Präzisionsexperimente am wasserstoffähnlichen Uran

Thomas Stöhlker
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Einführung

Die atomare Struktur im hohen Z Bereich

QED-Beitrag zum Grundzustand in schweren H-ähnlichen Ionen

Die 1s Lamb-Verschiebung

QED-Beitrag zum Grundzustand in schweren He-ähnlichen Ionen

Zwei-Elektronen QED

Zusammenfassung und Ausblick

Collaboration

Experiment

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Theory

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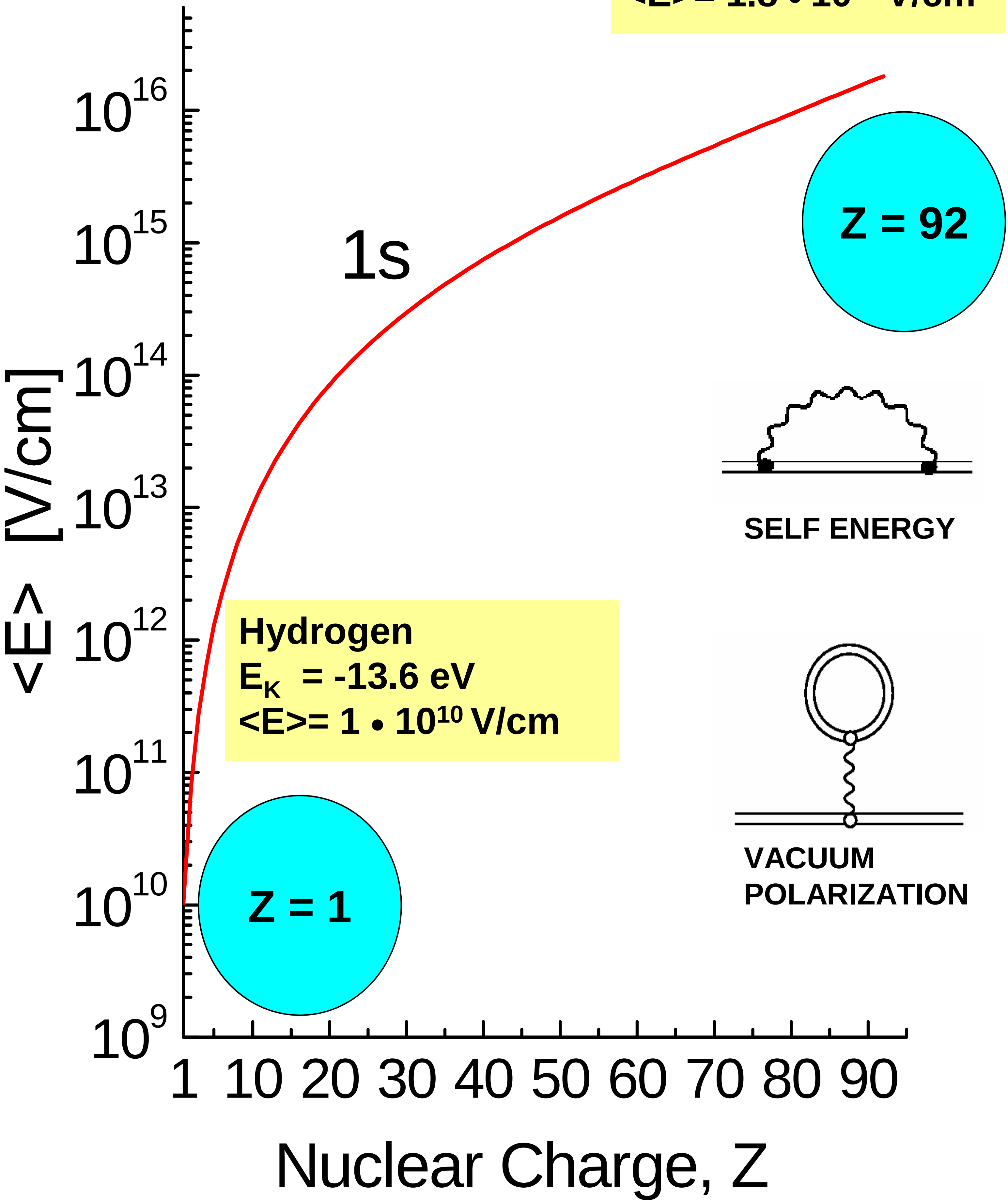
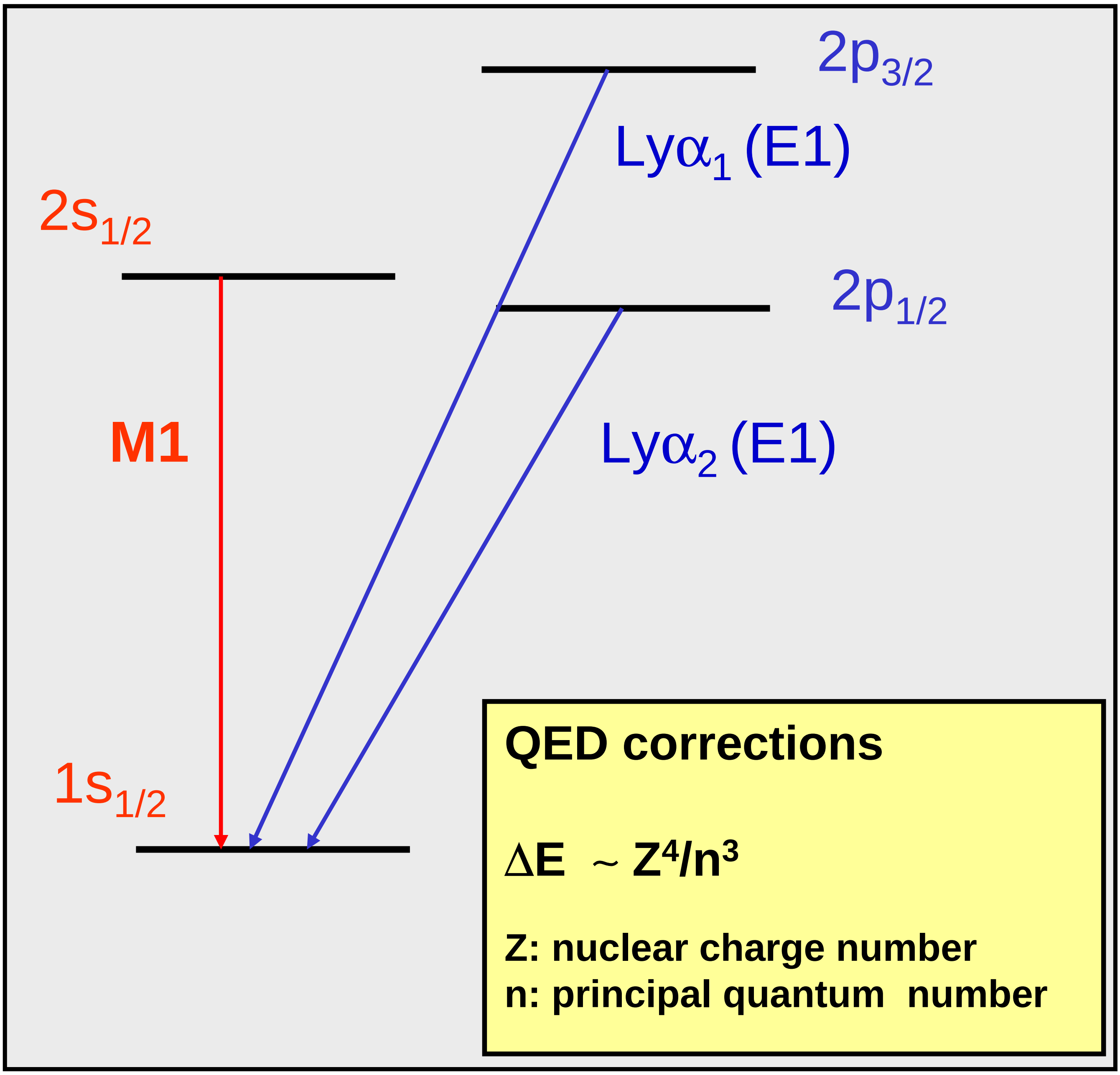
Atomic Physics in Extremly Strong Coulomb Fields

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



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

The Structure of One-Electron Systems

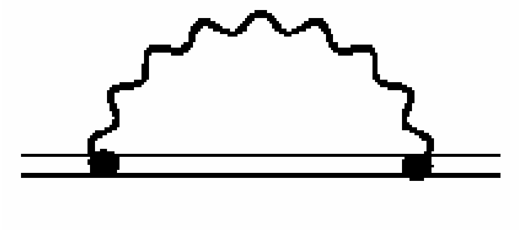


Atomic systems at high-Z

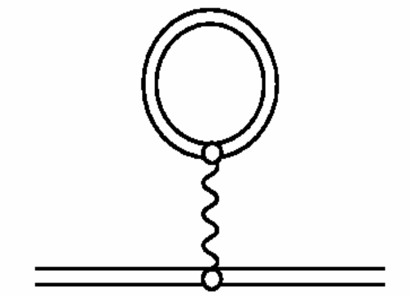
- Large relativistic effects on energy levels and transition rates (e.g. shell and subshell splitting)
- Large QED corrections
- Transition energies close to 100 keV

Bound-State QED: 1s Lamb Shift

Self energy



Vacuum polarization



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

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

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

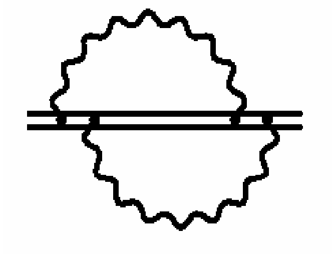
Low Z-Regime: $\alpha Z \ll 1$

$F(\alpha Z)$: series expansion in αZ

High Z-Regime: $\alpha Z \approx 1$

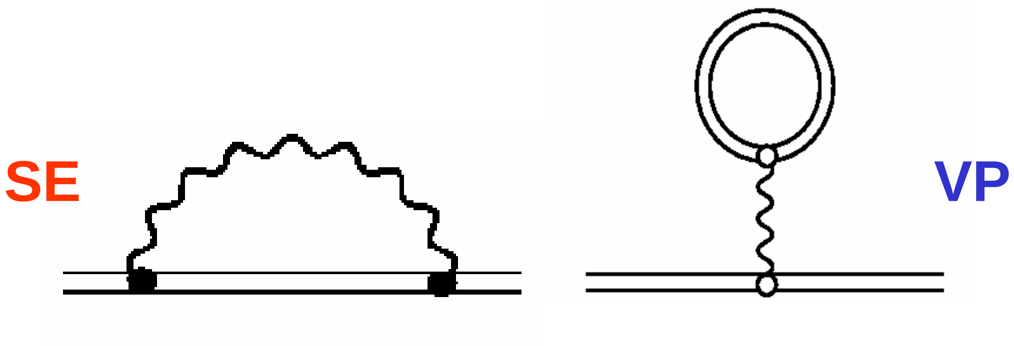
$F(\alpha Z)$: series expansion in αZ not appropriate

Goal:



$\pm$1 eV

Test of Bound-State QED at high-Z



Experiments

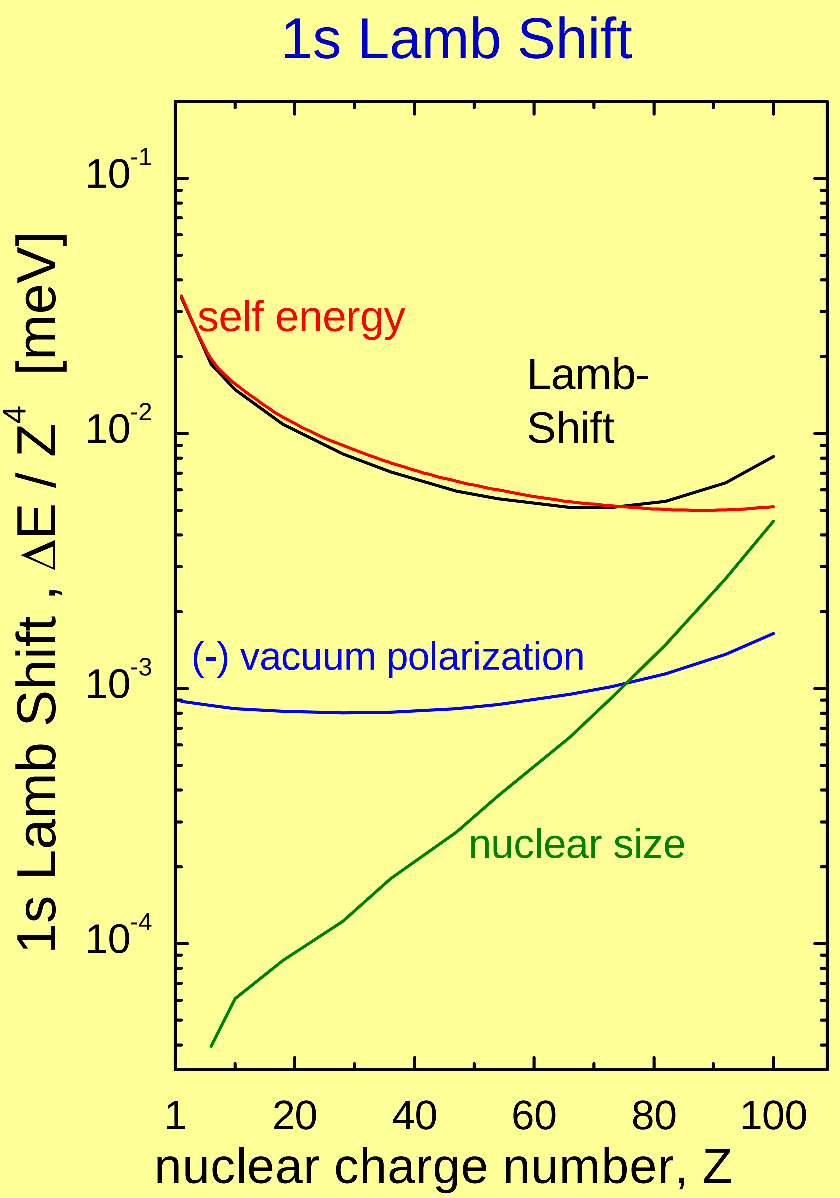
1s Lamb Shift

hyperfine-structure

g-factor of bound electrons

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

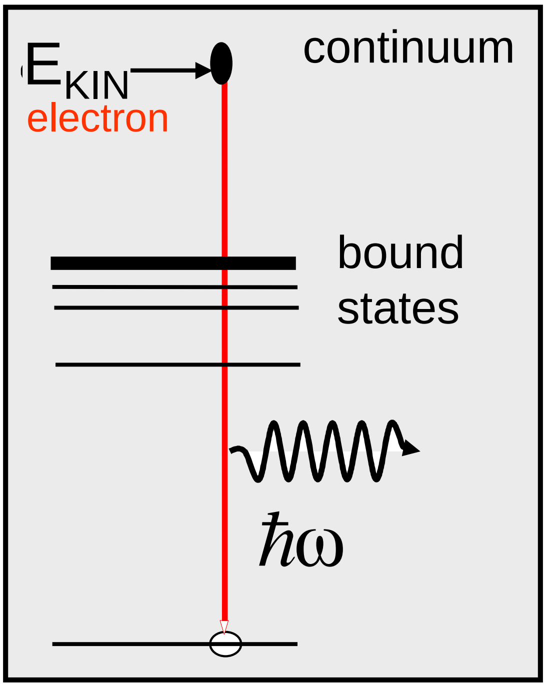
2eQED for He-like ions



Electron Pickup Processes of HCI in Collisions with Electrons (Dynamic Processes)

Radiative Recombination/Electron Capture

$$A^{Z+} + e^- \Rightarrow A^{(Z-1)+} + \hbar\omega$$

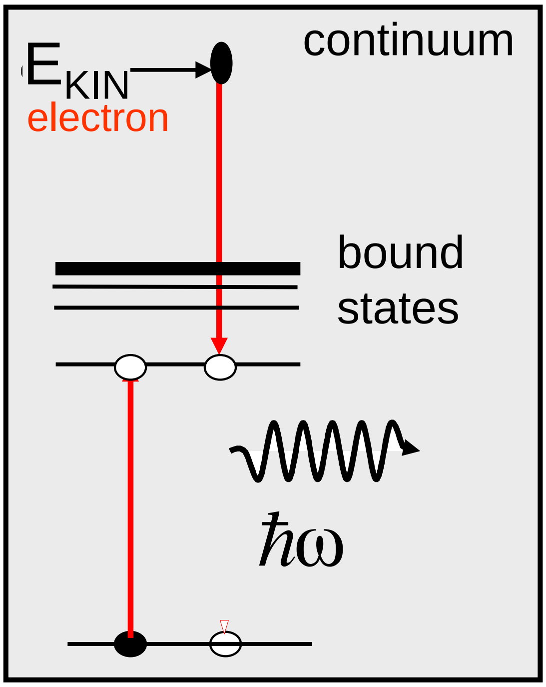


- *Electron capture into a bound ionic state by emission of a photon*

$$\hbar\omega = E_B + E_{KIN}$$

- *Time-reversed photionization*
- *Only possible capture/recombination process for bare ions colliding with electrons*

Dielectron Recombination/Electron Capture

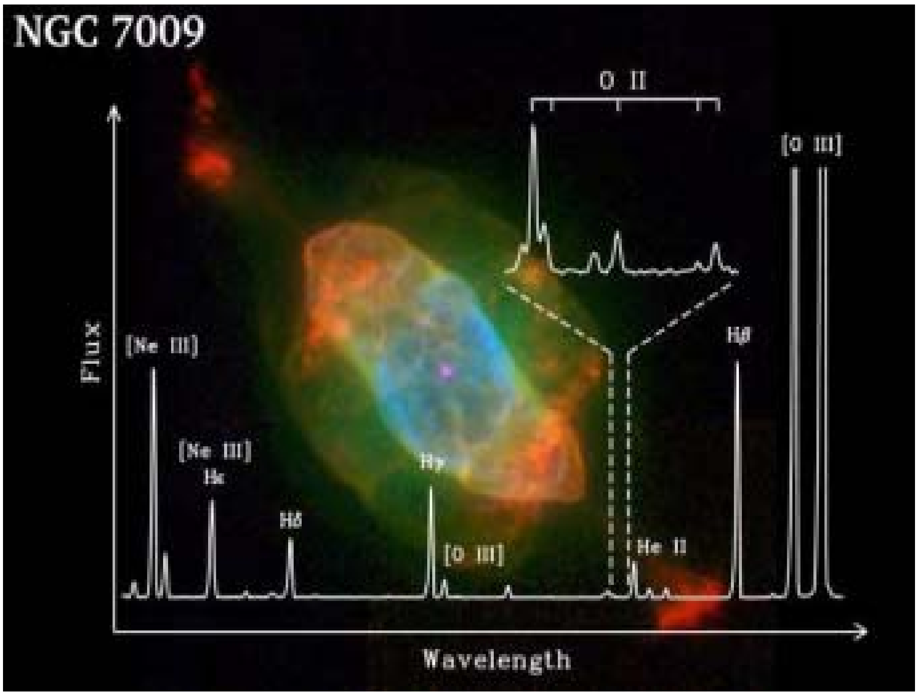


- *Resonant (non-radiative) capture of an electron into a bound state*
- *Time-reversed Auger process*
- *Important charge exchange process for multi-electron ions*

Recombination Processes: Elmentary Atomic Physics Process and of Outmost Importance when Dealing with Highly Ionized Matter

e.g.

