Test of bound state QED at the highest electric fields:

Atomic structure of high-Z one - and few-electron ions

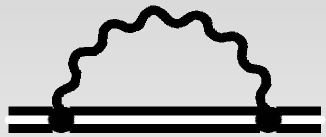
Thomas Stöhlker

Gesellschaft für Schwerionenforschung (GSI) / Darmstadt and University of Frankfurt

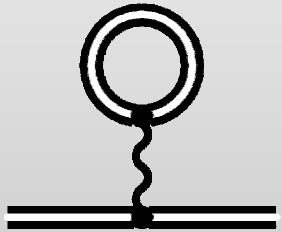
Atomic Physics in Extremly Strong Coulomb Fields

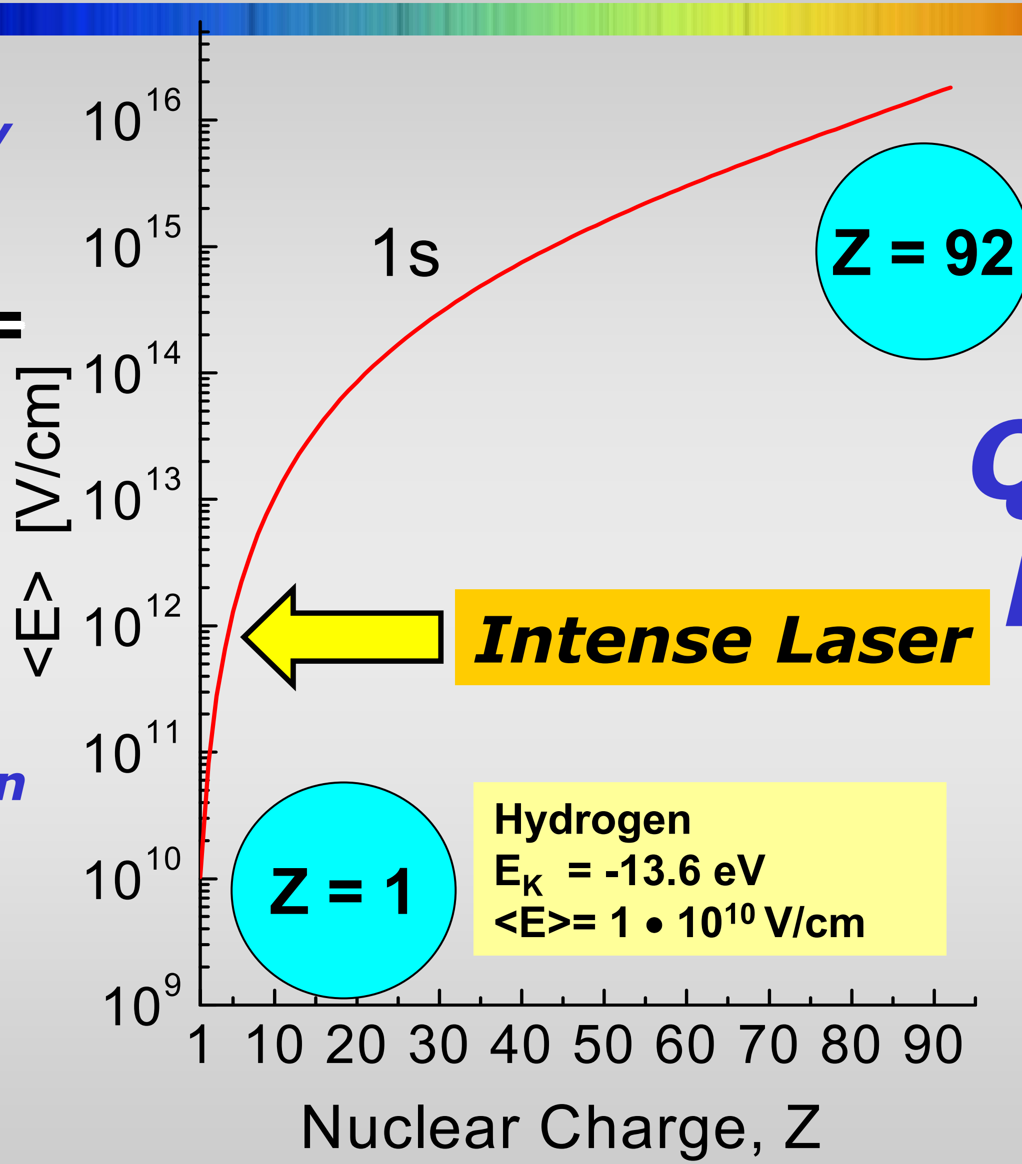
H-like Uranium
E_K = -132 • 10^3 eV
<E>= 1.8 • 10^{16} V/cm

Self Energy



Vacuum Polarization





Hydrogen
E_K = -13.6 eV
<E>= 1 • 10^{10} V/cm

Quantum
Electro-
Dynamics

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

QED

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

R. Feynman, 1983

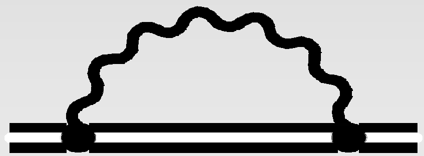
… having to resort to such hocus-pocus [renormali-zation] has prevented us from proving that the theory of QED is mathematically self-consistent.
… [renormalization] is what I would call a dippy process.

R. Feynman, 1985

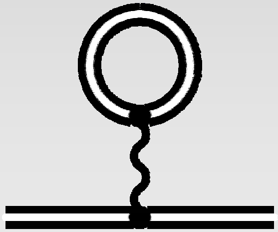
Bound-State QED: 1s Lamb Shift

Sum of all corrections, leading to deviations from the Dirac theory for a point like nucleus

Self energy



Vacuum polarization

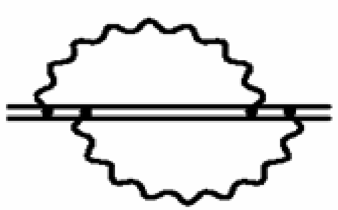


U^{92+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

$$\Delta E = \alpha/\pi\,(\alpha Z)^4\,F(\alpha Z)\,m_e c^2$$

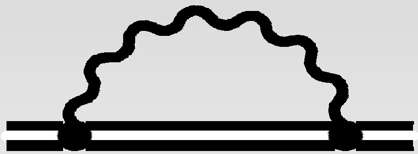
Low Z-Regime: $\alpha Z \ll 1$
F(αZ): series expansion in αZ

High Z-Regime: $\alpha Z \approx 1$
F(αZ): series expansion in αZ not appropriate

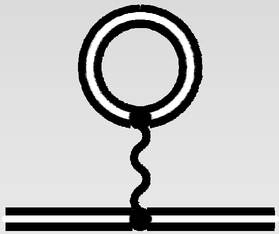
Goal:  **±1 eV**

Test of Bound-State QED at high-Z

Self Energy



Vacuum Polarization



Experiments

1s Lamb Shift

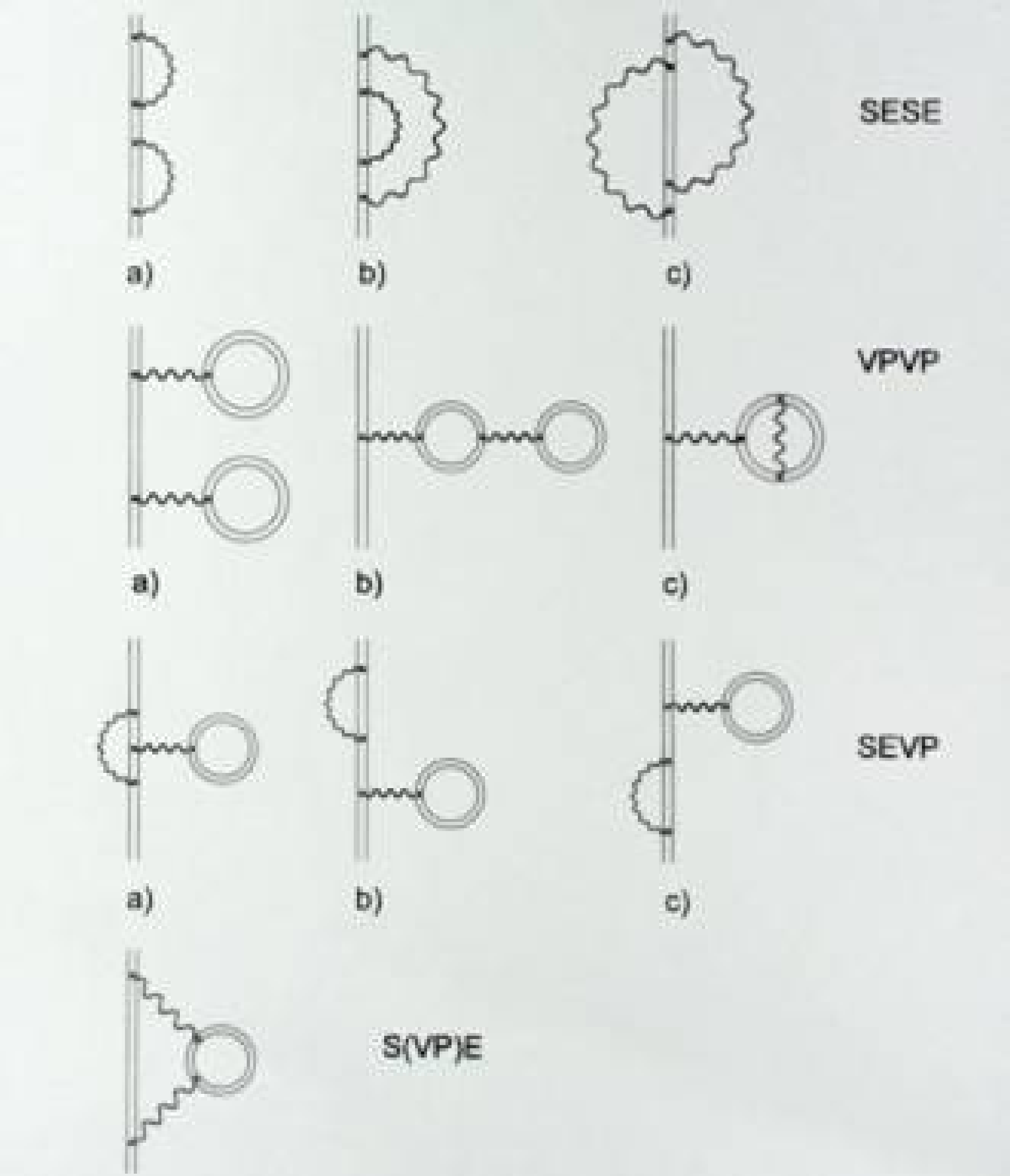
2eQED for He-like ions

2s-2p transitions in Li-like heavy ions

hyperfine-structure

g-factor of bound electrons

QED correction in second order α



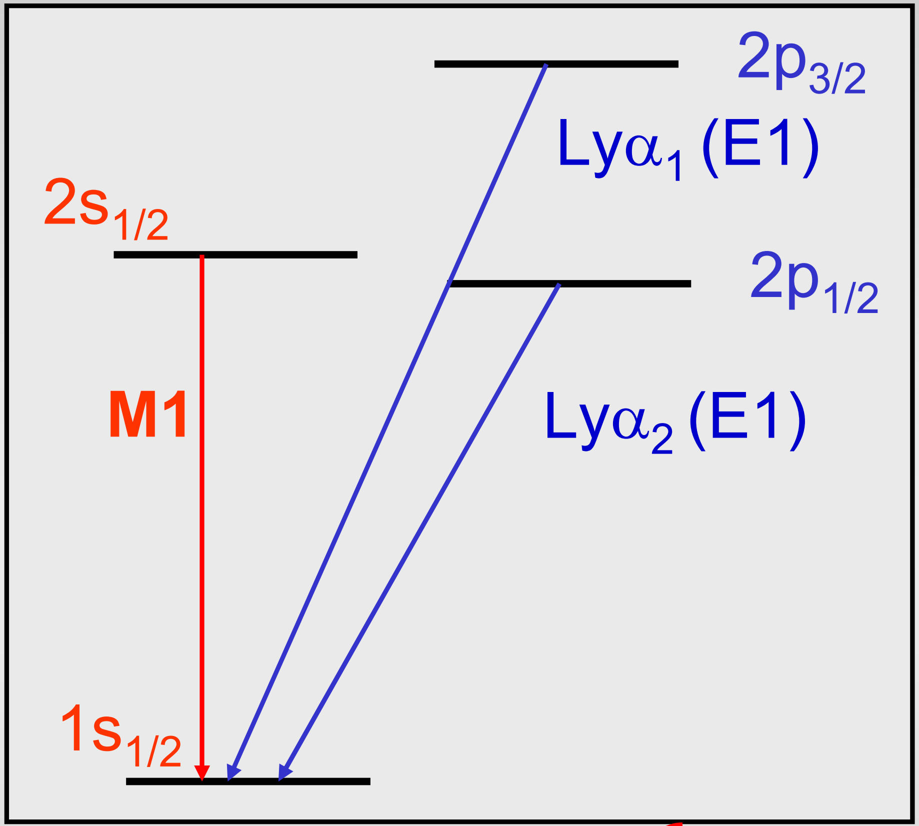
GSI Atomic Physics

The 1s-Lamb-Shift Collaboration

H.F. Beyer
K. Beckert
P. Beller
A. Bleile
D. Banas
J. Bojowald
F. Bosch
P. Egelhof
E. Förster
B. Franzke
A. Gumberidze
S. Hagmann
J. Hoszowska
P. Indelicato
O. Klepper
H.-J. Kluge
St. König
Chr. Kozhuharov
D. Liesen
X. Ma
B. Manil
D. McCammon
I. Mohos
A. Orsic-Muthig
F. Nolden
U. Popp
D. Protic
A. Simionovici
D. Sierpowski
U. Spielmann
C.K. Stahle
Z. Stachura
M. Steck
Th. Stöhlker
S. Tashenov
M. Trassinelli
A. Warczak
M. Weber
O. Wehrhan

Grenoble
Mainz
Paris
Jülich
Caen
Darmstadt
Cracow
Madison
Jena
Greenbelt

The Structure of One-Electron Systems



QED corrections

$\Delta E \sim Z^4/n^3$

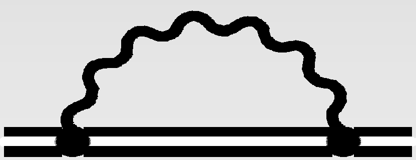
Z: nuclear charge number
n: prinzipal quantum number

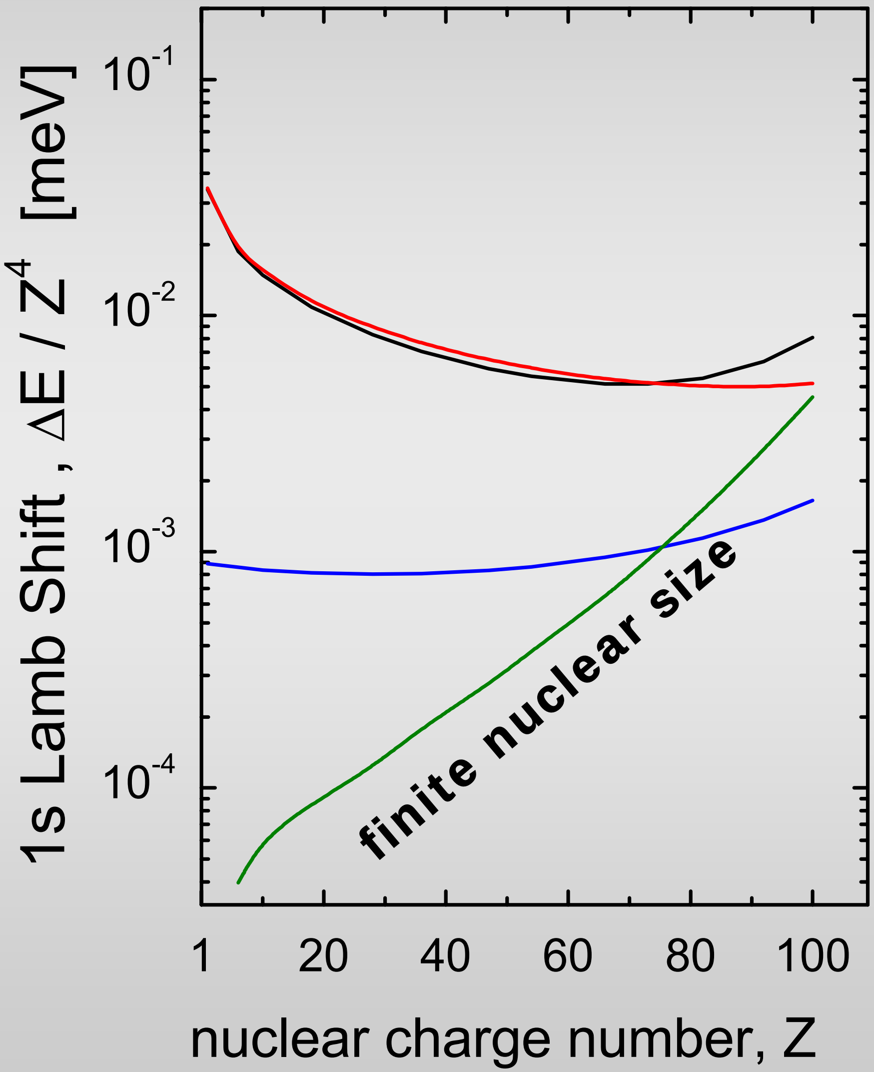
Atomic systems at high-Z

- Large relativistic effects on energy levels and transition rates (e.g. shell and subshell splitting)
- Large QED corrections
- Transition energies close to 100 keV

