Atomic physics at FAIR: Precision experiments with highly-charged ions

Alexandre Gumberidze

ExtreMe Matter Institute
Collaborations

APPA Physics (Atomic, Plasma Physics and Applications)

- **BIOMAT** (Biology and Material Science)
- **FLAIR** (Facility for Low-Energy Antiproton and Heavy Ion Research)
- **HEDgeHOB** (High Energy Density Matter generated by Heavy Ion Beams)
- **SPARC** (Stored Particles Atomic Research Collaboration)
- **WDM** (Warm Dense Matter) collaboration
Physics with highly-charged heavy ions

Atomic structure
QED, many body effects

Nuclear Physics:
masses, nuclear moments, charge radii
two body decay etc.

Accelerator physics

Physics beyond the standard model

Astrophysics

Plasma physics

Atomic reactions and dynamics
photon-matter interaction
Hydrogen

Neutral Atom

Hydrogen-like uranium:
92 Protons in the nucleus
and only one electron

Smaller distance between electron and nucleus
(for uranium: electron is *about 100 times closer to the nucleus* than in hydrogen)

Electrons move very fastly; they are relativistic
(for uranium: K-shell electron moves
*with about 70% of the speed of light*)
When in heavy ions with more than one electron relativistic effects become important on the top of quantum phenomena then it becomes really complicated:

the electrons move very fastly, i.e. relativistically each electron has its own time (own clock)
Quantum mechanics (non-relativistic)

Relativistic Quantum mechanics
Dirac’s theory

Quantum Electrodynamics (QED)

Theory of relativity

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The theory of quantum electrodynamics is, I would say, the jewel of physics – our proudest possession.

... having to resort to such hocus-pocus [renormalization] has prevented us from proving that the theory of QED is mathematically self-consistent.

... [renormalization] is what I would call a dippy process.

R. Feynman, 1983

Richard Feynman
1918-1988

QED

R. Feynman, 1985

Self-energy

Vacuum-polarization
Extremely strong EM fields

Electron-Positron Pair production out of vacuum

$eE_d = 2mc^2$

$10^5$

$10^{10}$

$10^{15}$

$10^{20}$

STRONG EM FIELDS [ V/cm ]

K-shell Uranium

Laser, z.B. PHELIX

Hydrogen atom

Accelerator

Spark Plug

H-like Uranium
$E_K = -132 \cdot 10^3 \text{ eV}$

Hydrogen
$E_K = -13.6 \text{ eV}$
Physics of extremely strong fields

Intense Laser fields

Uranium
Z=92
\( \Delta E_{\text{QED}} \approx 500 \text{ eV} \)

Hydrogen
\( \Delta E_{\text{QED}} \approx 10^{-6} \text{ eV} \)

Extraordinary experimental precision \( \sim 10^{-14} \)

Electron-positron pair production from vacuum

Intensity \( [\text{W/cm}^2] \)

Relative accuracy

Year

1920 1940 1960 1980 2000

Laser spectroscopy

Frequency measurements

Nuclear Charge, Z
Bound-State QED in Strong Fields: effects of the quantum vacuum

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

**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 to all orders)
Non-perturbative bound-state QED was developed in the last 20 years by excellent theoreticians like:

Beier, Blundell, Breit, Czarnecki, Glazov, Jentschura, Johnson, Karshenboim, Lindgren, Lee, Milstein, Mohr, Pachucki, Persson, Plunien, Salomonson, Sapirstein, Shabaev, Soff, Sunnergren, Terekhov, Tupitsyn, Volotka, Yerokhin, and others.

Lamb Shift: nuclear effects

\[ |r\psi(r)|^2 \]

\( n=1 \)
- \( 1s \)
- \( 2s \)

\( n=2 \)
- \( 2p_{1/2} \)
- \( 2p_{3/2} \)

Radius \([\text{fm}]\)
Level Scheme of Hydrogen

hydrogen

Z=1
\(E_b = 13.6 \text{ eV}\)
\(Z \cdot \alpha \ll 1\)

uranium ion

Z=92
\(E_b = 132 \text{ keV}\)
\(Z \cdot \alpha \approx 1\)

\(\lambda_{\text{Ly-}\alpha_1} \approx 121.6 \text{ nm}\)

\(\Delta E_{\text{HFS}} \approx B_I \mu_J\)
\(\lambda_{\text{HFS}} \approx 21 \text{ cm}\)

Bohr
\(\Delta E \propto Z^2\)

Dirac
\(\Delta E \propto Z^4\)

QED
\(\Delta E \propto Z^4\)

Hyperfine
\(\Delta E \propto Z^3\)
\[ \mu = g \cdot \frac{e}{2m} J \]

- **m**: magnetic moment
- **g**: g-factor
- **e**: charge
- **m**: mass
- **J**: angular momentum

**g-factor of an electron**
g-factor of an electron

mass $m$ (no theoretical prediction)

charge $e$ (no theoretical prediction)

magnetic moment $\mu$ (QED, most successful theory in physics)
Testing our current understanding of EM interactions (QED) in different regimes with fundamental atomic systems.