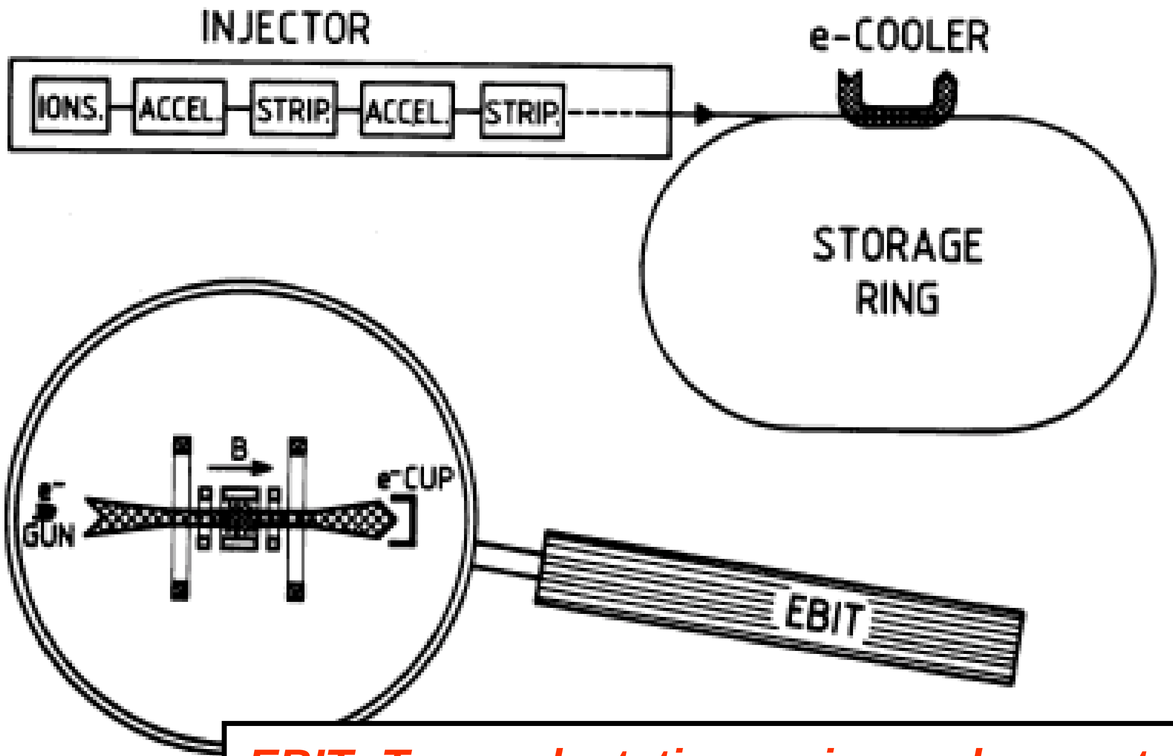
- ***ion sources***
- ***accelerator***
- ***charge state deveplopment /distributions of HCI in matter***
- ***photon emission and absorption characteristic of plasma sources***
- ***astrophysics***



The specta of ionized planetary Nebulae are dominated by strong H and He recombination lines, emitted following structure

Production of Highly Charged Heavy Ions

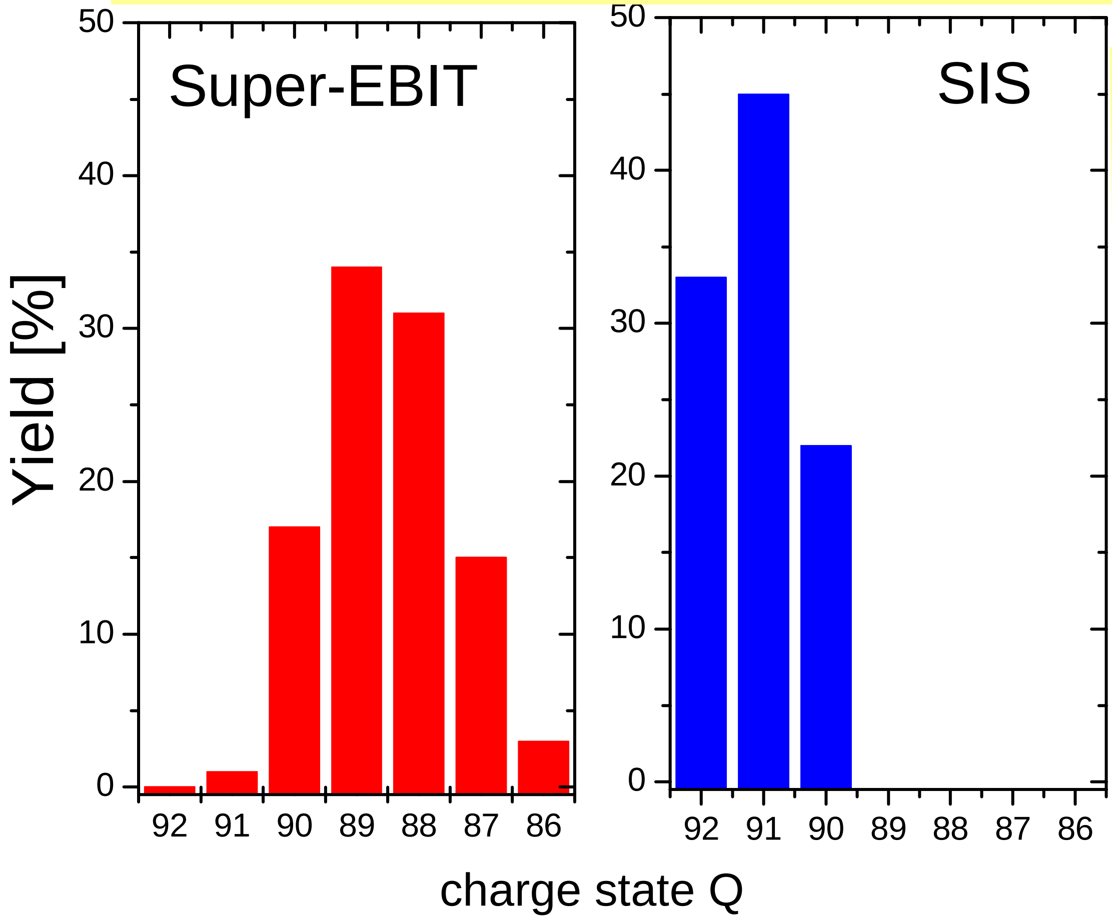
Accelerator: Fast moving ions, charge state production by penetration through stripper targets



EBIT: Trapped, stationary ions; charge state production by electron bombardment

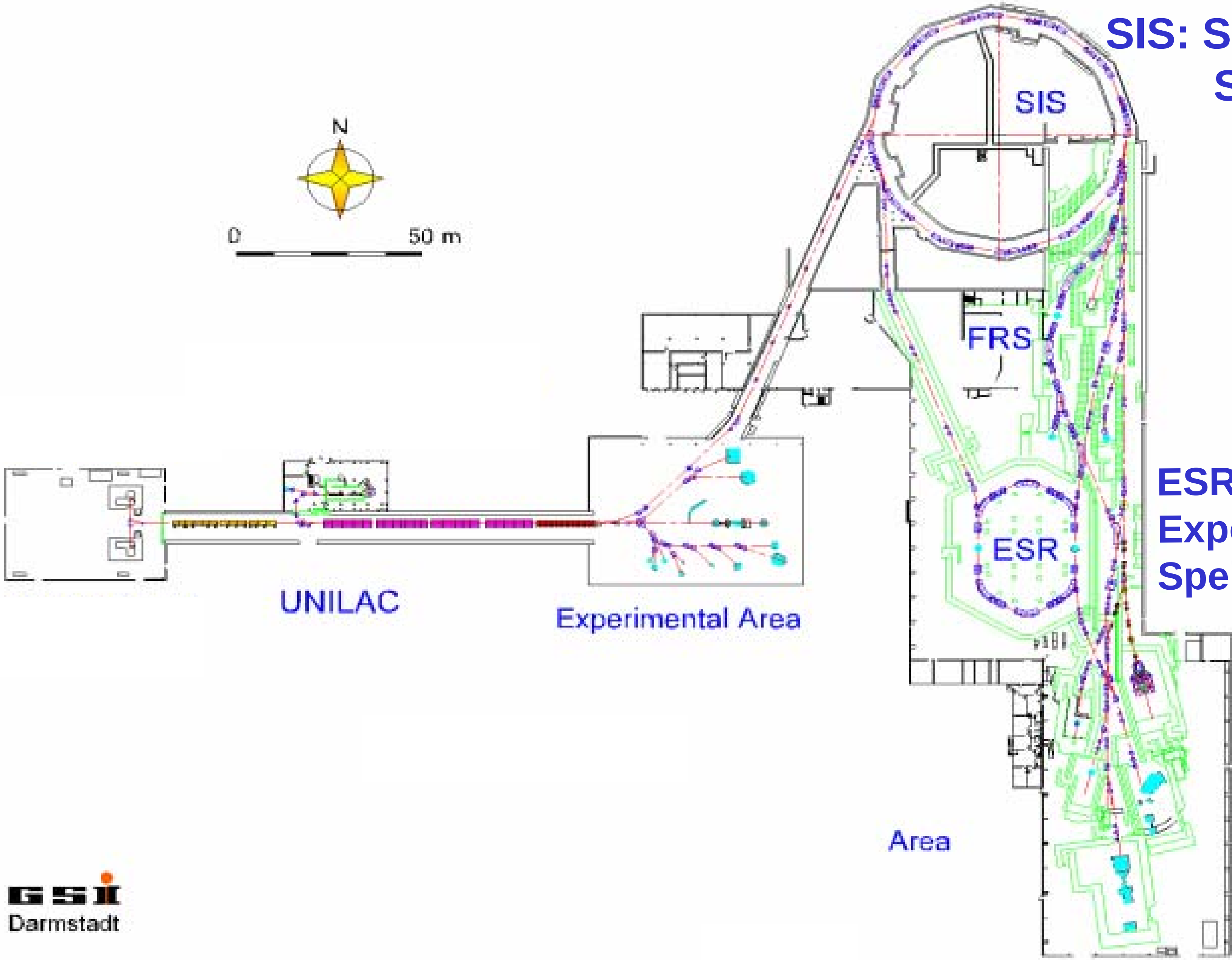
Charge State Distributions for Uranium

200 keV electron energy (ion at rest)



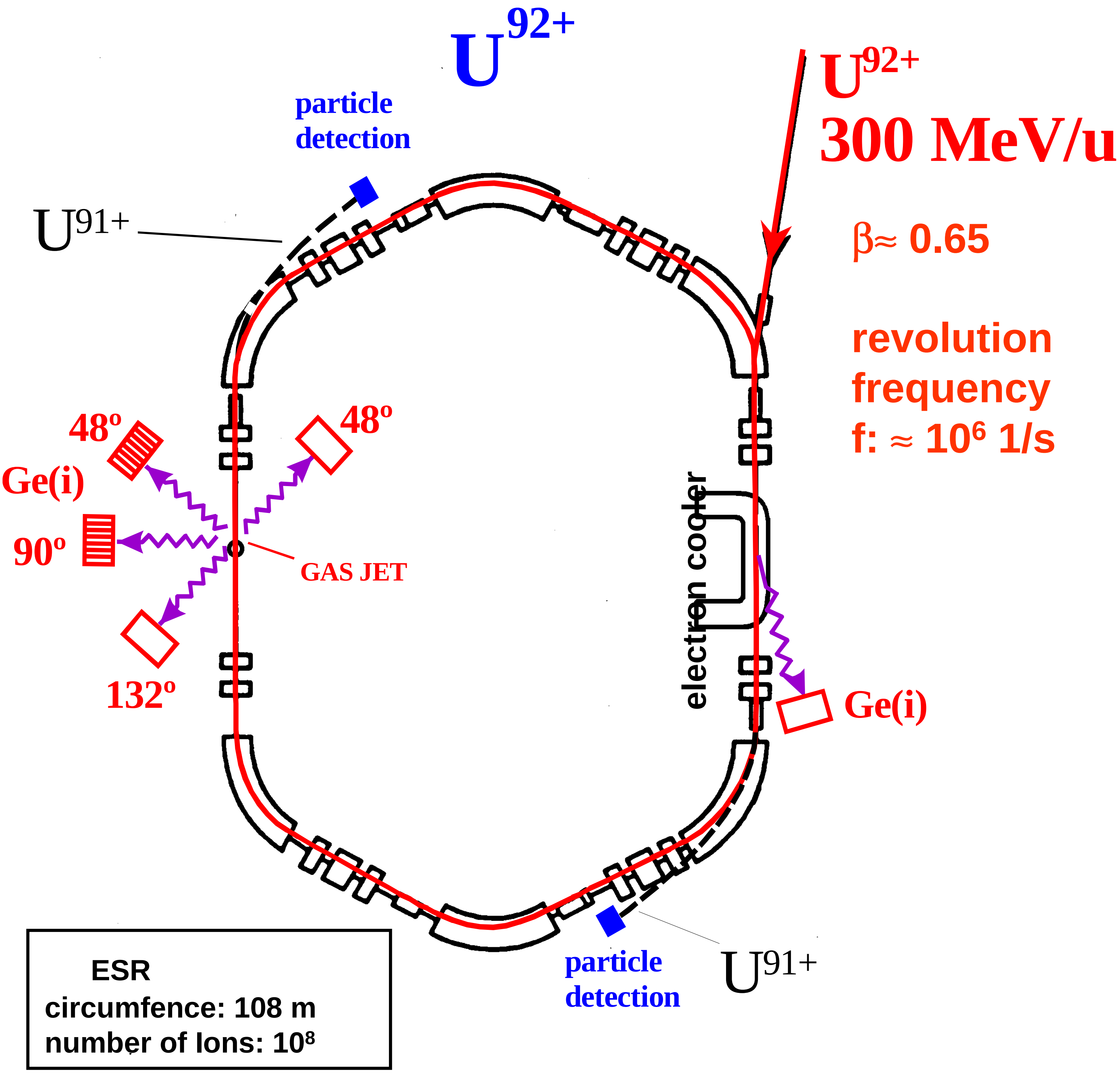
300 MeV/u (β ≈ 0.65)