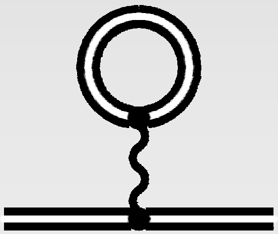
Test of Bound-State QED at high-Z

Self Energy

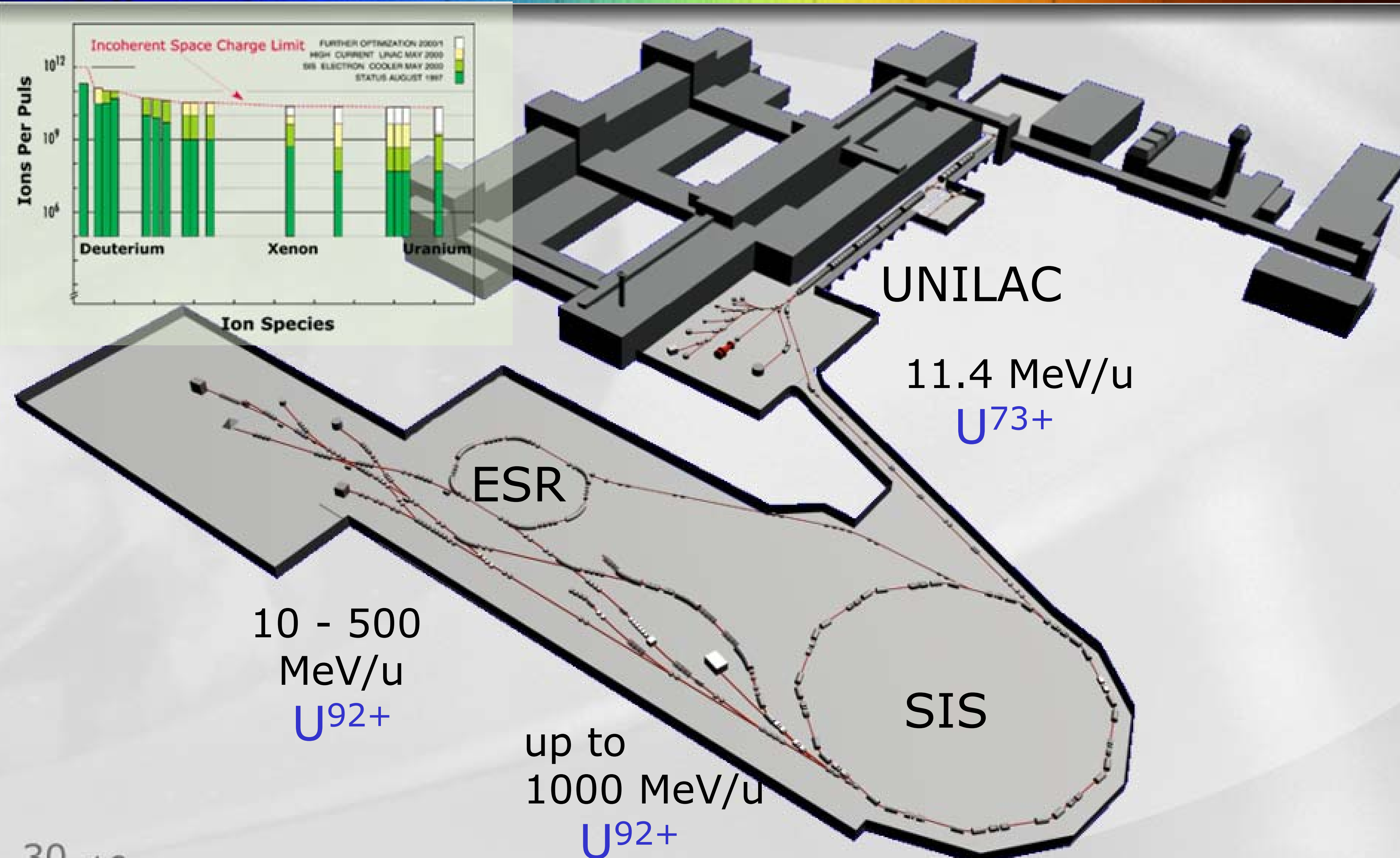




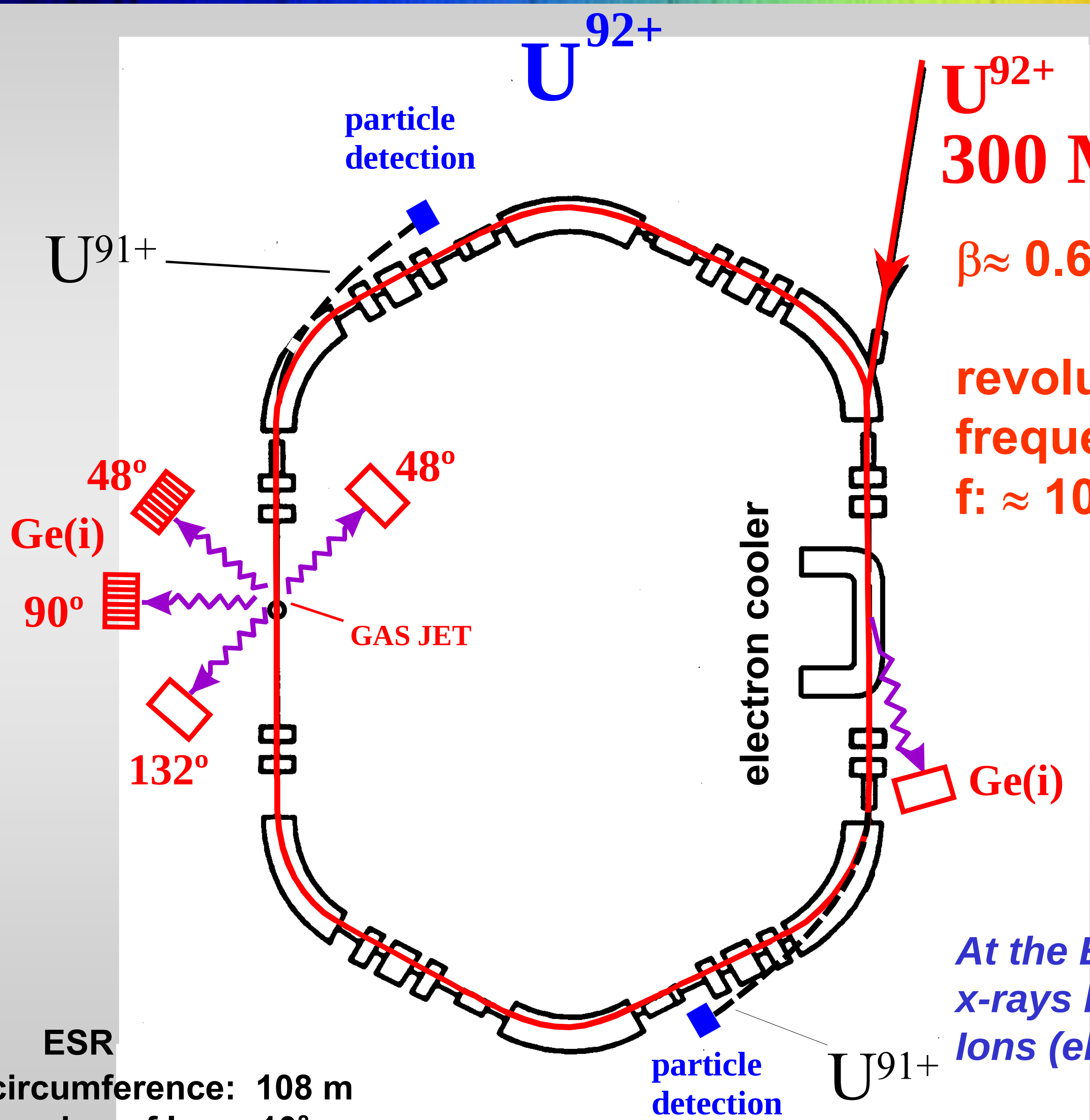
Vacuum Polarization



GSI-Accelerator Facility



X-Ray Experiments at the ESR Storage Ring



$\beta \approx 0.65$

revolution frequency f: $\approx 10^6$ 1/s

U^{92+} 300 MeV/u

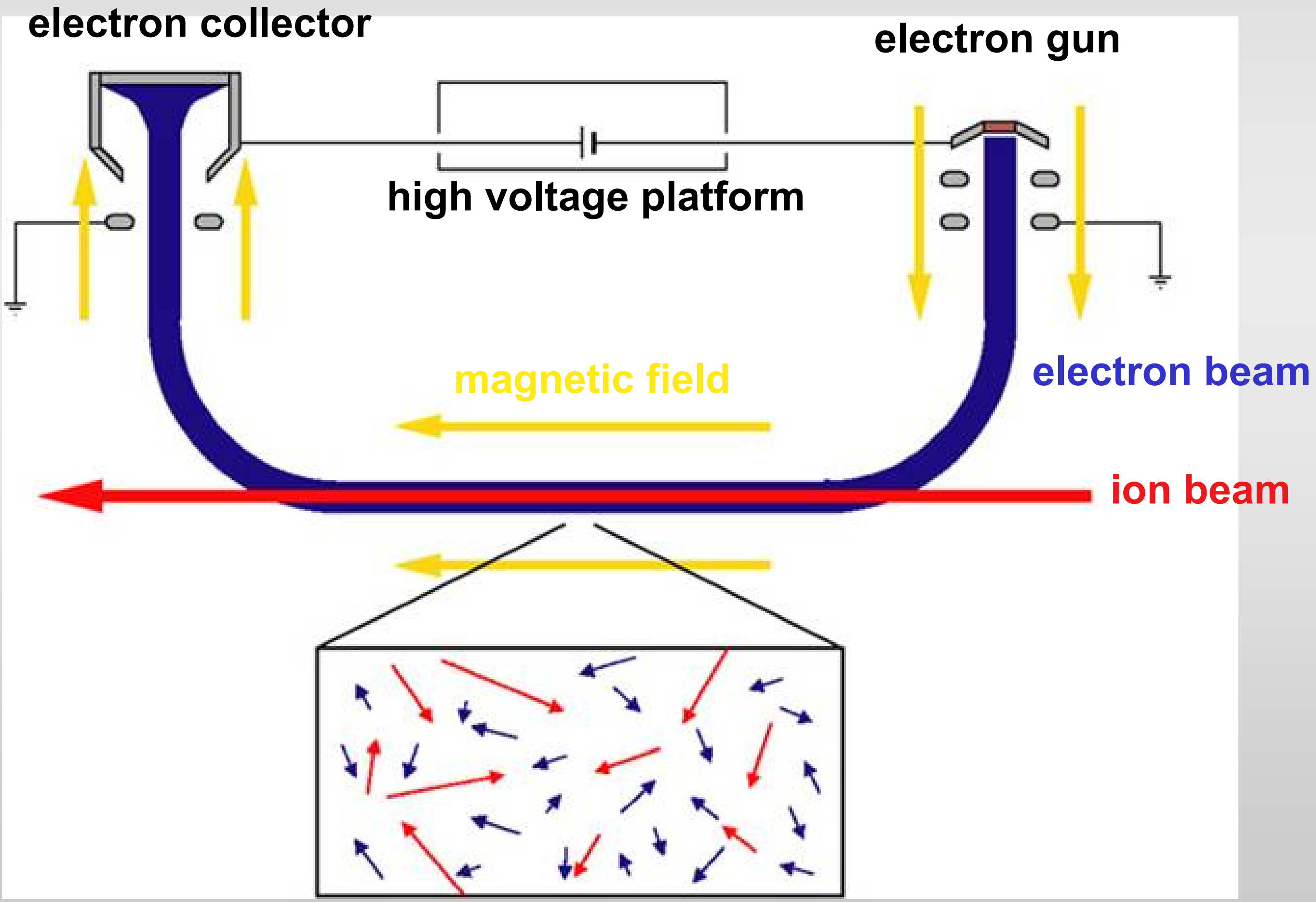
deceleration

U^{92+} 20 MeV/u

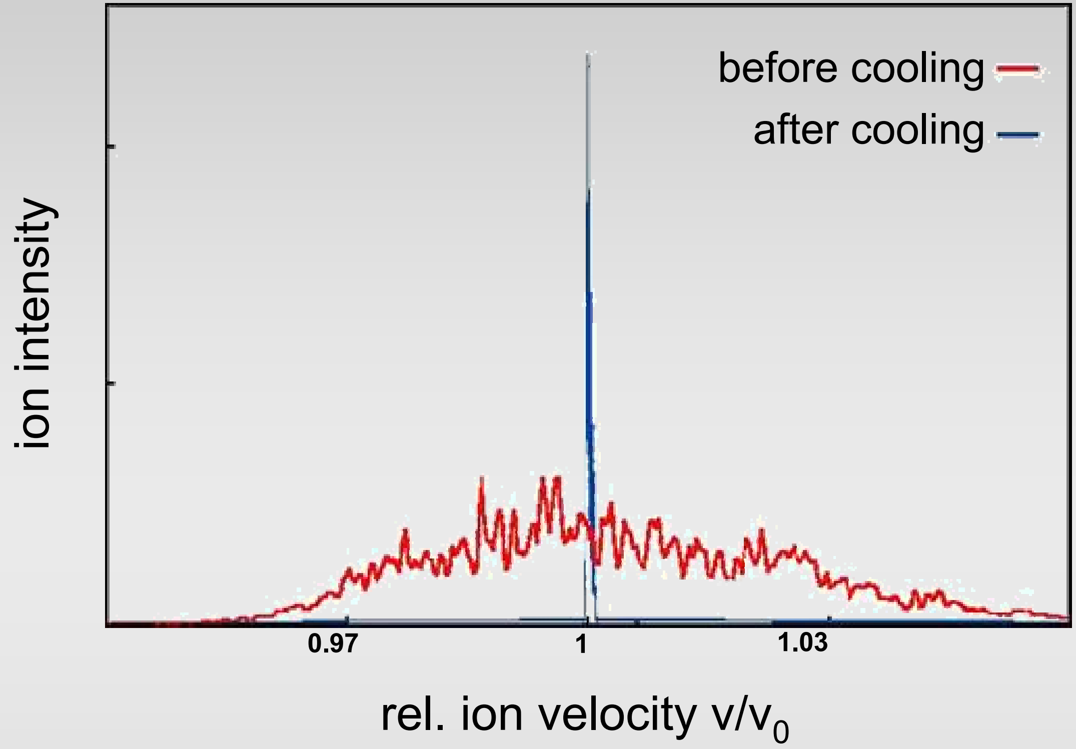
At the ESR, production of characteristic x-rays by electron capture into the bare Ions (electron cooler or jet-target)

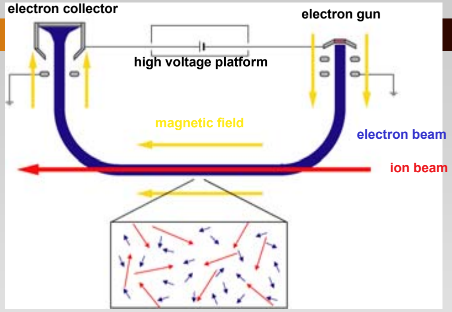
ESR
circumference: 108 m
number of Ions: 10^8

Storage Rings: Cooled Ion Beams



Storage Rings: Cooled Ion Beams





Ions interact 10^6 1/s with a collinear beam of cold electrons

Properties of the cold ions

Momentum spread	$\Delta p/p$: $10^{-4} - 10^{-5}$
Diameter	2 mm

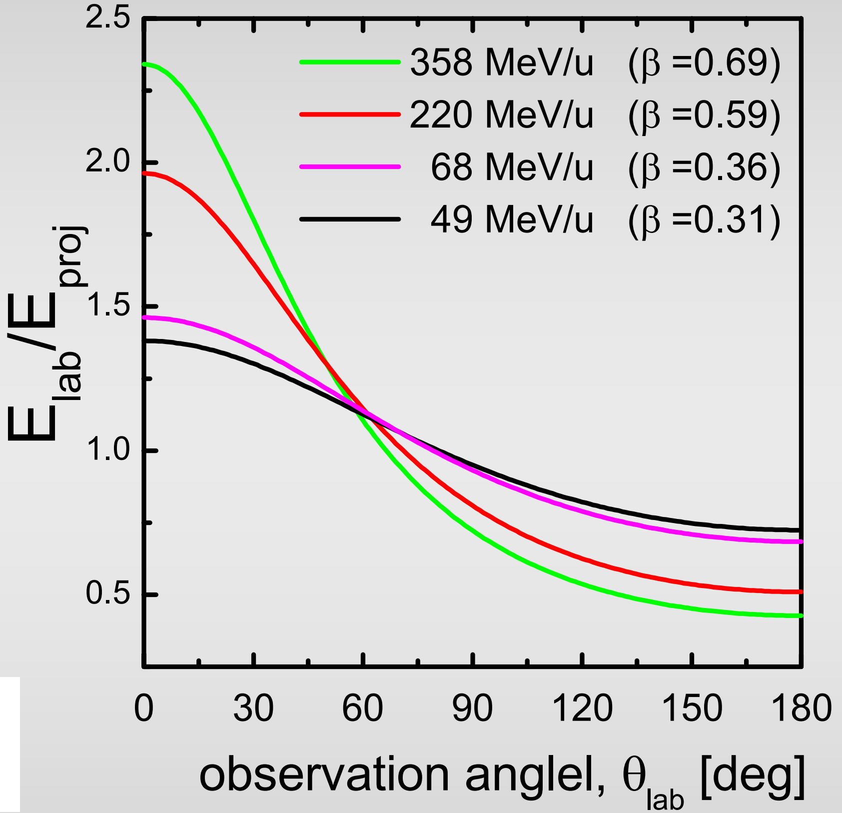
The Experimental Challenge

Relativistic Doppler-Transformation

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

E_{lab}: Photon energy in the laboratory system
E_{proj}: Photon energy in the emitter system

