X-ray Transitions Studied for Decelerated Bare and H-like Uranium Ions at the ESR Electron Cooler

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- **Introduction**
- **H-like systems**

  Lamb shift and structure of one electron systems

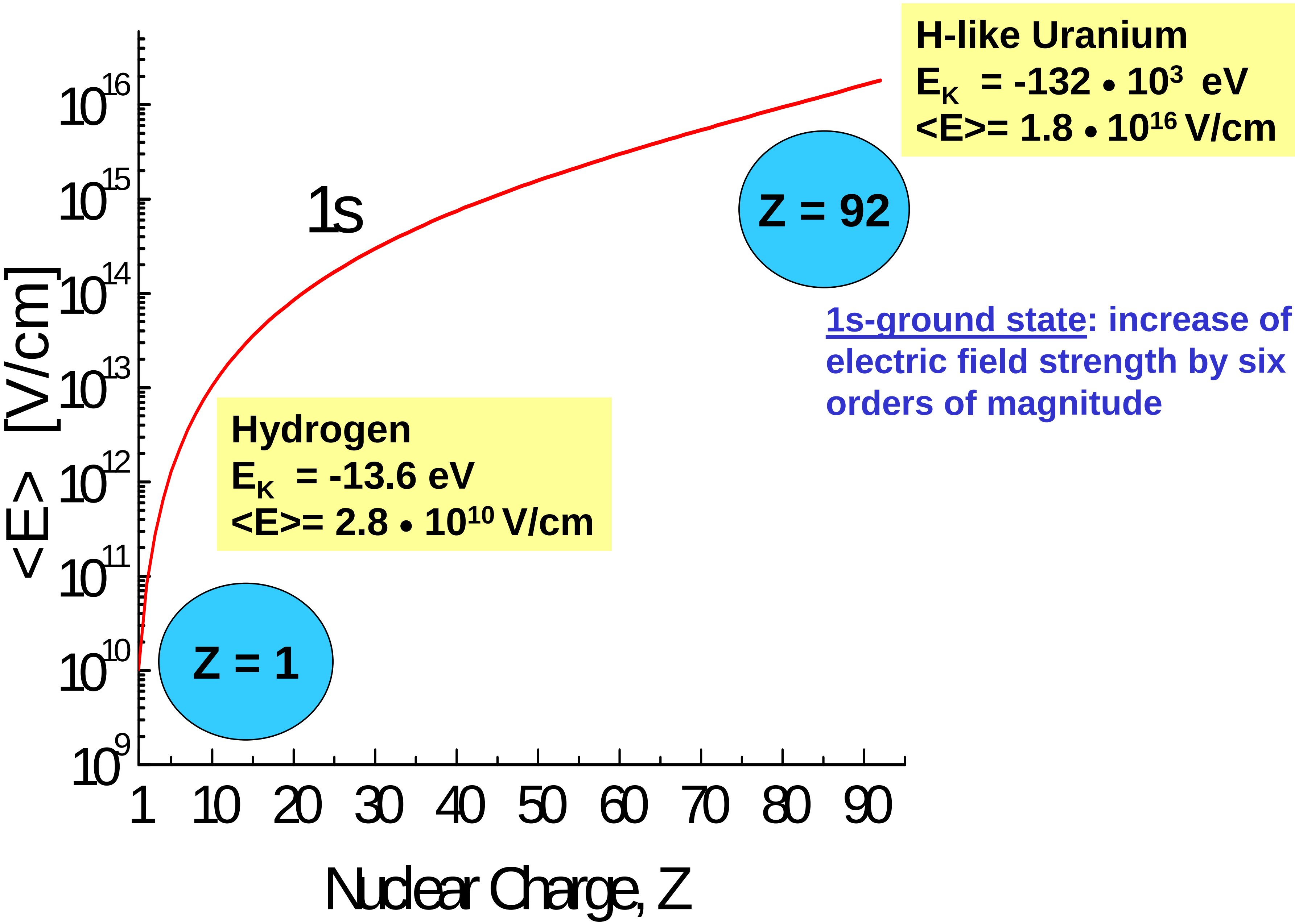
  Status of experimental and theoretical research
- **Helium-like systems**

  Two electron contribution to the binding energy

  Status of experimental and theoretical research
- **Experiment at the ESR storage ring**

  Data and results
- **Outlook and Summary**

Atomic Physics in Extremly Strong Coulomb Fields



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

The QED effects manifest in:

The Lamb shift in few electron systems;

1s Lamb shift in hydrogen-like ions

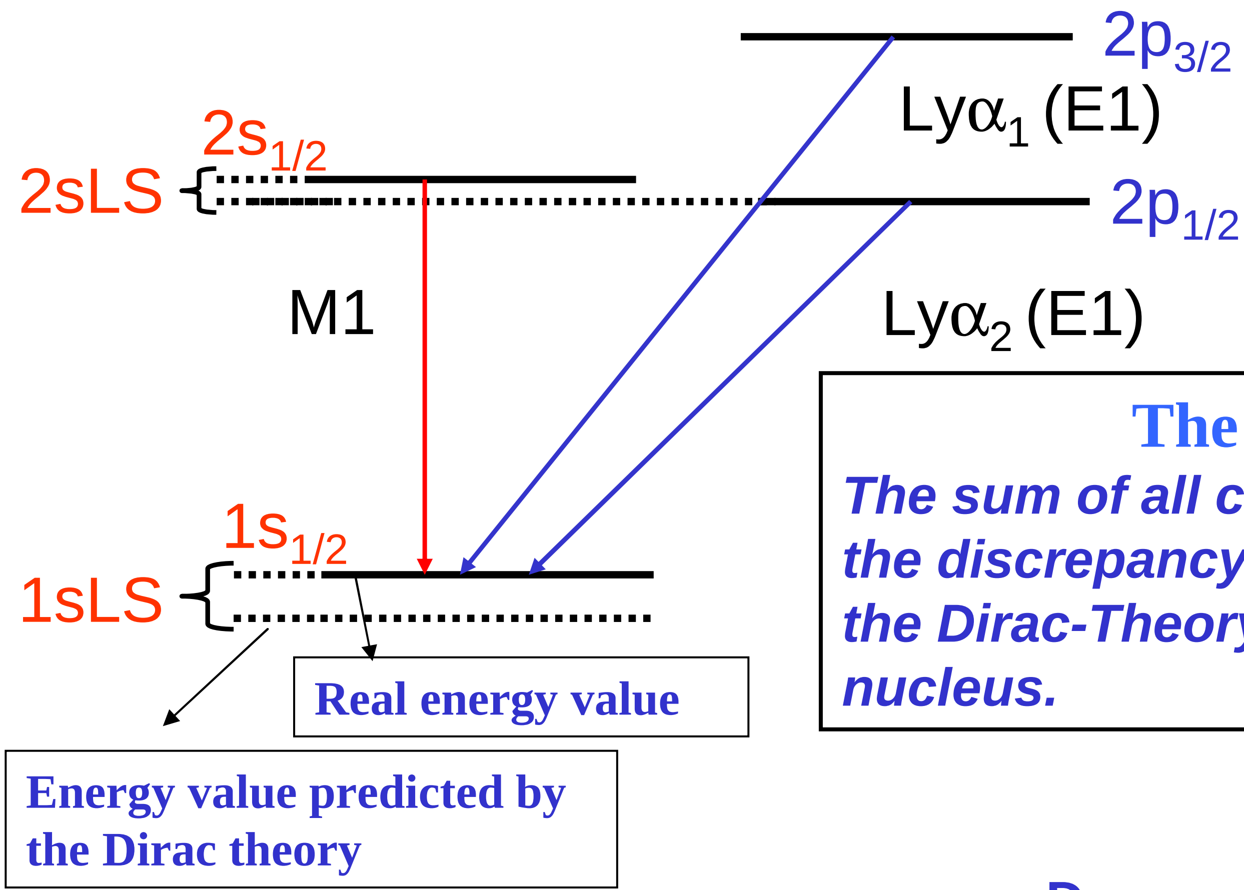
two electron Lamb shift in helium-like ions

2p-2s lamb shift in lithium-like ions

Hyperfine splitting

g-factor

The 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**

Example for 1s:	**Ge(Z=32)**	**Xe(Z=54)**	**U(Z=92)**
DIRAC(eV):	**-14 128**	**-41 347**	**-132 284**
1sLS (eV):	**8**	**47**	**466**
	0.06%	**0.11%**	**0.35%**

The Lamb shift

$\Delta E = \alpha/\pi\ (\alpha Z)^4/n^3\ F(\alpha Z)\ m_e c^2$

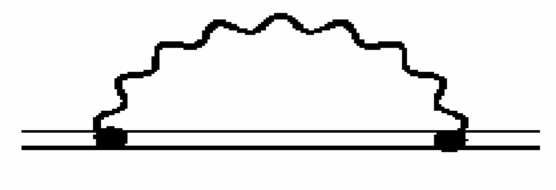
Lamb Shift (LS)

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

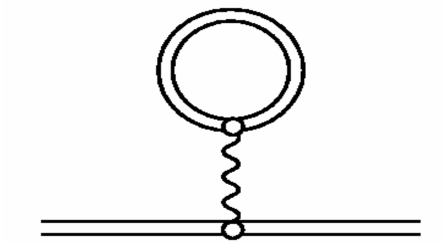
Z: nuclear charge
n: principal quantum number