SIS: Schwerionen Synchrotron

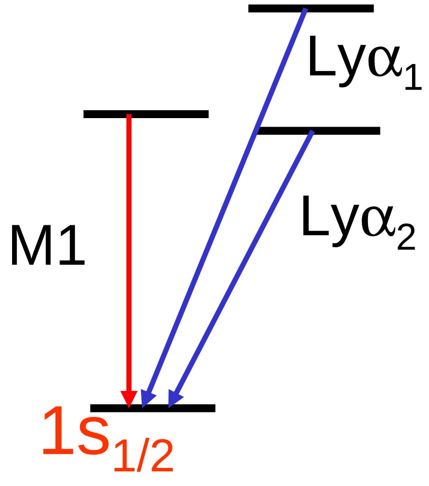


ESR: Experimentier Speicherring

Lamb-Shift Studies for High-Z Ions:
X-ray Spectroscopy at the ESR Storage Rings



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

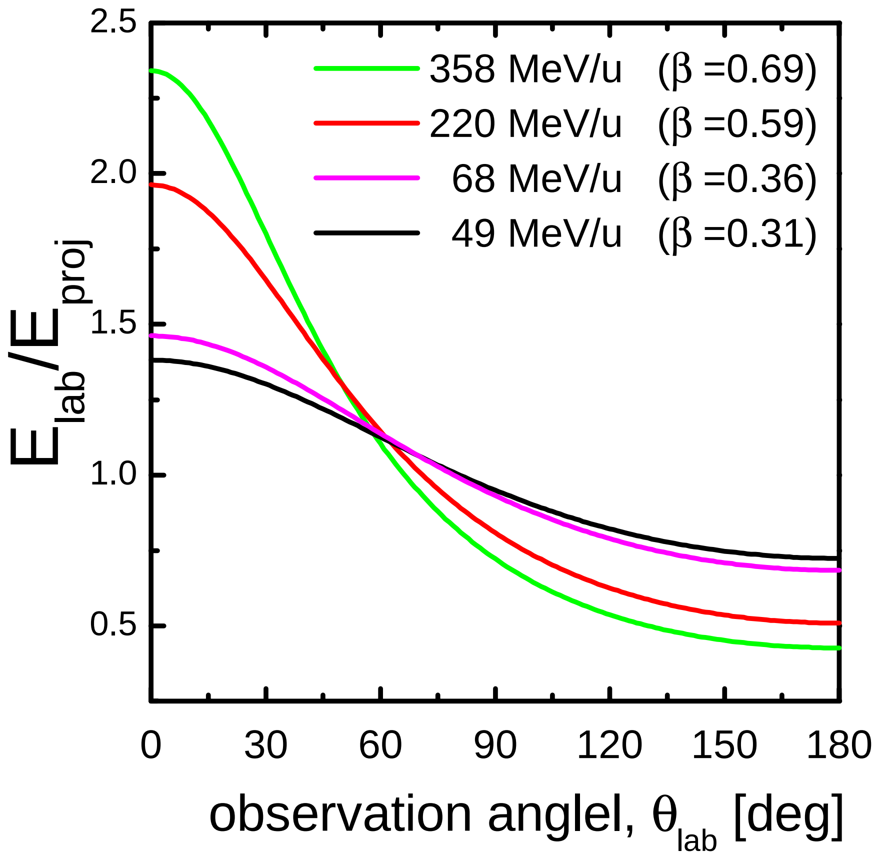


The Experimental Challenge

Relativistic Doppler-Transformation

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

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



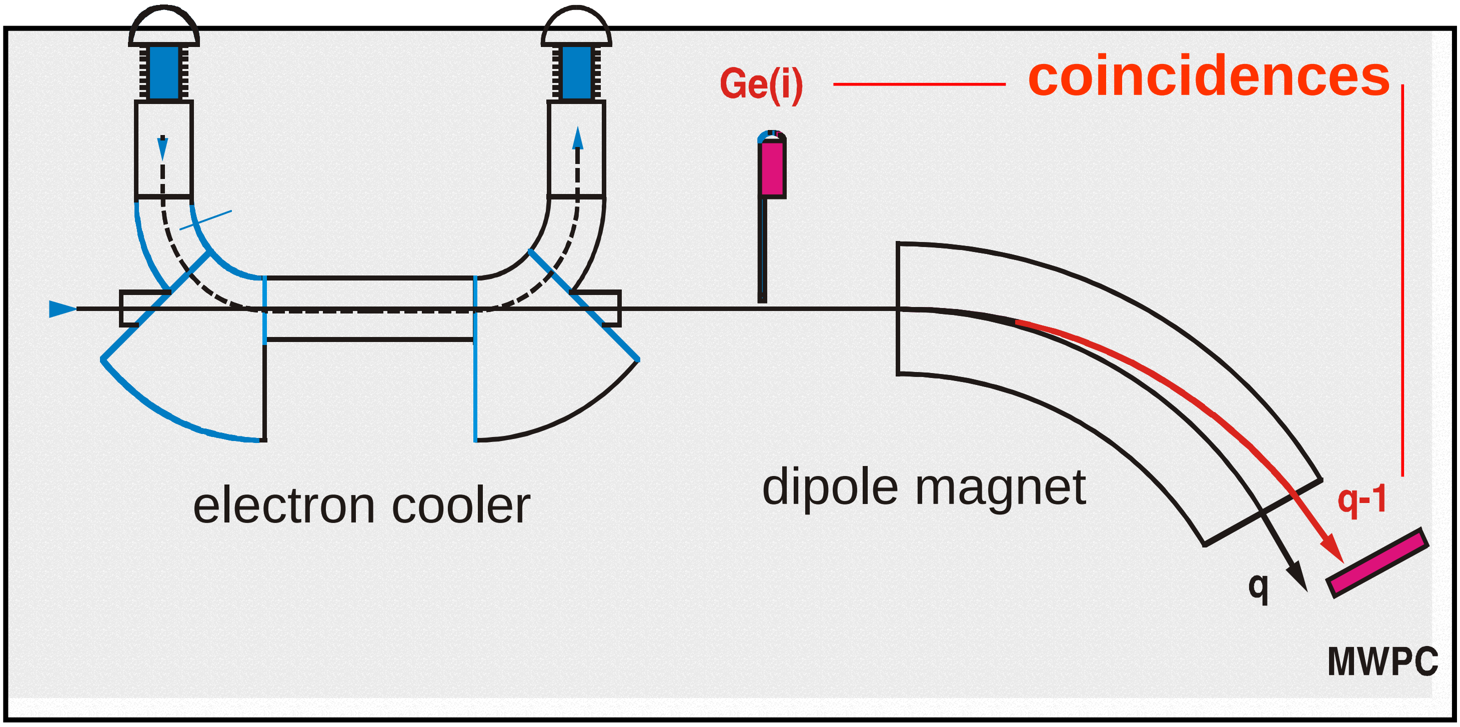
Doppler-Correction: *Strong dependence on velocity and the observation angle* θ_{LAB}

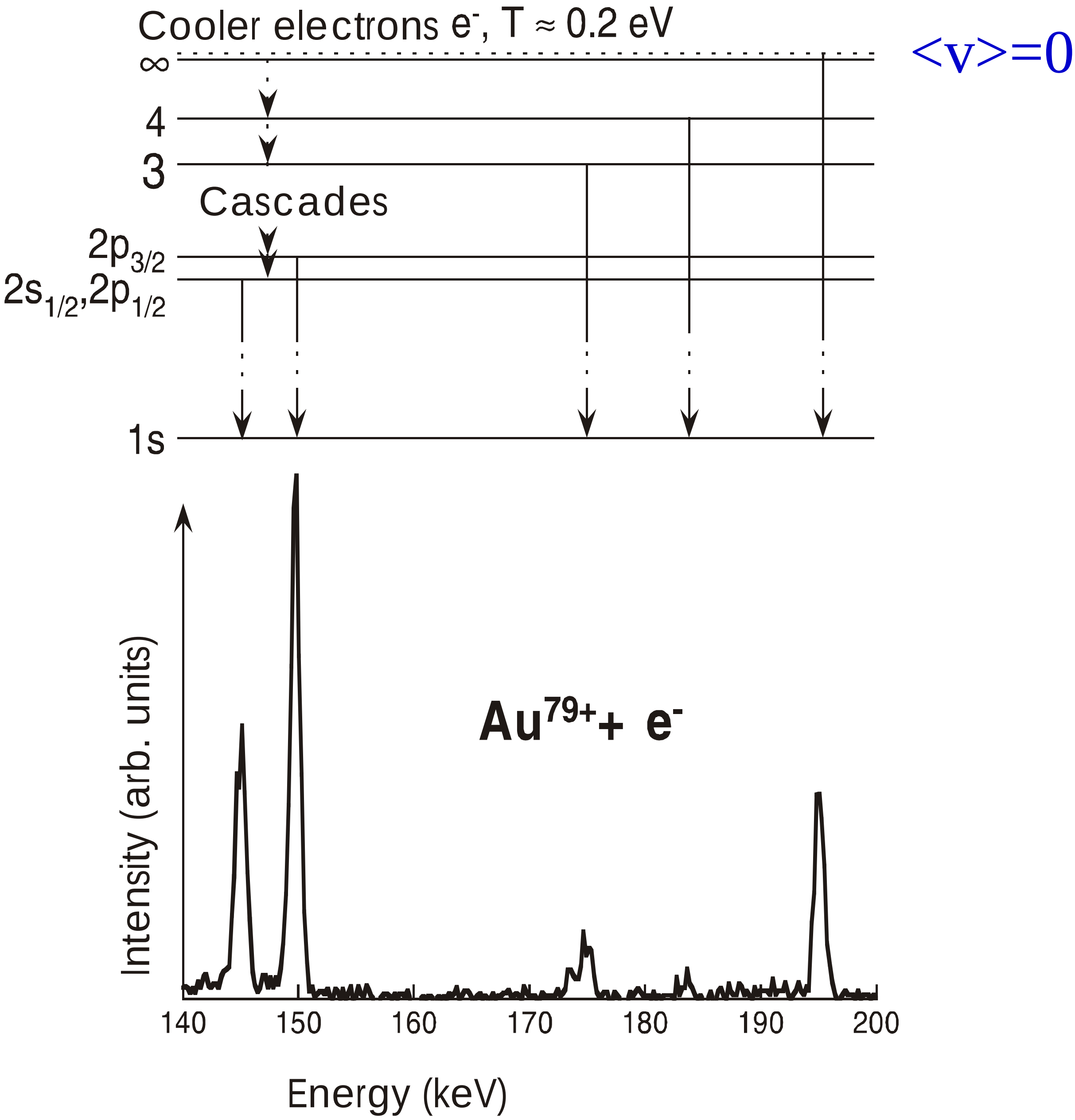
Principle of LS Experiments at ESR

1. *Production of bare ions*
2. *Stacking and 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

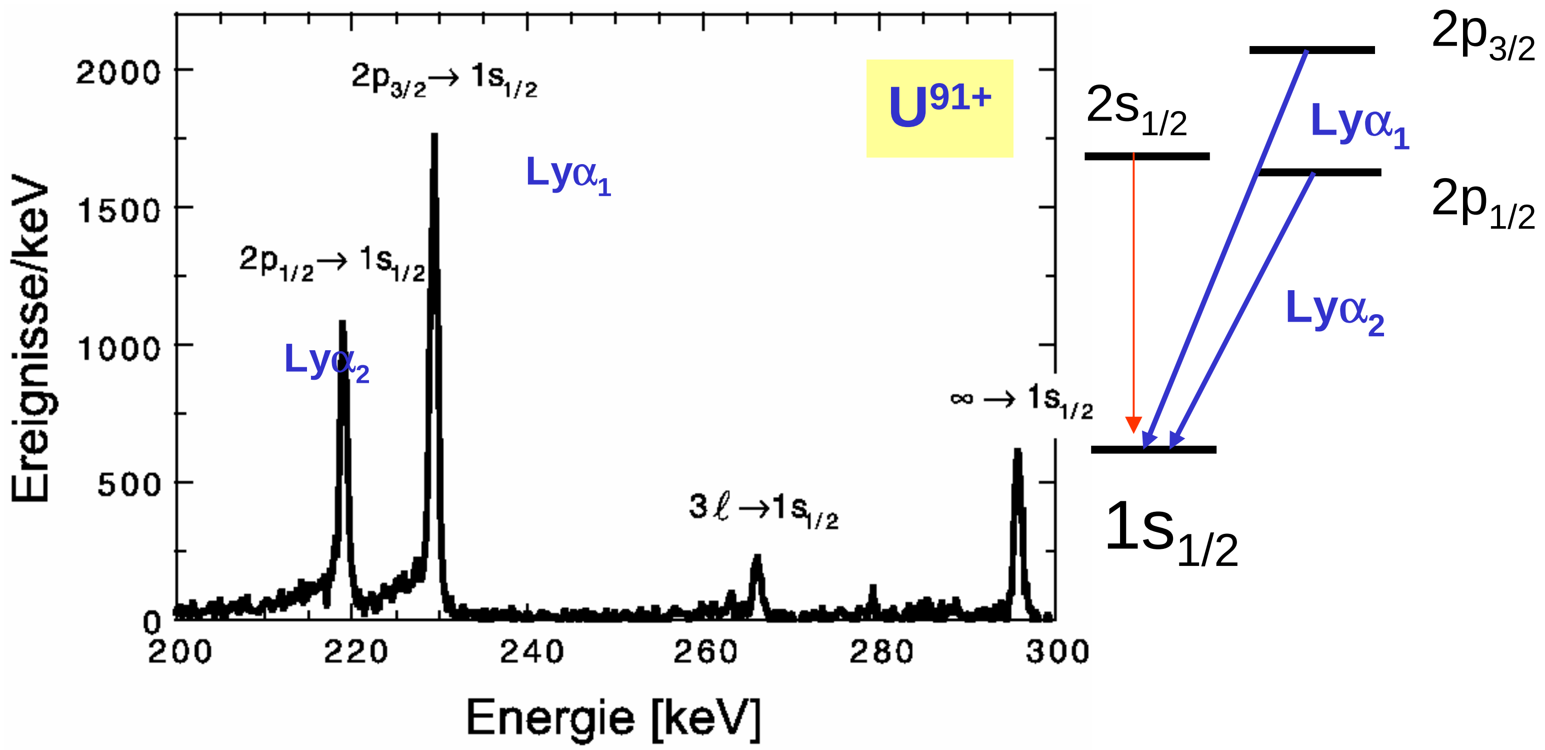
Experimental Scenario at the Electron Cooler