Doppler-Correction: *Strong dependence on velocity and the observation angle* θ_{LAB}



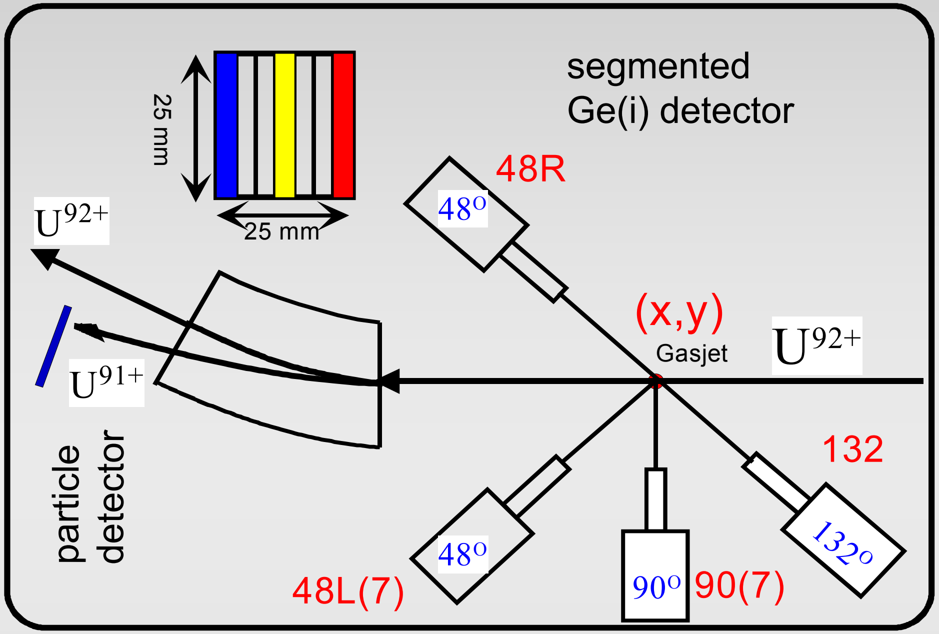
Principle of LS Experiments at ESR

1. *Production of bare ions*
2. *Cooling*
3. *Electron capture in excited states (jet-target or electron cooler)*
4. *Detection of x-rays*
5. *Doppler correction*
6. *Comparison with Dirac theory*

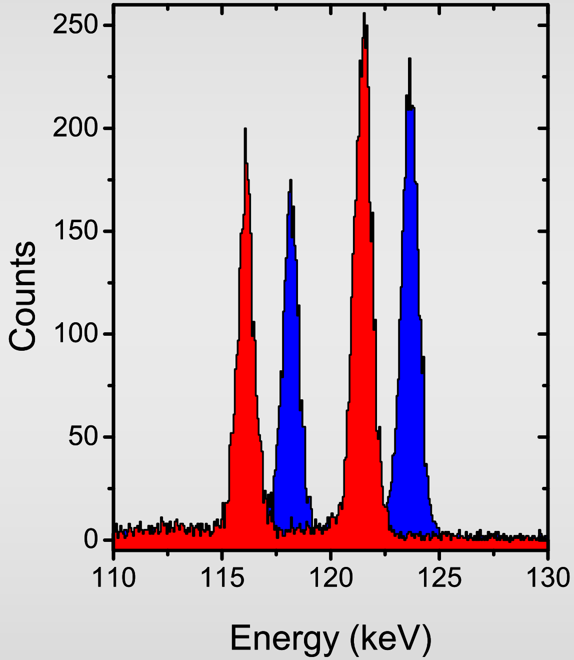
→ **1s Lamb Shift**

Lamb Shift-Experiment at the Jet-Target

Atomic Physics



Lyα_1 ($2p_{3/2} \rightarrow 1s_{1/2}$)
102 171 ± 13.2 eV



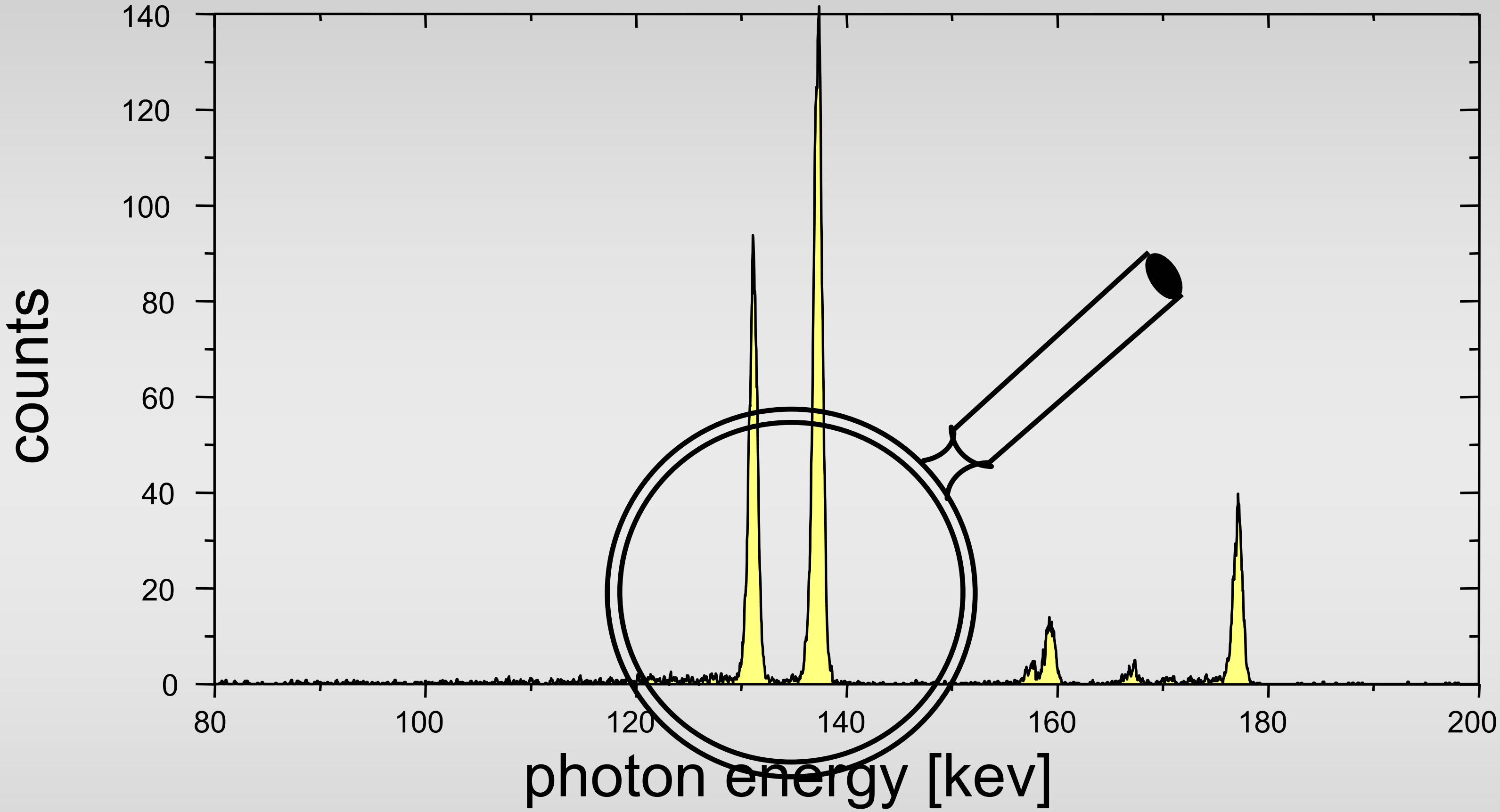
$\Delta\theta \approx 3.0$ deg

- *Simultaneous observation at various angles*
- *Forward/Backward symmetry*
- *Left/Right symmetry*

1s-Lamb Shift

Experiment: 468 eV ± 13 eV
Theory: 466 eV*

The ground state Lamb shift in H-like uranium



From the Lyman line centroid the value for the 1s Lamb shift in H-like uranium is obtained.

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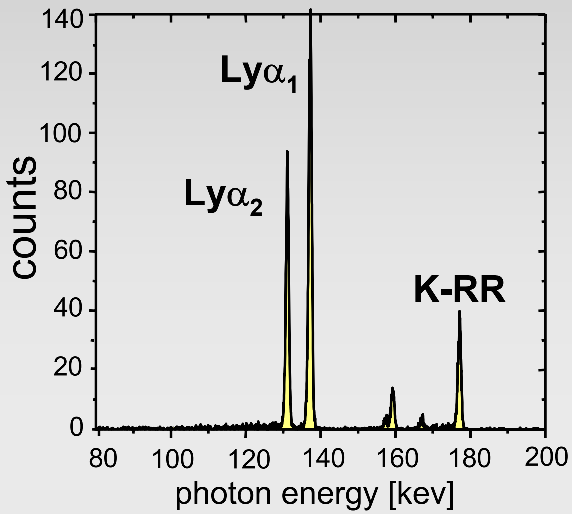
Test of Quantum Electrodynamics (1s-LS)

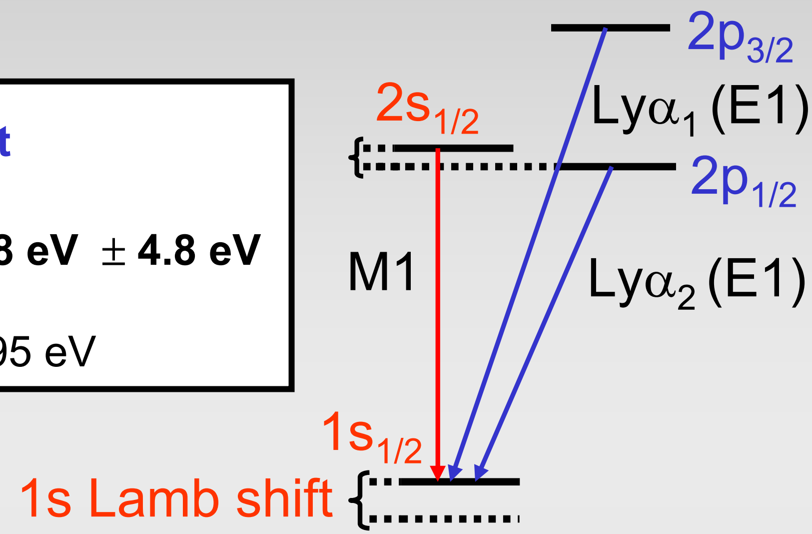
The 1s-LS in H-like Uranium

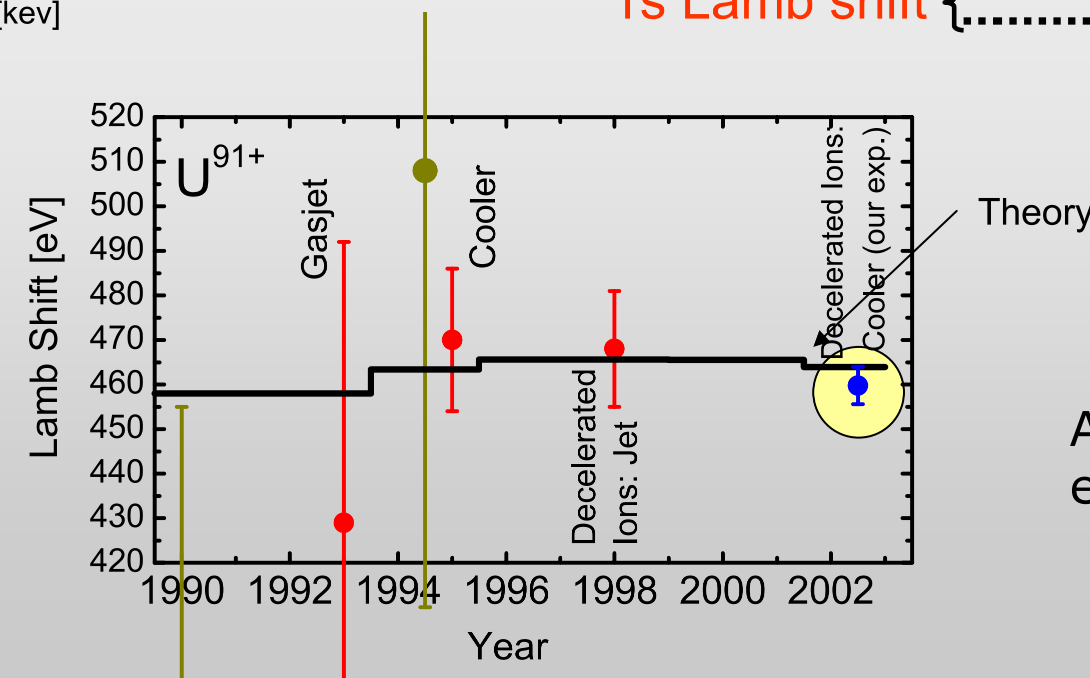


1s-Lamb Shift

Experiment: 459.8 eV ± 4.8 eV

Theory: 463.95 eV

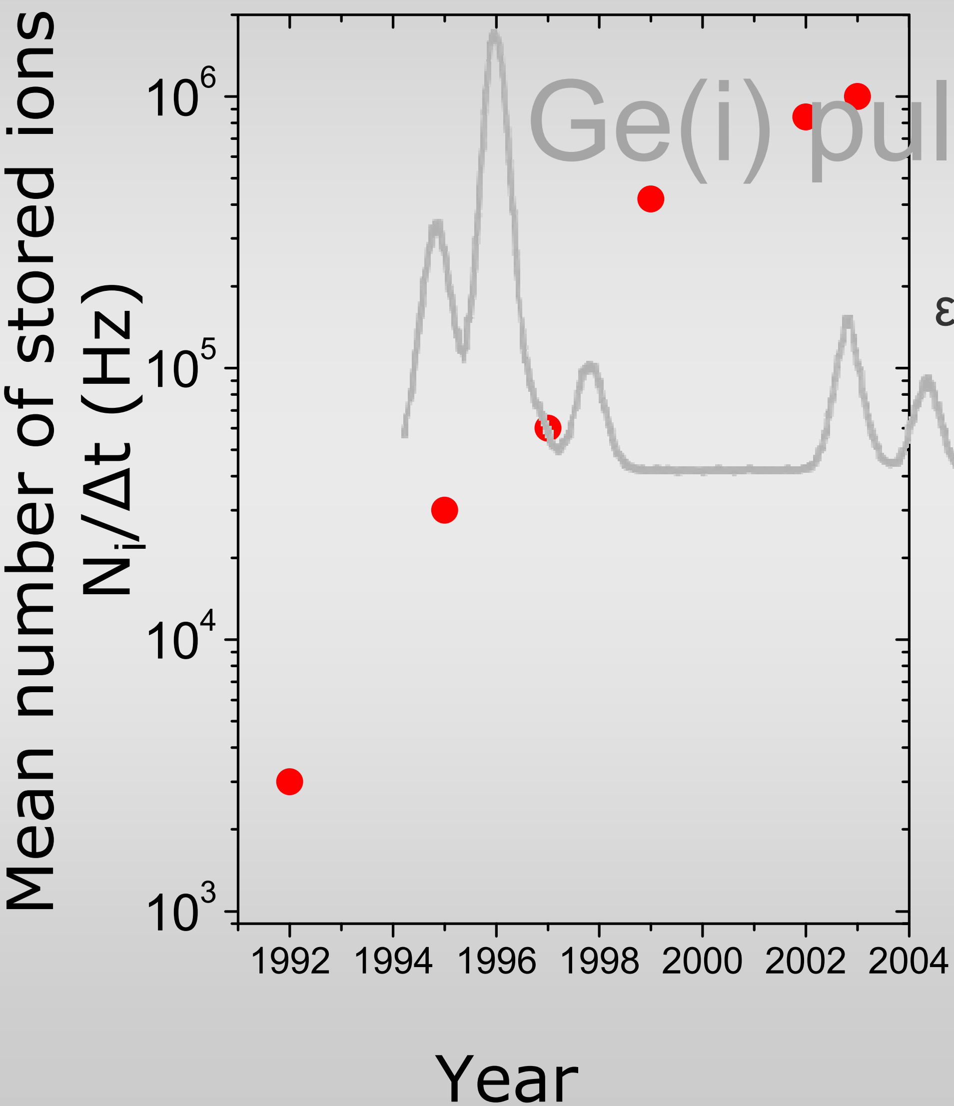




A. Gumberidze et al., 2003

GSI Atomic Physics

Towards an Accuracy of 1 eV



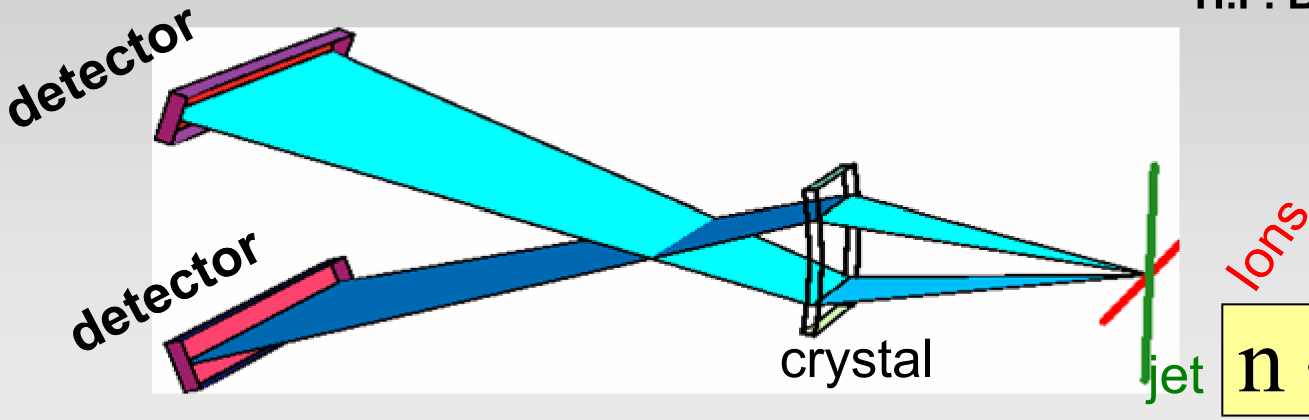
- **High Beam intensities**
  (10^8 Ions per Minute $\Rightarrow$ 4.5×10^5 Photons in 4π)
- **Slow Ions or Ions in Rest**
  Deceleration of the Ions
  $\Rightarrow$ Small Doppler correction
- **Detector and Spectrometer Development**