The QED contributions of the first order in α

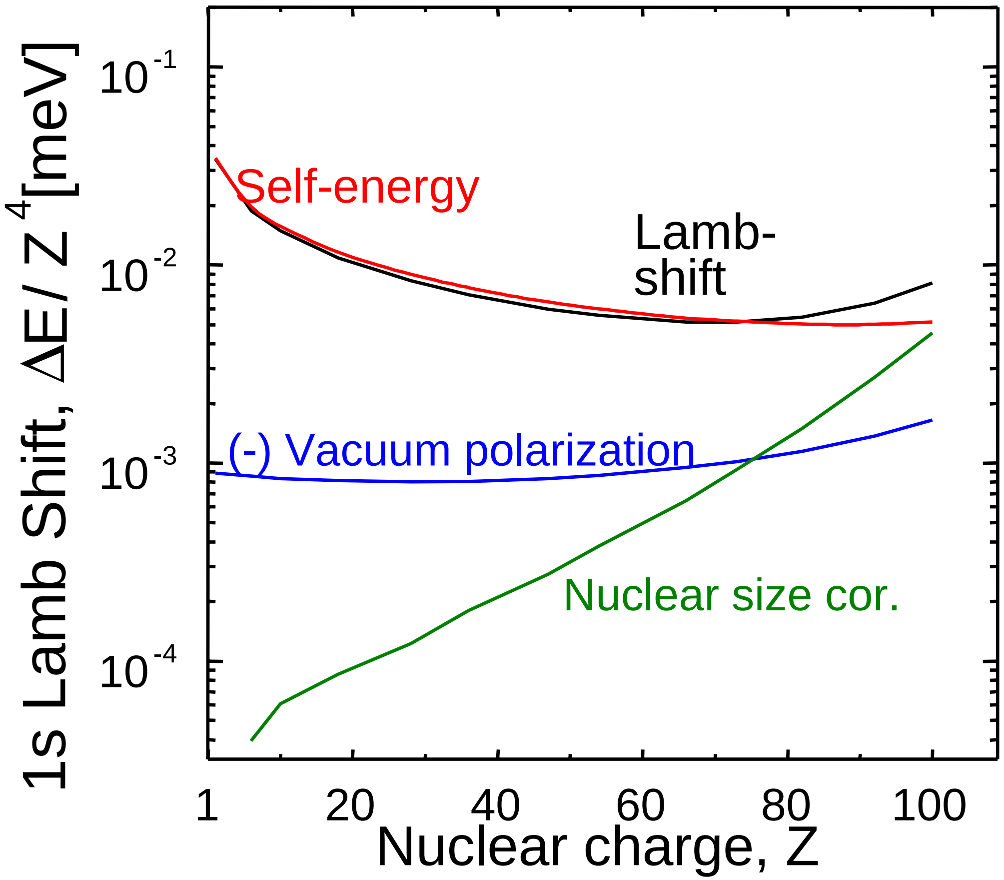
Self-energy

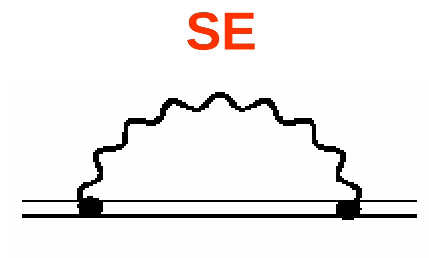


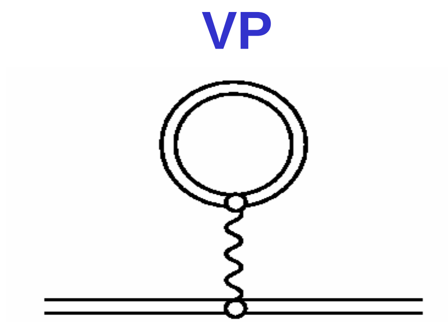
Vacuum polarization



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







1s-Groundstate in U^{91+}

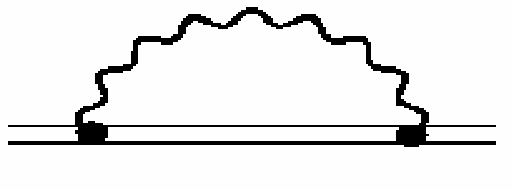
SE	VP	NS.
355.0 eV	-88.6 eV	198.7 eV

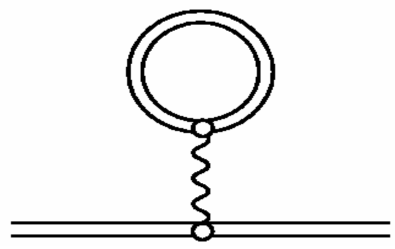
Theorie: T. Beier et al., 1998

Self-energy

Vacuum polarization

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



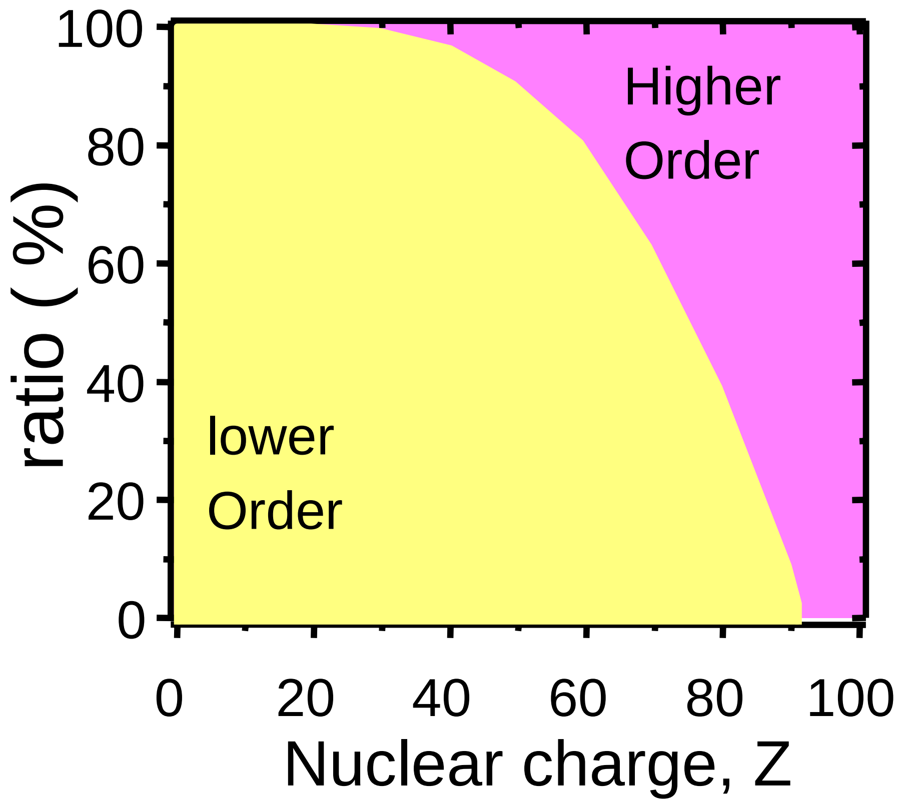


In a small Z regime: $\alpha Z \ll 1$

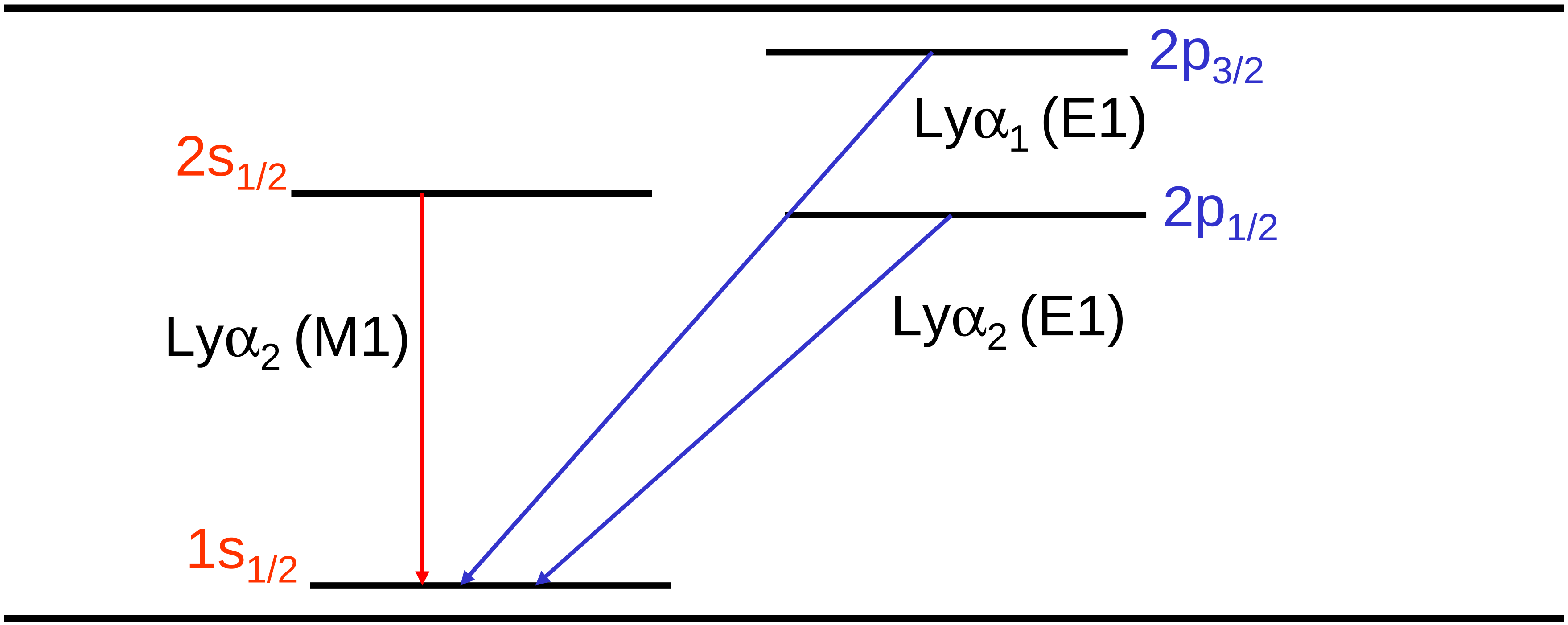
$F(\alpha Z)$: expansion in orders of αZ

In a high Z regime: $\alpha Z \approx 1$

$F(\alpha Z)$: expansion in orders of αZ
is not applicable

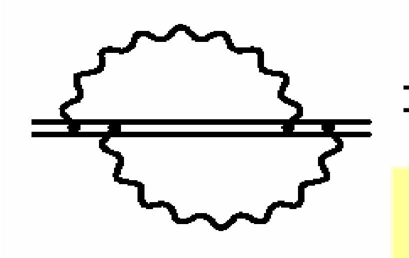


The basic experimental approach for the investigation of the QED effects (Lamb shift) is a precise determination of x-ray energies emitted by transitions to the ground state of the ion.



The goal of experiments is to become sensitive to the second order in α QED contributions.

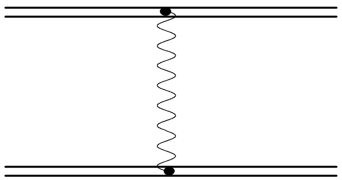
example:



±1 eV relative accuracy: $\sim 10^{-5}$

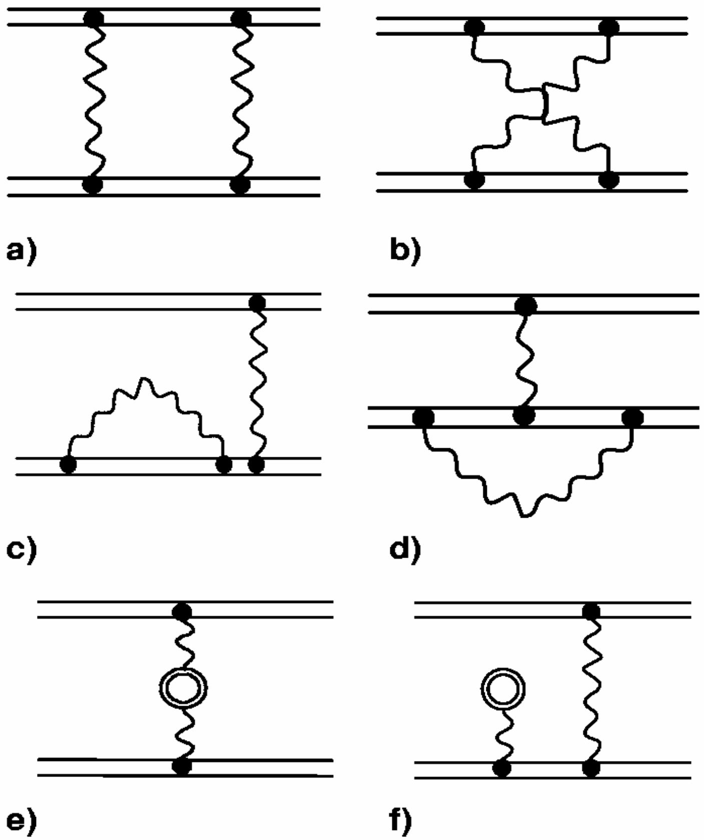
468 ±13 eV (Stöhlker et al. 2000)

The two-electron contribution to the ground state energy in He-like systems



two electron contribution of the first order in α

For the GS two-electron QED effects can be presently calculated completely to second order in α

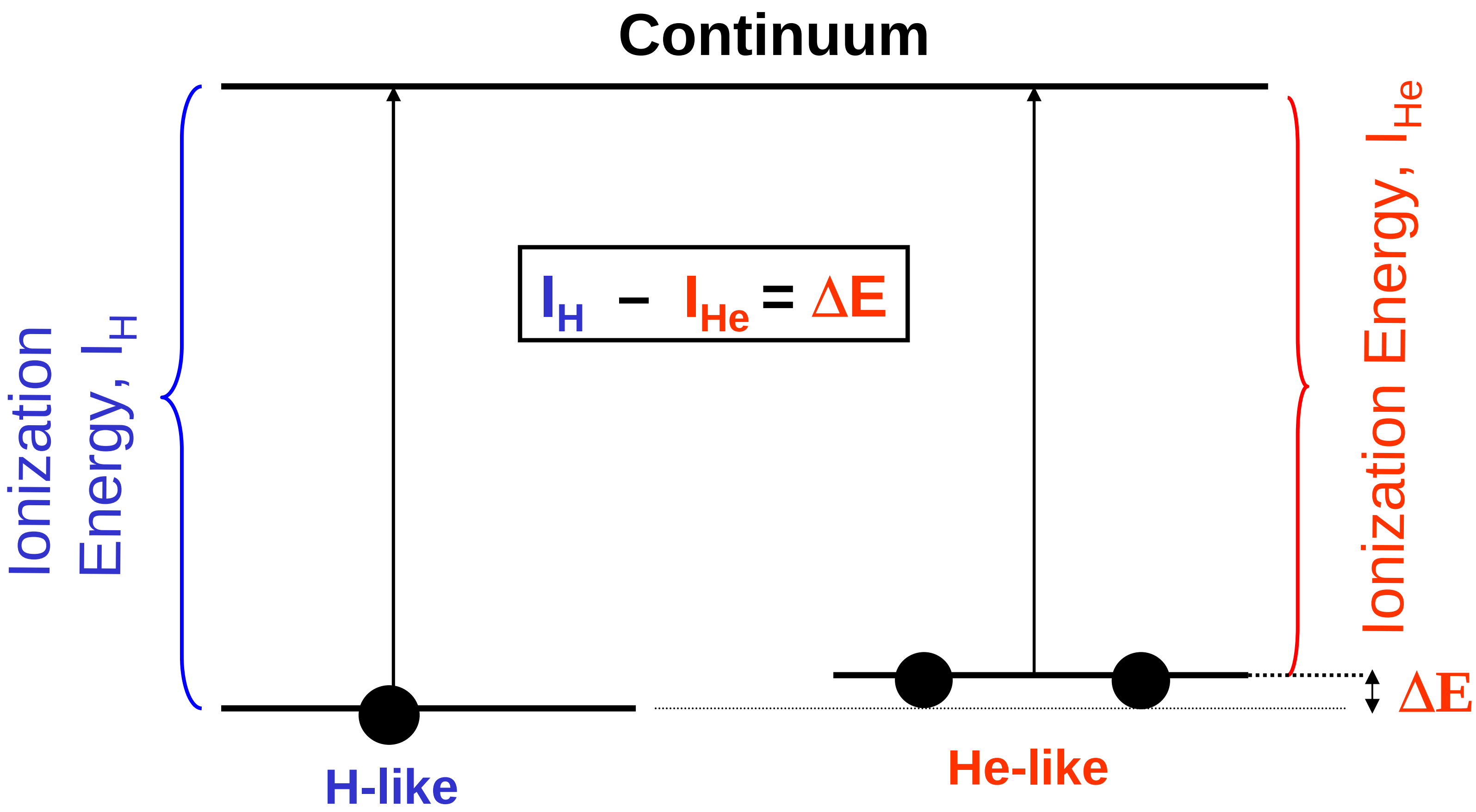


a,b) Non-Radiative QED
+1.3 eV [U^{90+}]
0.06%

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

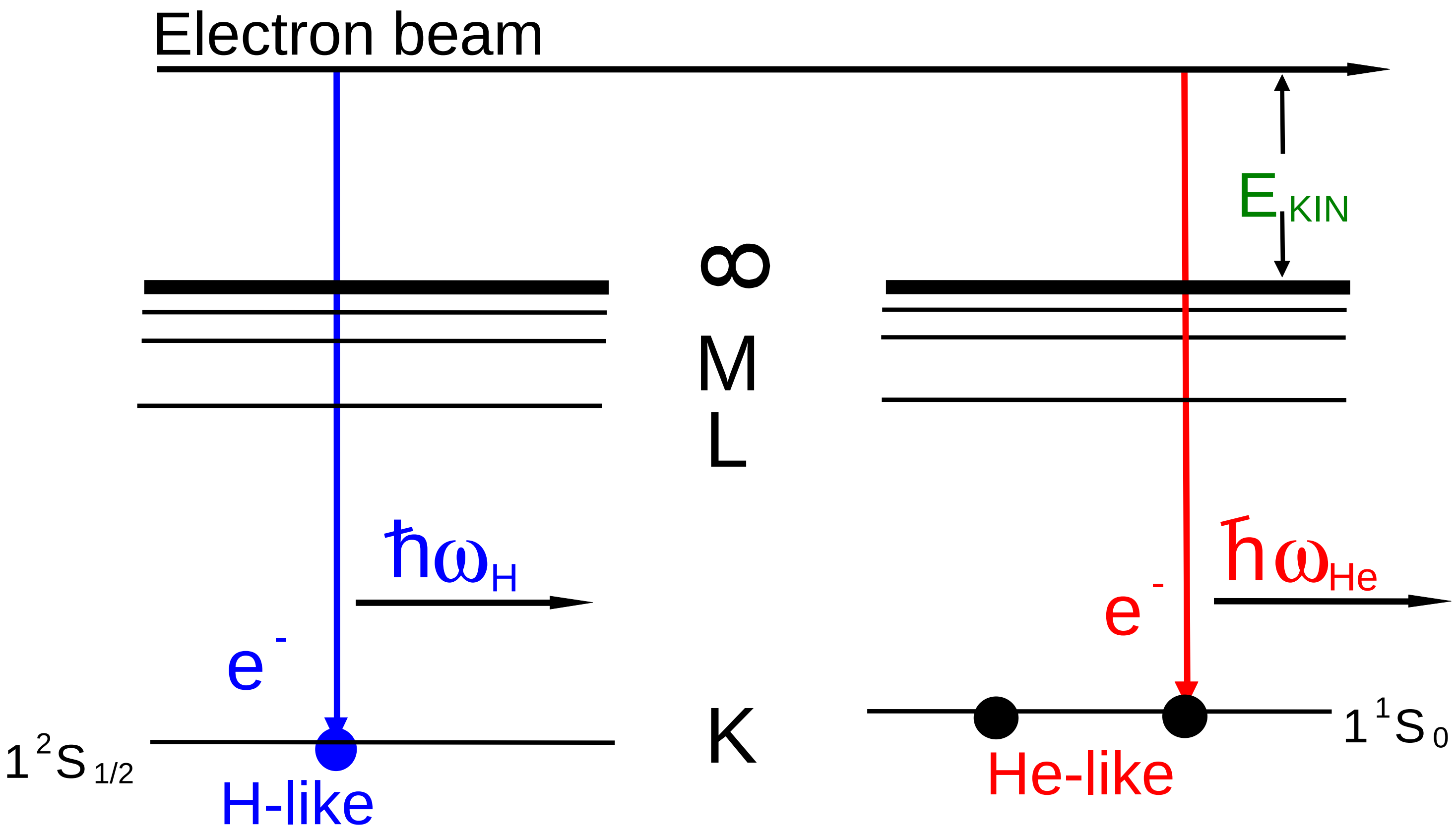
e,f) Two-Electron Vacuum Polarization
+2.6 eV [U^{90+}]
0.1%