0° 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 $\Delta\,\beta$

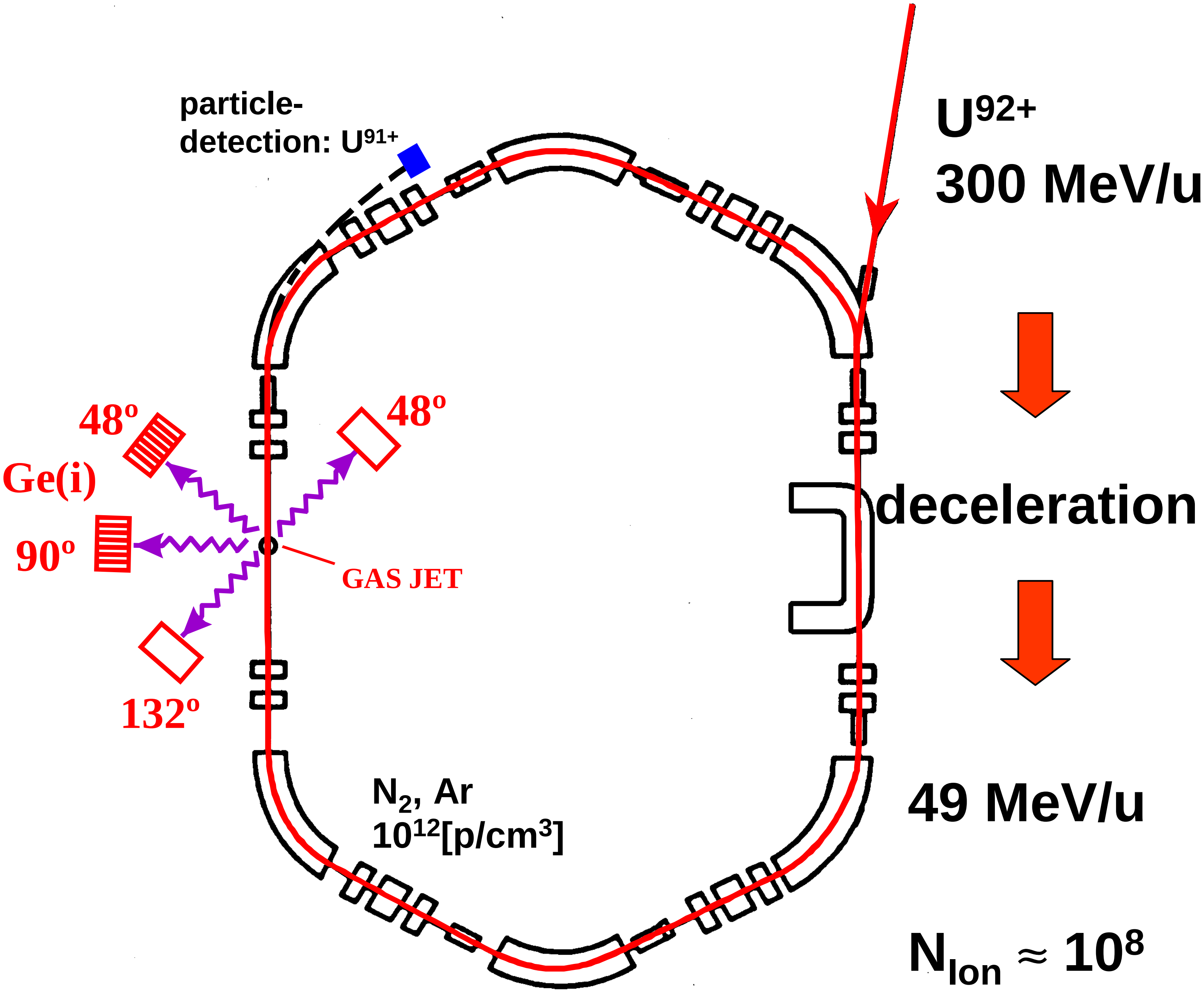


Exp.: - 131 810 ± 16 eV   Dirac: - 132 280 eV

LS: 470 eV ± 16 eV

H.F. Beyer et al., 1995

X-Ray Spectroscopy at the Jet-Target

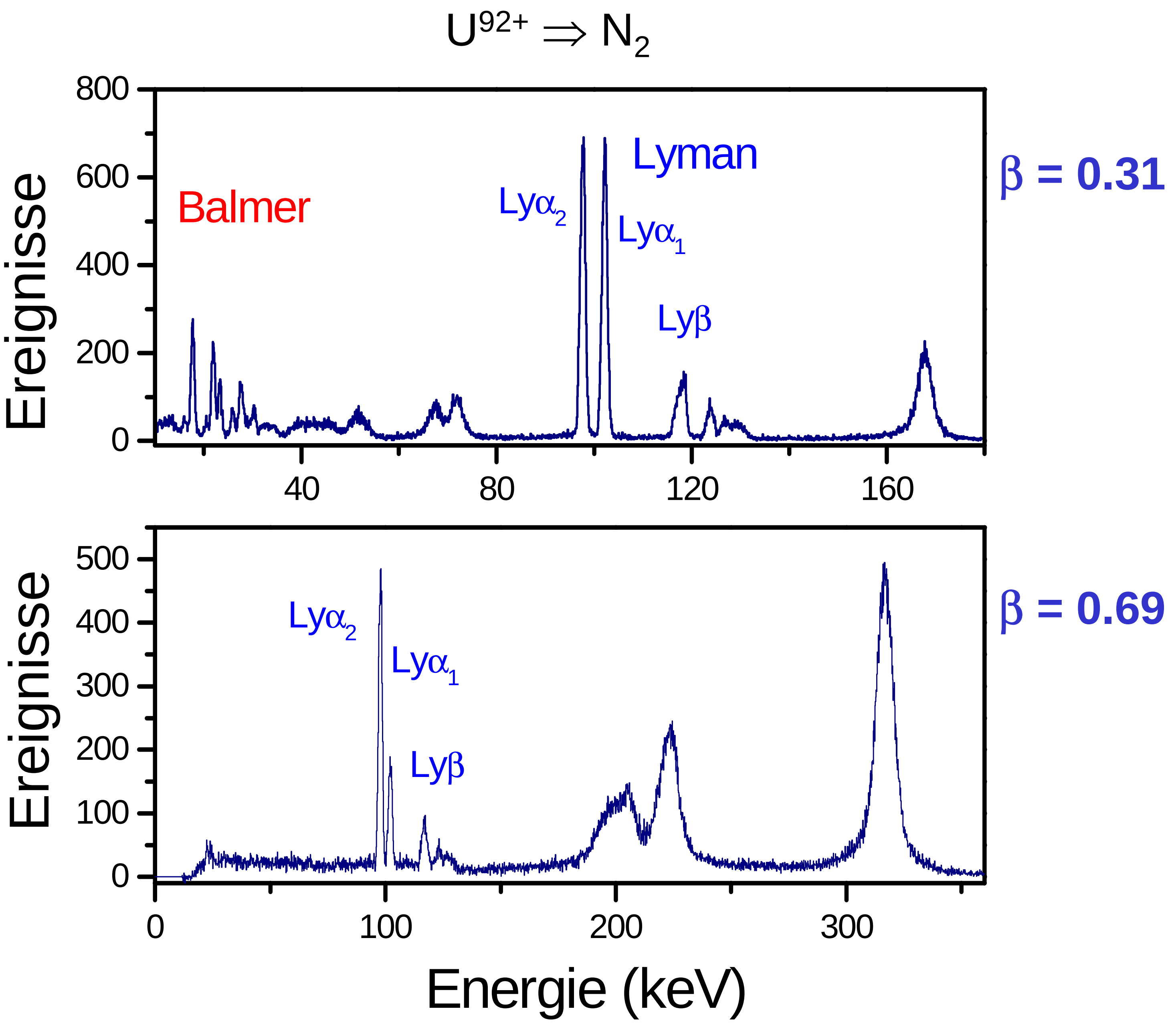


$$E_{lab} = \frac{E_{proj}}{\gamma \bullet (1 - \beta \bullet \cos\theta_{lab})}$$

E_{lab}: Photon energy in laboratory system

E_{proj}: Photon energy in emitter system

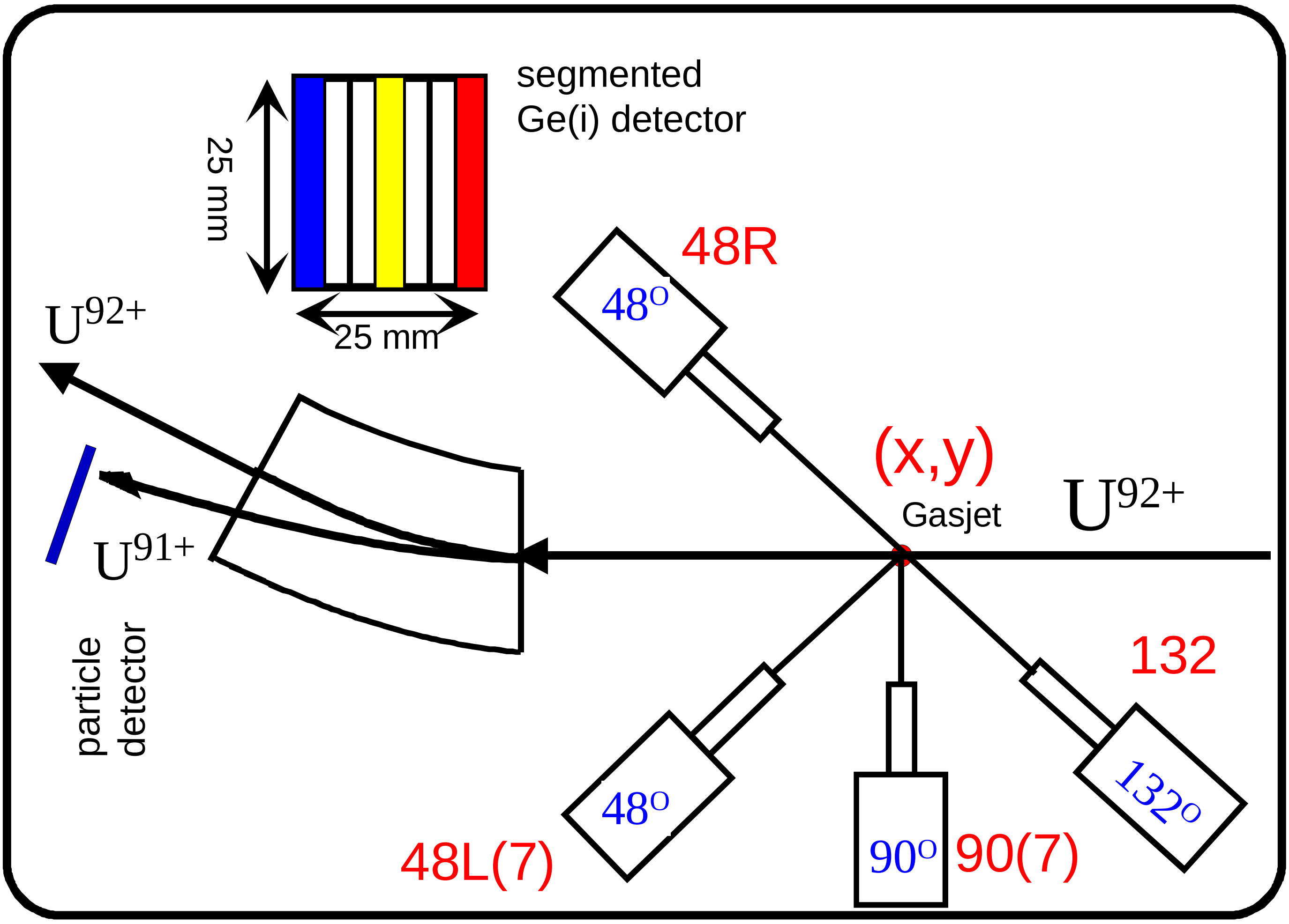
X-ray spectra of decelerated, bare uranium ions



decelerated ions:

- ***efficient production of characteristic x-rays (Lyman- and Balmer transitions)***
- ***improved energy resolution (reduced Doppler broadening).***

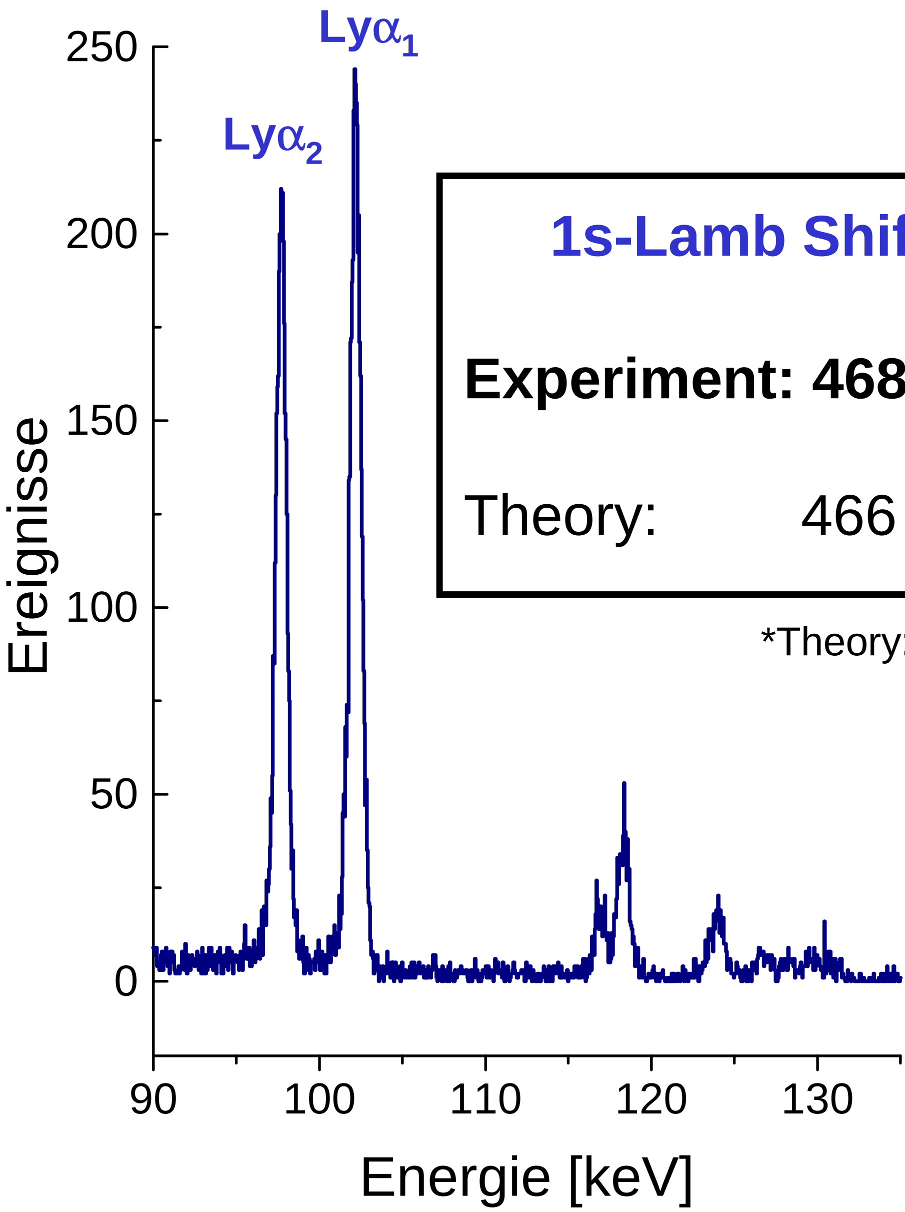
LS-Experiment at the Jet-Target



- ***Decelerated ions***
- ***Precise measurement of the relative detector geometry***
- ***Simultaneous observation at various angles***
- ***Forward/Backward symmetry***
- ***Left/Right symmetry***

Experiments at the Jet-Target

Geometry	$\Delta\beta$	Fit	Lyα_1 ($2p_{3/2} \rightarrow 1s_{1/2}$)
±8.5 eV	±2.6 eV	± 9.7 eV	102 171 ± 13.2 eV



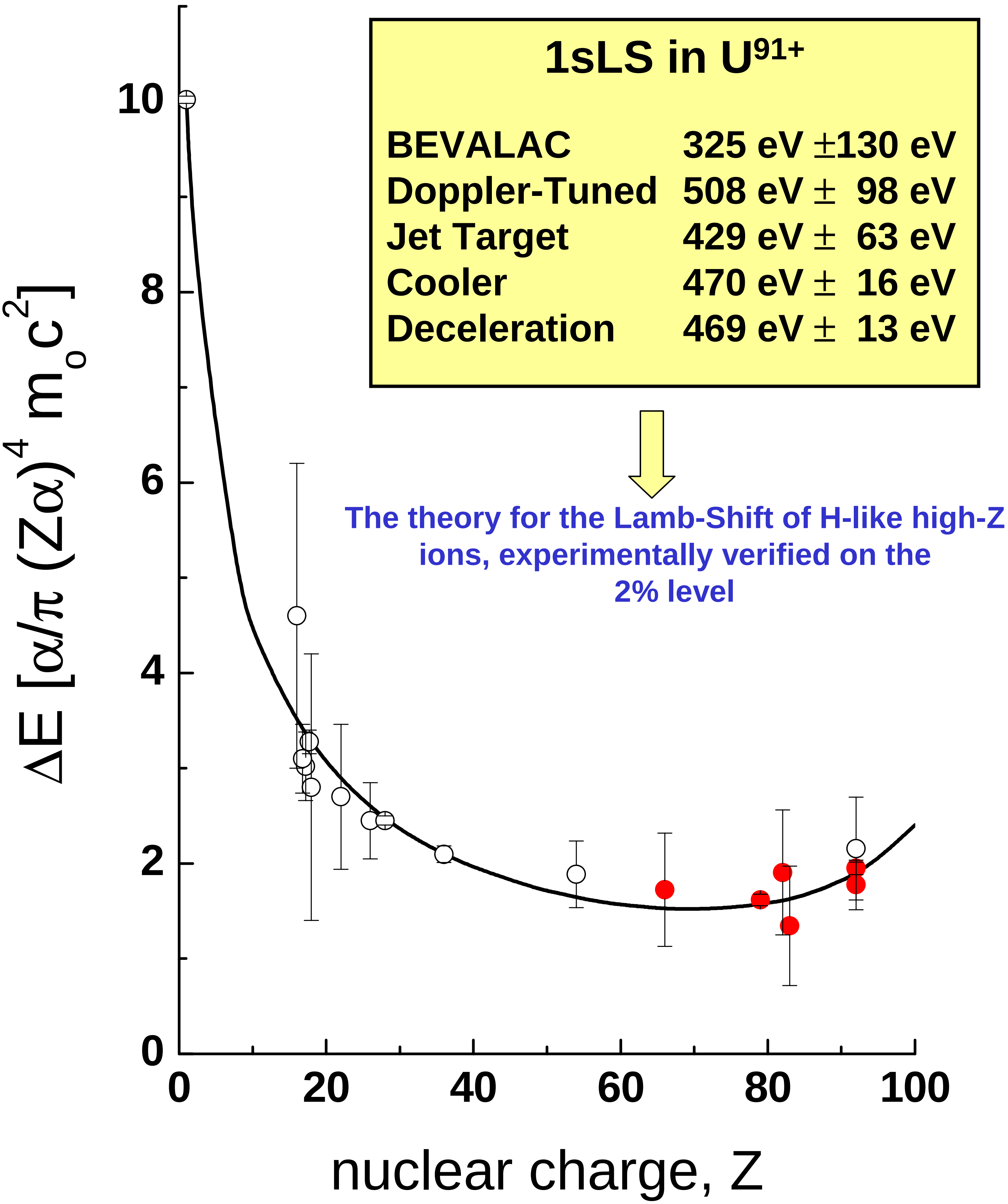
1s-Lamb Shift

Experiment: 468 eV ± 13 eV

Theory: 466 eV*

*Theory: T. Beier et al., 1998

Goal of future experiments



Additional improvement by one-order of magnitude (1 eV level) !!!