Crystal spectrometer
$\leq$ 50 eV
(requires position sensitive solid state detectors)

mircocalorimeter **?**

Transmission crystal spectrometer *towards an accuracy of 1 eV*

H.F. Beyer et al., GSI Report 2000



Bragg-Laue relation

$$n \cdot \lambda = 2 \cdot d \cdot \sin\theta$$

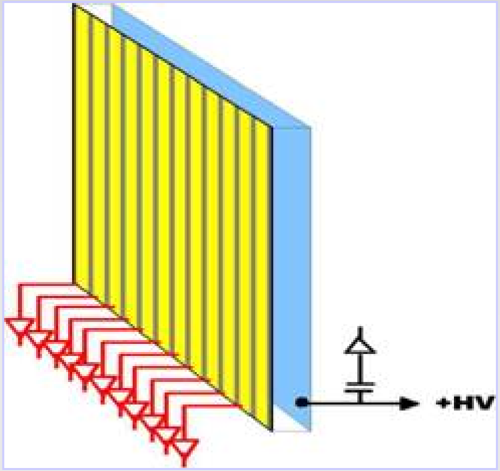
FOCAL spectrometer: $\varepsilon \approx 10^{-8}$ $\Rightarrow$ 5 events per hour

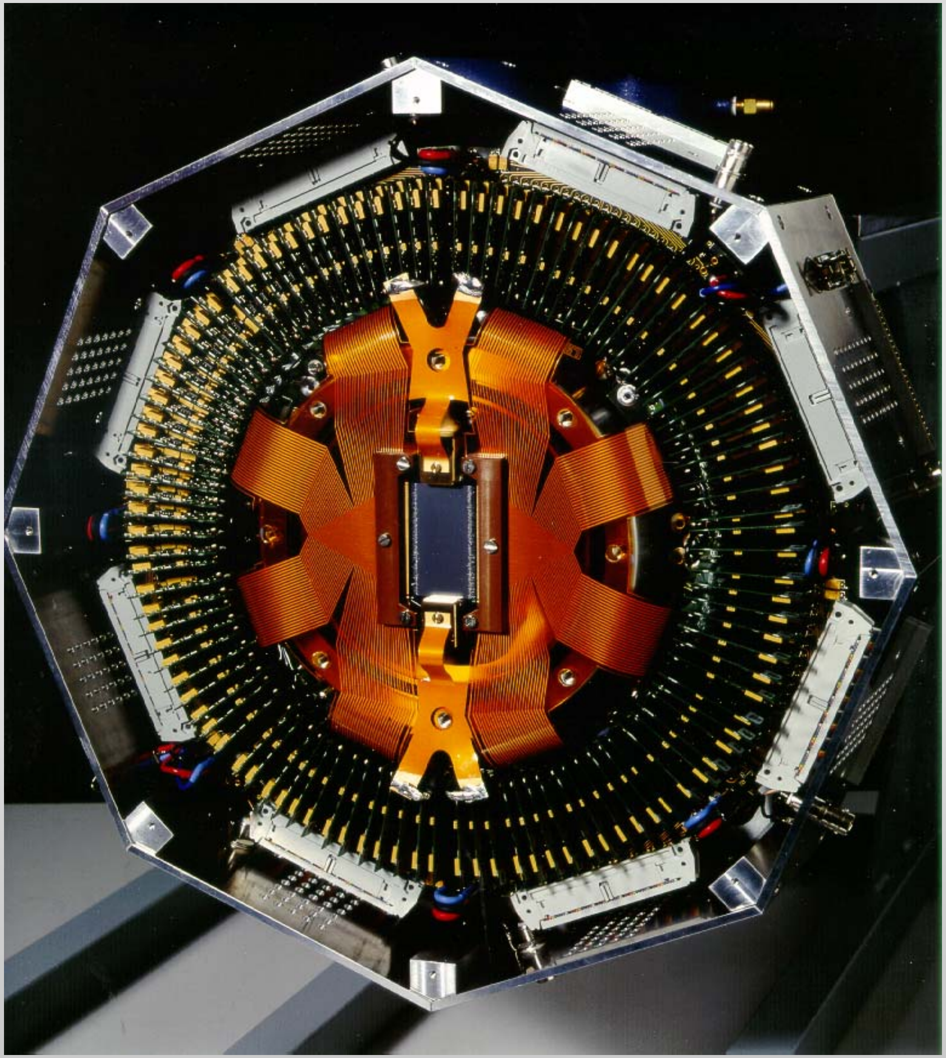
gas counters (drift chambers)

Position Sensitive Ge(i) Detectors

Micro-Strip Germanium Detector Development:

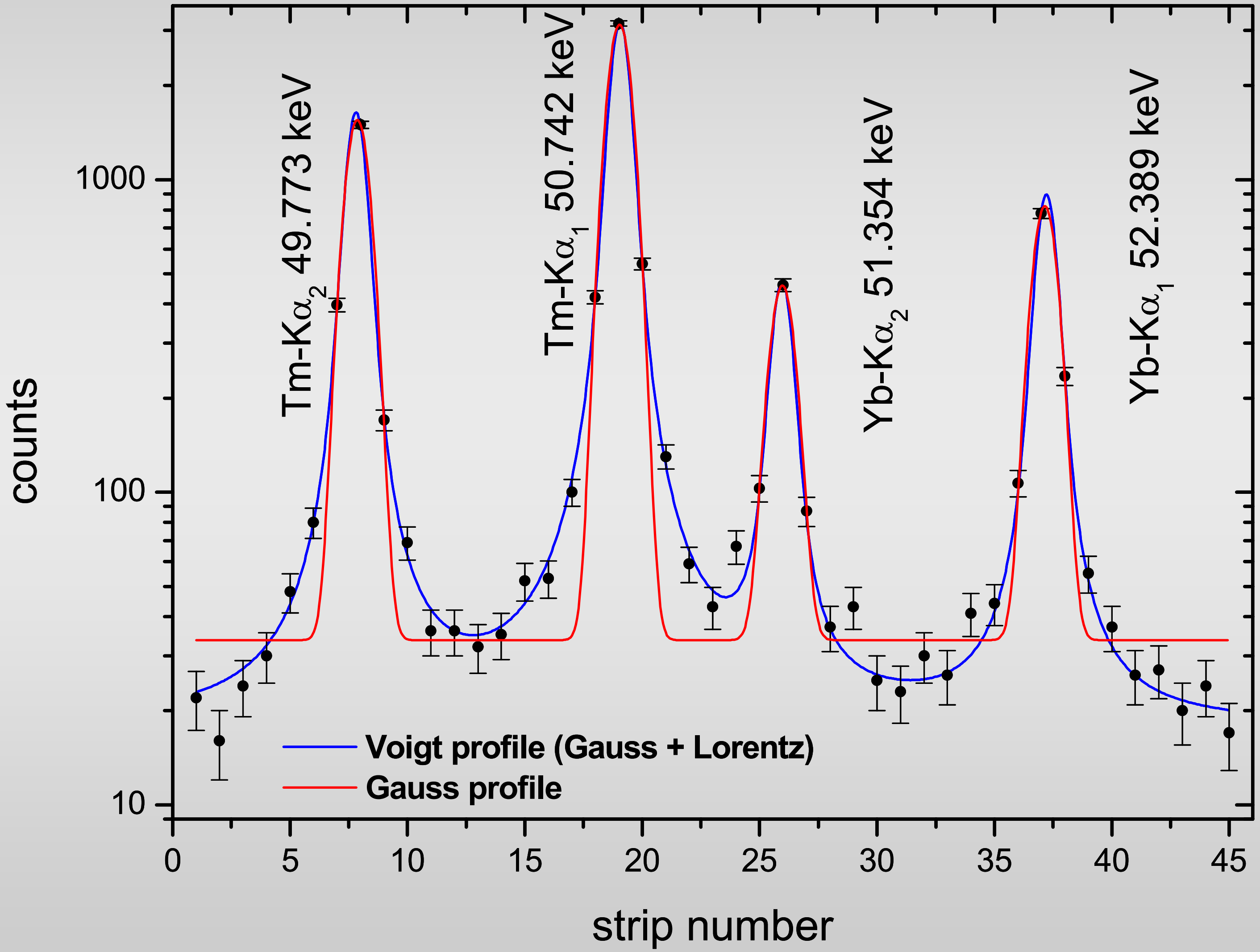
Energy Resolved X-Ray Imager, Timing, Multi-Hit Capability





- crystal spectrometer
- polarization studies
- Compton cameras

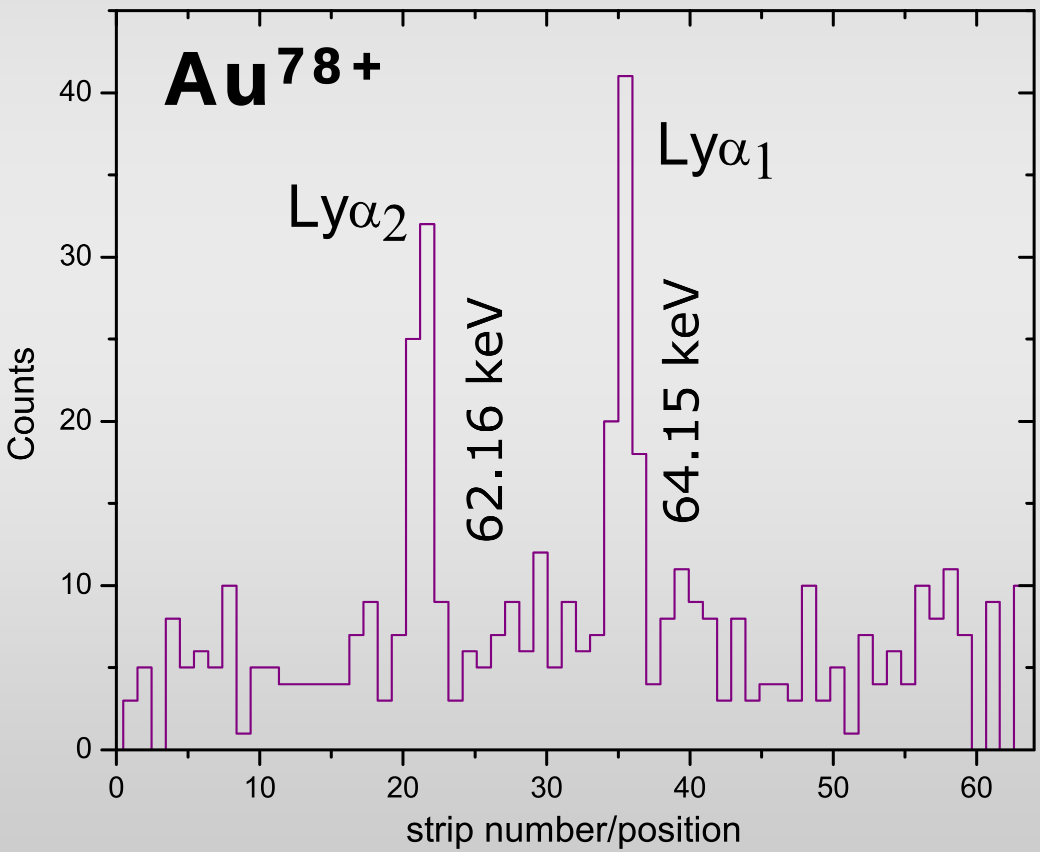
FOCAL + Micro-Strip Germanium Detectors
LABORATORY

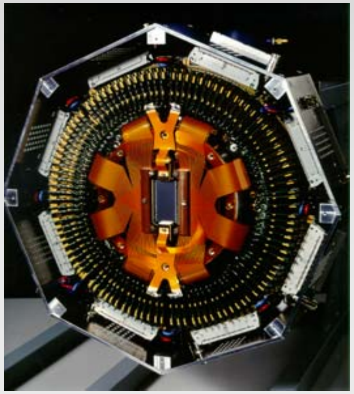


natural line width: 38 ± 9 eV

(50 μm: 18.9 eV: 1 strip: 89 eV)

Commissioning at the beam line





for data analysis
following conditions used

position

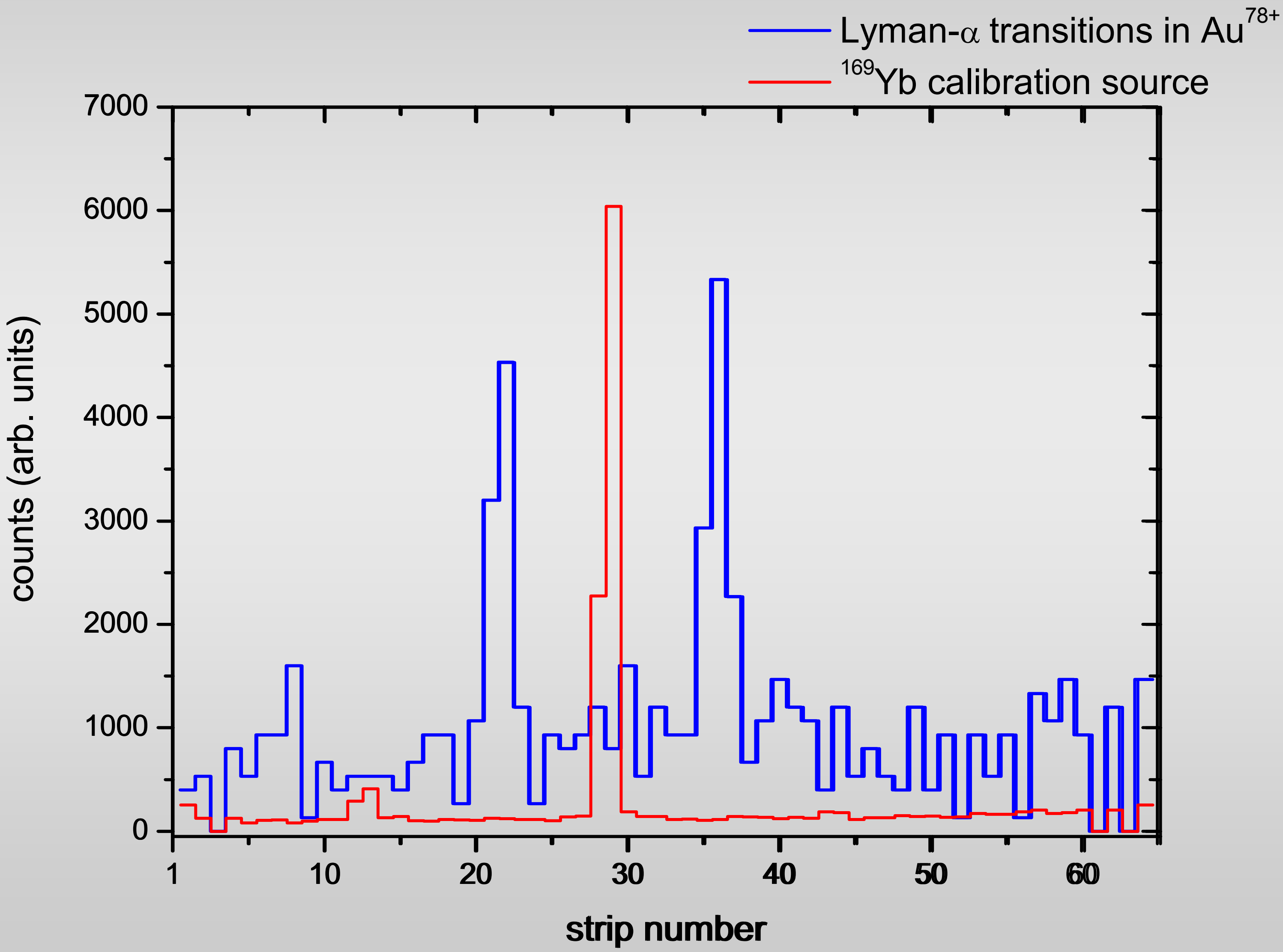
energy

coincidence time

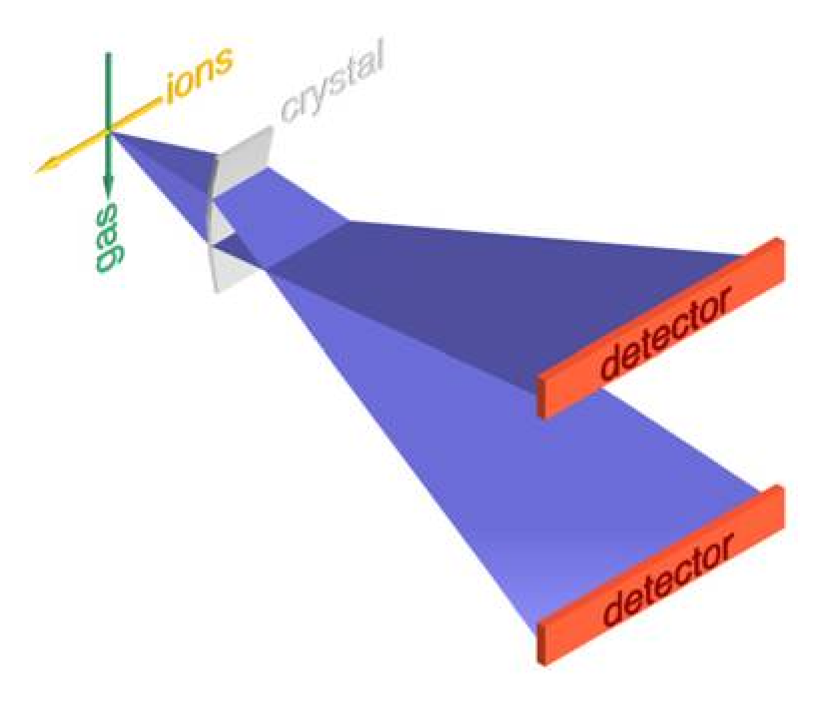
(5 counts per hour)