Electron-Electron Interaction in Strong Fields



ΔE: *Two-Electron Contribution to the Ionization potential in the He-like System*: ***Second order in*** α

THE METHOD



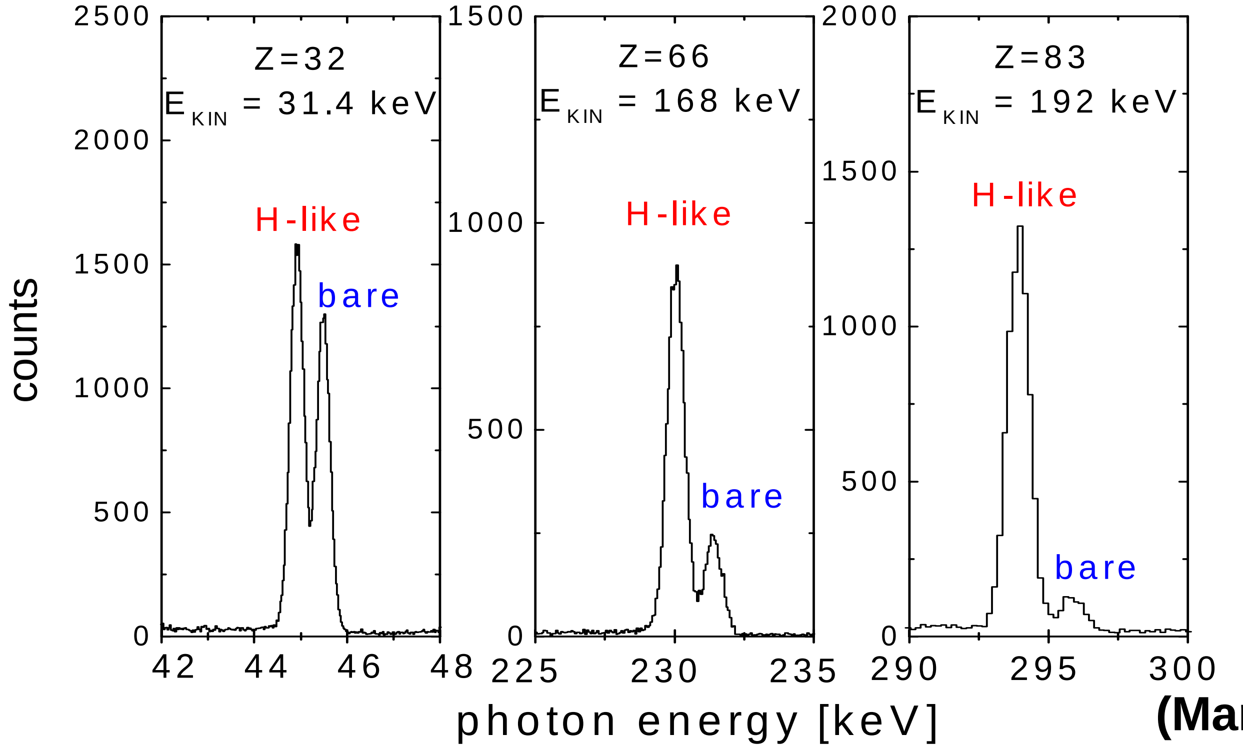
$E_{KIN} + I_H = \hbar\omega_H$ $\quad$ $E_{KIN} + I_{He} = \hbar\omega_{He}$

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

Advantage of relative measurment:

All one electron contributions cancel out

THE RESULTS



(Marrs et al. 1995)

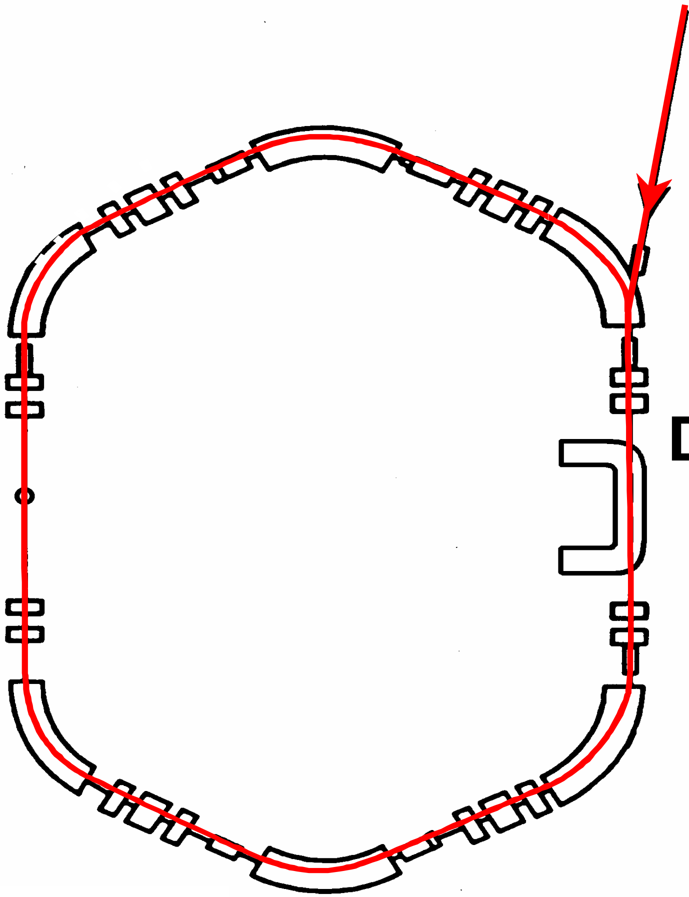
Z	32	54	66	74	76	83
Exp. [eV]	562.6 ±1.6	1027.2 ±3.5	1341.6 ±4.3	1568.9 ±15	1608 ±20	1876 ±14
$\Delta E/E$	2.8 x 10^{-3}	3.4 x 10^{-3}	3.0 x 10^{-3}	1 x 10^{-2}	1.2 x 10^{-2}	0.7 x 10^{-2}

Results are limited by counting statistics

X-Ray Spectroscopy at the ESR

$\beta \approx 0.65$

Revolution
Frequency
f: $\approx 10^6$ 1/s



SIS

U^{92+} $N_{Ion} \approx 10^8$
300 MeV/u

Deceleration

20 MeV/u

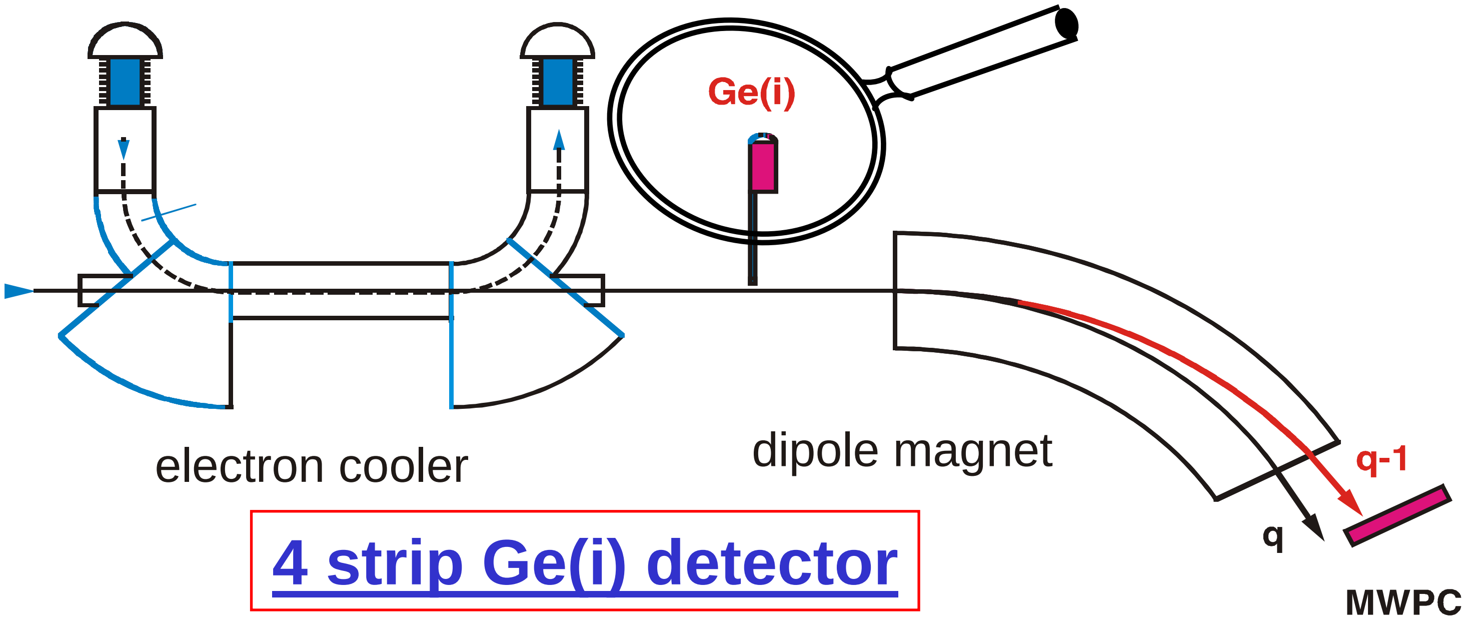
$$E_{lab} = \frac{E_{proj}}{\gamma \bullet (1 - \beta \bullet \cos\theta_{lab})}$$

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

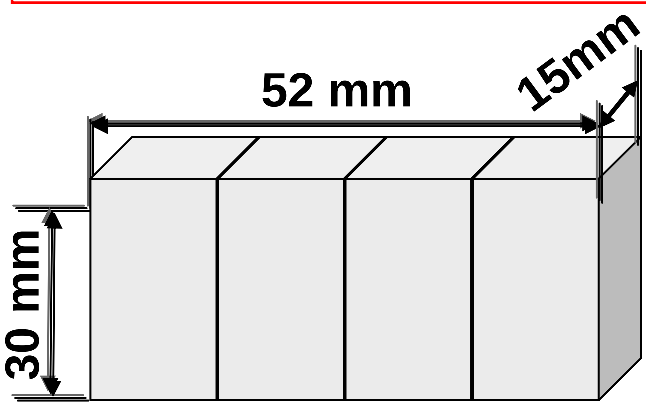
0 Deg spectroscopy at the ESR electron cooler