Towards an Accuracy of 1 eV

Detector and Spectrometer Development

High Resolution X-Ray Spectrometer (50 eV to 100 eV resolution at 100 keV)

	Resolution	*Accuracy*
Cristal spectrometer	≤ 50 eV	1 - 10 eV
Bolometer	≤ 50 eV	1 - 10 eV
Absorption edge spectroscopy (Doppler tuned)		1 - 10 eV
and position sensitive x-ray detectors (200 μm)		

Slow ions or ions at rest

Deceleration of the ions in the ring ⇒ small Doppler correction
(energies between 50 MeV/u and 3 MeV/u)

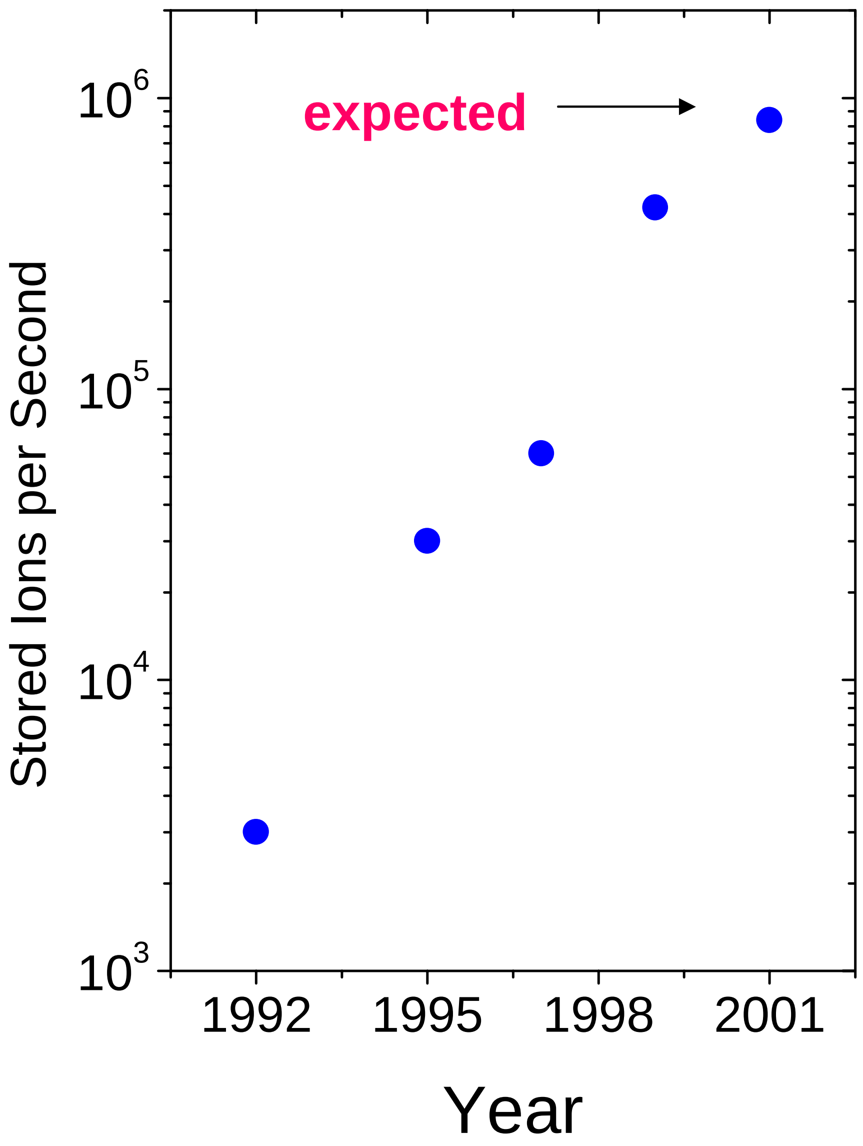
The Status of the Deceleration Technique at the ESR

1995: Deceleration down to 50 MeV/u routinely available

1999: First experiment with bare high-Z ions (Pb^{82+}) at 25 MeV/u

2000: Deceleration of U^{92+} down to 9 MeV/u (M. Steck et al.)

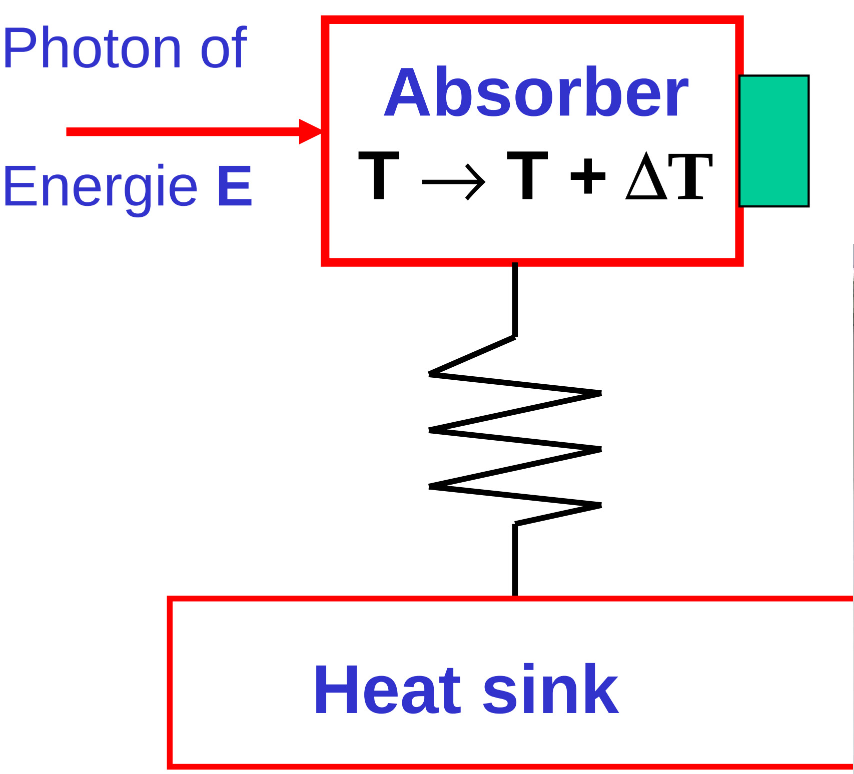
Intensity Increase at the ESR



Increase by more than two-orders of magnitude

Development of a Bolometer System for the High Energy Regime

Detection of Photons instead of Electrons



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Specific heat capacity : c

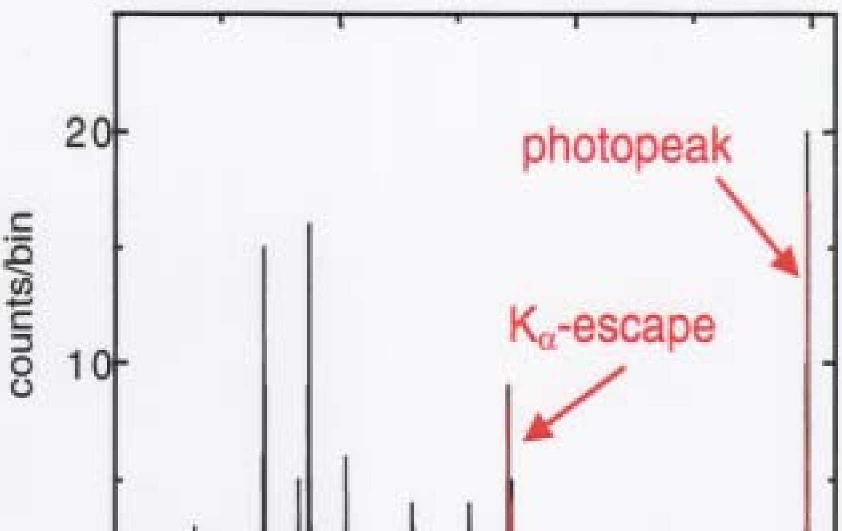
Detector mass: m

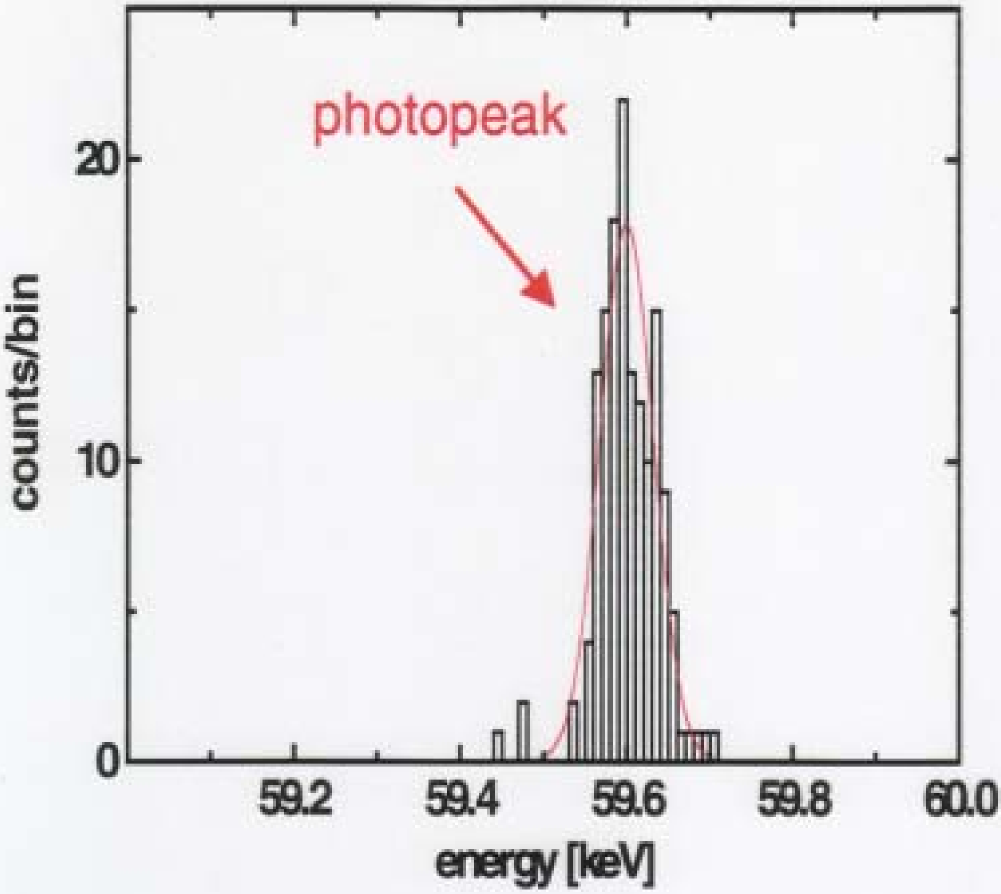
P. Egelhof et al., 1999

Detector operates at temperatures of 50 mK

energy spectrum for an ^{241}Am-source:

detector: Sn-absorber ($V = 0.3\ mm^2 \times 66\ \mu m$)





energy resolution for $E\gamma = 59.6$ keV:

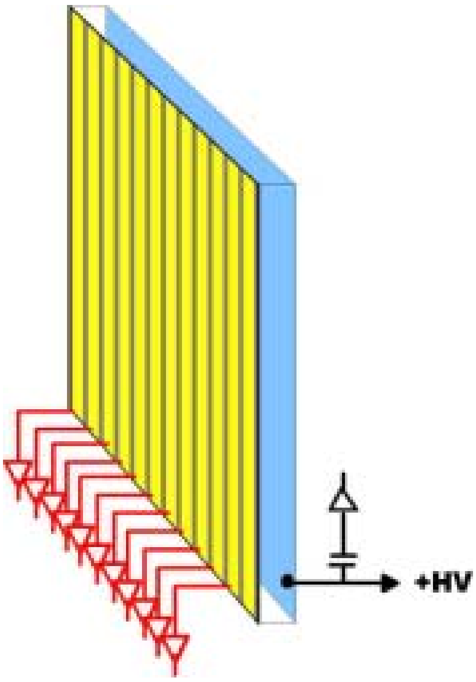
$\Delta E = 75$ eV

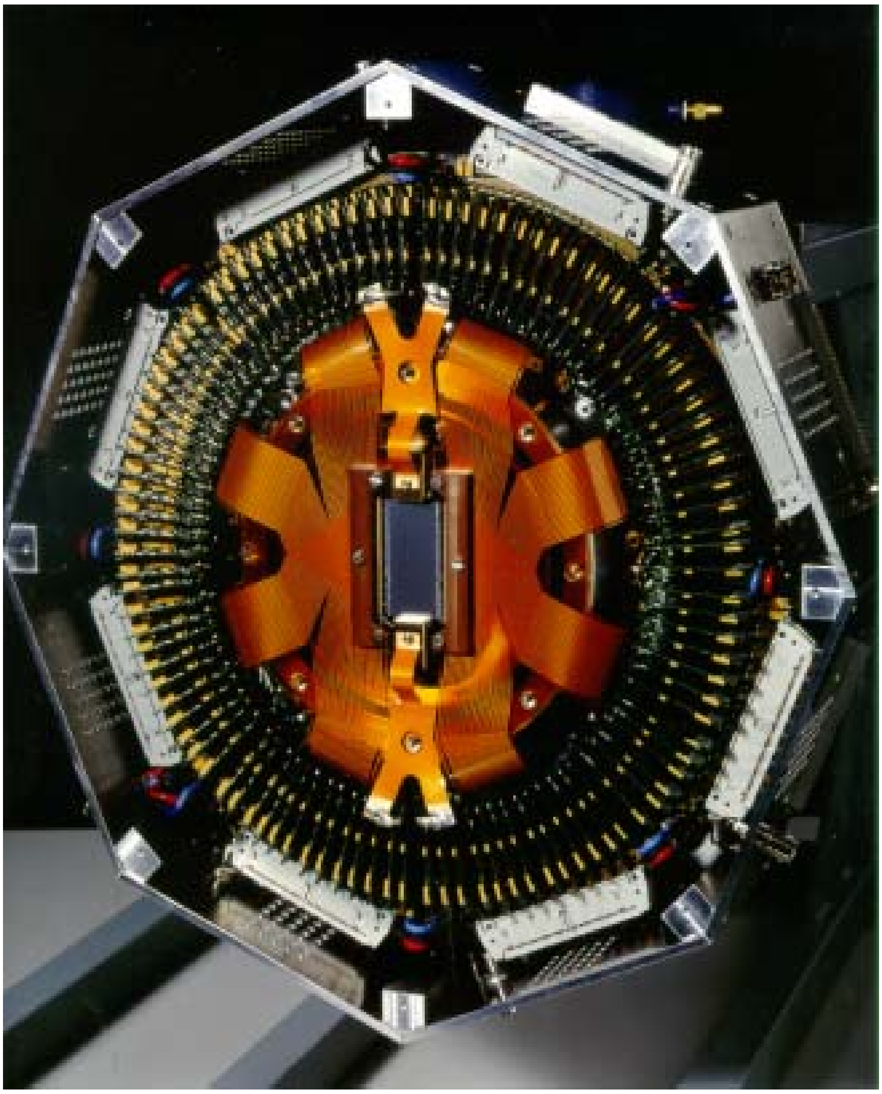
(theoretical limit for conventional Si-semiconductor detector: $\Delta E \geq 350$ eV)

Position Sensitive Ge(i) Detectors

Micro-Strip Germanium Detector Development:

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





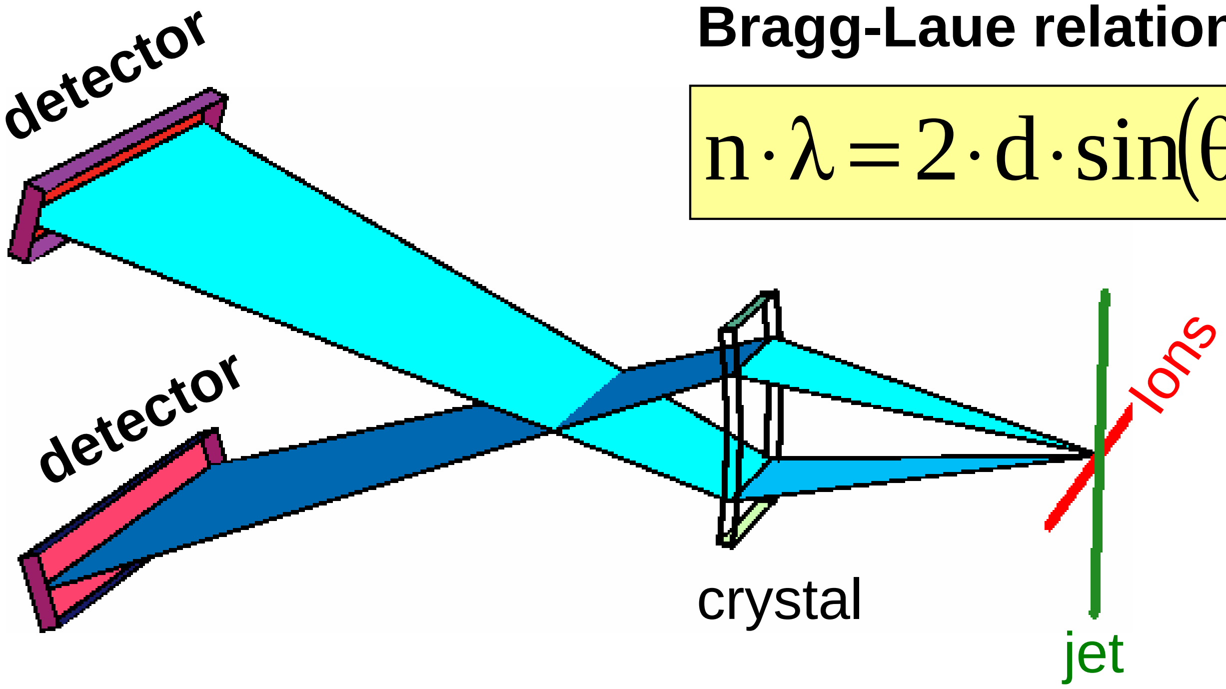
- **crystal spectrometer**
- **doppler tuned**
- **polarization studies**