- Precision calculations: QED, many body effects, extreme fields
- Obervables: (B.E., g-factor, HF-structure, etc.) measured with high precision
- Fundamental constants: Rydberg, $\alpha$, electron mass
- Nuclear ground state properties: masses, nuclear moments, charge radii

H-like Uranium: $<E> \sim 10^{16}$ V/cm
Bohr criteria: *Largest ionization cross section at* $V \approx V_K$

$$v_K/c \approx 0.67$$  $E_{\text{KIN}} \approx ?$

Why relativistic velocities?
Facilities for Atomic Physics at FAIR MSV

cooled and stored HCl: from relativistic energies to rest

\( \eta = (\gamma - 1) mc^2 / E_{\text{rel}} = 1 \)
Experimental Conditions at the HESR

- species: p, pbar, HCI, RIB
- circumference 574 m
- injection energy 740 MeV/u
- $B_\rho = 50 \text{ Tm}$
- for $\text{U}^{92+}$: 4.937 GeV/u
- $\gamma_{\text{MAX}} = 6.30; \beta_{\text{MAX}} = 0.987$
- momentum (energy) range: (0.8-14.1 GeV)
- stochastic cooling / e-cooling
  - electron-, gasjet-, fiber-targets (!)
  - Particle detectors
  - ion stacking
  - luminosity (number of stored ions)
  - beam diameter/charge separation
  - acceleration and deceleration
  - coupling of laser to the ion beam line
  - building / space for setups

Worldwide premiere: Precision experiments using cooled relativistic ion beams
Explore correlated electron dynamics
- on sub-attosecond time-scale
- not accessible by other means

Explore relativistic quantum dynamics
- particle production
- non-perturbative regime
- coupling to the radiation field

$E \propto 1/\gamma^2$
Physics program at high energies (HESR)

**pair-production phenomena**
- non-perturbation regime \(\alpha Z_1 \approx \alpha Z_2 \approx 1\)
- multiple pairs (???)
- negative continuum dielectronic recombination

**radiative processes**
- recombination (polarization phenomena etc.)
- Photon-photon angular correlations (2E1-decay)

**target ionization**
- correlated electron motion – exploring the ultrafast, extremely strong transient fields of relativistic ions

**electron impact phenomena**
- electron impact excitation and ionization

**bound state QED and nuclear parameters**
- laser excitation in Li-like ions \(\Delta n = 0\)

**Laser-ion Interaction at high \(\gamma\)**
- test of special relativity
- laser cooling

**Tests of the standard model**
- PNC effects in high-Z ions
cooled and stored HCI: from relativistic energies to rest

\[ \eta = (\gamma - 1)mc^2 / E_{BK} = 1 \]

Low-energy branch

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already at SIS18/ESR: unique physics opportunities !!!

with RESR: e-cooled low-energy pbars
Let us come back to Dirac energy of a single hydrogen-like ion:

\[ E_{1s} = mc^2 \sqrt{1 - (Z \alpha)^2} \]

What happens if we increase the nuclear charge \(Z\)?

If nuclear charge of the ion is greater than \(Z_{\text{crit}}\) the ionic levels can “dive” into Dirac’s negative continuum.

Physical vacuum becomes unstable: creation of pairs may take place!
Supercritical fields: Formation of Quasi-Molecules

Merged Beams

\[ U^{91+} \]

\[ U^{92+} \]

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

Ni\(^{28+}\) 400 \(\rightarrow\) 30 \(\rightarrow\) 4 MeV/u

ESR cycle during recent experiment:

- 5..20 s: injection, **stoch. cooling**
- 3..10 s: deceleration 400 – 30 MeV/u
- 2..6 s: e\(^-\) cooling, rebunching
- 2..5 s: deceleration 30 – 4 MeV/u
- 2..5 s: e\(^-\) cooling, ejection
- 3 s: reset magnets

signal:
- RF amplitude
- magn. dipole field
- ion current

1100 \(\mu\)A \(\rightarrow\) 180 \(\mu\)A \(\rightarrow\) 25 \(\mu\)A
$g$-factor of the bound electron in a HCI

**Lamor frequency**

$$\omega_L = g_S \frac{e}{2m_e} B$$

**cyclotron frequency**

$$\omega_c = \frac{e}{m_e} B$$

'Experimental g-factor' comparison with theory

$$g = 2 \left( \frac{q}{e} \right) \left( \frac{m_e}{M_i} \right) \left( \frac{\omega_L^e}{\omega_C^i} \right)$$

External input parameter

Measurement
High-precision measurement of the atomic mass of the electron


Affiliations | Contributions | Corresponding author

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The quest for the value of the electron’s atomic mass has been the subject of continuing efforts over the past few decades. Among the seemingly fundamental constants that parameterize the Standard Model of physics and which are thus responsible for its predictive power, the electron mass $m_e$ is prominent, being responsible for the structure and properties of atoms and molecules. It is closely linked to other fundamental constants, such as the Rydberg constant $R_\infty$ and the fine-structure constant $\alpha$ (ref. 6). However, the low mass of the electron considerably complicates its precise determination. Here we combine a very precise measurement of the magnetic moment of a single electron bound to a carbon nucleus with a state-of-the-art calculation in the framework of bound-state quantum electrodynamics. The precision of the resulting value for the atomic mass of the electron surpasses the current literature value of the Committee on Data for Science and Technology (CODATA) by a factor of 13. This result lays the foundation for future fundamental physics experiments and precision tests of the Standard Model.
Scientific Goal: Precision Studies of the Quantum Dynamics of Atomic Systems in Critical and Super-Critical Fields