Goal of the experiment

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

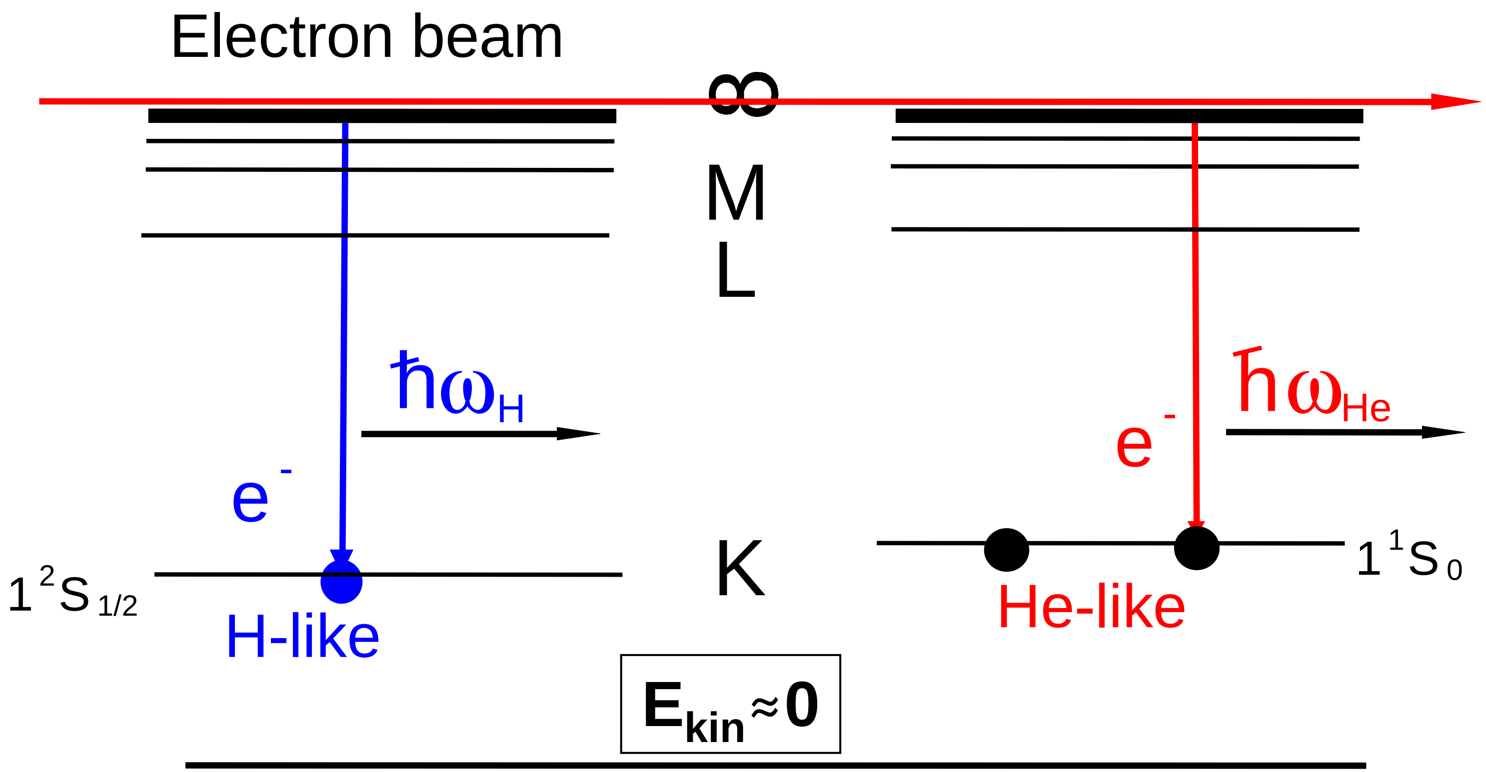


4 strip Ge(i) detector



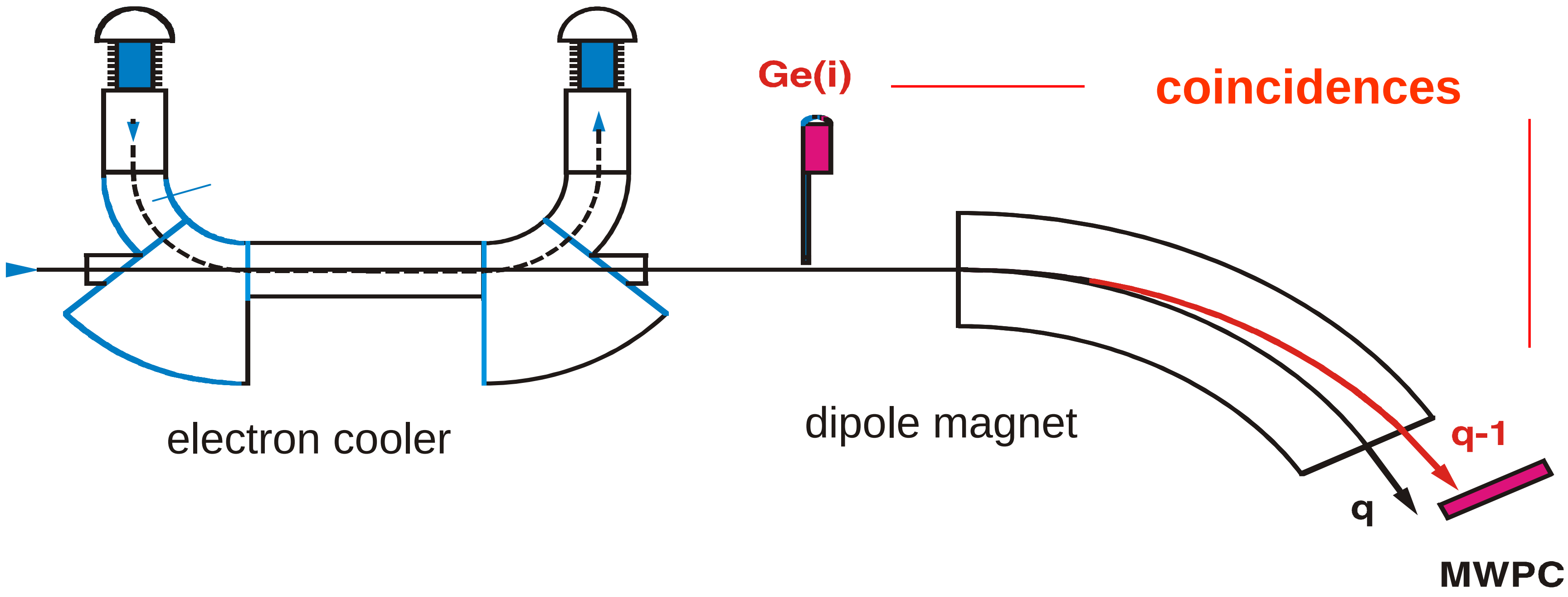

Ge(i) Detector

THE METHOD



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

A relative energy of the electron and ion beams is 0 eV. Therefore a K-RR photon has much smaller energy then in the case of the EBIT experiment which implies a better detection efficiency and a better resolution.

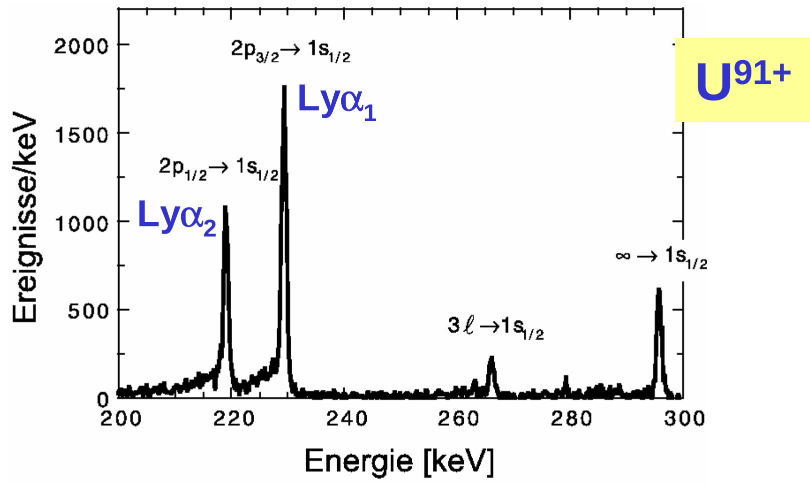


0º Spectroscopy at the Electron Cooler

- **strongest blue shift**
  $\beta \approx 0.65 \;\Rightarrow E_{lab} \approx 2.2 \times E_{proj}$

- $\Delta\theta_{LAB}$ **not critical, Doppler width has its minimum**

- **Uncertainty is caused by** $\Delta\beta$



H.F. Beyer et al., 1995

0 Deg spectroscopy at the ESR electron cooler

No Doppler broadening

practically, no uncertainties introduced by the geometry of the set-up

X-ray projectile coincidences

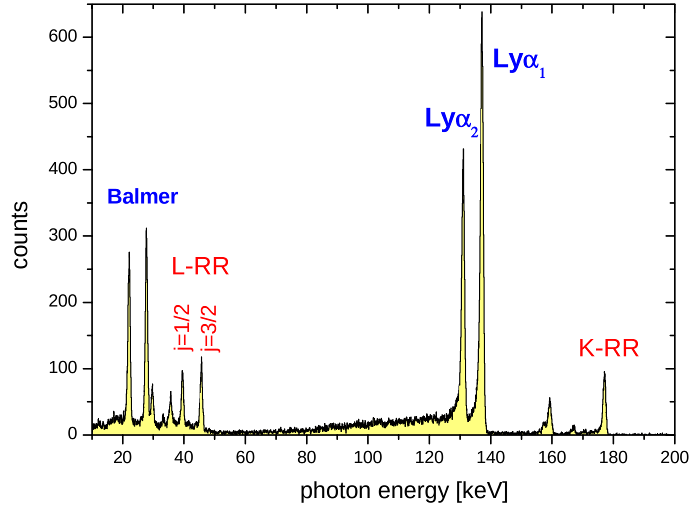
The relative measurement can be performed in sequential steps by changing frequently between bare and H-like uranium

Application of the deceleration mode of the ESR

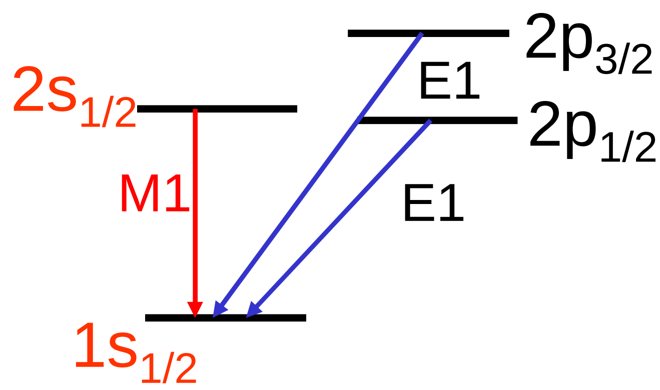
➡ **strongly reduced bremsstrahlung**
uncertainty in β not critical

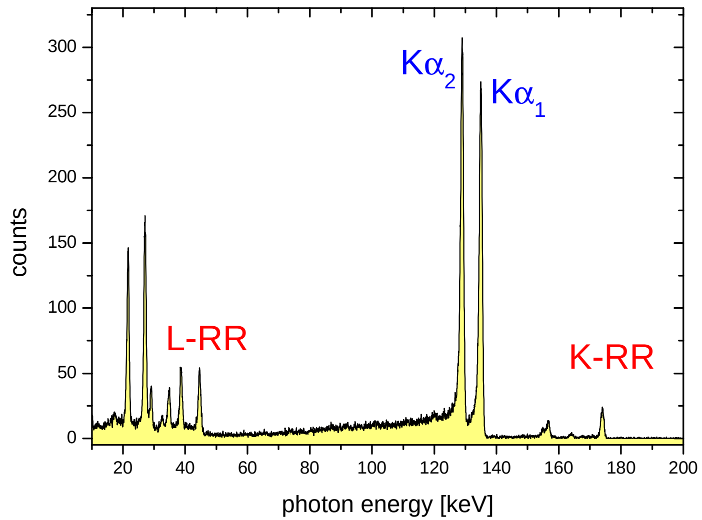
To probe the QED corrections for the ground state in helium like uranium, a relative accuracy of only $\Delta E/E \approx 10^{-3}$ is required