D. Protic et al., IEEE in print (2001)

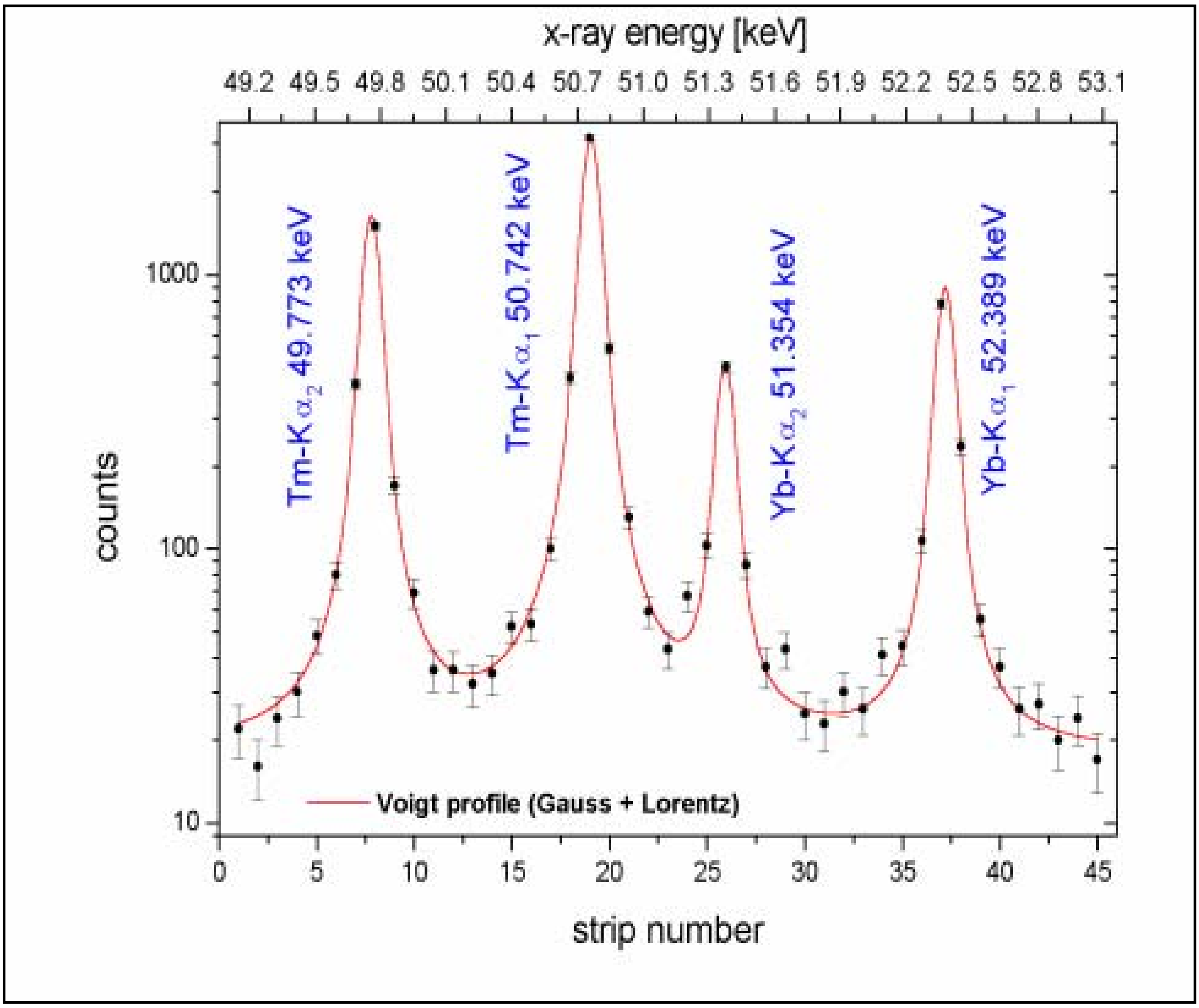
Transmission crystal spectrometer

Bragg-Laue relation

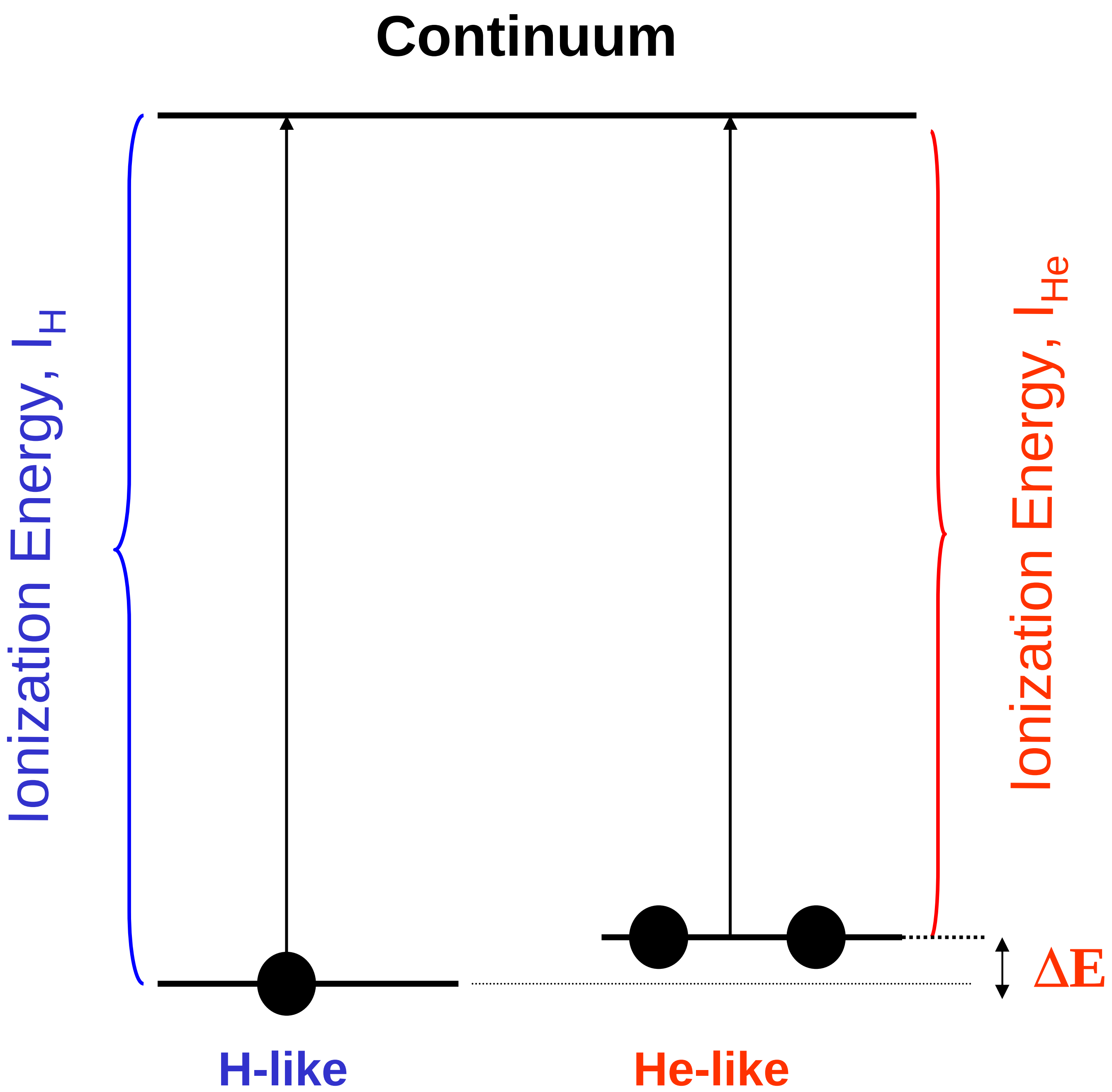
$$n \cdot \lambda = 2 \cdot d \cdot \sin(\theta)$$



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



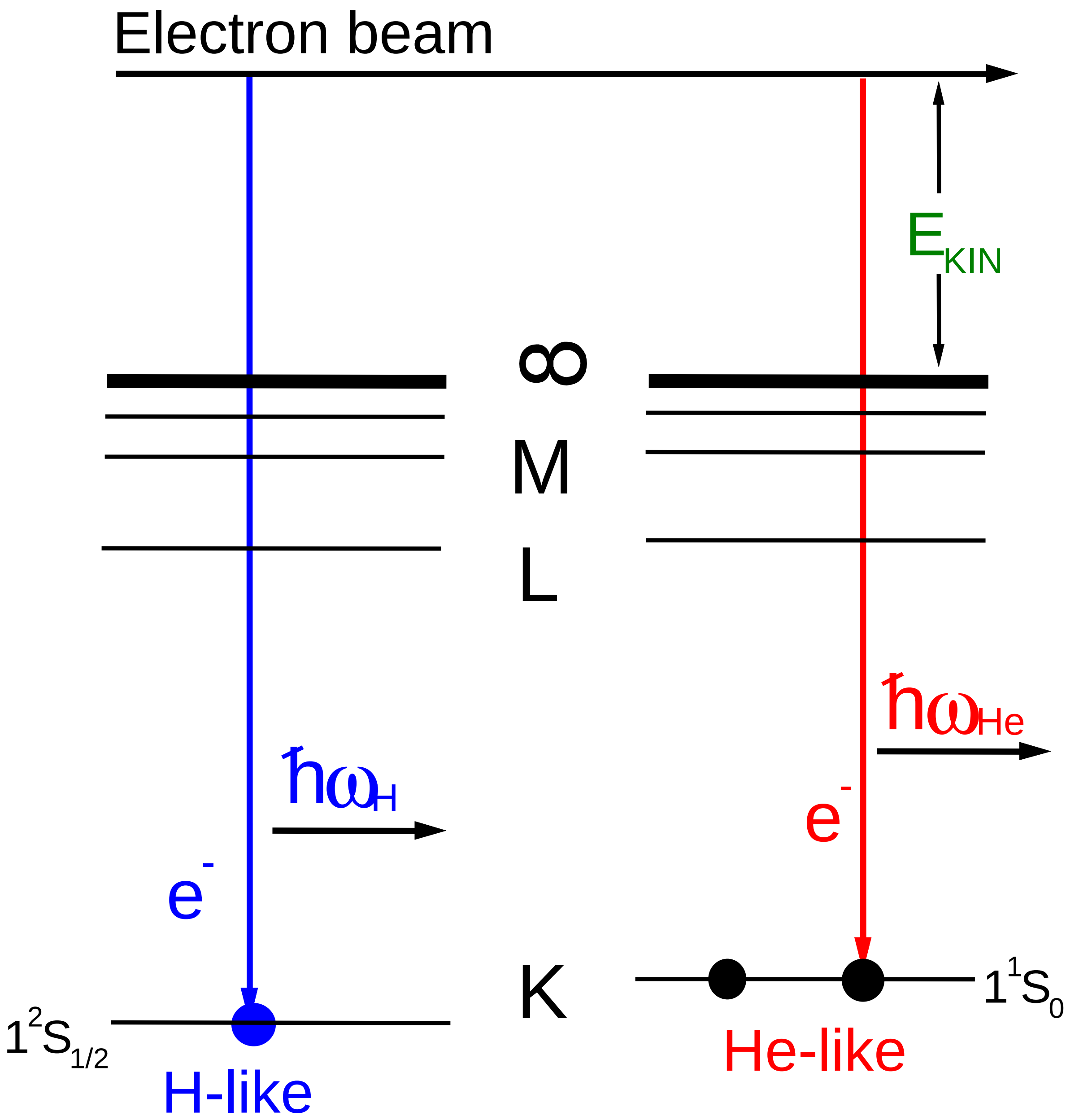
Electron-Electron Interaction in Strong Fields



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

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

The Method



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

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

Advantage of relative measurement:

All one electron contributions cancel out

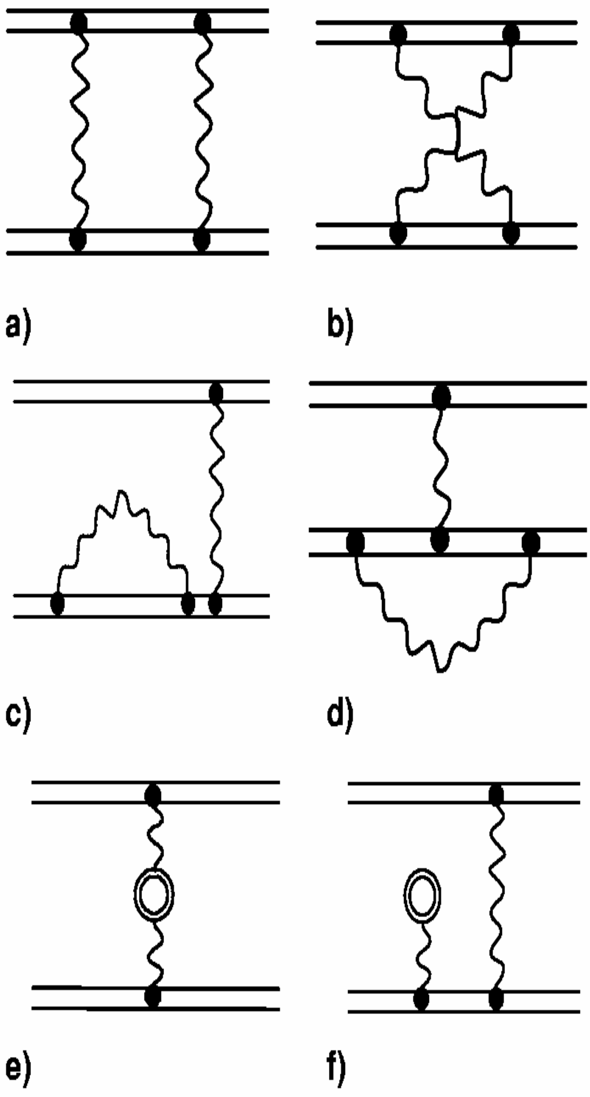
Electron-Electron Interaction in Strong Fields

Measurement of the 2eQED for Uranium at

Accuracy:
2 eV; ΔE/E ≈ 0.1%

Z=92

Two-Electron Contribution: 2246.0 eV

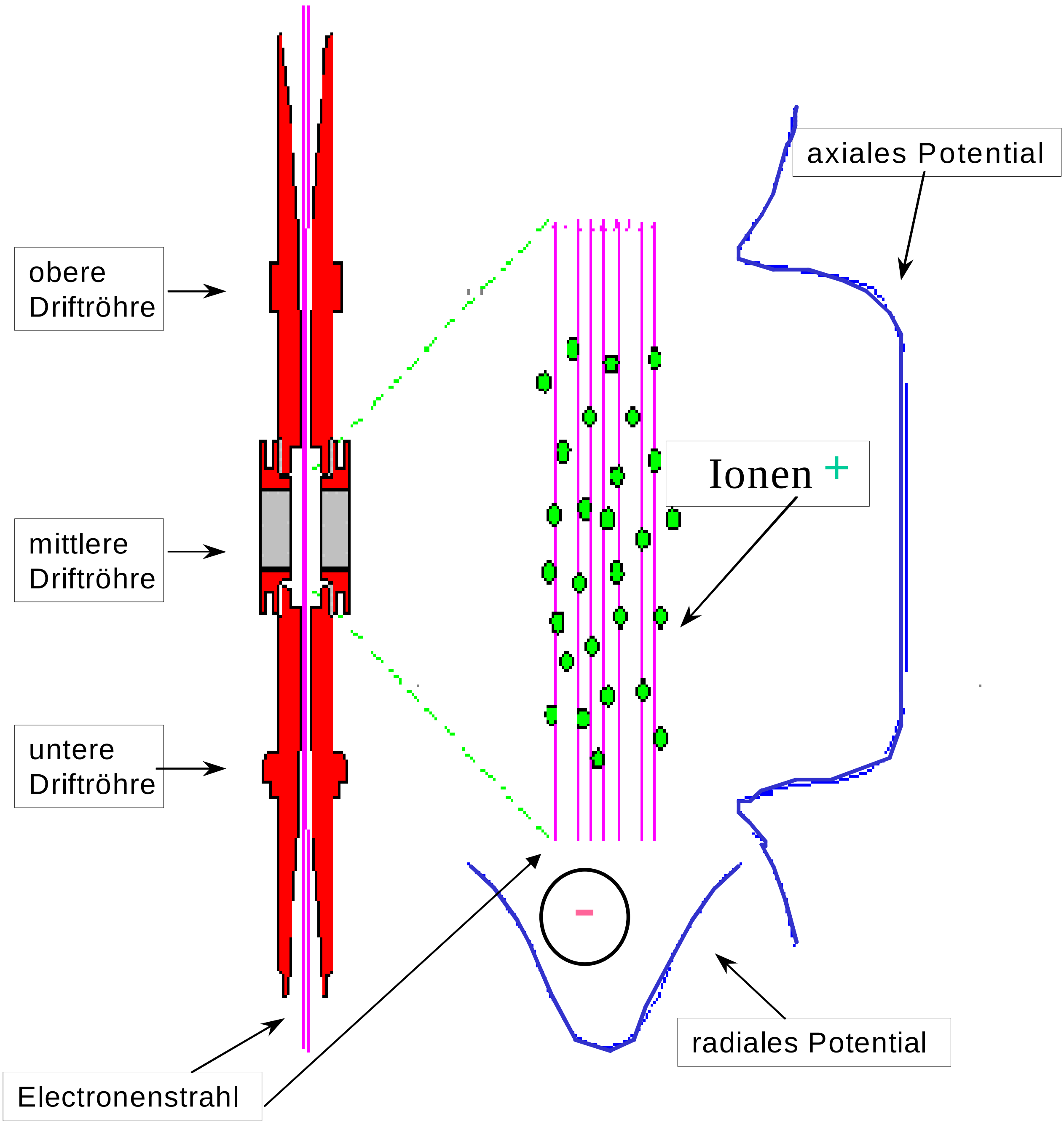


a,b) Non-Radiative QED
+1.3 eV [U^{90+}]
0.06%

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

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

Super-EBIT (Electron Beam Ion Trap)