Discovery Potential:
- new concepts for QED in extreme fields
- inside into the correlated many-body dynamics via ultrashort and super intense field pulses (<10^{-18} s)
- precision determination of fundamental constantes ($\alpha, m_e$)
- proof of fundamental symmetries
- discovery and understanding of new decay modes of nuclei
- determination of fundamental nuclear properties via atomic data

Observables: x-rays, electrons, positrons, ions (projectiles, recoil)
PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS: Ground state Lamb shift in H-like uranium

Electron Cooler

X-ray Detector

The ESR Dipole Magnet

e^{-}
QED effects on the energy levels of high-Z few-electron systems

One-electron QED corrections of second order in $\alpha$
Non-perturbative calculations (in $Z\alpha$)

Goal
$\sim 1$ eV

Recent progress: Evaluation of the two-loop self-energy diagrams
(V.A. Yerokhin, P. Indelicato, and V.M. Shabaev, JETP, 2005; PRL, 2006).
Towards an accuracy of 1 eV

Ge(i)-detector

FWHM \approx 500 \text{ eV}
\varepsilon = 10^{-4}

crystal spectrometer and/or microcalorimeter

FWHM \approx 50 \text{ eV}
\varepsilon = 10^{-8}
A Laue Crystal Spectrometer

Bragg-Laue Relation

\[ \lambda = 2 \cdot d \cdot \sin \Theta \]

Crystal Spectroscopy

- measurement of angles
  \[ \Rightarrow \text{measurement of wavelength} \]
- resolution: \( \sim 75 \text{ eV} \) @ 60 keV

Crystal radius of curvature: 2 m
\[ \Theta_{\text{Bragg}} = \sim 2.9^\circ \]

\[ \Delta y \Rightarrow \Delta \Theta \Rightarrow \Delta E \]
1 mm 750 eV

X-rays

\( d \)

\( \Theta_{\text{Bragg}} \)

X-ray source

bent crystal

\( \lambda_1 < \lambda_2 \)

\( \lambda_1 \)

\( \lambda_2 \)

\( \Delta y \)

Position-sensitive detector
Prototype 2D $\mu$STRIP X-Ray Detector

$2D \mu$STRIP planar detector systems for precision x-ray spectroscopy experiments (FOCAL)

energy resolution – timing - 2D position sensitivity

front: 128 strips pitch $\sim250\mu m$
back: 48 strips pitch $\sim1167\mu m$

equivalent to 6144 pixel

$\mu$STRIP detector developed by
The FOCAL setup: dedicated transmission spectrometers + 2D μSTRIP x-ray detectors

The FOCAL setup:
dedicated transmission spectrometers + 2D μSTRIP x-ray detectors
Raw 2D spectrum

2D spectrum with energy and time condition
Micro-calorimeter detector: large wavelength acceptance, large quantum efficiency, and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).

- **Detector** operates at about 50 mK

**Micro-calorimeter Detector**

- Operates at about 50 mK
- Large wavelength acceptance
- Large quantum efficiency
- Excellent energy resolution

**Physics Behind**

- **Photoelectron**
- **Absorber**
- **Thermometer**
- **Phonons**
- **Heat Sink**

**Equation**

\[
\Delta T = \frac{E}{C}
\]

**Heat Capacity**

- **Heat capacity**: \( C = c \cdot m \)
- Specific heat capacity: \( c \sim T^3 \)
- Detector mass: \( m \)
maXs-20 Prototyp Spectrum

A. Fleischmann, C. Enss, University of Heidelberg

$^{55}\text{Mn}, K_{\alpha}$

$\Delta E_{\text{FWHM}} = 1.6 \text{ eV} \at 6 \text{ keV}$

World record together with TES-sensors of NASA-GSFC!
maXs-200: detector arrays for hard x-rays

First characterization with an $^{241}$Am-source

$^{237}$Np

$^{210}$Pb

Energy [keV]

$\Delta E_{FWHM} = 40 \text{ eV} \ @ \ 0\text{-}10 \text{ keV}$

$\Delta E_{FWHM} = 60 \text{ eV} \ @ \ 60 \text{ keV}$

Slight degradation towards higher energies due to

- Poor temperature stability in this first experiment
- Possible marginal position dependence, to be fixed by stems between absorber and sensor
Novel instrumentation: other ongoing developments

- X-ray lasers
- Trapping/measurement techniques
- DR spectroscopy
- non-destructive in-ring ion detection systems
- particle detectors in UHV (in-ring)
- RCE spectroscopy
- ...

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Wordwide Unique Research Opportunities

& Challenges for Atomic Physics

Thank you very much for your attention!

Extreme Static Fields
Extreme Dynamic Fields
Antimatter and Fundamental Physics