untested beyond 1st order effects, 2nd order QED is ppm effect and currently untested!
- QED tested to threshold of 3rd order effects

\[ a_0 \]

\[ Z \]

Nuclear Charge, \( Z \)
Precision spectroscopy of highly-charged ions (HCl)

Theory-experiment comparison of QED effects in two-electron atoms (He-like) for transitions to the ground state (Lyman-alpha)

New QED effects?

Figure adapted from P. Indelicato, Topical Review: QED tests with highly-charged ions, Journal of Physics B 52 (2019) 232001
The Double Crystal Spectrometer

**Highest precision x-ray spectroscopy** (2 keV—200 keV)

- **crystal spectrometers**
  - Analyse x rays based on Bragg diffraction from crystal lattice
  - Requires precise knowledge of crystal structure and dynamical diffraction theory

\[ n\lambda = 2d \sin(\theta_{Bragg}) \]

- X-ray wavelength
- Crystal lattice spacing
- Measured Bragg angle
The Source “SIMPA” for highly-charged ion production

Microwaves: 14.5 GHz
Extraction voltage: 0 V to 25 kV

- Direct connection to plasma, 50μm thick Be window
- In the plasma the ions are trapped in the space charge of the electrons ($\sim 10^{11}$ e/cm$^3$), $\sim$ few eV trapping depth
- Intense source, provides access to forbidden transitions, narrow linewidths
The Paris Double Crystal Spectrometer

- Si$_{111}$ crystals from NIST, lattice spacing (d) known to 10^{-8}
- Angular encoder for second axis: Heidenhain RON 905 with AWE 1024 interpolator → 0.2” of arc angular accuracy
- Detector: LAAPD (large area avalanche photodiode) cooled at -10°C
Parallel
Energy Non-dispersive

Antiparallel
Energy Dispersive

width : DCS response function

width : intrinsic line width
Doppler broadening DCS response function
DCS Recent Results

Highest precision, reference-free measurements in core-excited Li-like ions

Sulfur peak ratio: 0.46 [theory], 0.627(22) [exp]
Argon peak ratio: 0.44 [theory], 0.397(14) [exp]
Cannot be explained by known contaminant lines

J. Machado, G. Bian, N. Paul, et al,
PRA 101, 062505 (2020)

First ppm measurements of the relativistic magnetic dipole transition in He-like S

Test of 2e QED effects, sensitive to crystal form factors

J. Machado, N. Paul, et al,
PRA 107, 032821 (2023)
Impact of He-like S M1 measurement

We have made the first absolute, reference-free measurement of the 1s^2 1S_0 → 1s^2 3S_1 relativistic magnetic dipole transition in He-like sulfur. The highly-charged ionic beams were provided by an electron-cyclotron resonance ion source, and the x rays were analyzed with a high-precision double crystal spectrometer. A transition energy of 2430.3650(57) eV was obtained, and is compared to most advanced bound state quantum electrodynamics calculations, providing an important test of two-electron QED effects and precision atomic structure methods in medium-Z species. Thanks to the extremely narrow natural line width of this transition, and to the large dispersion of the spectrometer at this energy, a complementary study was also performed evaluating the impact of different alien crystal atomic form factor models in the transition energy analysis. We find no significant dependence on the model used to determine the transition energy.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>1s^2 1S_0</th>
<th>1s^2 3S_1</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔE_{Dirac}</td>
<td>-3495.0044</td>
<td>-874.5000</td>
<td>2620.5044</td>
</tr>
<tr>
<td>ΔE_{ph}</td>
<td>270.4822</td>
<td>80.9665</td>
<td>-189.5157</td>
</tr>
<tr>
<td>ΔE_{QED}</td>
<td>0.7562</td>
<td>0.1014</td>
<td>-0.6548</td>
</tr>
<tr>
<td>ΔE_{1el}</td>
<td>-0.0715</td>
<td>-0.0110</td>
<td>0.0605</td>
</tr>
<tr>
<td>ΔE_{2el}</td>
<td>0.0009</td>
<td>0.0002</td>
<td>-0.0007</td>
</tr>
<tr>
<td>ΔE_{rec}</td>
<td>0.0563</td>
<td>0.0137</td>
<td>-0.0426</td>
</tr>
<tr>
<td>Theo. [40]</td>
<td>-3223.7803</td>
<td>-793.4292</td>
<td>2430.3511  (3)</td>
</tr>
<tr>
<td>Theo. [41]</td>
<td>2430.35208</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Exp. (this work)</td>
<td>2430.3685</td>
<td>(97)</td>
<td></td>
</tr>
</tbody>
</table>
Limitations with HCl: Nuclear physics!