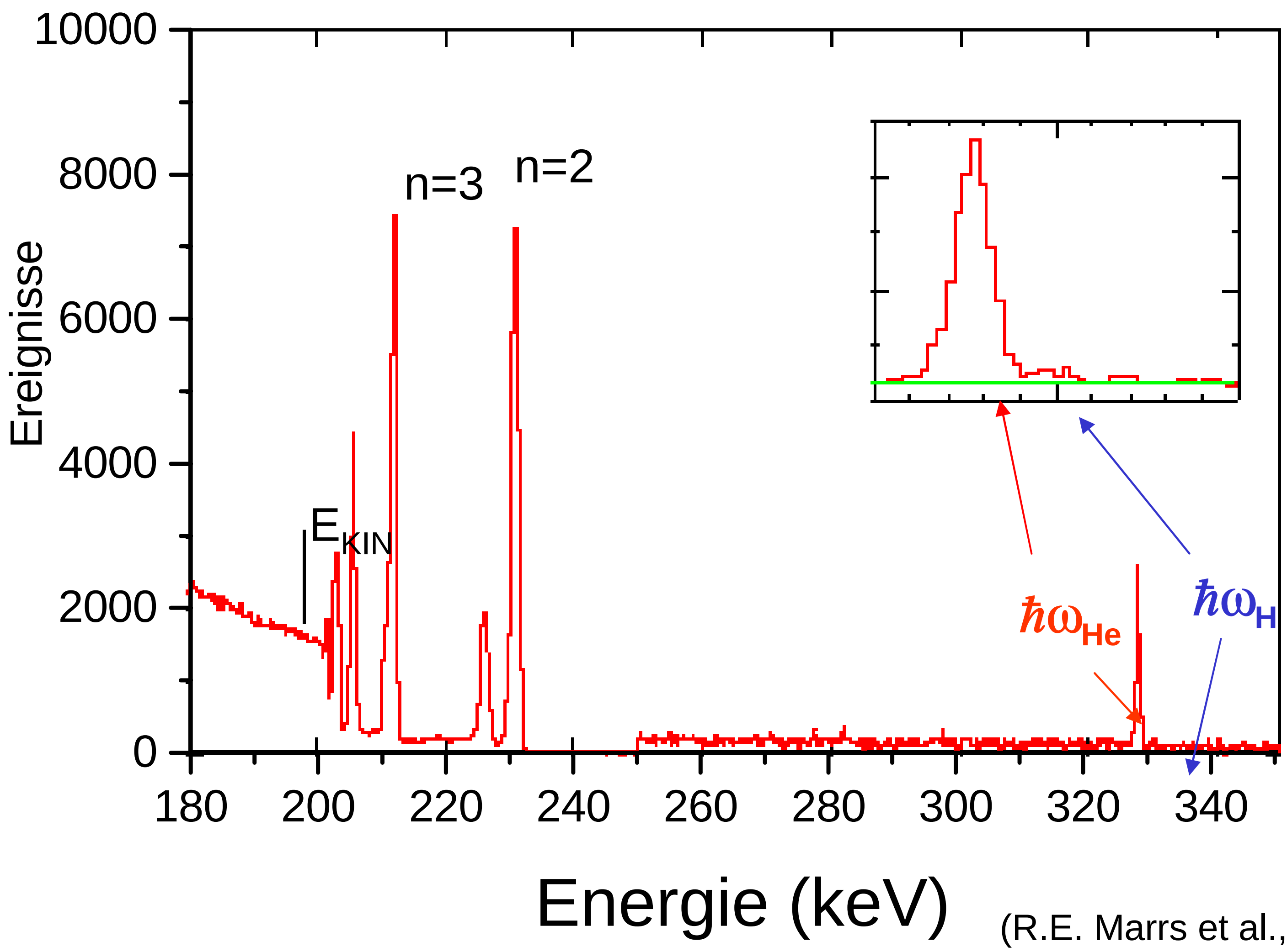


(S.R. Elliott: Nucl. Instr. and Meth, B98, 114 (1995))

EBIT- Parameter

• **Elektronenstrahlenergie:**	**10 –210 keV**
• **Max. Elektronenstrom:**	**200 mA**
• **Strahlradius:**	**50µm**
• **Stromdichte:**	**5000 A/cm^2**
• **Magnetfeld:**	**3 T**

Erzeugung stationärer, nackter Uranionen



(R.E. Marrs et al., 1994)

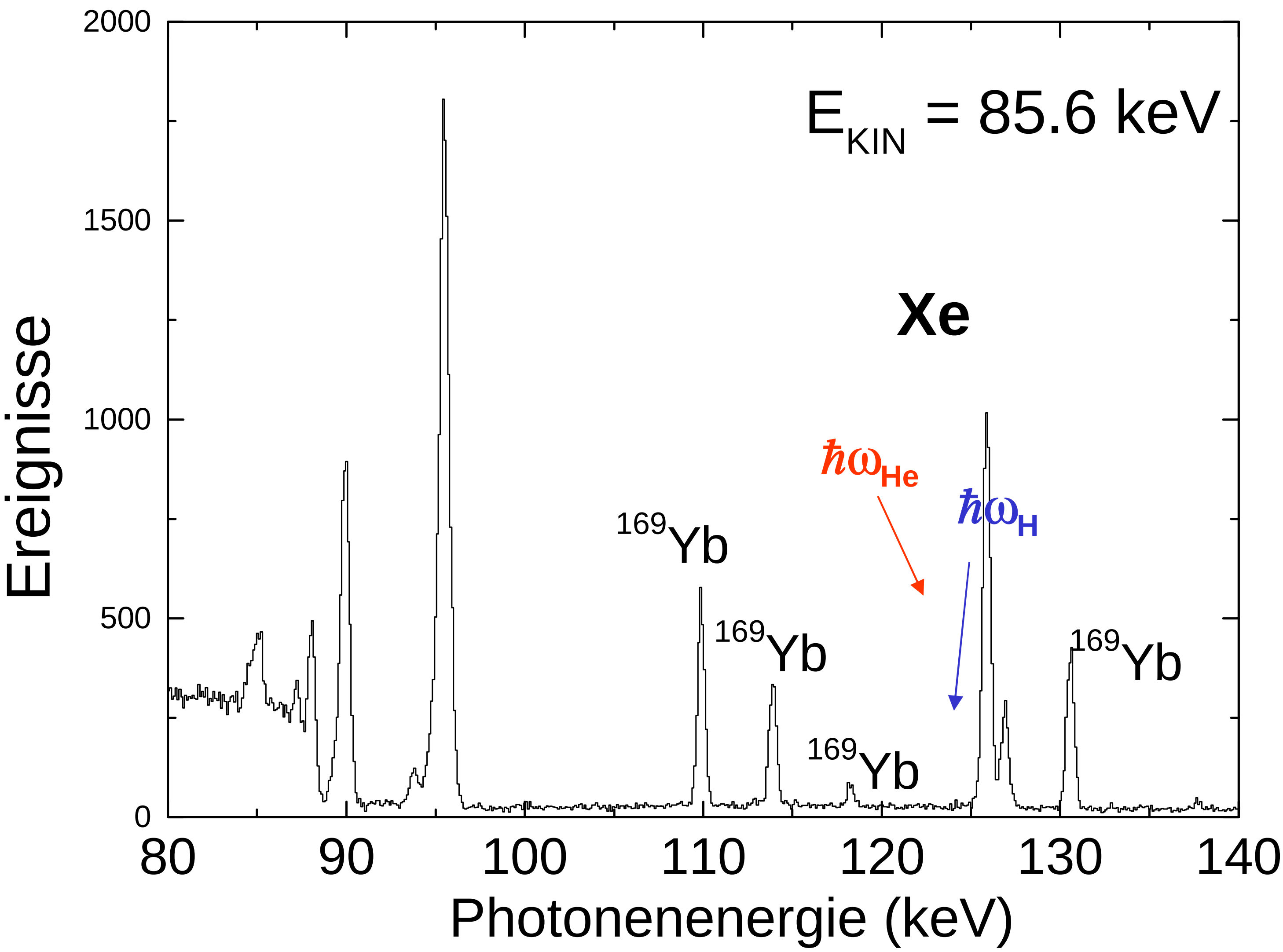
EBIT Einstellung:	
Spannung	**198 kV**
Strom	**200 mA**

$\hbar\omega_{He}$: Einfang in den Grundzustand H-artiger Ionen

$\hbar\omega_{H}$: Einfang in den Grundzustand nackter Ionen

Vorteil der Super-EBIT für die Spektroskopie: Stationäre Ionen, d.h. keine Dopplerkorrekturen.

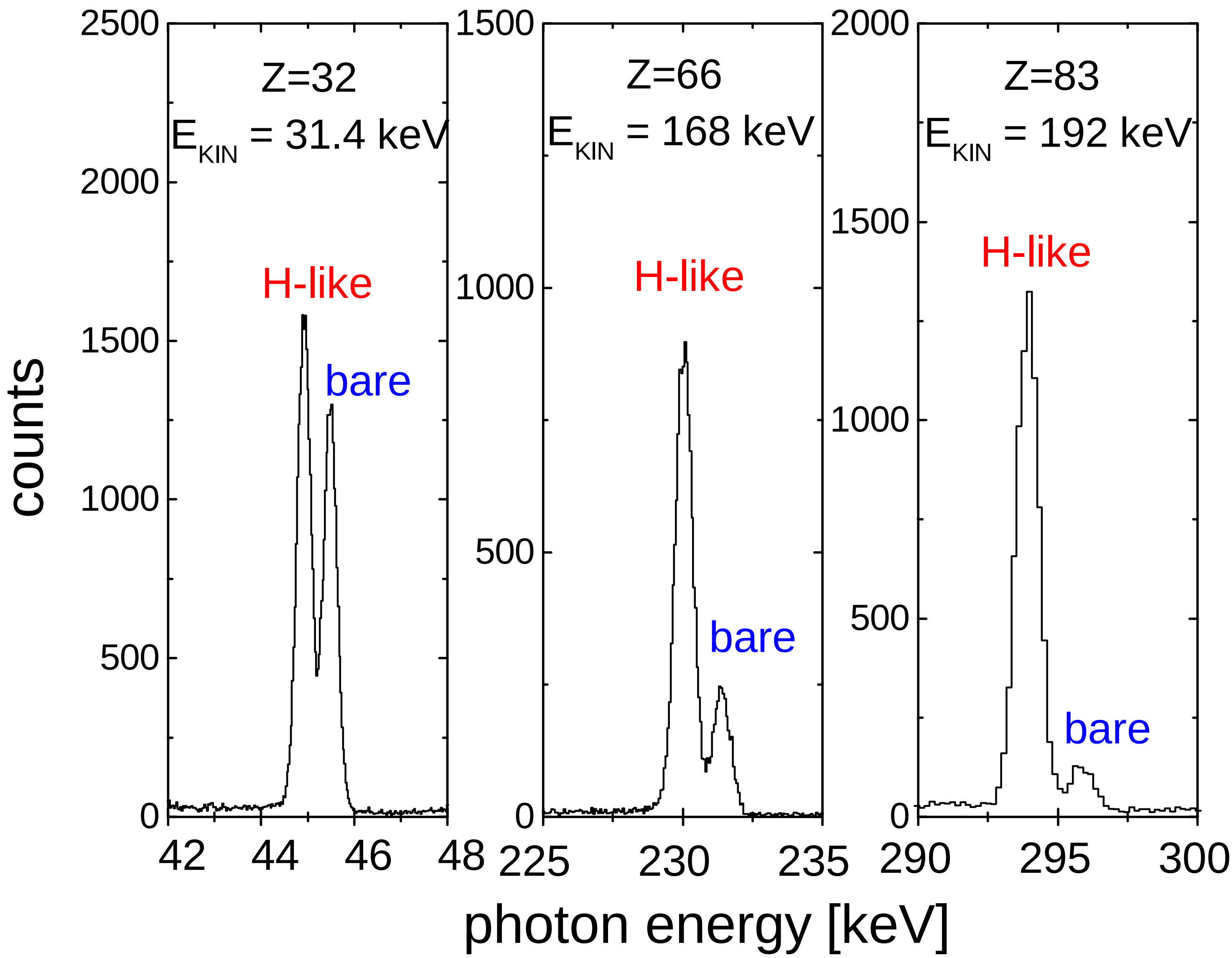
Typical X-ray spectrum



Insgesamt wurde die Messung an sechs verschiedenen Elementen durchgeführt:

Ge(Z=32), Xe(Z=54), Dy(Z=66), W(Z=74), Os (Z=76), Bi(Z=83)

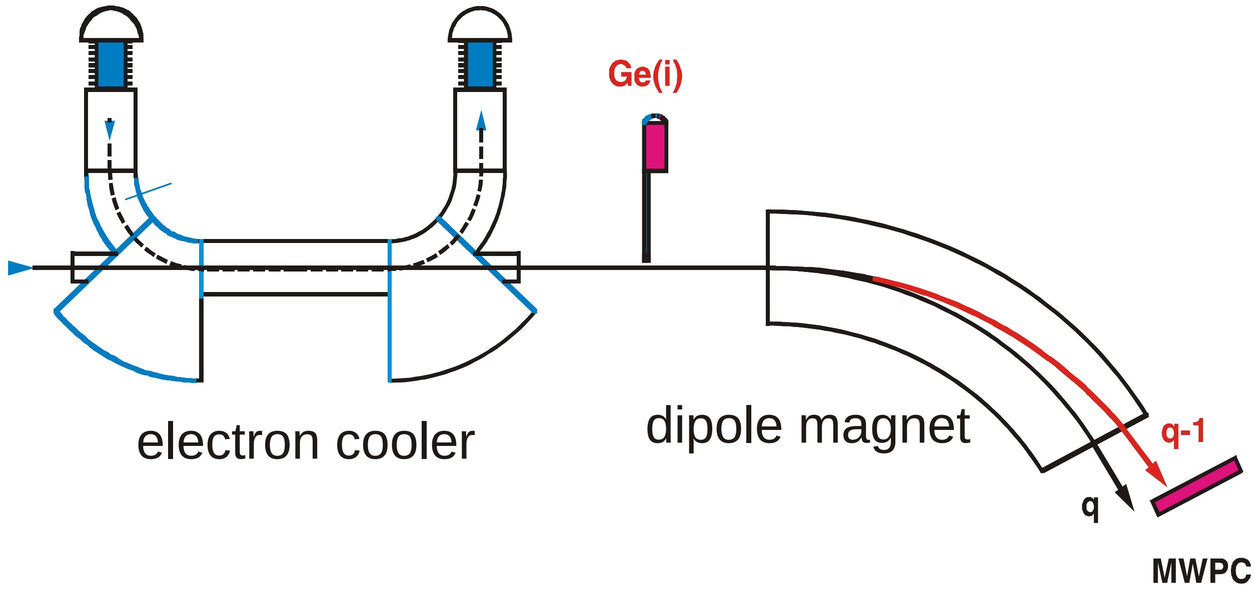
Results from Super-EBIT

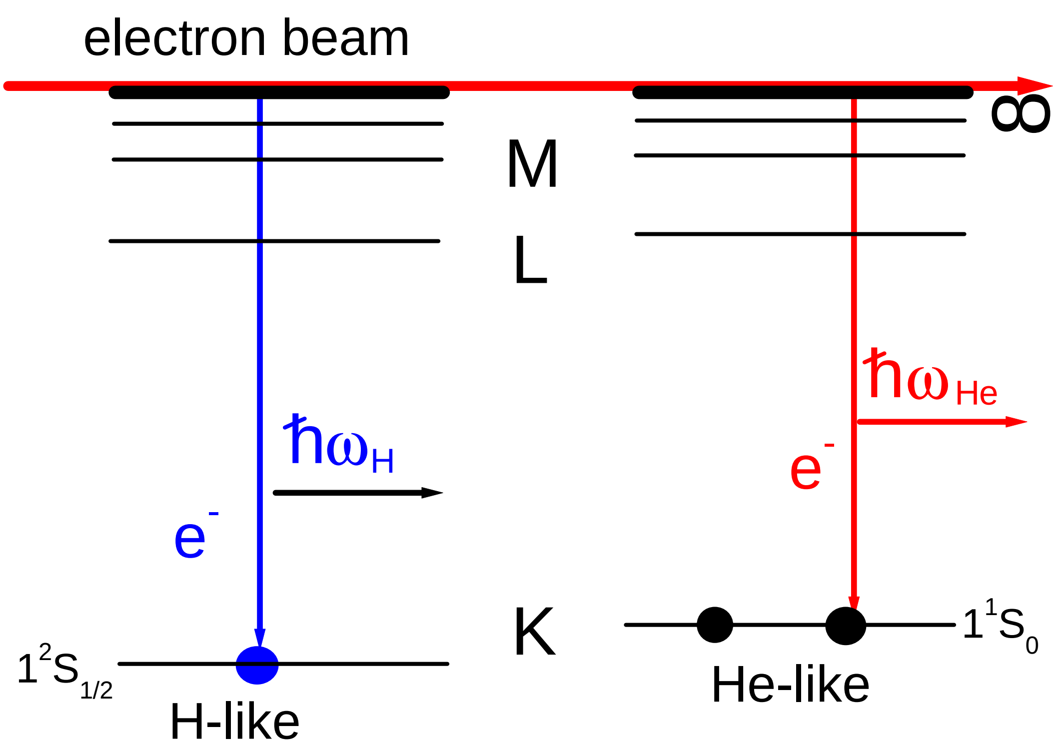


Z	32	54	66	74	76	83
Exp. [eV]	562.6 ±1.6	1027.2 ±3.5	1341.6 ±4.3	1568.9 ±15	1608 ±20	1876 ±14
ΔE/E	2.8 x 10^{-3}	3.4 x 10^{-3}	3.0 x 10^{-3}	1 x 10^{-2}	1.2 x 10^{-2}	0.7 x 10^{-3}

