PRECISION TESTS OF QED IN STRONG FIELDS: EXPERIMENTS ON HYDROGEN- AND HELIUM-LIKE URANIUM


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PRECISION TESTS OF QED IN STRONG FIELDS: EXPERIMENTS ON HYDROGEN- AND HELIUM-LIKE URANIUM

• **Introduction:** QED, Lamb shift and the structure of one- and two-electron systems at high-Z

• *Experiment at the storage ring ESR at GSI*
  • Production and storage of high-Z few-electron (or bare) ions
  • X-ray spectroscopy at the ESR electron cooler, relativistic doppler effect

• *Results in comparison with theoretical predictions*

• **Summary**

• **Outlook**
  
  *(towards ~1 eV precision)*
  • Crystal spectrometer
  • Detector development
QED

- One of the most precise predictions in physics
- Prototype (first) of all field theories
- Fundamental theory of EM interactions
- Fundamental constants
- Masses
- ...
Atomic Physics in Extremely Strong Coulomb Fields

Quantum Dynamics

Intensive Laser

1s-ground state: increase of the electric field strength by six orders of magnitude

H-like Uranium
\[ E_K = -132 \times 10^3 \text{ eV} \]
\[ \langle E \rangle = 1.8 \times 10^{16} \text{ V/cm} \]

Hydrogen
\[ E_K = -13.6 \text{ eV} \]
\[ \langle E \rangle = 1 \times 10^{10} \text{ V/cm} \]
The Atomic Structure of One-electron System

The Lamb shift:
*The sum of all corrections which lead to the discrepancy from the predictions of the Dirac-Theory for a point-like nucleus.*

- Decrease of the binding energies
- dominantly for s-states

- Decrease of the binding energies
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Bound-State QED: 1s Lamb shift

Self-energy

Vacuum-polarization

U^{91+} SE VP NS
355.0 eV -88.6 eV 198.7 eV

\[ \Delta E = \frac{\alpha}{\pi} (\alpha Z)^4 F(\alpha Z) m_e c^2 \]

Low Z-regime: \( \alpha Z \ll 1 \)
F(\alpha Z): expansion in \( \alpha Z \)

High Z-regime: \( \alpha Z \approx 1 \)
F(\alpha Z): expansion in \( \alpha Z \) not applicable (calculation of all orders)

Tests of Bound-state QED

\pm 1 \text{ eV}
Production of highly charged heavy ions

Traps (EBIT): production of highly charged ions by collisions with high energy electron beams

Accelerator: production of highly-charged ions by fast collisions with target atoms.

Charge-state distribution for Uranium

200 keV electron energy (ions at rest)

Super-EBIT

SIS

300 MeV/u

Experimental Area
GSI-ACCELERATOR FACILITY

UNILAC
11.4 MeV/u
U^{73+}

SIS
10 - 500 MeV/u
U^{92+}

up to 1000 MeV/u
U^{92+}

ESR
Experiments at the ESR

- $\beta \approx 0.65$
- $E \approx 300 \text{ MeV/u}$
- Revolution Frequency $f: \approx 10^6 \text{ 1/s}$

**ESR**
- Circumference: 108 m
- Number of Ions: $10^8$
**Electron cooler**

*Voltage: 5 to 200 kV*

*Current: 10 to 1000 mA*

*2.5 m interaction zone*
COOLED HEAVY-ION BEAMS

ions interact $10^6$ 1/s with the collinear cold electron beam

properties of cold ion beams

momentum width $\Delta p/p : 10^{-4} - 10^{-5}$

size 2 mm
Experiments at the ESR

\[ \beta \approx 0.65 \]

\[ E \approx 300 \text{ MeV/u} \]

Revolution Frequency
\[ f: \approx 10^6 \text{ 1/s} \]

ESR

circumference: 108 m
number of ions: \(10^8\)
Spectroscopy at the Electron Cooler

- Maximum blueshift
  \[ \beta \approx 0.29 \Rightarrow E_{\text{lab}} \approx 1.43 \times E_{\text{proj}} \]

- \[ \Delta \theta_{\text{LAB}} \] not critical, minimum Doppler broadening

- Uncertainty due to \[ \Delta \beta \] maximum

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**H-like Uranium**

- Balmer
- L-RR
- K-RR

**Energy vs. Energetics**

- \( \bar{\text{h}} \omega \)
- \( E_{\text{kin}} \)
- \( \infty \)
- \( L \)
- \( K \)