Lyman-\(\alpha\) transitions in hydrogen-like ions

- 1st order QED
- 2nd order QED
- Experimental Uncertainty
- Uncertainty from Nuclear Size
Limitations with HCl: Nuclear physics!

Lyman-α transitions in hydrogen-like ions

- 1st order QED
- 2nd order QED
- Experimental Uncertainty
- Uncertainty from Nuclear Size

Contribution [ppm]

Z
Strong-field QED with exotic atoms

Exotic atoms

- $\mu^-$
- $\pi^-$
- $K^-$
- $\bar{\rho}$
Strong-field QED with exotic atoms

Strongest field QED $\rightarrow$ Highest sensitivity

$m_\mu \sim 200 m_{e^-}$
$r_\mu \sim \frac{1}{200} r_{e^-}$
Strong-field QED with exotic atoms

Strongest field QED → Highest sensitivity

Energy levels in muonic ions

Energy levels in HCl

$m_\mu \sim 200 \, m_{e^-}$

$\frac{r_\mu}{200} \sim \frac{1}{r_{e^-}}$

• Heavy exotic particle → small Bohr radius → strong electric field strength
• Higher order QED effects magnified and become measurable with new techniques

PAX theory paradigm—N. Paul et al, PRL 126 (2021)
First proof-of-principle with muonic atoms—T. Okumura et al, PRL 130 (2023)
Strong-field QED with exotic atoms

- Strong field QED
- Nuclear effects ≥ QED effects
- STRONGEST field QED
- Nuclear effects << QED effects

<table>
<thead>
<tr>
<th>Atom</th>
<th>Transition</th>
<th>Transition energy</th>
<th>1st order QED</th>
<th>2nd order QED</th>
<th>Nuclear effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-like U</td>
<td>Lyman α1</td>
<td>~100 keV</td>
<td>3x10⁻³</td>
<td>1x10⁻⁵</td>
<td>2x10⁻³</td>
</tr>
<tr>
<td>antiprotonic-Xe</td>
<td>n=12→n=11</td>
<td>~100 keV</td>
<td>7x10⁻³</td>
<td>6x10⁻⁵</td>
<td>1x10⁻⁵</td>
</tr>
</tbody>
</table>

QED x 3-6

Nuclear effects / 100
Strong-field QED with muonic atoms

Muonic ions

First experiments @ JPARC

H-like HCl, n=1
First experiments with muonic atoms at J-PARC

- **5-year accepted scientific program** at J-PARC muon facility in Japan (2020-2025)
- QED tests=precision x-ray spectroscopy of Rydberg states in muonic atoms

HEATES Collaboration: RIKEN, JAEA, JAXA, KEK, Osaka University, Rikkyo University, Tohoku University, Tokyo Metropolitan University, NIST, CNRS
First experiments with muonic atoms at J-PARC

Key technology

- High energy resolution ($\Delta E/E \sim 10^{-4}$)
- High efficiency ($\sim 10^{-4}$)

Transition Edge Sensing (TES) $\mu$-calorimeter (NIST)

Key technology: Transition Edge Sensing microcalorimeter

- Two-stage pulse tube (60K, 3K)
  (300K → 3K: 16 hours)
- Mo-Cu bilayer TES
- 4-μm-thick Bi absorber
- Size: 300 x 320 μm²

HEATES TES @ J-PARC D2
25 Hz pulsed μ-beam
Key technology—TES x-ray detector

Transition Edge Sensing (TES) \( \mu \)calorimeter (NIST, Boulder, CO, USA)

Quantum Sensing Division

Figures from Ullom and Bennett 2013
TES calibration

- Pixel-by-pixel energy calibration
- Continuous calibration lines from x-ray gun
Experimental $\mu$Ne spectrum Okumura et al, PRL 130 (2023)

Shift due to presence of 1 electron: $\sim 1.5$ eV
### Theory and Sensitivity

Okumura et al, PRL 130 (2023)