Typical X-ray spectra

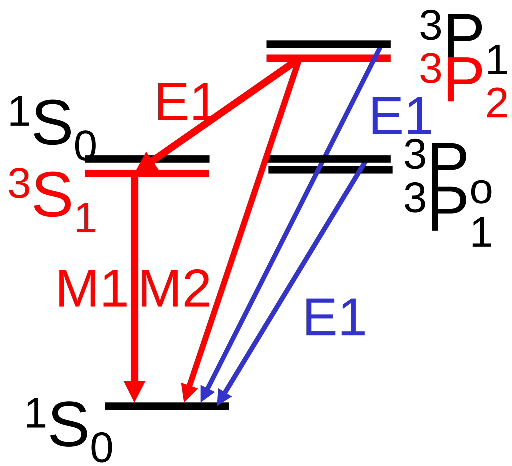


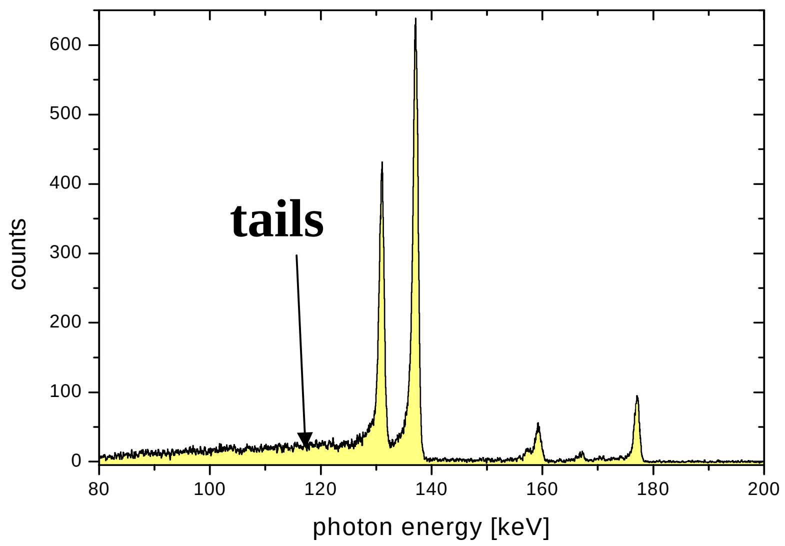
H-like uranium

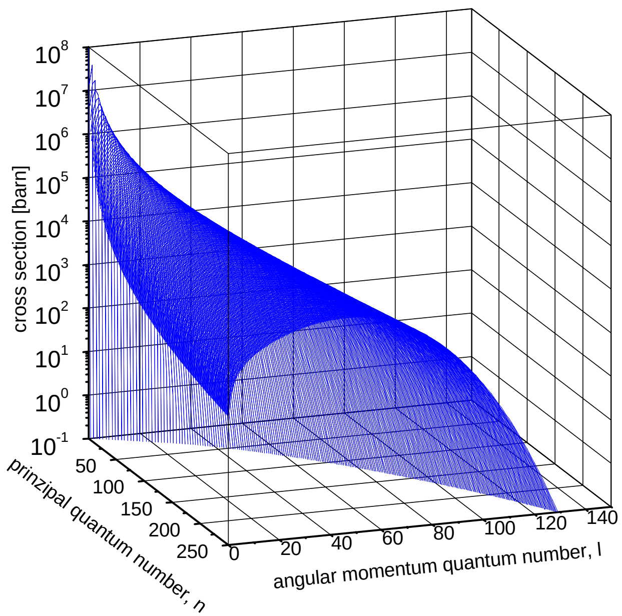


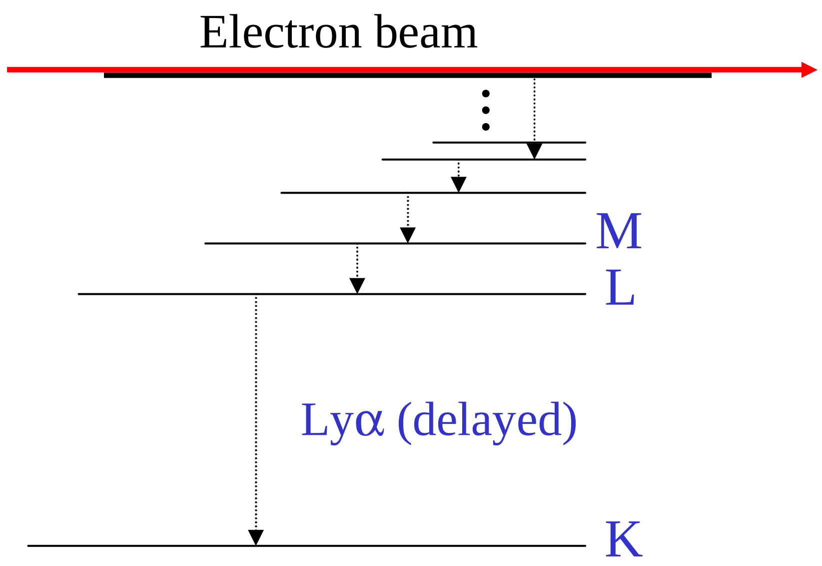


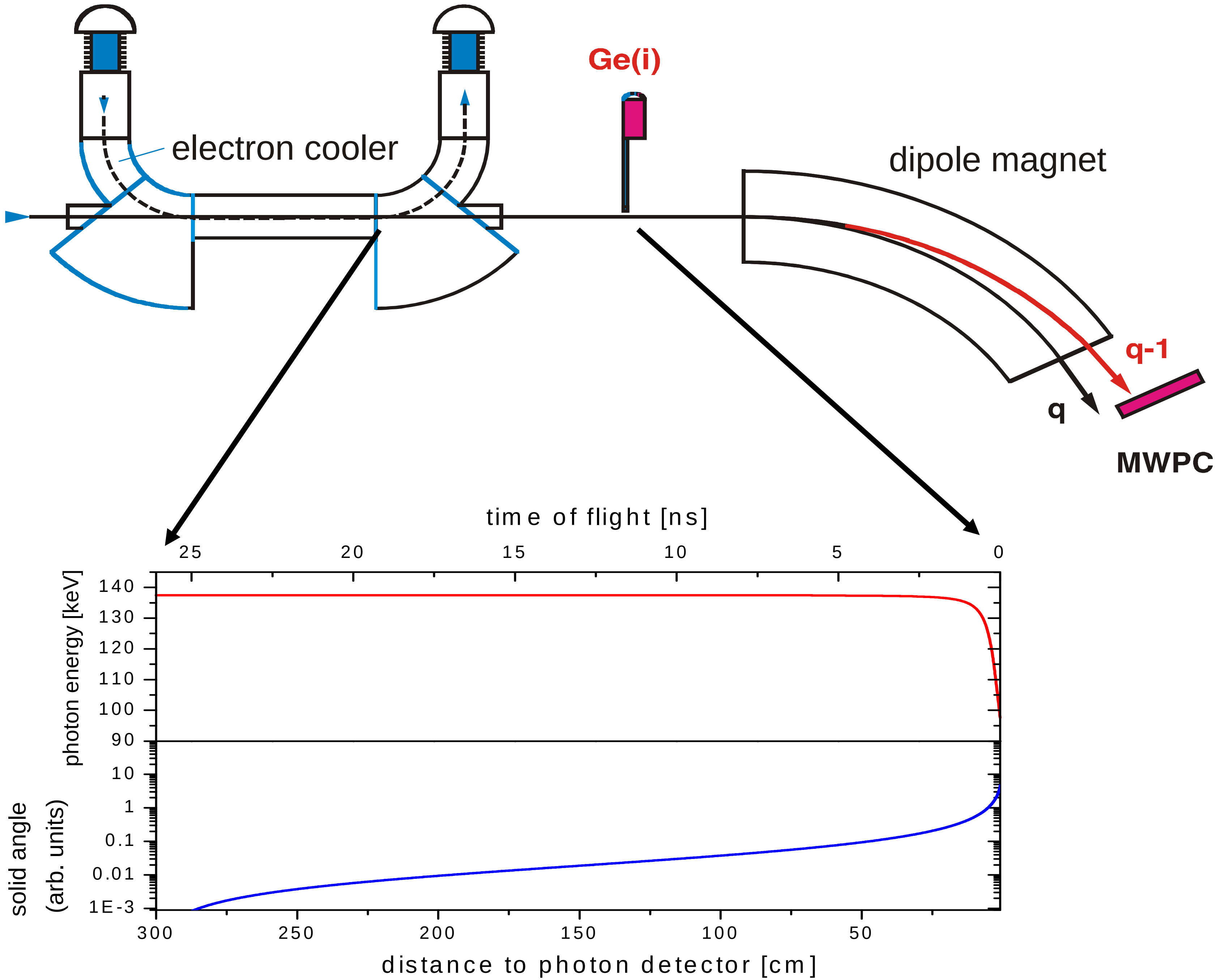
He-like uranium



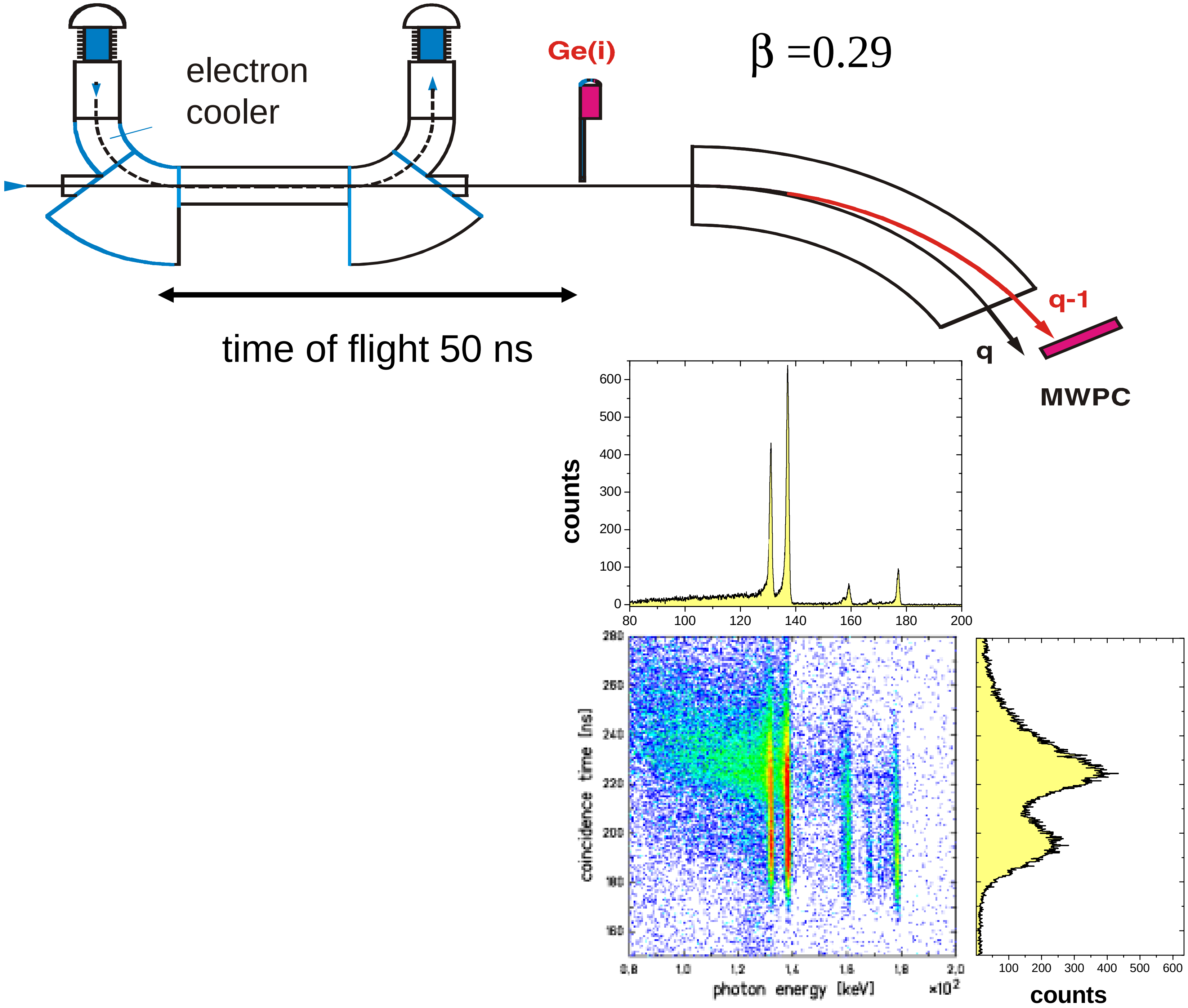

tails
counts
photon energy [keV]
0
100
200
300
400
500
600
80
100
120
140
160
180
200


cross section [barn]
prinzipal quantum number, n
angular momentum quantum number, l

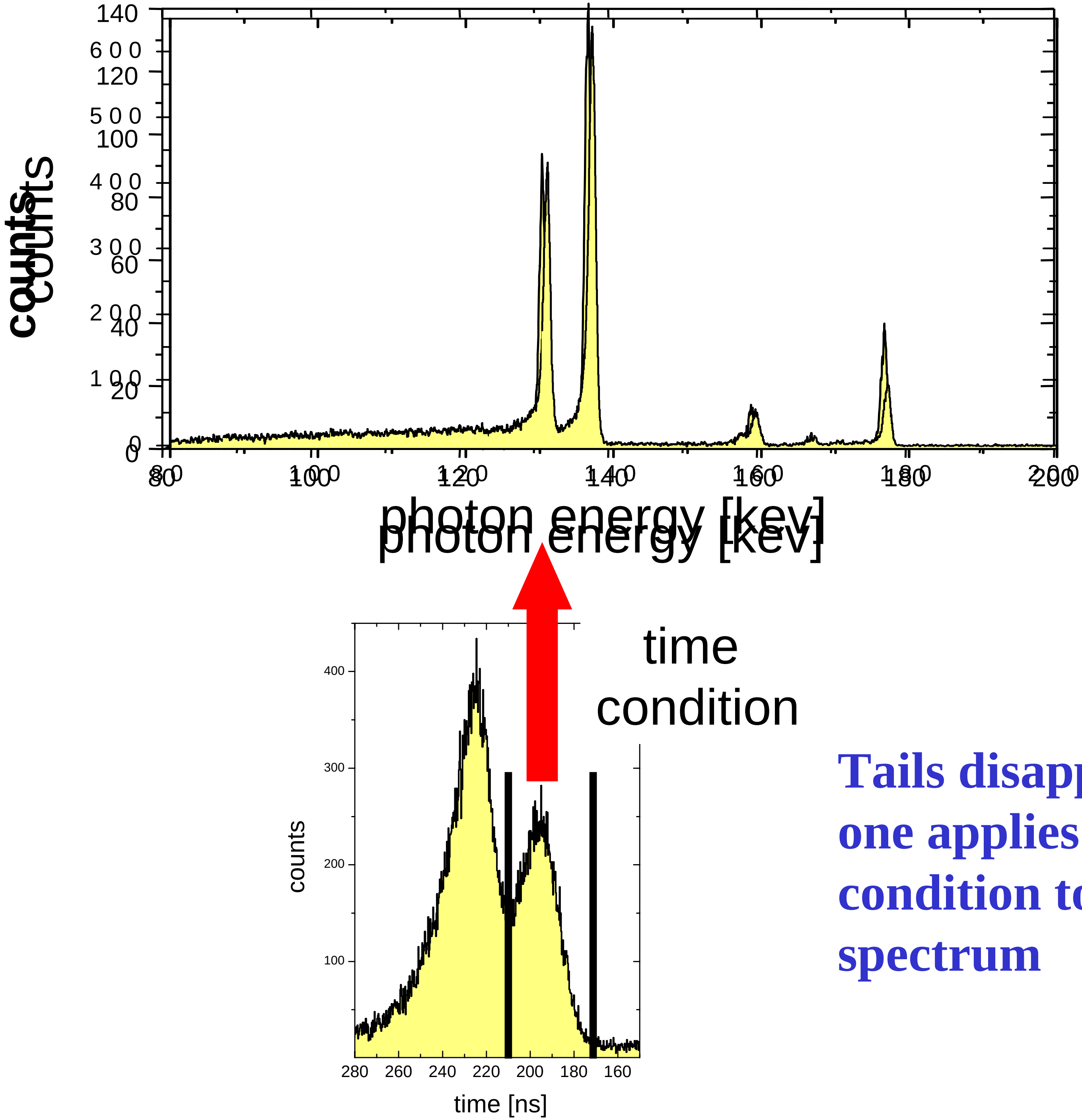

Electron beam
M
L
Lyα (delayed)
K



electron cooler
Ge(i)
dipole magnet
q-1
q
MWPC
time of flight [ns]
25
20
15
10
5
0
photon energy [keV]
140
130
120
110
100
90
solid angle
(arb. units)
10
1
0.1
0.01
1E-3
300
250
200
150
100
50
distance to photon detector [cm]

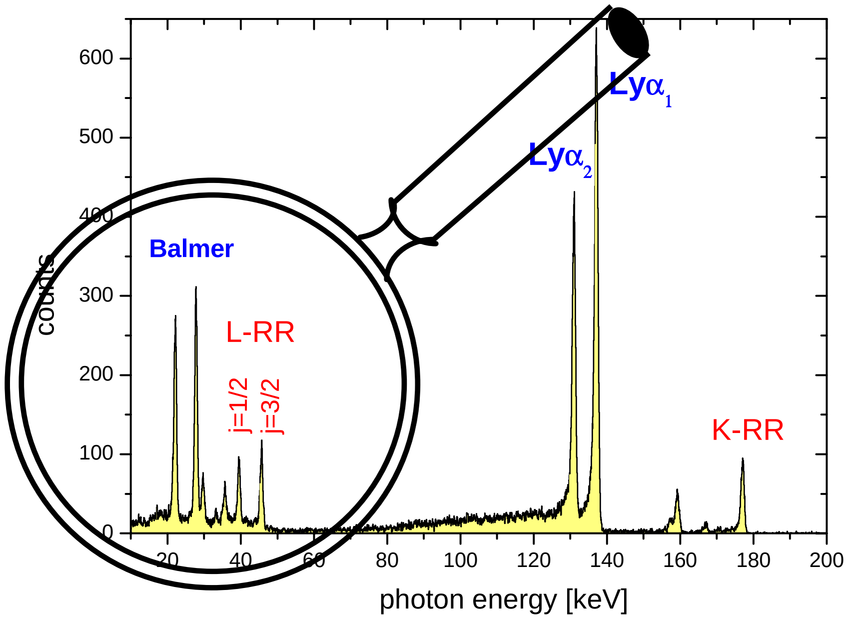


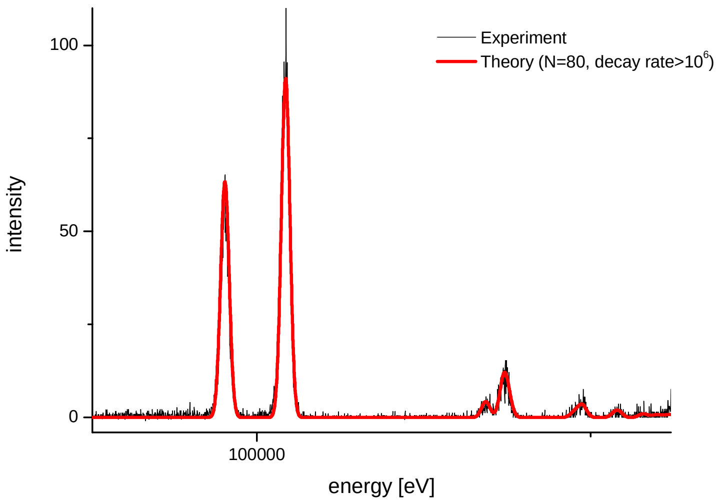
electron
cooler
Ge(i)
β =0.29
time of flight 50 ns
q-1
q
MWPC
counts
photon energy [keV]
coincidence time [ns]
counts