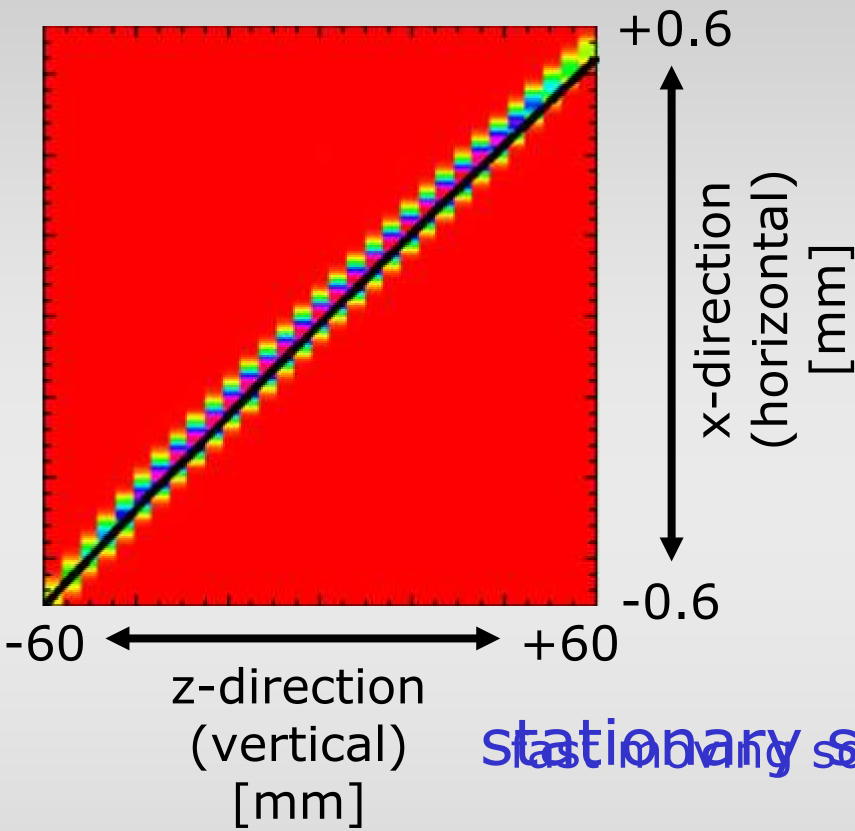
Atomic Physics

High Resolution Spectroscopy of High-Z H-Like Ions



High Resolution Spectroscopy of High-Z H-Like Ions





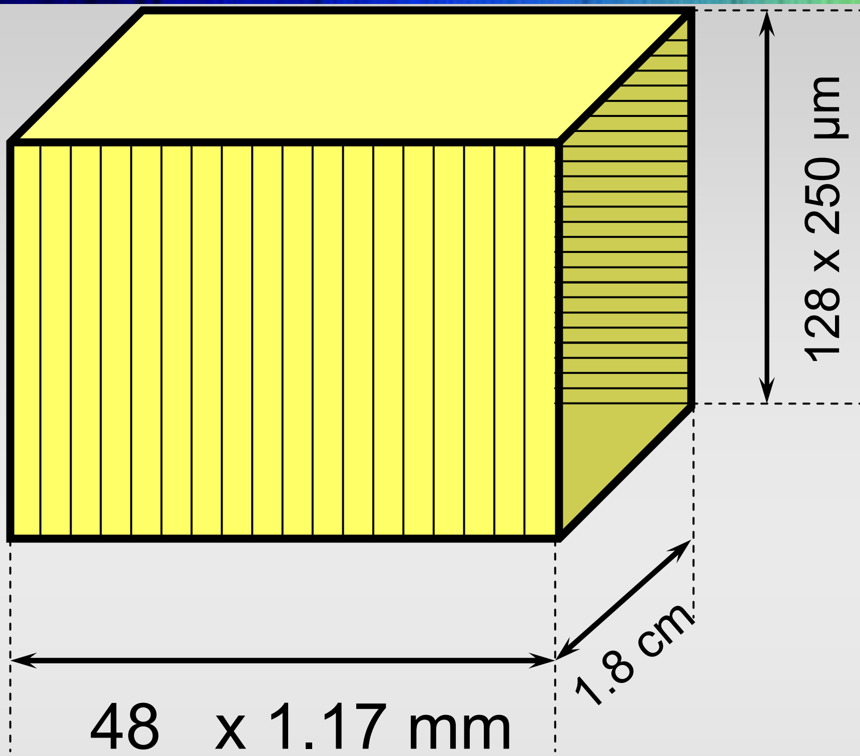
stationary source

fast moving source

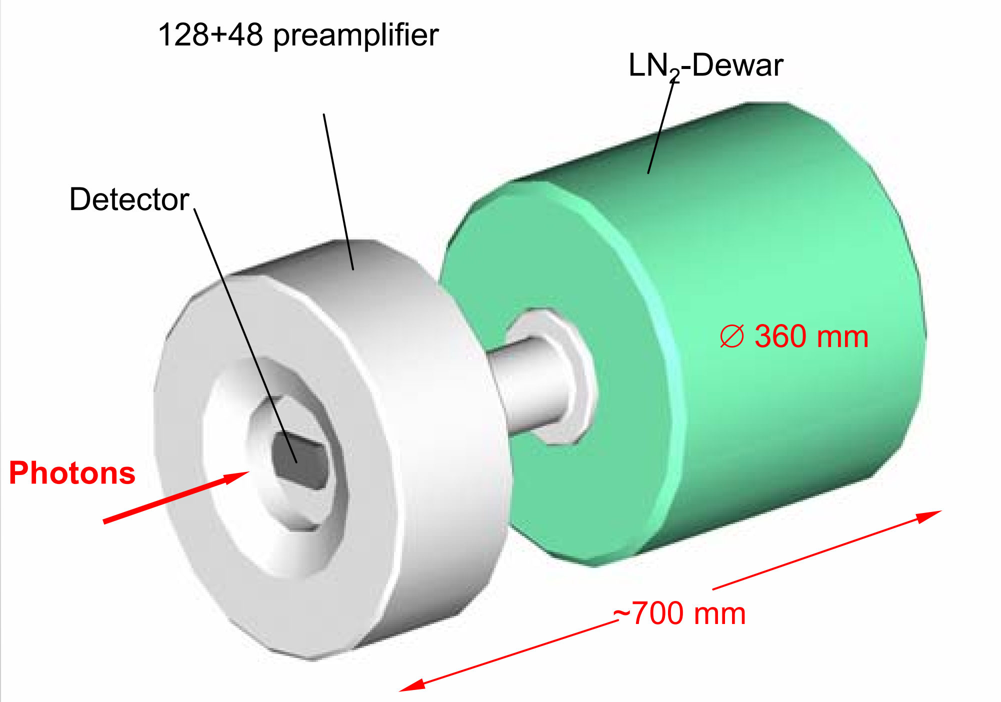
There is a need for 2D detectors !

Atomic Physics

2D detector system for future Lamb Shift experiments



double sided Ge(i)
strip detector
(2D position sensitive)

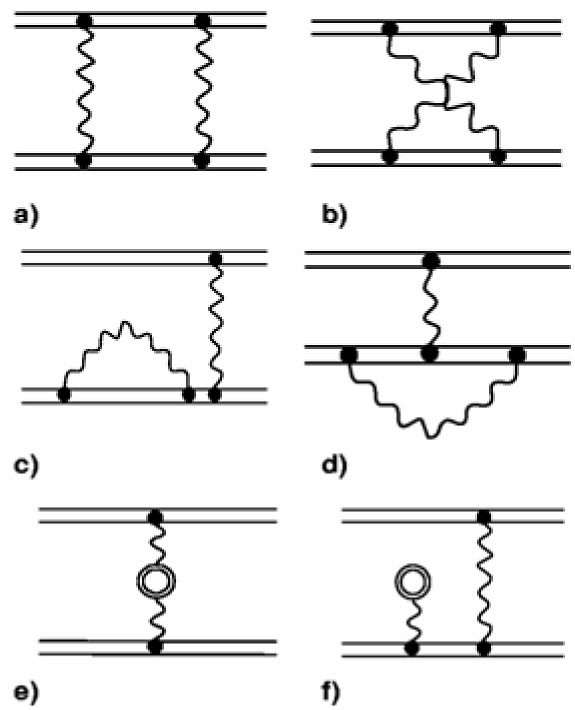


Electron-Electron Interaction in Strong Fields

Measurement of the 2eQED for Uranium at
Accuracy: 2 eV; $\Delta E/E \approx 0.1\%$

Z=92

Two-Electron Contribution: 2246.0 eV

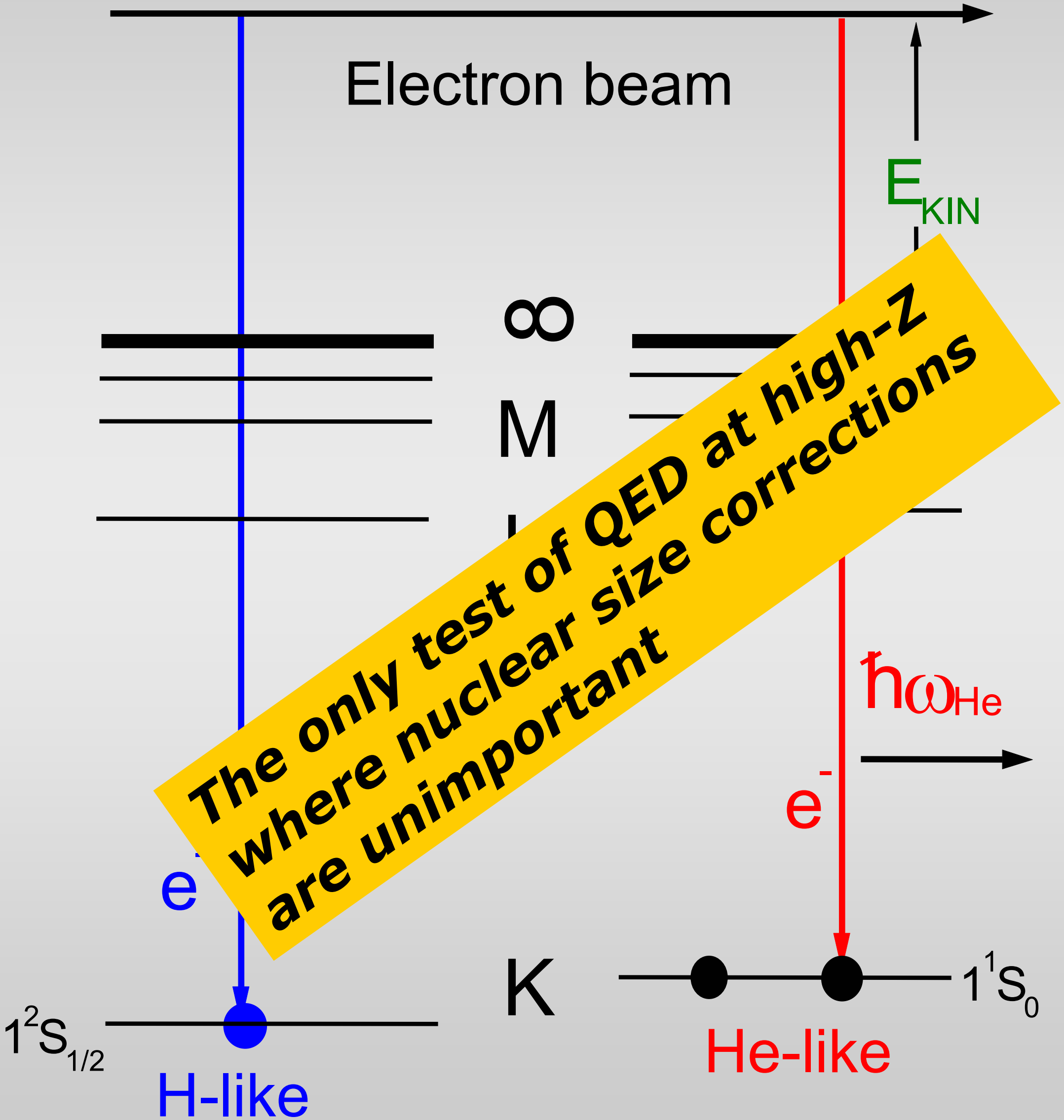


a,b) Non-Radiative QED
+1.3 eV [U^{90+}]
0.06%

c,d) Two-Electron Self Energy
-9.7 eV [U^{90+}]
0.4%

e,f) Two-Electro Vacuum Polarization
+2.6 eV [U^{90+}]
0.1%

The Method



H-like:

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

He-like:

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

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

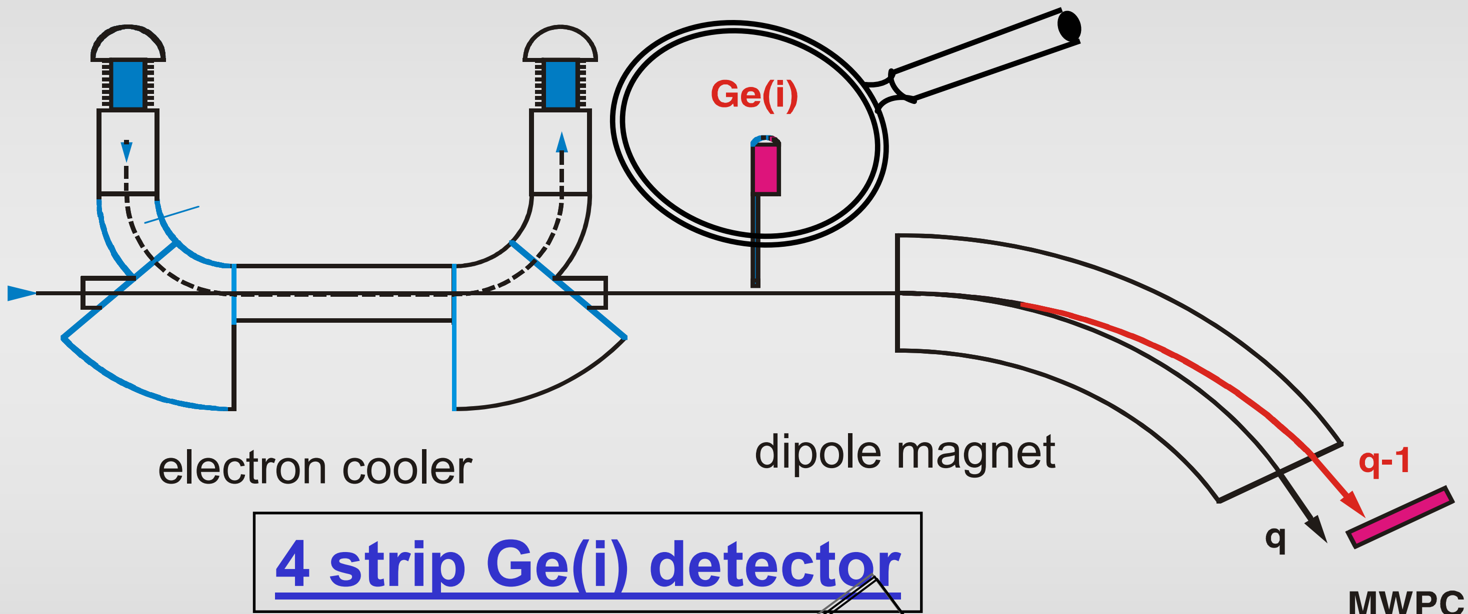
Advantage of relative measurement:

All one electron contributions cancel out e.g. nuclear size

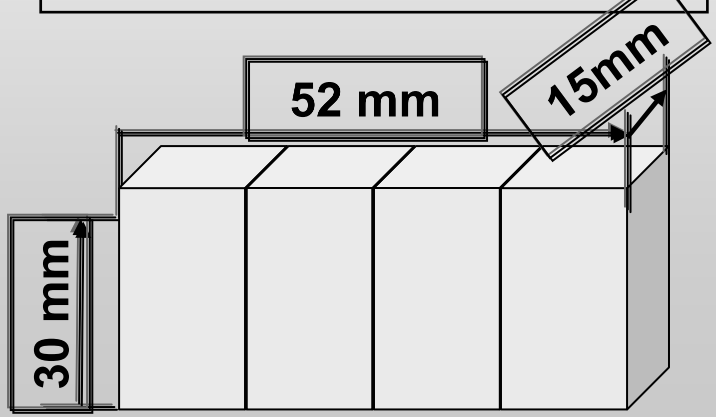
0 Deg spectroscopy at the ESR electron cooler

Goal of the experiment

To probe the first time higher order QED (in α) corrections in the domain of high-Z systems

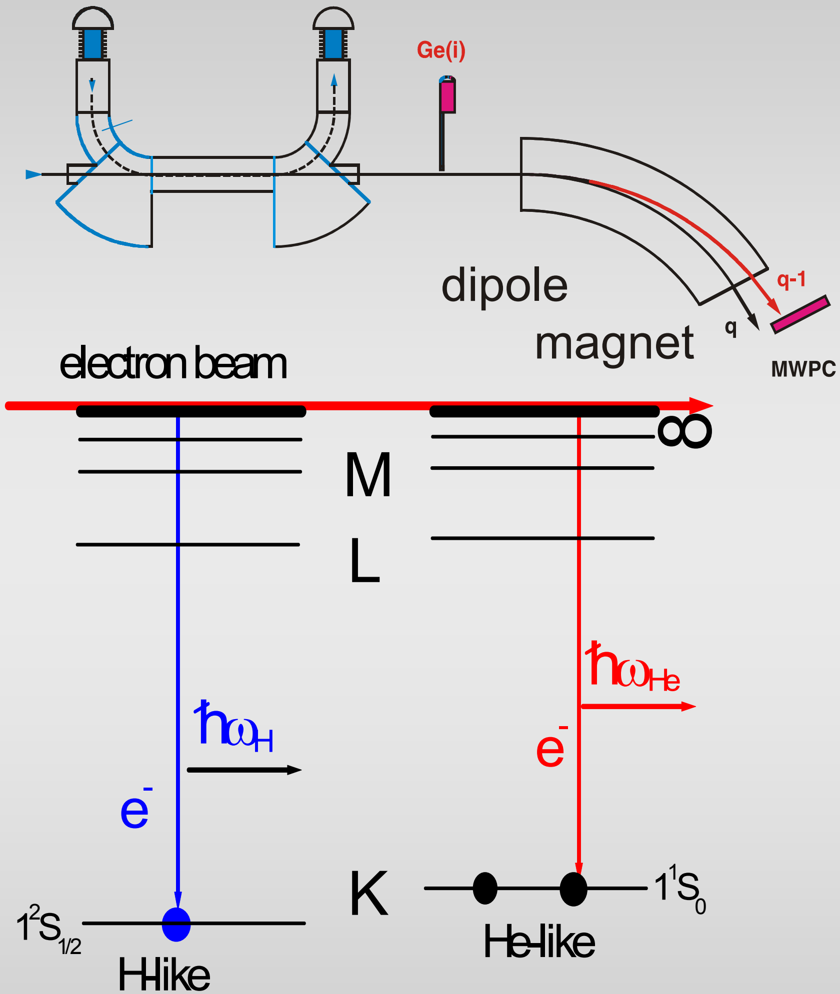


4 strip Ge(i) detector



2eQED Studies for the Ground State

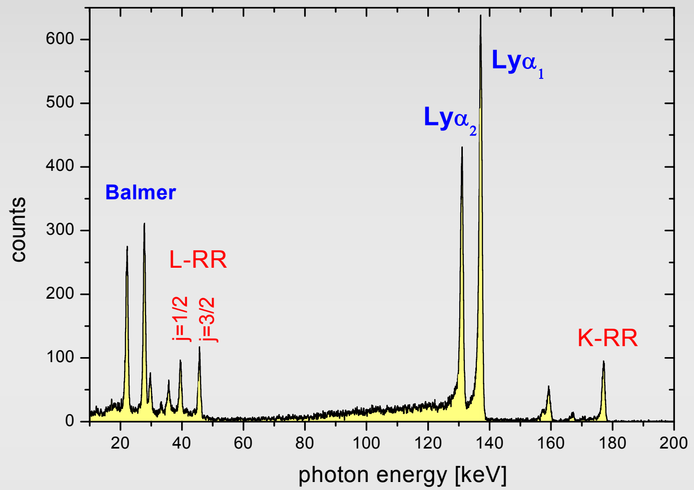
0 deg spectroscopy at the electron cooler



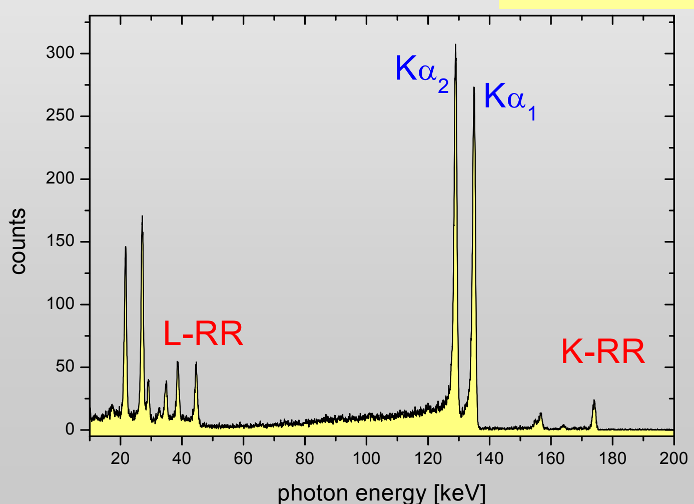
$E_{KIN} + I_H = \hbar\omega$ $E_{KIN} + I_{He} = \hbar\omega$

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

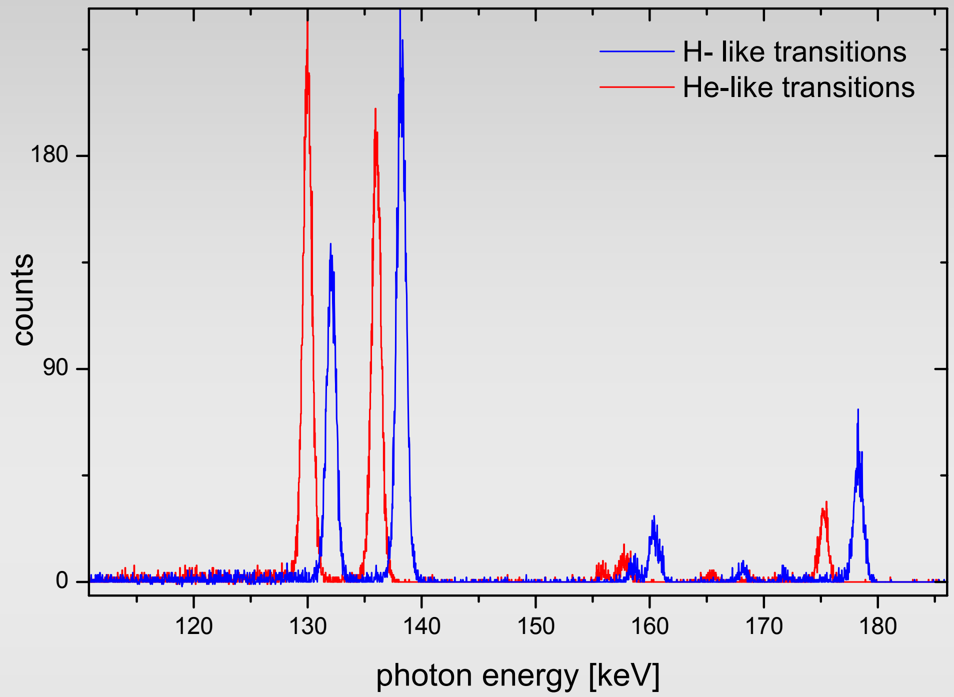
H-like uranium



He-like uranium



Relative measurement at the electron cooler



RR

Result

2.248keV ± 9 eV

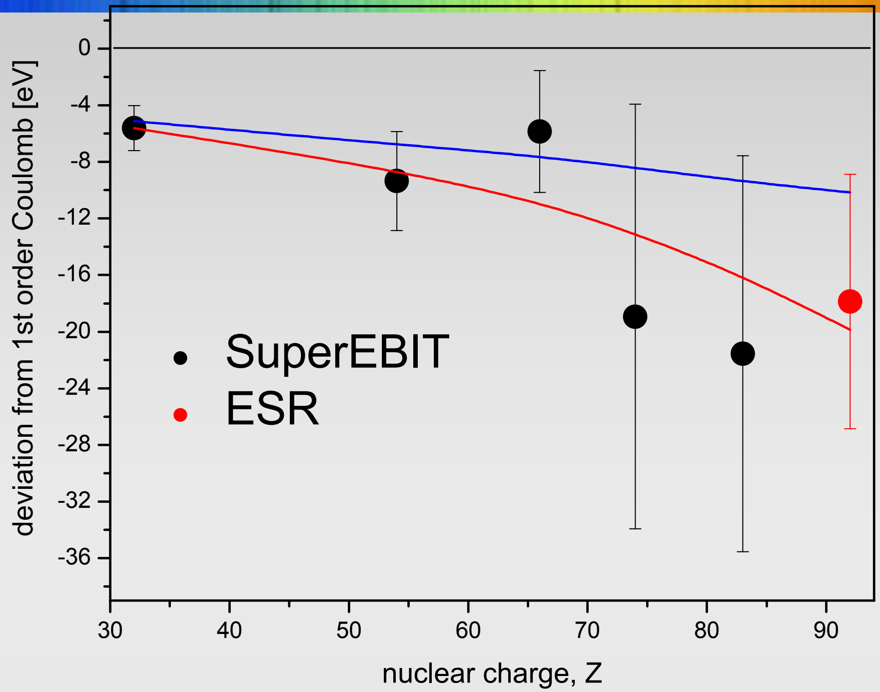
A. Gumberidze et al., PRL 2004

Two Electron

SE
-9.7 eV [U^{90+}]

VP
+2.6 eV [U^{90+}]

Experimental results in comparison with theory



Persson et al.	Plante et al.	Drake et al.	Experiment
2246.0	2249	2255.1	2248(9)

(all values are in eV)

For medium Z ions, there are also data from Tokyo-EBIT available

Excited States in Helium-Like Uranium

He-like ions

simplest atomic multibody system

He-like at high-Z

test of relativity, correlation and QED

BUT

almost no experimental information available for the excited states at high-Z.

Excited States in Helium-Like Uranium

Accurate Transition Energy Measurements Utilizing a Microcalorimeter

E. Silver, H. Schnopper, G. Austin, R. Ingram, G. Guth CFA
N. Madden, D. Schneider LLNL
D. Landis, J. Beeman, E.E. Haller LBNL
R.D. Dunford ANL
E.A. Livingston, University of Notre Dame
R. Schuch University of Stockholm
A. Warczak University of Cracow
D. Banas and M. Pajek University of Kielce

Atomic Physics Division at GSI

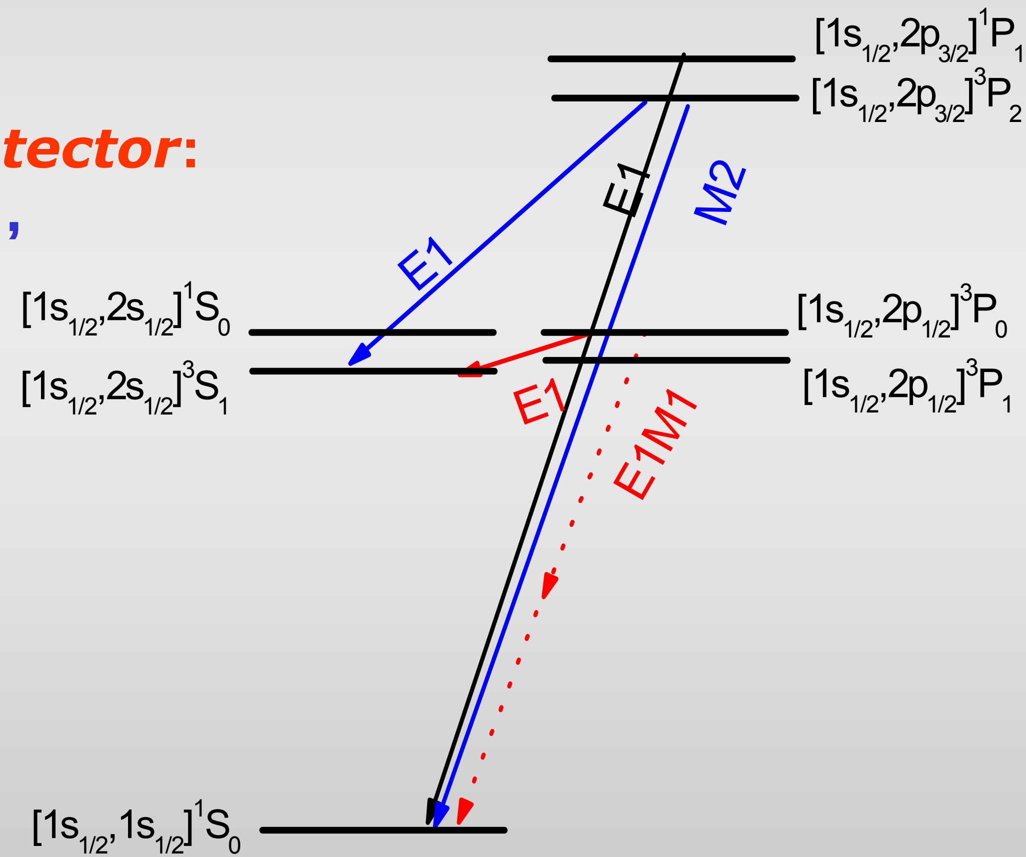
Atomic Physics

Excited States in Helium-Like Uranium

A study of the L-shell binding energies in ***He-like Uranium*** by measuring the ***Balmer transitions*** and the ***Δn=0 intrashell transition at 4.5*** keV [4 keV – 30 keV].

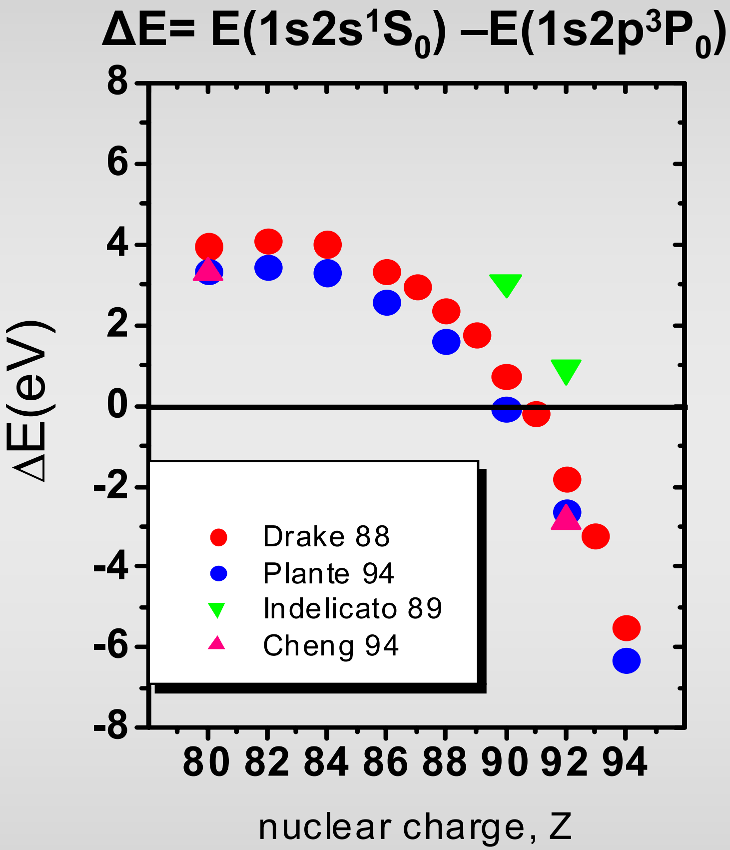
Using a *micro-calorimeter detector*: large wavelength acceptance, quantum efficiency and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).

Doppler correction: measuring relative to the Balmer transitions in H-like uranium.