<table>
<thead>
<tr>
<th>Theoretical Contributions (5g9/2→4f7/2)</th>
<th>eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vac. Pol. (1st order)</td>
<td>-2.34061</td>
</tr>
<tr>
<td>Self-energy (1st order)</td>
<td>0.0015</td>
</tr>
<tr>
<td>Vac. Po. (2nd order)</td>
<td>-0.0212</td>
</tr>
<tr>
<td>Finite nuclear size</td>
<td>-0.00031</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5g9/2→4f7/2</th>
<th>0.1 atm</th>
<th>0.4 atm</th>
<th>0.9 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured energy</td>
<td>6297.13</td>
<td>6297.06</td>
<td>6297.05</td>
</tr>
<tr>
<td>Statistical error</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Systematic error: Total</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>(1) Calibration</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>(2) Low-energy tail</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>(3) Thermal crosstalk</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Note: The table represents the transition energy and uncertainties for the reaction 5g9/2→4f7/2, including contributions from various theoretical aspects such as vacuum polarization, self-energy, and finite nuclear size.
Muonic atom cascade and electronic transitions

spectrum of muonic Fe with Mn Ka transitions

Muonic atom cascade and electronic transitions

(a) $K_{\alpha}$

Counts / 3 eV

Energy (eV)

(b) $K_{\beta}$

Counts / 3 eV

Energy (eV)

(c) $K_{\alpha}^h$

Counts / 3 eV

Energy (eV)

(d) $K_{\beta}$

Counts / 3 eV

Energy (eV)
Next step….QED with antiprotons

Even stronger field QED!

Bohr radius

Electric field

antiproton

muon

electron
Next step….QED with antiprotons

Antiprotonic atoms

Typical Rydberg state in antiprotonic atoms (n=13)

Even stronger field QED!

- antiproton
- electron
- muon
Next step….QED with antiprotons

Antiprotonic atoms

![Graph showing internal electric field of antiprotonic atoms vs atomic number Z.](image)

- Typical Rydberg state in antiprotonic atoms (n=13)

**QED with antiprotons**
(precision methods) x (antimatter)

Largest BSQED effects!

The $\bar{p}AX$ project—antiprotonic Atom X-ray spectroscopy
100 keV antiprotons from ELENA

ELENA:
« Extra Low ENergy Antiprotons »
Beams of slow antiprotons since August 2021

TES x-ray detector
Cyclotron trap
Gas handling and pumping

access for detector calibration
\[ \overline{\rhoAX} \text{ in detail} \]

1. **Novel new device**
   - Antiproton injection
   - X-rays
   - Coil sections

2. **Antiprotons stop in gas-filled trap**
   - Antiprotons capture and emit radiative x-ray cascade

3. **First-ever application to antimatter beams**
   - X-ray spectroscopy with large-area TES detector
   - 100 pixel microsnout
   - 31 mm
The $\bar{p}AX$ physics program

<table>
<thead>
<tr>
<th>Transition ($n_i \rightarrow n_f$)</th>
<th>Appx. Transition energy (keV)</th>
<th>1st order QED</th>
<th>2nd order QED</th>
<th>Nuclear effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}$Ne (6→5)</td>
<td>30</td>
<td>4 E-3</td>
<td>3 E-5</td>
<td>2 E-6</td>
</tr>
<tr>
<td>$^{40}$Ar (6→5)</td>
<td>100</td>
<td>5 E-3</td>
<td>5 E-5</td>
<td>1 E-5</td>
</tr>
<tr>
<td>$^{84}$Kr (9→8)</td>
<td>100</td>
<td>5 E-3</td>
<td>5 E-5</td>
<td>1 E-5</td>
</tr>
<tr>
<td>$^{133}$Xe (10→9)</td>
<td>170</td>
<td>5 E-3</td>
<td>5 E-5</td>
<td>2 E-5</td>
</tr>
<tr>
<td>$^{184}$W (12→11)</td>
<td>180</td>
<td>5 E-3</td>
<td>5 E-5</td>
<td>2 E-5</td>
</tr>
</tbody>
</table>

Highest field system ever accessed in the laboratory!

$\bar{p}AX$ firsts

- Study second-order QED effects across $10 \leq Z \leq 74$
- Achieve $10^{-5}$ experimental precision for heavy exotic atom spectroscopy

**Perspectives:** Strong interaction studies, exotic physics searches

\[ N_x = N_p M \varepsilon_{geo} \varepsilon_{det} \varepsilon_{trap} \]

\[ N_p = 1 \times 10^6 / \text{spill} \]
\[ M = 10 \]
\[ \varepsilon_{geo} = 6 \times 10^{-4} \]
\[ \varepsilon_{det} = 0.4 \]
\[ \varepsilon_{trap} = 0.5 \]

$N_x = 1200 \text{ counts/spill}$

< 1 week measurement time / transition
The $\bar{p}AX$ next steps

Test setup at GBAR

- Full simulations and design of cyclotron trap and vacuum solution
- Simulation and measurement of annihilation background
- In beam test with prototype TES at ELENA (2025)
And now let's use the idea backwards…
For nuclear physics!
Determinations of nuclear RMS charge radii

- For $Z < 3$: Laser spectroscopy of muonic atoms, limited by nuclear theory

- For $Z > 6$: Measured x-rays from muonic atoms using solid-state detectors. $10 < Z$: limited by theory. $Z < 10$: limited by experiment (resolution).