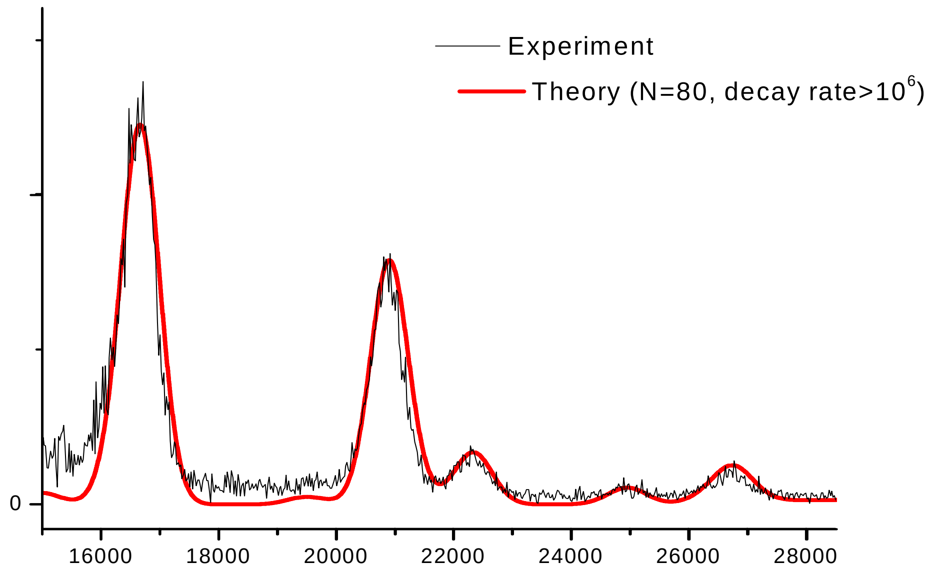


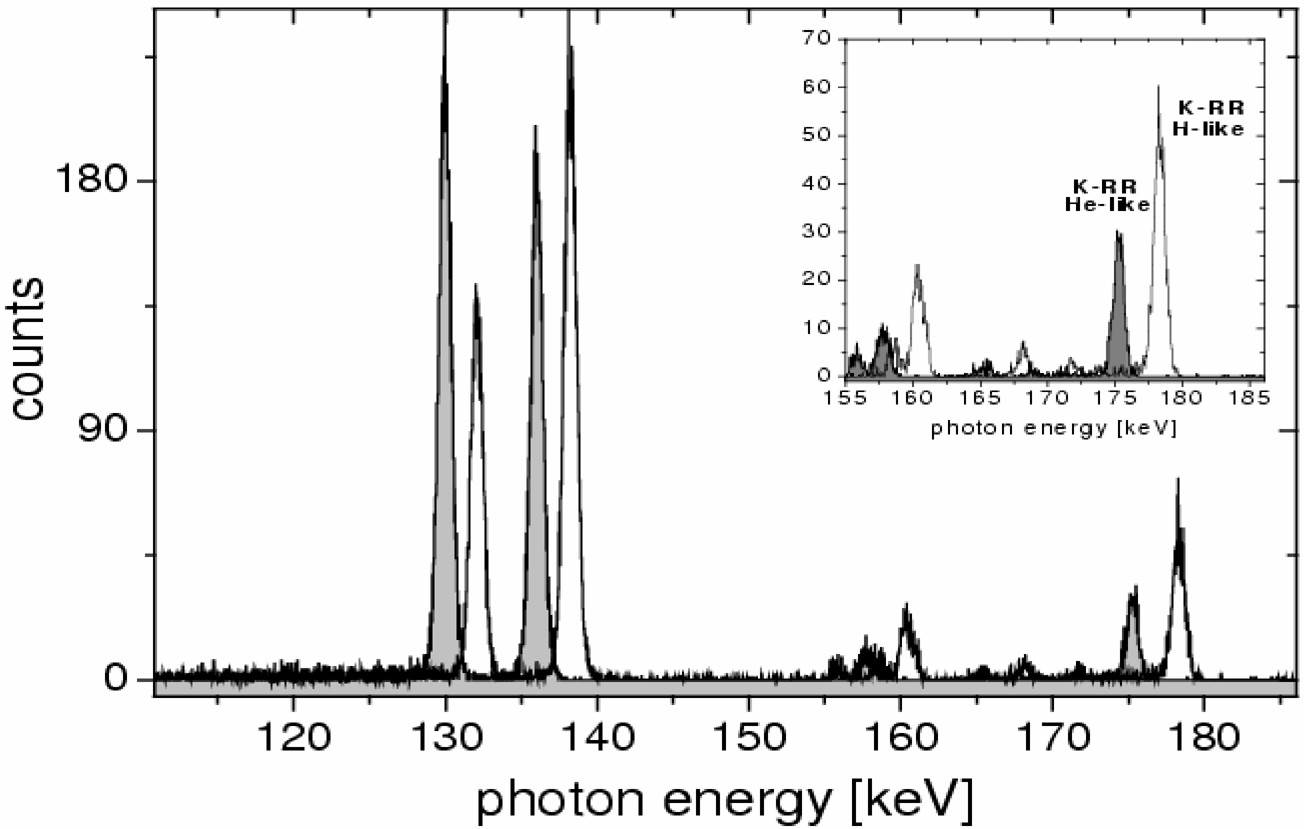
Tails disappear when one applies a proper condition to the time spectrum

The Balmer radiation



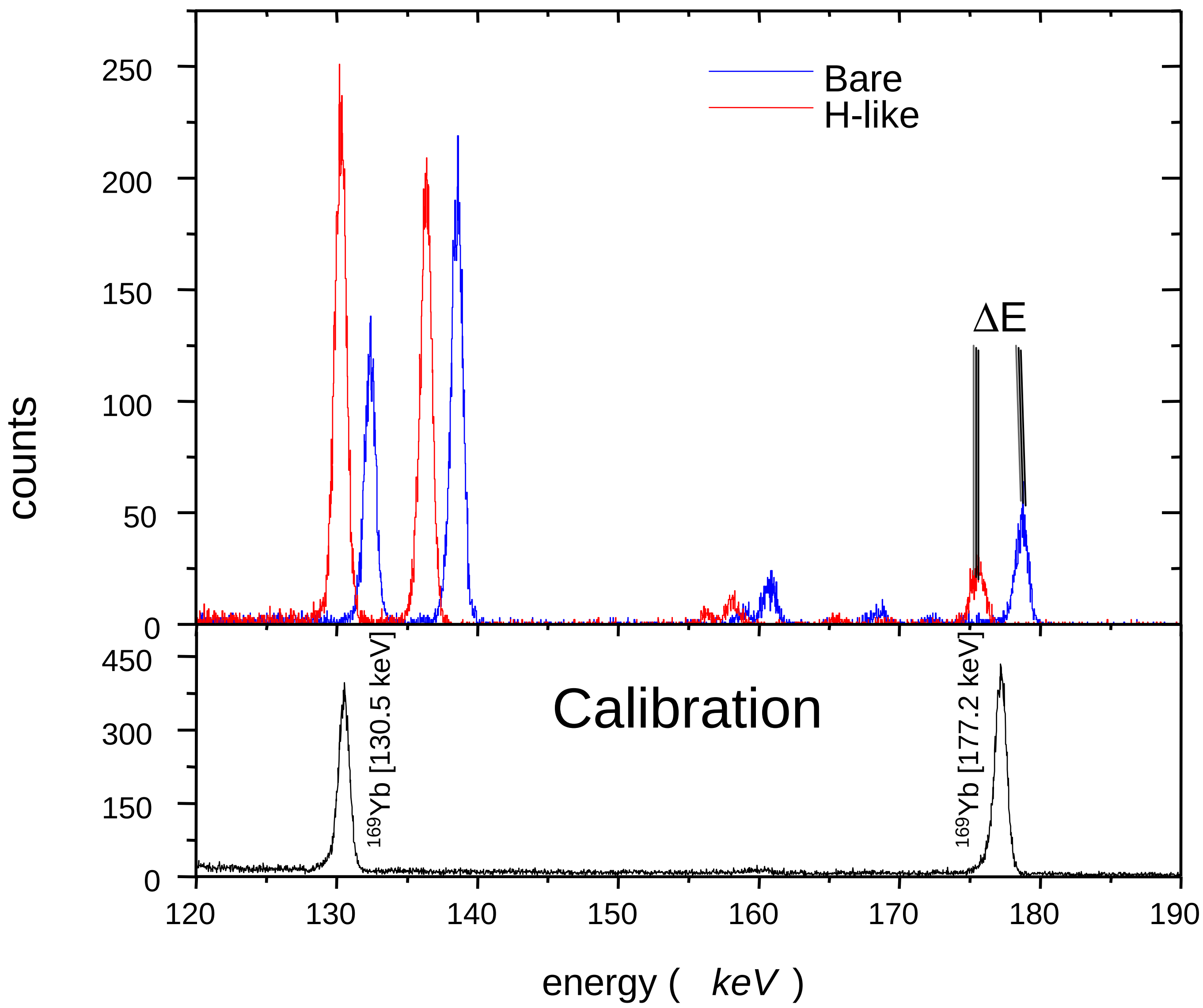






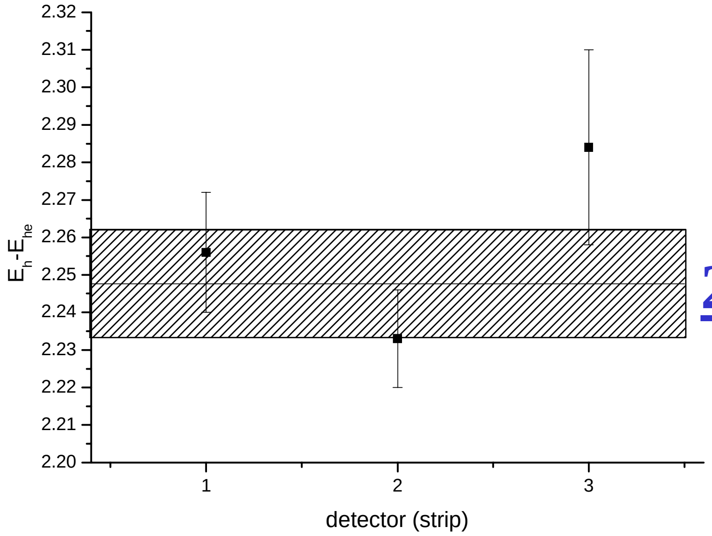
K-RR
H-like
K-RR
He-like
photon energy [keV]
counts
photon energy [keV]

Relative measurement for decelerated ions at the electron cooler



Relative measurement for decelerated ions at the electron cooler

- data subdivided into several groups
- checked for consistency



2248 ± 9 eV

Statistical uncertainty for ΔE: 9 eV

~~Uncertainty caused by doppler shift:~~

The result for the splitting ΔE is 2248 ± 9 eV

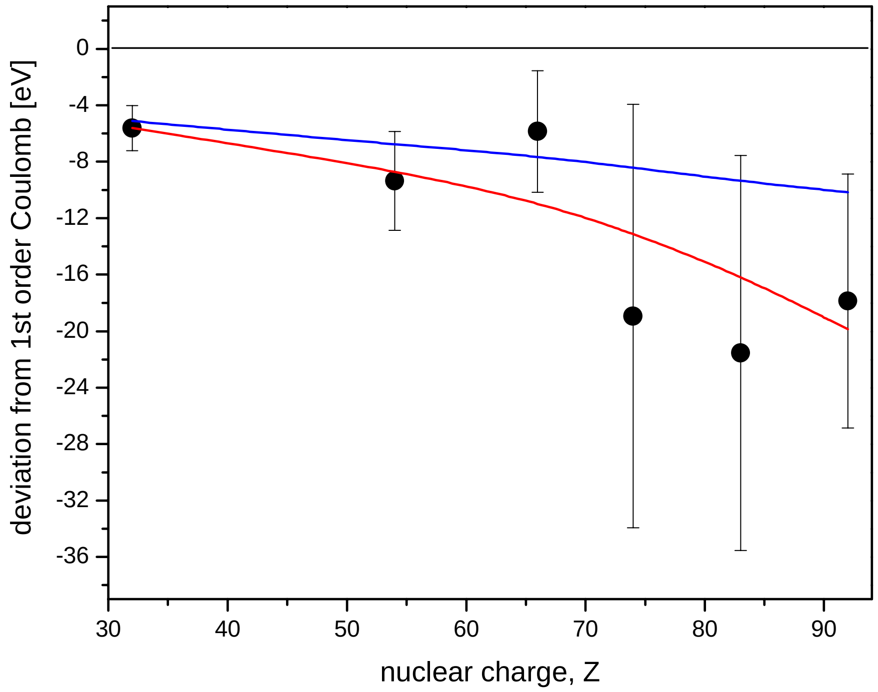
Experimental results in comparison with theory

Z	1st order RMBPT	2nd order RMBPT	NR	2eSE	2eVP	Total theory	Experiment
32	567.61	-5.2	0.0	-0.5	0.0	562.0	562.5(1.6)
54	1036.56	-7.01	0.2	-1.8	0.2	1028.2	1027.2(3.5)
66	1347.45	-8.56	0.4	-3.2	0.6	1336.6	1341.6(4.3)
74	1586.93	-9.87	0.6	-4.6	0.9	1573.9	1568(15)
83	1897.56	-11.73	0.9	-6.7	1.6	1881.5	1876(14)
92	2265.87	-14.11	1.3	-9.7	2.6	2246.0	2248(9)

(*H. Persson et al., 1996) (all values are in eV)

The individual two-electron contributions to the ground state binding energy in some He-like ions in comparison with the experimental results from superEBIT (Marrs et al.) and from the ESR electron cooler (NR: non-radiative QED as defined by Persson et al.; 2eVP: two-electron vacuum polarization; 2eSE: two-electron self energy; Total theory: predicted difference in the ionization potentials between the H- and He-like systems.