Accuracy to achieve: better than 1 eV

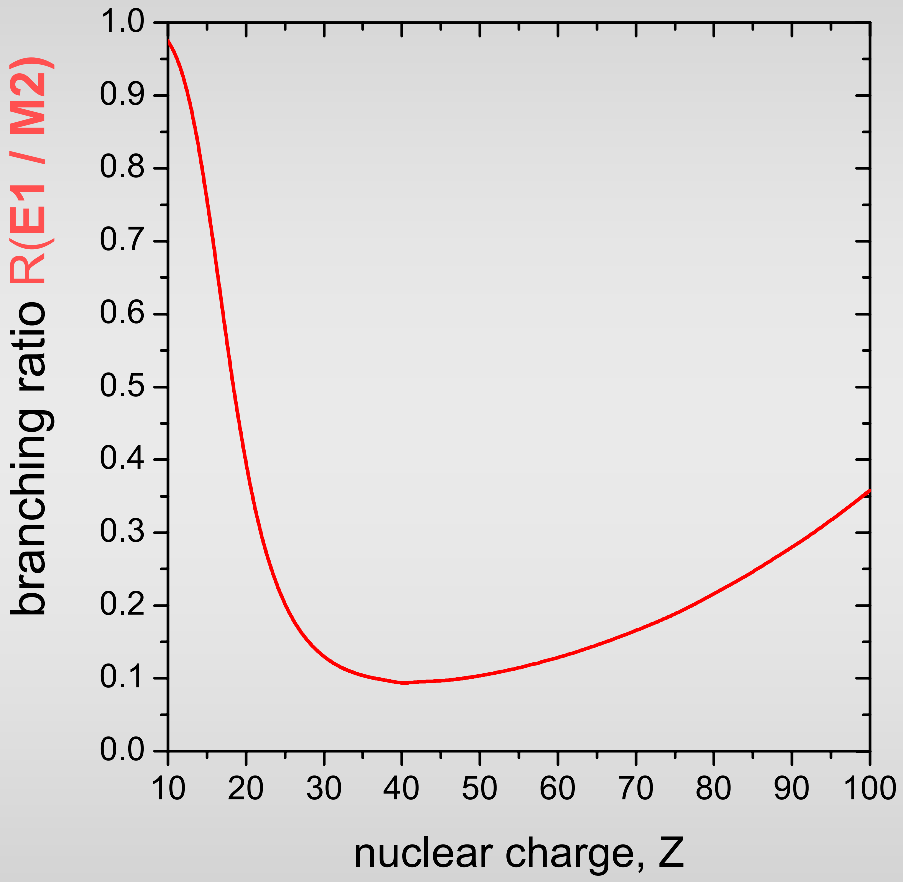
For He-like Systems a Benchmark Test for Structure Theory is Needed

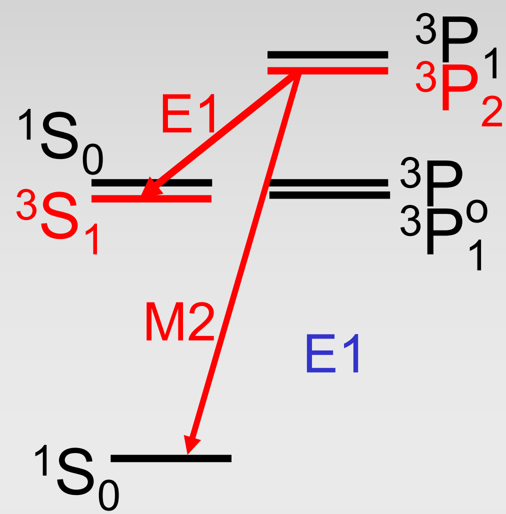


Compared to Li-like ions, theory for the excited states in He-like high-Z ions is still quite incomplete !

A near degeneracy for excited states of opposite parity $1s2s\,^1S_0$ and $1s2p\,^3P_0$ is expected to occure at Z=66 and Z=92 in He-like ions

Δn=0 intrashell transitions in high-Z heliumlike ions

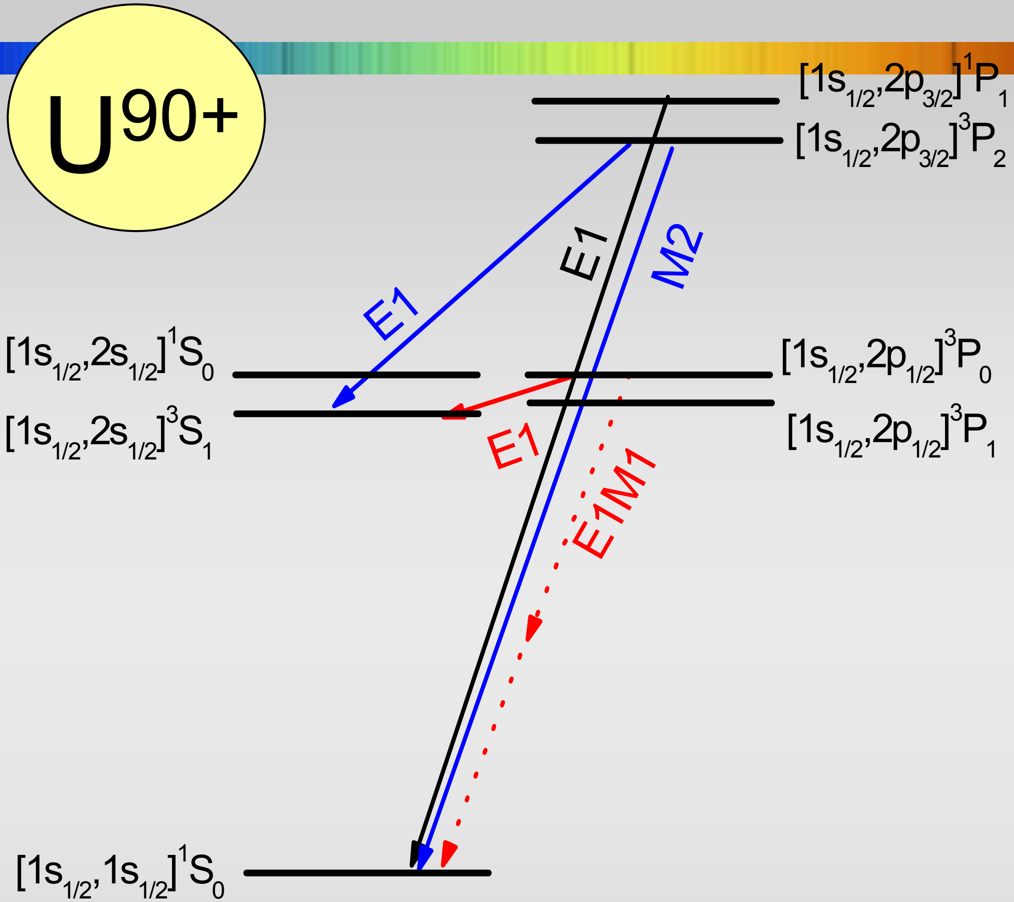




Branching ratio for uranium

R(E1 / M2) = 0.3

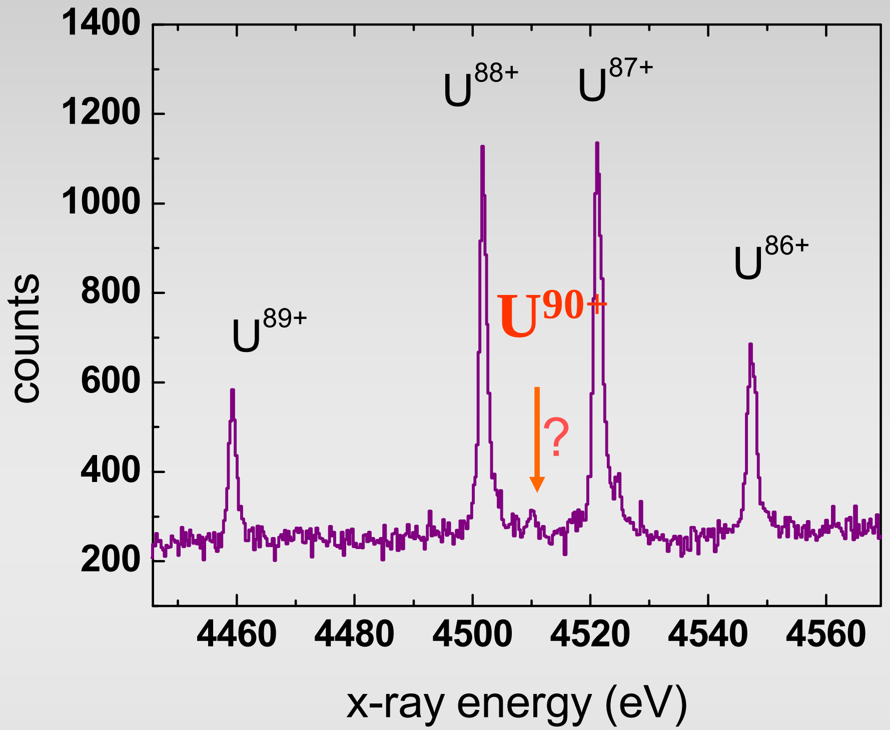
First excited states in He-like uranium



Δn=0 intrashell transition in heliumlike ions

E1:	**4510.0 eV**	**Γ≈ 8.6 x 10 $^{+13}$ 1/s**
M2:		**Γ≈ 2.1 x 10 $^{+14}$ 1/s**

the 1s2p$^3P_2$ - 1s2s$^3S_1$ transition energy (4.5 keV)



Can we populate the $^3P_2$ level efficiently ?

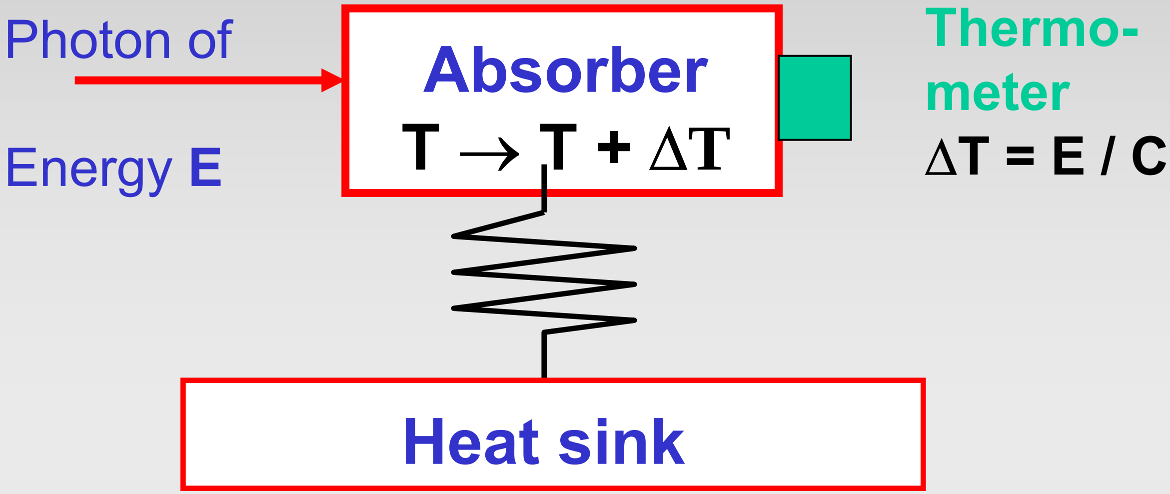
at an EBIT: No

at the ESR: YES

At Super-EBIT (P. Beiersdorfer et al.), the intra-shell transitions in high-Z Li- to Ne-like ions were measured with high-accuracy.

At Super-EBIT, the population of the $^3P_2$ level by electron impact excitation was not sufficient for measuring the transition energy in U^{90+} (P. Beiersdorfer et al., PRA 53, 4000 (1996)).

Detection of Phonons instead of Electrons



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Spezific heat capacity : c

Detector mass: m

A. Bleile et al., NIM A 444, 488 (2000)

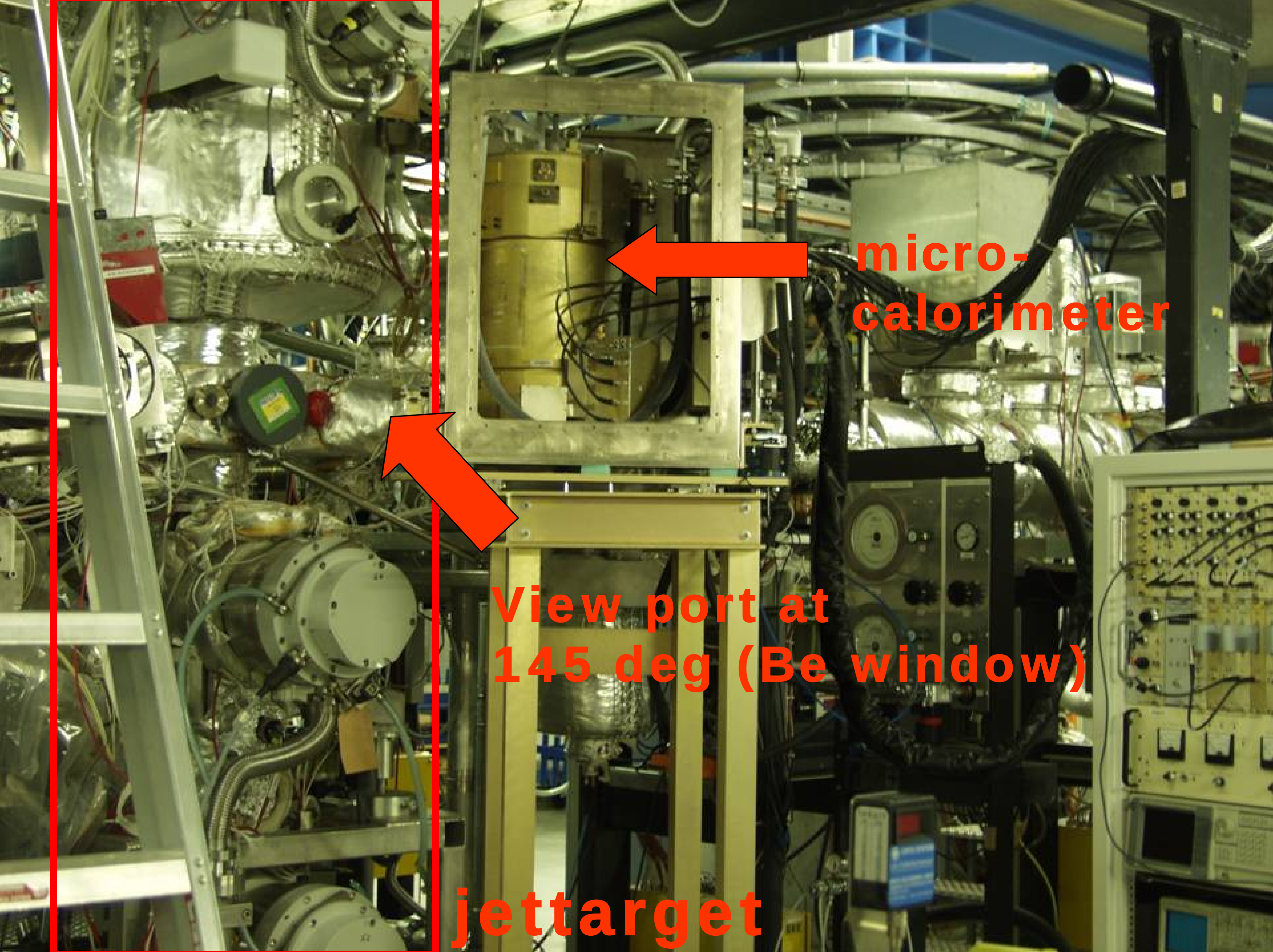
Detector operates at temperatures of 50 mK

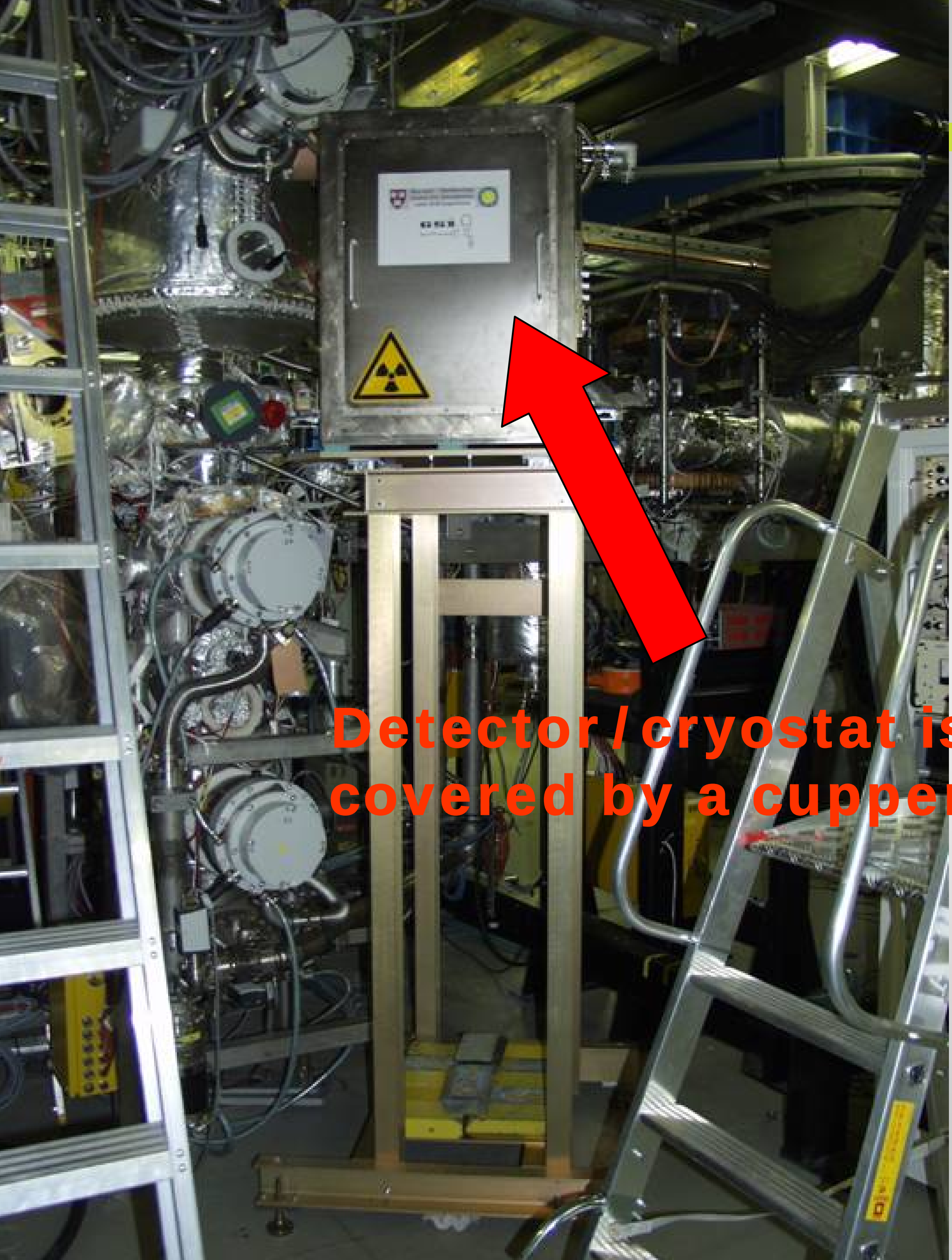
Smithsonian Astrophysical Observatory

Commissioning of a *microcalorimeter* at the ESR Storage Ring

March 2003

array of 3 Sn absorber
(pixel size: 0.3 mm x 0.3 mm)