**Rate vs. Energy**

- \( \text{Ereignisse} \)
- \( \text{Energie [keV]} \)
The Experimental Challenge

Relativistic Doppler-Transformation

\[ E_{\text{lab}} = \frac{E_{\text{proj}}}{\gamma \cdot (1 - \beta \cdot \cos \theta_{\text{lab}})} \]

- \( E_{\text{lab}} \): Photon energy in the laboratory frame
- \( E_{\text{proj}} \): Photon energy in the Emitter frame

Doppler correction

*Strong dependence on velocity \( v \) and on observation angle \( \theta_{\text{LAB}} \)

\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} ; \beta = \frac{v}{c} \]
Experiments at the ESR

\[ \beta \approx 0.65 \]

\[ E \approx 300 \text{ MeV/u} \]

Revolution Frequency
\[ f \approx 10^6 \text{ 1/s} \]

300 MeV/u
deceleration
4 MeV/u

ESR
- Circumference: 108 m
- Number of Ions: \(10^8\)

Ions from SIS
electron cooler
gas jet
Ge(i) Detector
Recombination into Rydberg states leads to the delayed Lyman emission, by up to microsecond.
Tails disappear when one applies a proper condition to the time spectrum.
The Ground State Lamb Shift in H-like Uranium

1s Lamb shift in U$^{91+}$

460.2±2.3±3.5 eV

statistical

4.6 eV

uncertainty in the β
Experimental Results in Comparison with Theory

Experiment: $460.2 \pm 4.6$ eV

Theory (Yerokhin et al. 2003): $464.26 \pm 0.5$ eV

$SE = 355.0$ eV, $VP = -88.6$ eV

$NS = 198.7$ eV, $HO \sim 1.8$ eV

1% sensitivity to the 1s Lamb shift
4% Sensitivity to the self energy
15% Sensitivity to the vacuum polarization
Relative Measurement of the Two-electron Contribution to the Ground State Binding Energy in He-like Uranium

Electron-Electron Interaction in Strong Fields

Relativistic Many Body (RMB) + 2eQED

Ionization Energy, $I_H$

$\Delta E$: Two-Electron Contribution to the Ionization potential in the He-like System

Ionization Energy, $I_{He}$

$\Delta E = I_H - I_{He}$

$E_{Kin} + I_H = \hbar \omega_H$

$E_{Kin} + I_{He} = \hbar \omega_{He}$

$\Delta E (\hbar \omega_H - \hbar \omega_{He}) = I_H - I_{He}$

Relative measurement

All one electron contributions cancel out (e.g. finite nuclear size)
Relative Measurement of the Two-electron Contribution to the Ground State Binding Energy in He-like Uranium

- Data subdivided into several groups
- Checked for consistency

Statistical uncertainty for $\Delta E$: 9 eV

Uncertainty caused by doppler shift:

The result for the splitting $\Delta E$ is $2248 \pm 9$ eV

![Graph showing data points with error bars and a shaded region, indicating the statistical and doppler uncertainties.](image)
Experimental Results in Comparison with Theory

ESR (First experiment for the two-contribution U^{90+}): 2248(9) eV

Theory (Yerokhin et al. 1997): 2246 eV

2 photon exchange \sim 14 eV 2eSE \sim 9.7 eV

Super-EBIT (First measurement of the 2e contribution)
(Marrs et al, 1995)

But!! Results limited by counting statistics (Z<83)

As an example; for Bismuth an uncertainty of 14 eV has been achieved for the value of 1876 eV. 2eQED \sim 6.7 eV

- Our result agrees well with the most recent theoretical value.
- The experimental uncertainty is of the order of two-electron QED contributions.
- Compared to the former studies at Super-EBIT in Livermore, we could substantially improve the statistical accuracy and extend studies to the higher-Z regime.
SUMMARY AND OUTLOOK

- Two-electron QED Studies at the ESR
  - First measurement for helium-like uranium (U90+)
    - Improvement of experimental sensitivity by a factor of two compared to former exp.
    - Result sensitive to two-electron self energy (2eSE) contribution
    - The result is limited only by counting statistics.

Simultaneous measurement at 0 and 180 deg.
High resolution detection devices; spectrometer + PSG, calorimeter

Excellent agreement between experimental results and theory for both cases

‘No test can prove a theory but any single test can disprove it.’

Karl Popper