Experimental results in comparison with theory

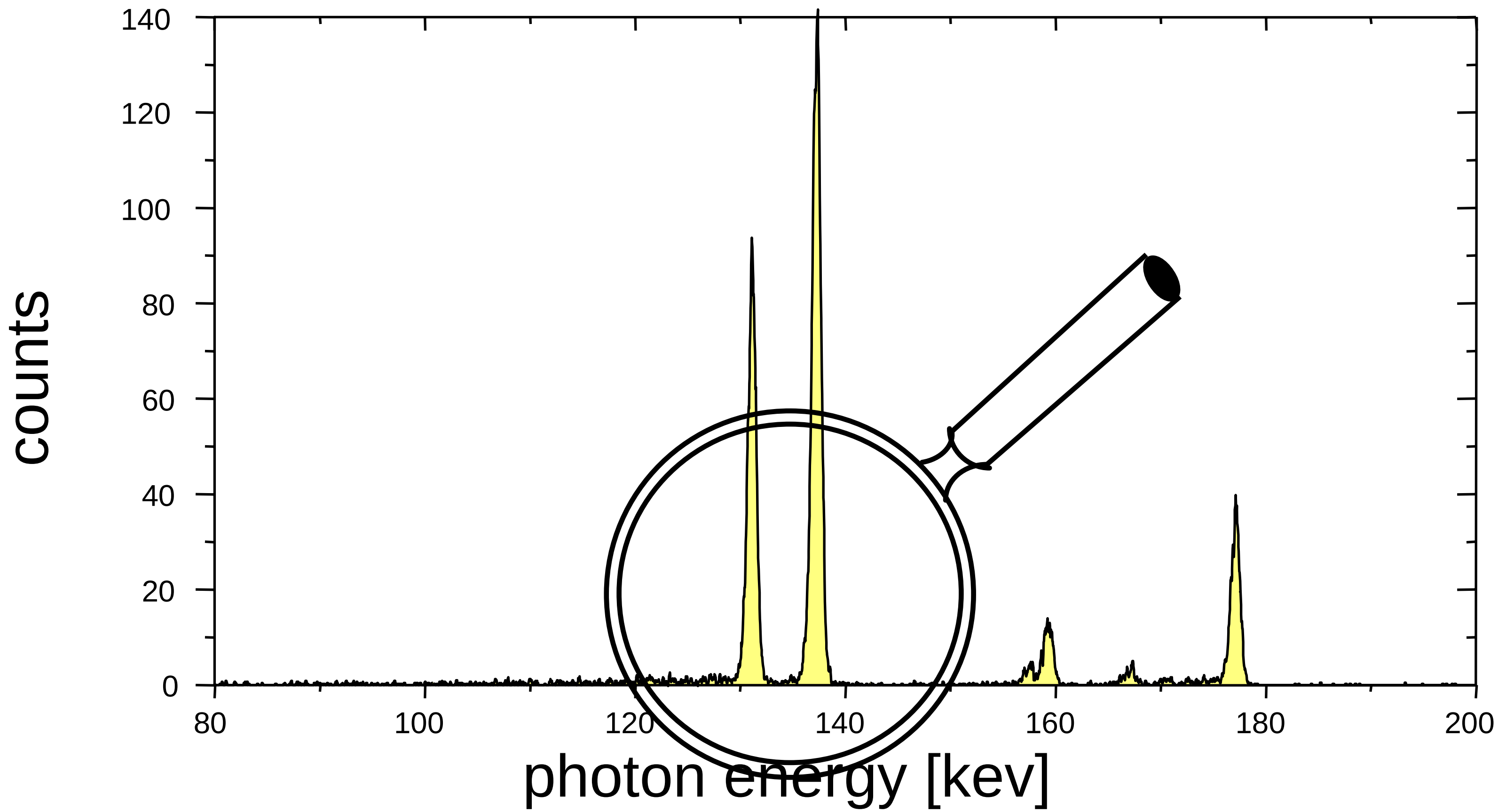


Persson et al.	Plante et al.	Drake et al.	Experiment
2246.0	**2249**	**2255.1**	**2248(9)**

(all values are in eV)

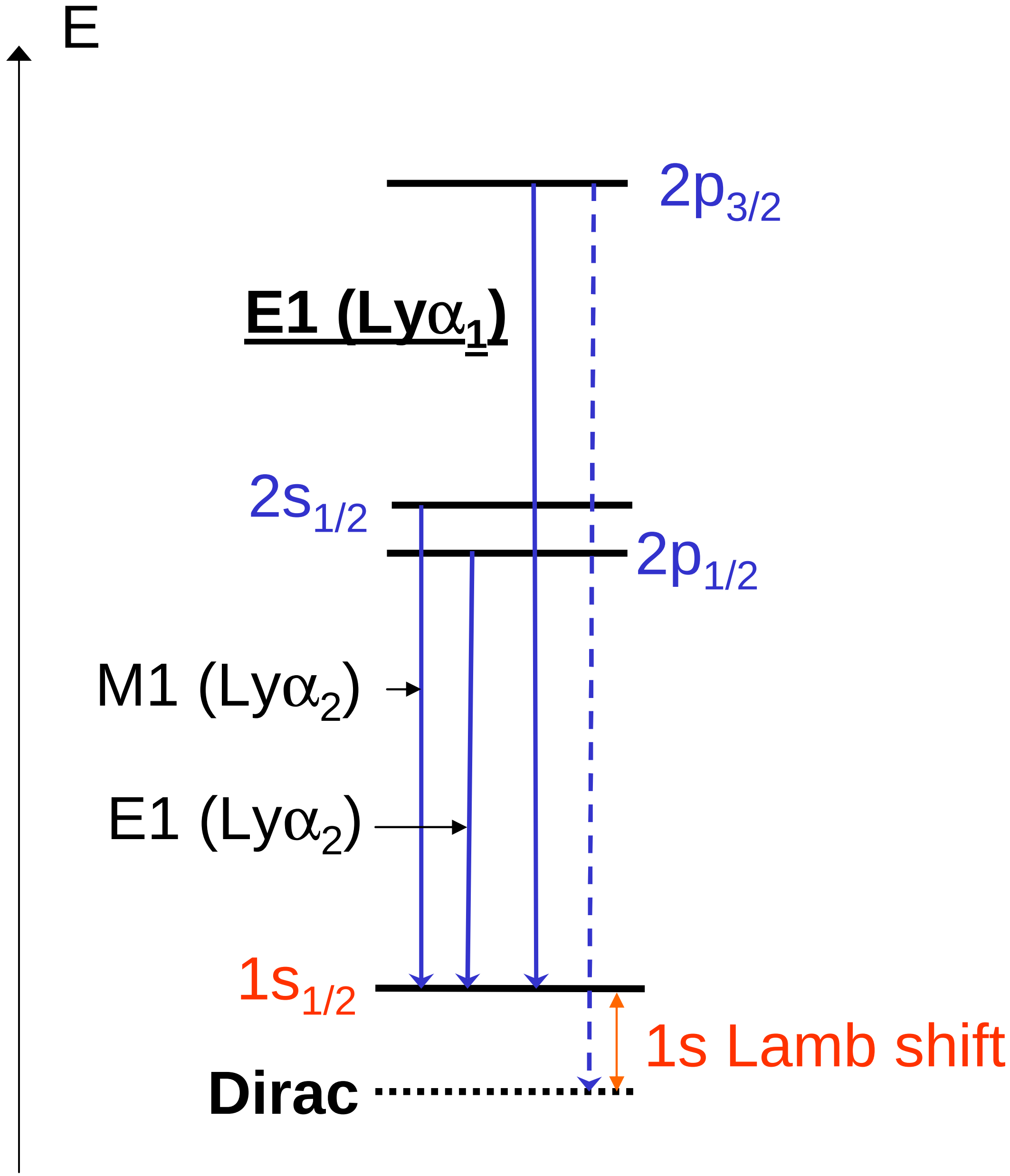
Compared to the former studies at Super-EBIT in Livermore we could substantially improve the statistical accuracy and extend studies to the higher-Z regime.

The ground state Lamb shift in H-like uranium

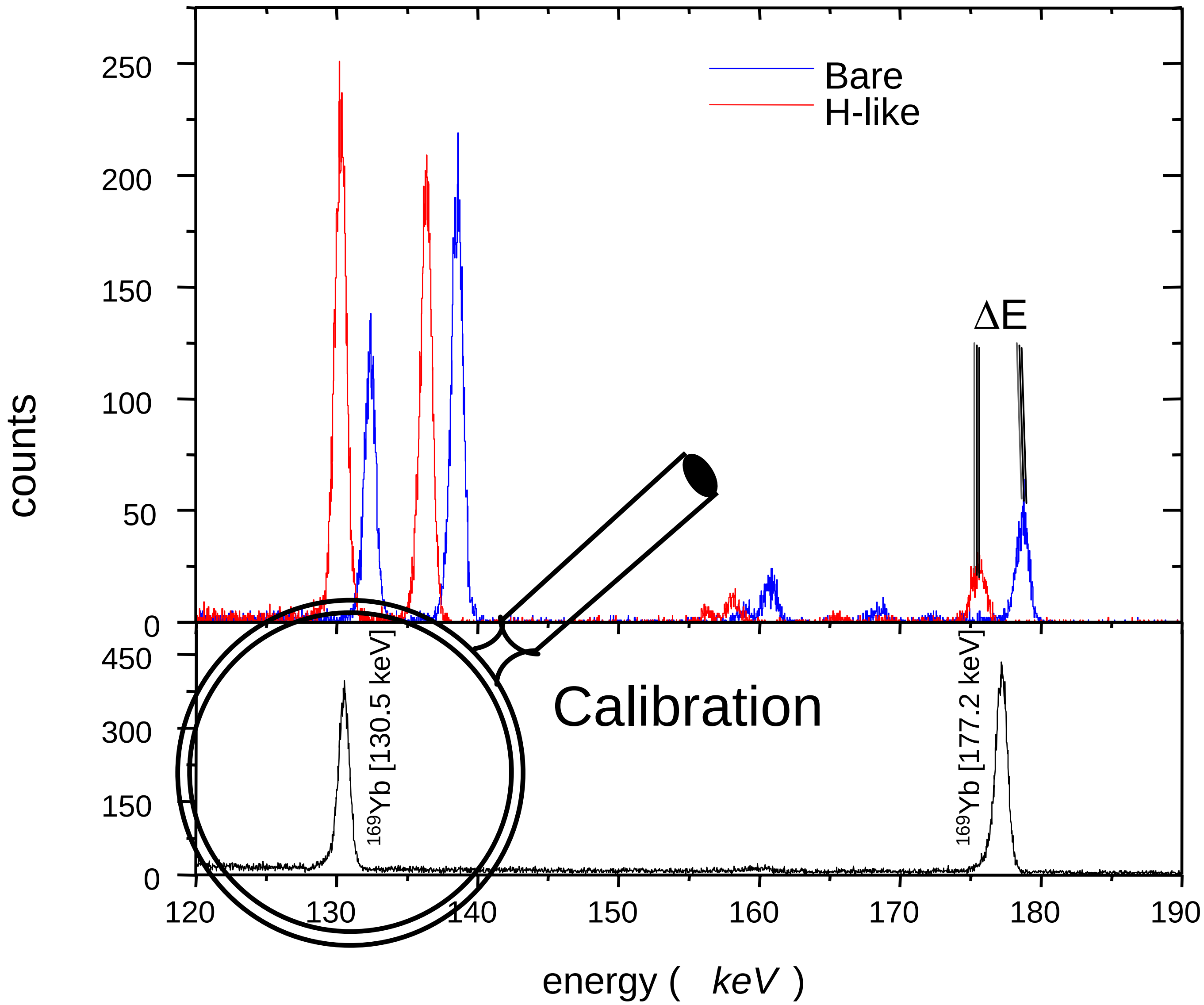


From the Lyman line centroid the value for the 1s Lamb shift in H-like uranium can be obtained.

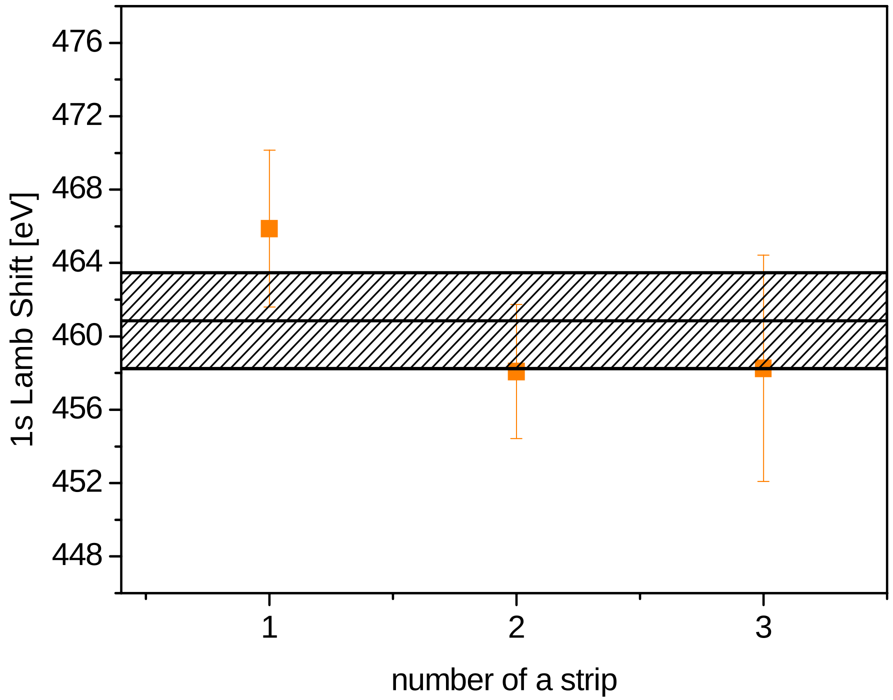
The ground state Lamb shift in H-like uranium