- For $Z = 3 – 5$, and others: Electron scattering, less accurate and systematics usually NOT under control

- For $Z = 6$: $E(2P-1S) \sim 75$ keV, measured with crystal spectrometer. Limited by resolution $\sim 75$ eV
• Determine $E(2P-1S)$ for $3 \leq Z \leq 8$ with 10 ppm accuracy 0.2-1 eV.

• Improve radii by factor 3-10.
The QUARTET experiments

The Heidelberg Metallic magnetic calorimeter (MMC)

maxs-30 mounted on coldfinger of a dry dilution fridge

PIE1 beamline at PSI, continuous ~50kHz μ⁻/s

Picture courtesy of the MIXE collaboration
The QUARTET collaboration

Who we are:

- Loredana Gastaldo
- Andreas Fleischmann
- Andreas Knecht
- Klaus Kirch
- Nancy Paul
- Jorge Machado
- Paul Indelicato
- Frederik Wauters
- Randolf Pohl
- Ben Ohayon*
- Ab. Initio. Nuclear theory
- Quantum Sensors group
- Experimenters in exotic atoms
- QED in exotic atoms
- Petr Navratil
-ting
- T. Cocolios

* Spokespersons: npaul@lkb.upmc.fr, benohayon@physics.technion.ac.il
The QUARTET collaboration

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Expected rates:

\[ 0.8 \times 10^{-4} \times \frac{10^3}{s} = 0.1 \text{ event/s} \]

Detection efficiency, Solid angle, 2P-1S rate

Stat. accuracy per nominal week:

\[ \frac{10 \text{ eV}}{2.4} / \sqrt{10^5} \approx 0.02 \text{ eV} \]

Resolution, Events

First test beam in October 2023
\[ \mu^{-6,7}\text{Li}, \mu\text{Be}, \mu^{-10}\text{B} \]
Impact on BSM physics searches

• Combining isotope shifts between electronic and muonic atoms to search for new lepton-neutron interactions

• Best limits come from Hydrogen-Deuterium pair. Z enhancement favors heavier pairs.

• Novel measurements of bound electron g-factors in H-like ions limited by muonic isotope shifts

T. Sailer et. al., Nature 606 (2022)
• World-leading precision x-ray spectroscopy at LKB for strong-field QED tests
• **Exotic atoms** offer a new way to probe high-field QED by avoiding the problems associated with nuclear physics
• New **quantum sensor detector technologies** make precision studies of exotic atoms possible
• Experiments ongoing with **muonic atoms** at JPARC, Ne, Ar, Xe
• **New experimental program, pAX, with antiprotonic atoms** for BSQED
• **New experimental program, QUARTET, with muonic atoms** at PSI for charge radii.
THANK YOU
What are radii good for?

*First application, with MaXs-30 (10 eV resolution up to 60 keV)*

- **Li/Be/B absolute radius** → calibrate entire chains, test nuclear calculations inc. $^7$Li-$^7$Be and (future) $^8$Li-$^8$B mirrors
- **$^6$Li-$^7$Li and $^{10}$B-$^{11}$B isotope shifts** (can be determined with higher accuracy) → compare with optical IS to test many-body QED (mostly recoil) and search for new physics.
- Upcoming optical determinations of absolute radii for helium-like Li to C (Wuhan, Mainz). Important cross check and strong test for new physics beyond isotope shifts.

![Graphs showing nuclear charge radius vs lithium isotope and Be isotope](image)

**All limited by reference**

- PRC 84, 024307 (2011)
- PRL 122, 182501 (2019)
- PRL 108, 142501 (2012)
Perspectives

Existing data on antiprotonic cascade
Simulated TES data
Pileup correction

Total calibration spectrum at 0.1 atm

Energy shift ($t_{\text{muon}} - t_{\text{x-ray}}$)

Pileup correction

Energy shift \((t_{\text{muon}} - t_{\text{x-ray}})\)

*Dynamical Response of Transition-Edge Sensor Microcalorimeters to a Pulsed Charged-Particle Beam*, T. Okumura, T. Azuma, D.A. Bennett, P. Caradonna, I.H. Chiu, W.B. Doriese, M.S. Durkin.