micro-
calorimeter
View port at
145 deg (Be window)
jettarget

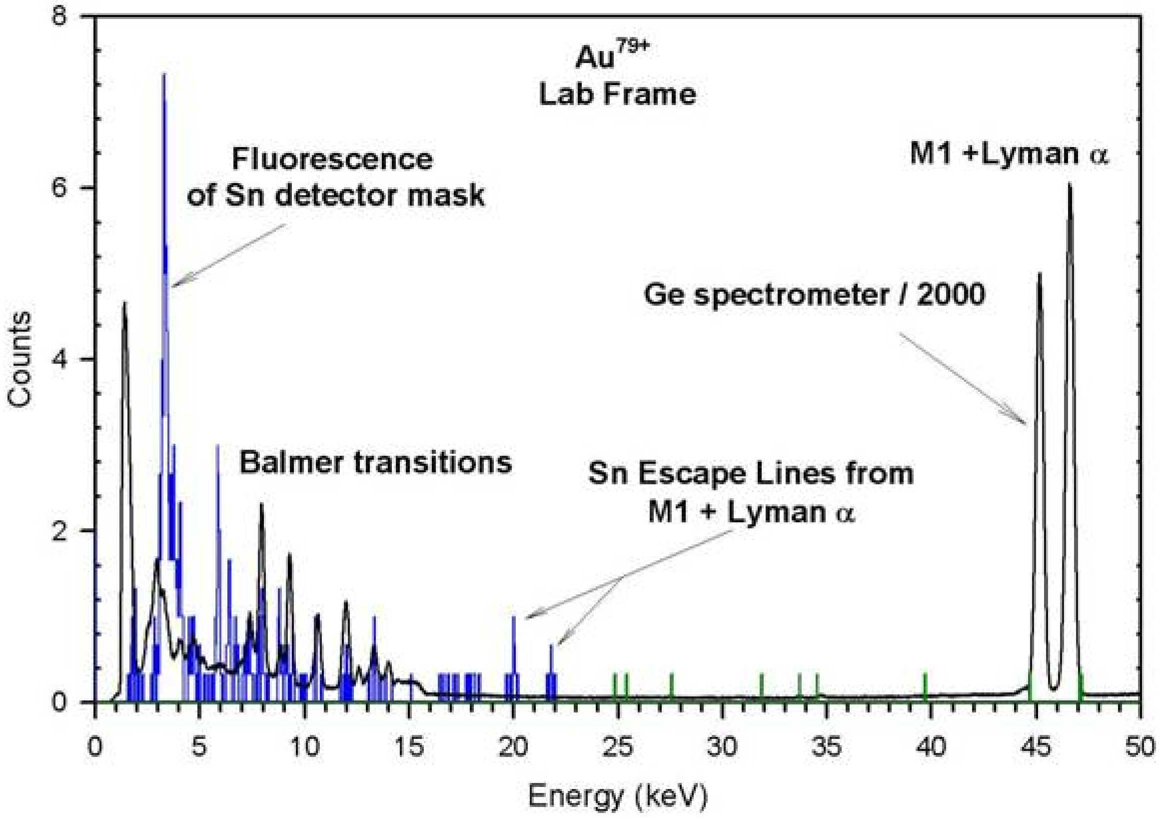


The cryostat / shield assembly positioned at the ESR beam line by its support stand.

Detector / cryostat is completely covered by a cupper EM shield

Smithsonian Astrophysical Observatory

Spectrum obtained during a parasitic beam time at the ESR in March 2003



Energy resolution:
10 eV to 20 eV for the
10 keV to 20 keV regime

Within 17 hours of beam time 330 photons were recorded (basically Balmer transitions).

Lamb shift in lithiumlike heavy ions

$2s_{1/2} - 2p_{1/2}$ and $2_{s1/2} - 2p_{3/2}$ transitions

U^{89+} $2s_{1/2} - 2p_{1/2}$: 280.59 (.09) eV

BEVALAC (Schweppe et al.)

U^{89+} $2s_{1/2} - 2p_{3/2}$: 4459.37 (.35) eV

SEBIT (Beiersdorfer et al.)

Th^{87+} $2s_{1/2} - 2p_{3/2}$: 4025.23 (.14) eV

SEBIT (Beiersdorfer et al.)

Bi^{80+} $2s_{1/2} - 2p_{3/2}$: 2788.139 (.039) eV

SEBIT (Beiersdorfer et al.)

Very accurate transition energy measurements

but large nuclear effects

$2s_{1/2} - 2p_{1/2}$ in lithiumlike uranium

Total theory: 280.44 (20) eV
Experiment: 280.59 (9) eV

Shabaev, Artemyev, Yerokhin

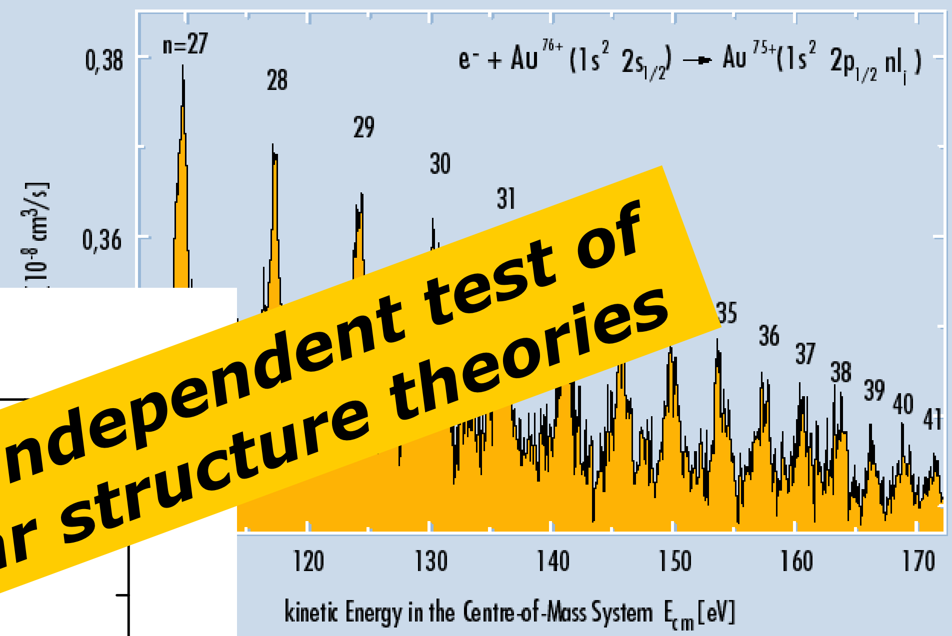
Nuclear size: -33.35 eV

Experiment provides a sensitivity to α^2 contributions on the 15% level

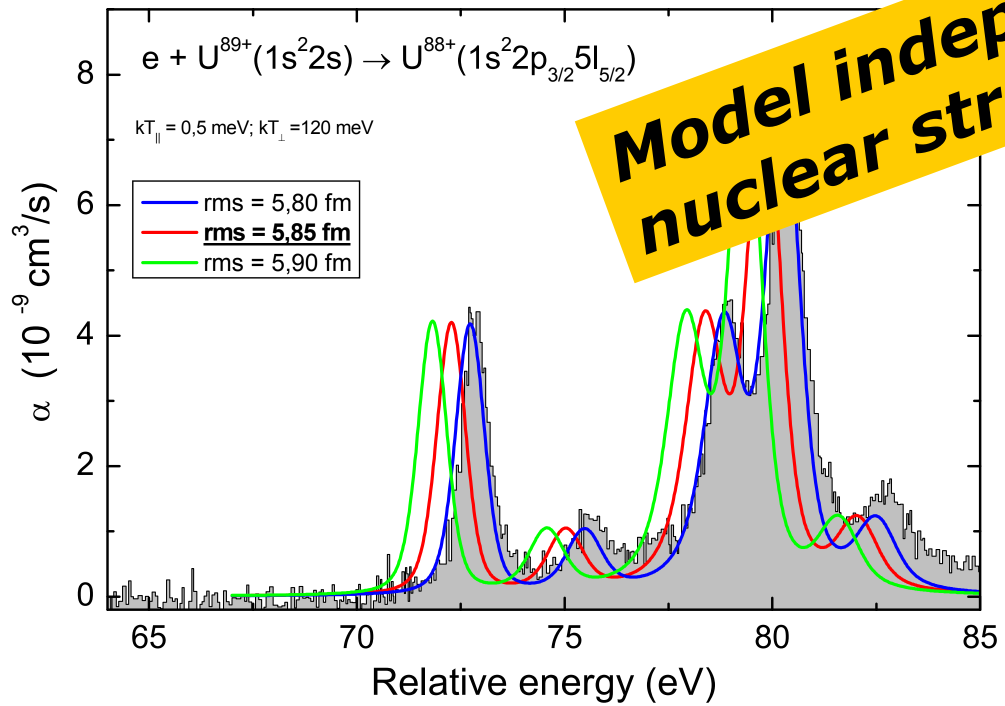
Atomic Physics

Dielectronic Recombination Experiments ´Determination of Nuclear RMS Radii

DR experiments for Li-like heavy ions at the ESR:
The already achieved accuracy is comparable with the most precise x-ray experiments



Model independent test of nuclear structure theories



Experiment and theory for three different rms radii of ^{238}U

A. Müller, C. Kozhuharov et al

Atomic Physics

Hyperfine Structure

Bi^{82+} Klaft et al., 1994

ΔE(Theory –Exp) | ΔE_{QED}

1.26 (2) nm | **1**

In the case of HFS, disagree[...] between experiment and atomic str[...] theory based on [...]

Very similar findi[...]

[Ho] Cres[...]z-Urrutia et al., 1996

[Re] Cresp[...] Lopez-Urrutia et al., 1998

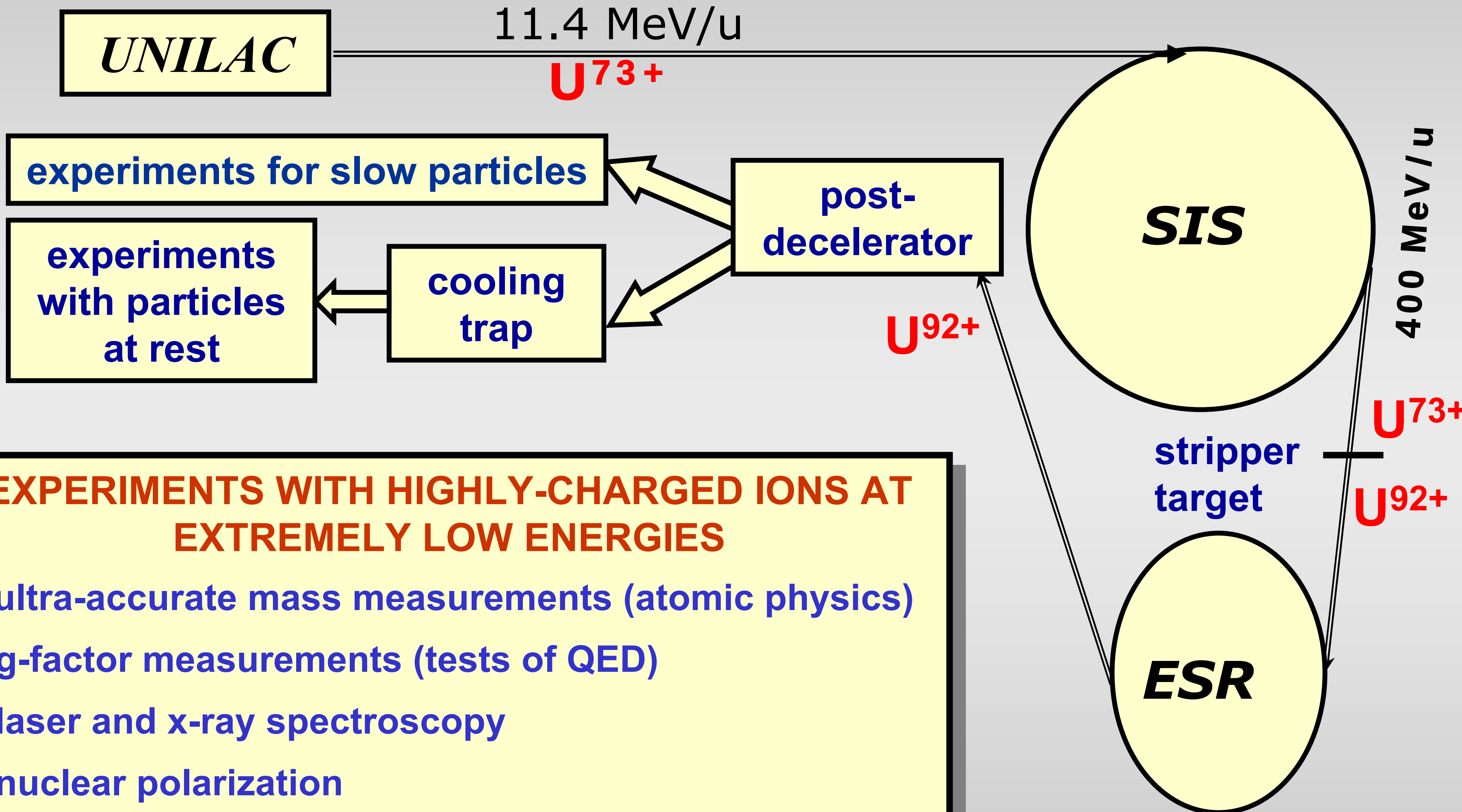
[Pb] Seelig et al., 1998

[Tl] Beiersdorfer et al., 2001

Are the nuclear structure data needed for the calculation correct ?

GSI Atomic Physics

The HITRAP Project at GSI



EXPERIMENTS WITH HIGHLY-CHARGED IONS AT EXTREMELY LOW ENERGIES

- ultra-accurate mass measurements (atomic physics)
- g-factor measurements (tests of QED)
- laser and x-ray spectroscopy
- nuclear polarization
- surface studies and hollow-atom spectroscopy
- collisions at very low velocities

HITRAP

Determination of the electron‘s mass from g-factor measurements

	electron’s mass ***m_e*** *[u]*
CODATA 1998:	0.000 548 579 911 0 (12)
g-factor ($^{12}C^{5+}$):	0.000 548 579 909 3 (3)
g-factor ($^{16}O^{7+}$):	0.000 548 579 909 2 (5)

	proton/electron mass ratio
CODATA 1998:	1836.152 667 5 (39)
g-factor ($^{12}C^{5+}$):	1836.152 673 1 (10)
g-factor ($^{16}O^{7+}$):	1836.152 673 6 (16)

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New Determination of the Electron’s Mass

Thomas Beier,[1] Hartmut Häffner,[1,2] Nikolaus Hermanspahn,[2] Savely G. Karshenboim,[3,4] H.-Jürgen Kluge,[1]
Wolfgang Quint,[1] Stefan Stahl,[2] José Verdú,[1,2] and Günther Werth[2]
[1]*Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany*
[2]*Institut für Physik, Universität Mainz, 55099 Mainz, Germany*
[3]*D.I. Mendeleev Institute for Metrology (VNIIM), 198005 St. Petersburg, Russia*
[4]*Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
(Received 29 August 2001; published 19 December 2001)

g-Factor of a bound electron

- We have seen:
  Determination of the
  mass of the electron from $^{12}C^{5+}$.

- Fine structure constant α:

$$\frac{\delta\alpha}{\alpha} \sim \frac{1}{(Z\alpha)^2}\frac{\delta g}{g}$$

only $\sim 10^{-3}$ for carbon,
but $\sim 10^{-9}$ for uranium (!).

Summary

It needs more than just one isolated kind of experiment to proof the validity of QED at High-Z

To proof the validity of QED at high-Z, a broad range of different experimental approaches is needed

- 1s-Lamb shift
- g-factor
- two-electron QED
- Hyperfine structure
- 2s2p in Li-like ions

and ...

Challenges and Opportunities

For Atomic Physics at

The Future GSI-Facility

Atomic Physics Experiments at the International Accelerator Facility for Beams of Ions and Antiprotons

The SPARC-Collaboration:

Atomic Physics with Heavy Stable and Radioactive Ions

http://www-linux.gsi.de/~sparc

SPARC

Stored Particle Atomic Research Collaboration

The FLAIR-Collaboration:

Atomic Physics with Slow Antiprotons

http://www-linux.gsi.de/~flair

FLAIR

Facility for Low-Energy Anti-Protons and Ion Research