The ground state Lamb shift in H-like uranium

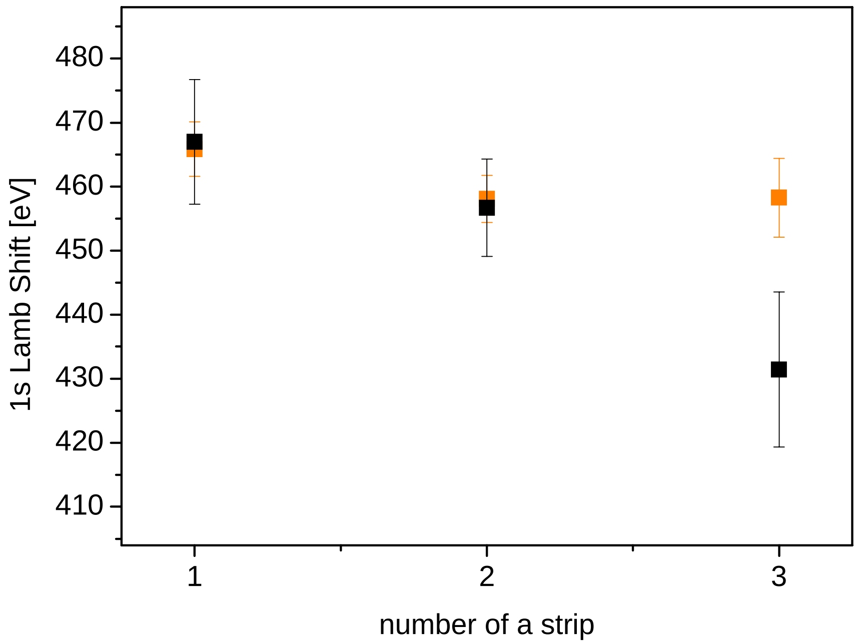


The ground state Lamb shift in H-like uranium

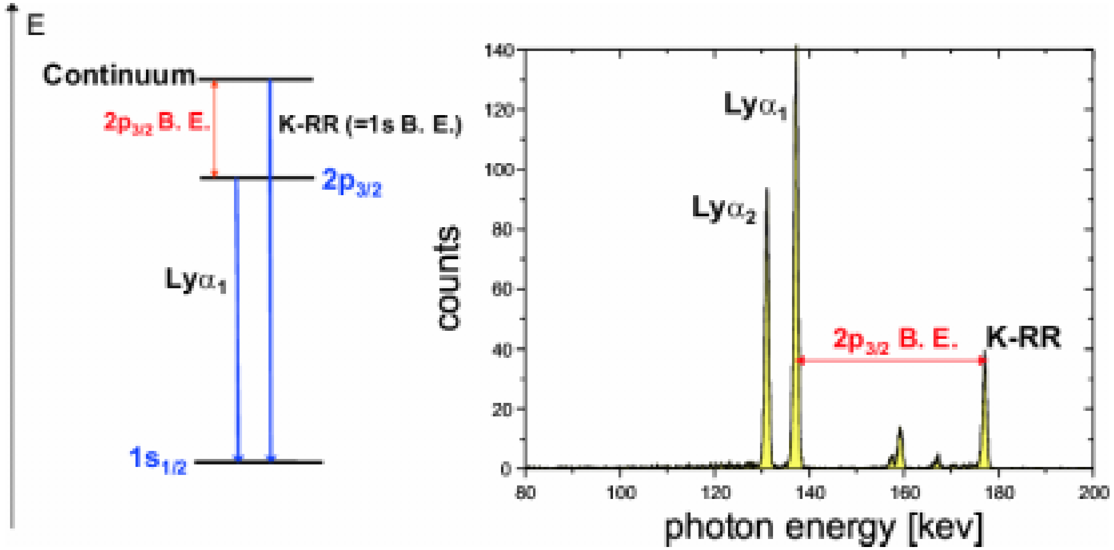


STRIP	1s Lamb shift	
	Lyman	K-RR
1	465.9 ± 4.3	467.0 ± 9.7
2	458.1 ± 3.7	456.7 ± 7.6
3	458.3 ± 6.2	431.4 ± 12.1

Comparison between the ground state Lamb shift values deduced from the K-RR (black squares) and the Lyα_1 (orange squares) centroid energies.



The ground state Lamb shift in H-like uranium



STRIP	$2p_{3/2}$ Binding energy
1	29639.9 ± 10.6
2	29631.8 ± 8.3
3	29667.5 ± 13.3
Mean value	**29641.3 ± 5.9**

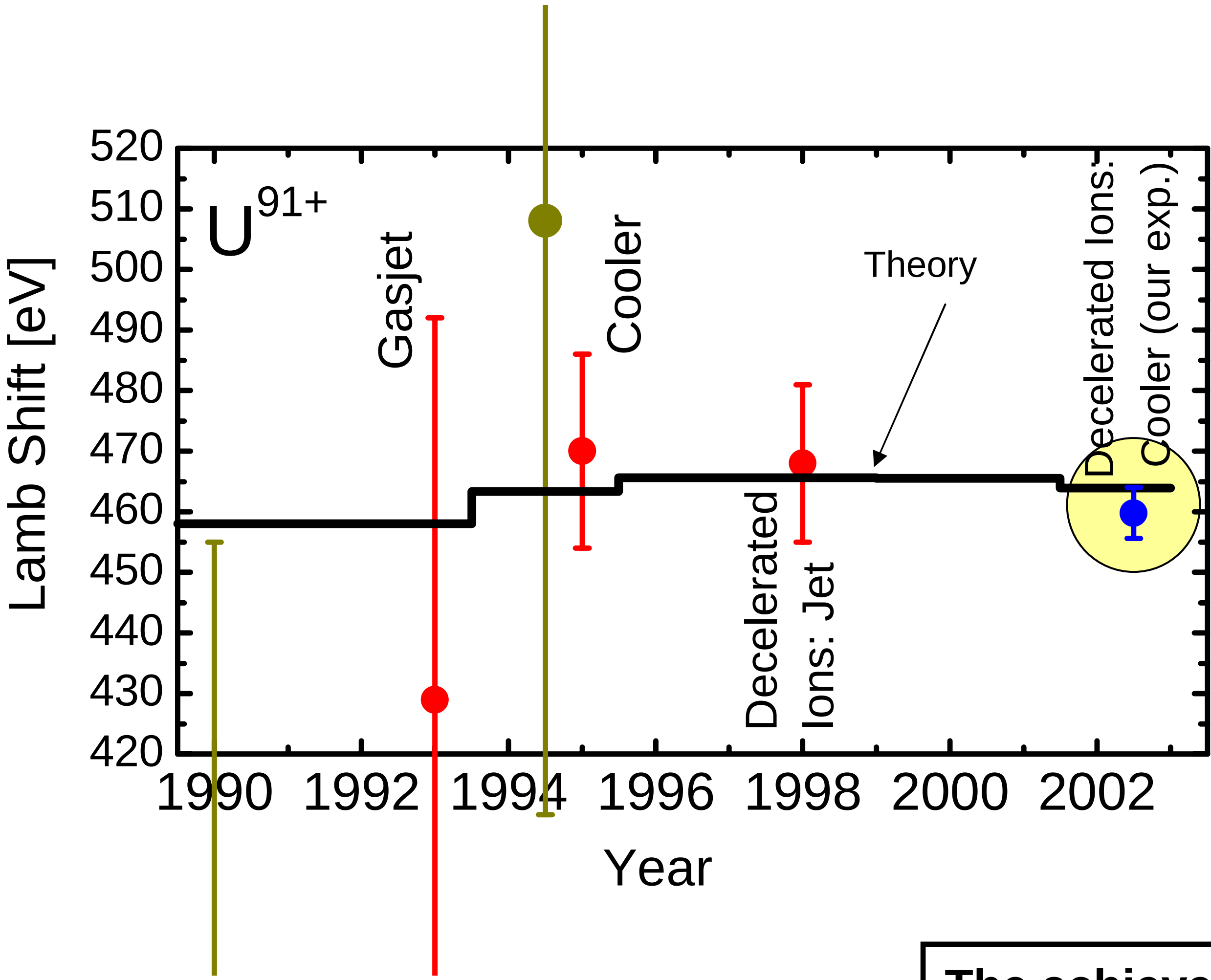
Theory; 29640.99

1s Lamb shift in U^{92+}

459.8±2.3±3.5 eV

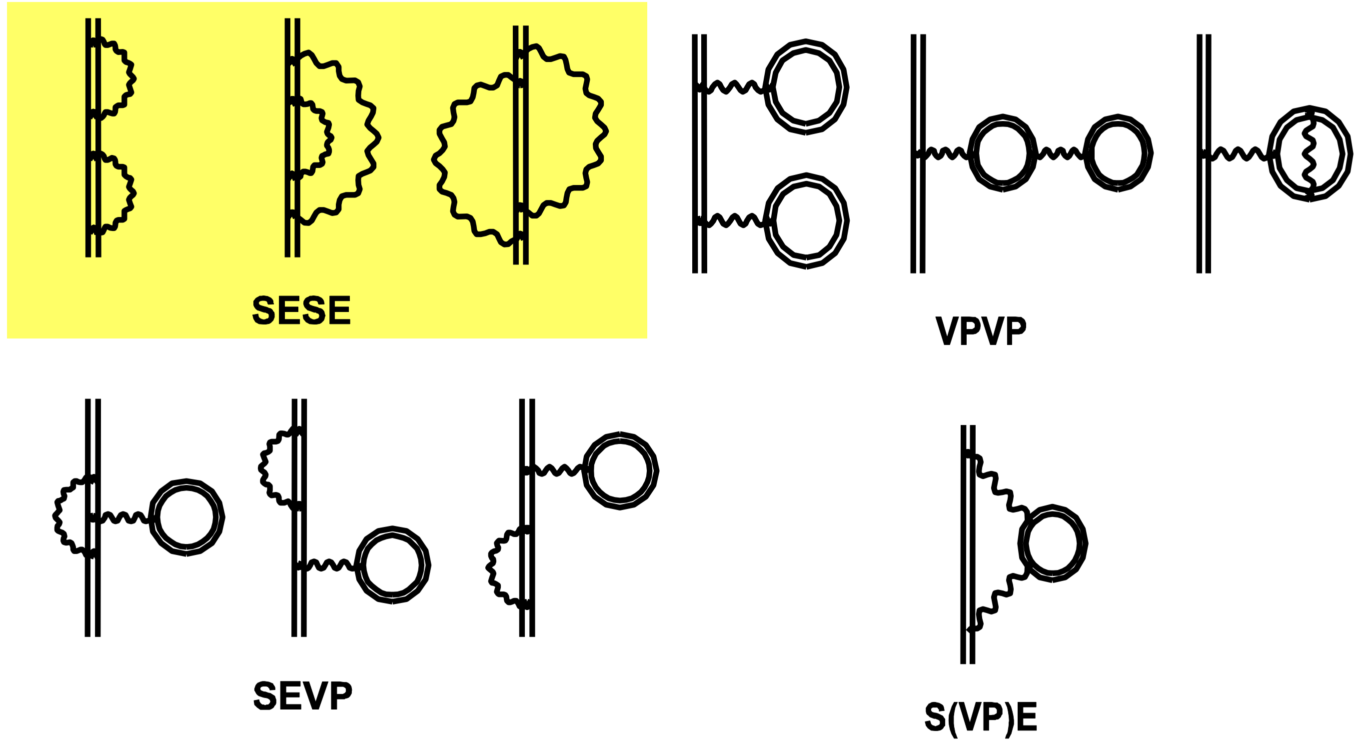
4.2 eV

The ground state Lamb shift in H-like uranium



The achieved accuracy of 4.2 eV is a substantial improvement by a factor of 3 compared to the most precise value up to now.

The ground state Lamb shift in H-like uranium



1s Lamb shift in U^{92+}	Theory	Experiment
	463.95±0.5 eV	459.8±4.2 eV

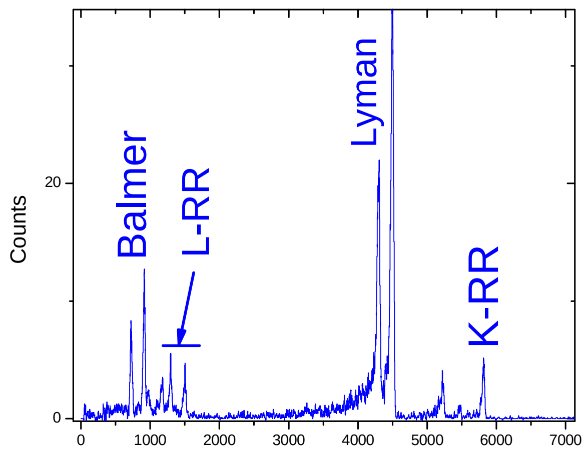
As an example; the SESE contributes on the level of about -1.87 eV

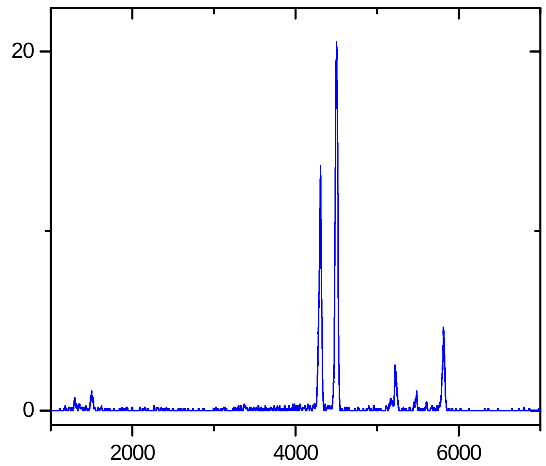
Theory: Yerokhin et al. 2001

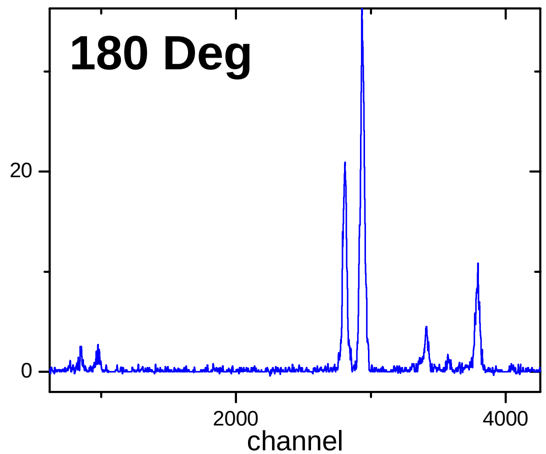
Experiment at 20 MeV/u

Much better separation in the time spectrum

Observation of the electron beam interaction zone from two angles: 0 and 180 Deg







to be continued

Summary and outlook

- Two-electron QED Studies at the ESR
  - First measurement for helium-like uranium (U^{92+}),
  - Improvement of experimental sensitivity by a factor of two,
  - Result sensitive to two-electron self energy (2eSE) contribution,

- 1s Lamb shift Experiment for Hydrogen-like uranium (U91+)
  - First experiment with decelerated ions at the ESR electron cooler,
  - Kinematic separation of Rydberg transitions,
  - Improvement in precision compared to the former experiment by factor of three,
  - The result is limited by an uncertainty in the velocity determination,

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Simultaneous measurement at 0 and 180 deg.

Collaboration

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