Results are only limited by counting statistics

2eQED Studies for the Ground State

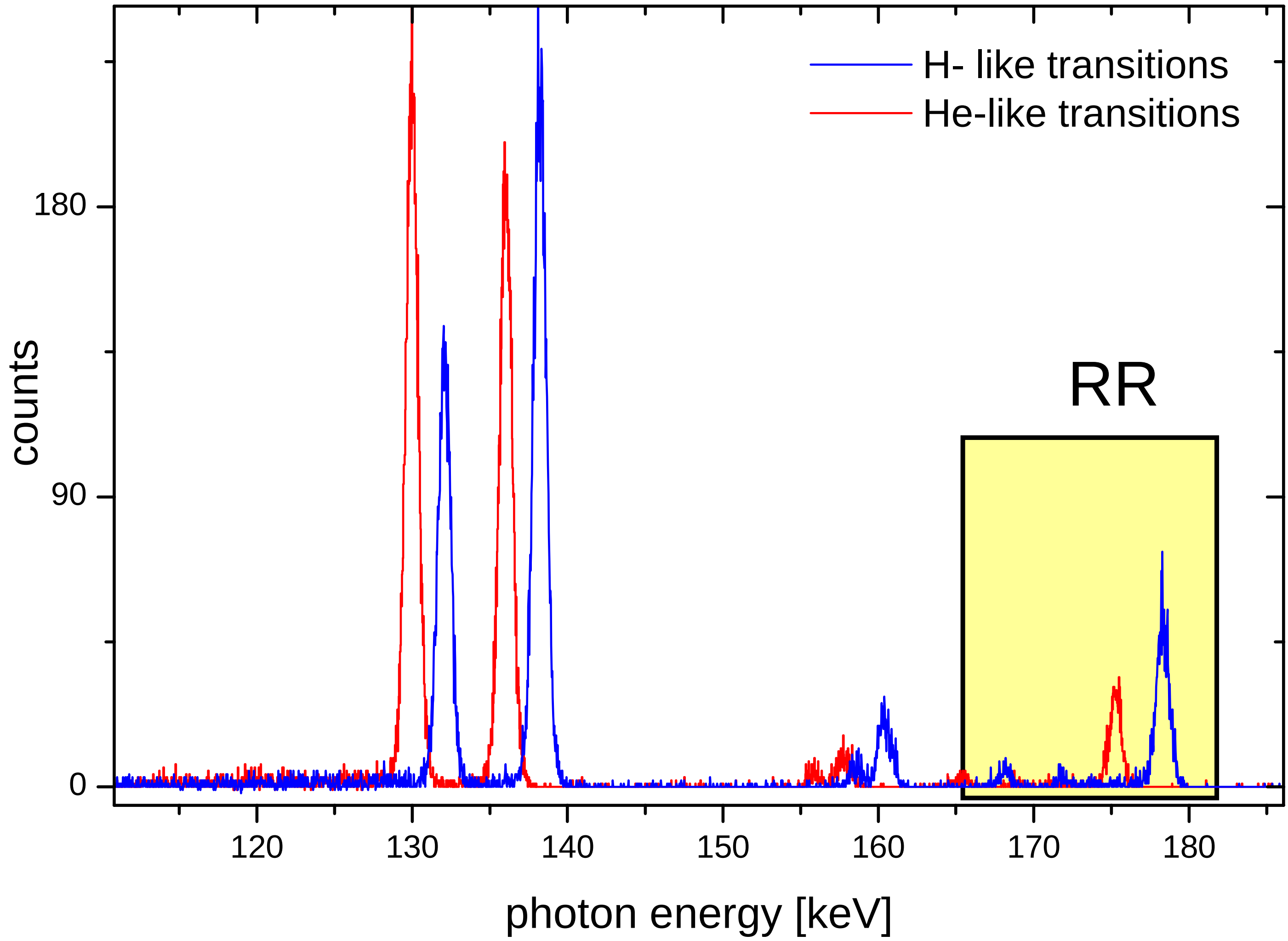




$$E_{KIN} + I_H = \hbar\omega \qquad E_{KIN} + I_{He} = \hbar\omega$$

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

Relative measurement at the electron cooler



Estimated statistical uncertainty for RR into H- and He-like uranium: ≈ 7eV

~~**Uncertainty caused by doppler shift:**~~

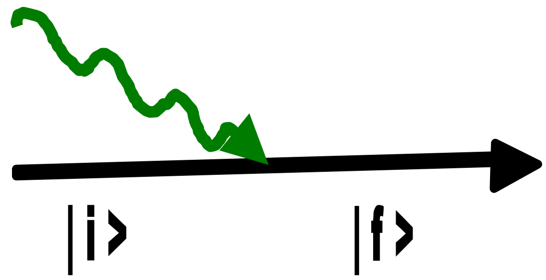
Additional systematic errors: ?

Two Electron

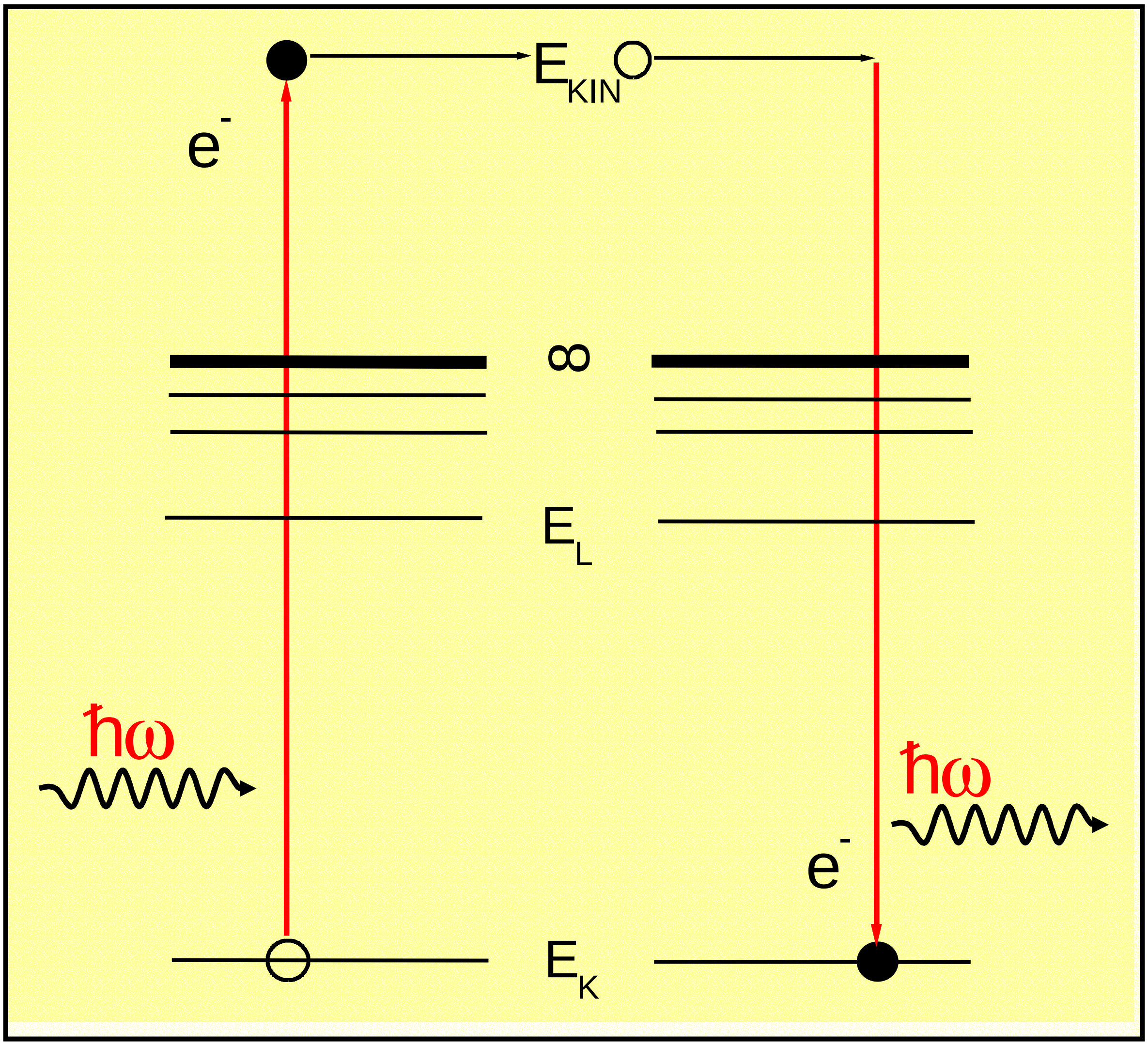
Self Energy
-9.7 eV [U^{90+}]

Vacuum Polarization
+2.6 eV [U^{90+}]

Photon-Matter Interaction in the Relativistic Regime:
Radiative Electron Capture

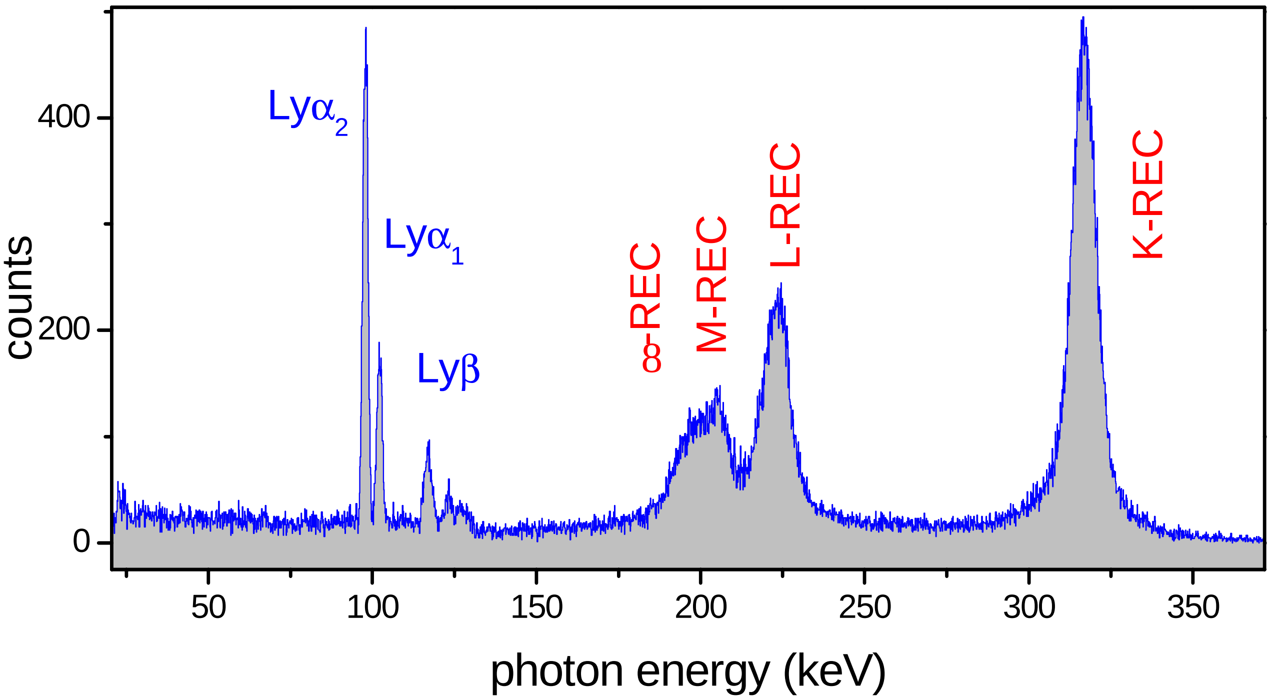


Photoionization **Radiative Electron Capture**



Radiative Electron Capture
Capture of Quasifree Targetelectrons

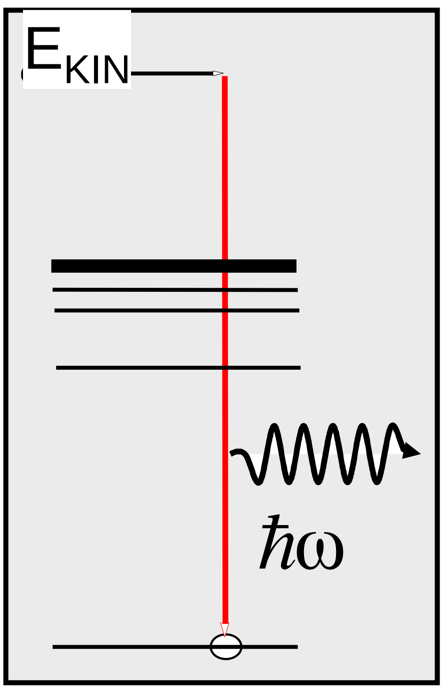
U^{92+} => N_2, 358 MeV/u



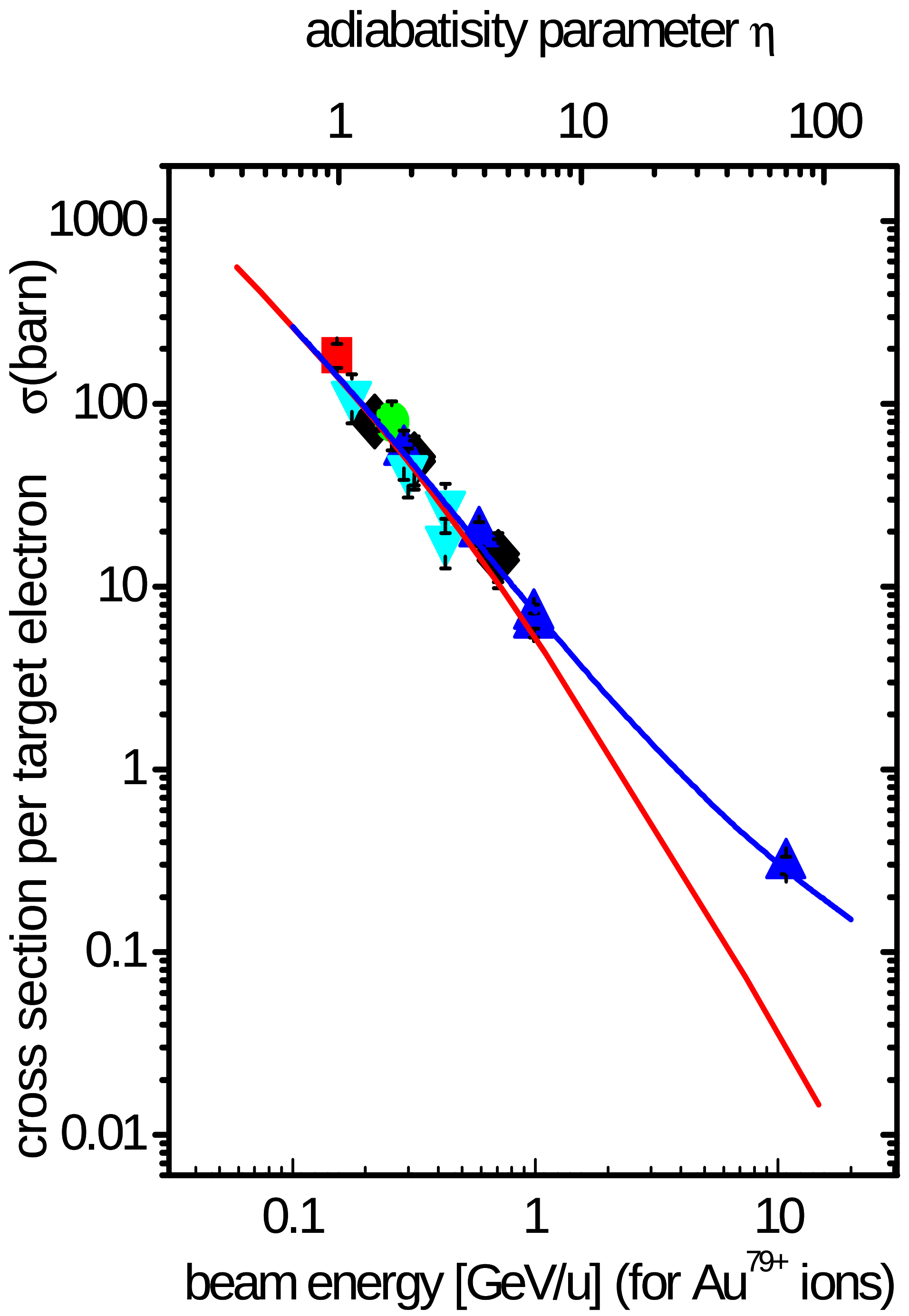
REC photon energy

$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$

Shape and width of REC lines are determined by the momentum distribution of the target electrons



Total REC cross sections for bare ions



$$\eta = \frac{E_{KIN}}{E_K}$$

E_K: K-shell binding energy

E_{KIN} : kinetic projectile energy

Data cover the Z range between Z=54 to 92

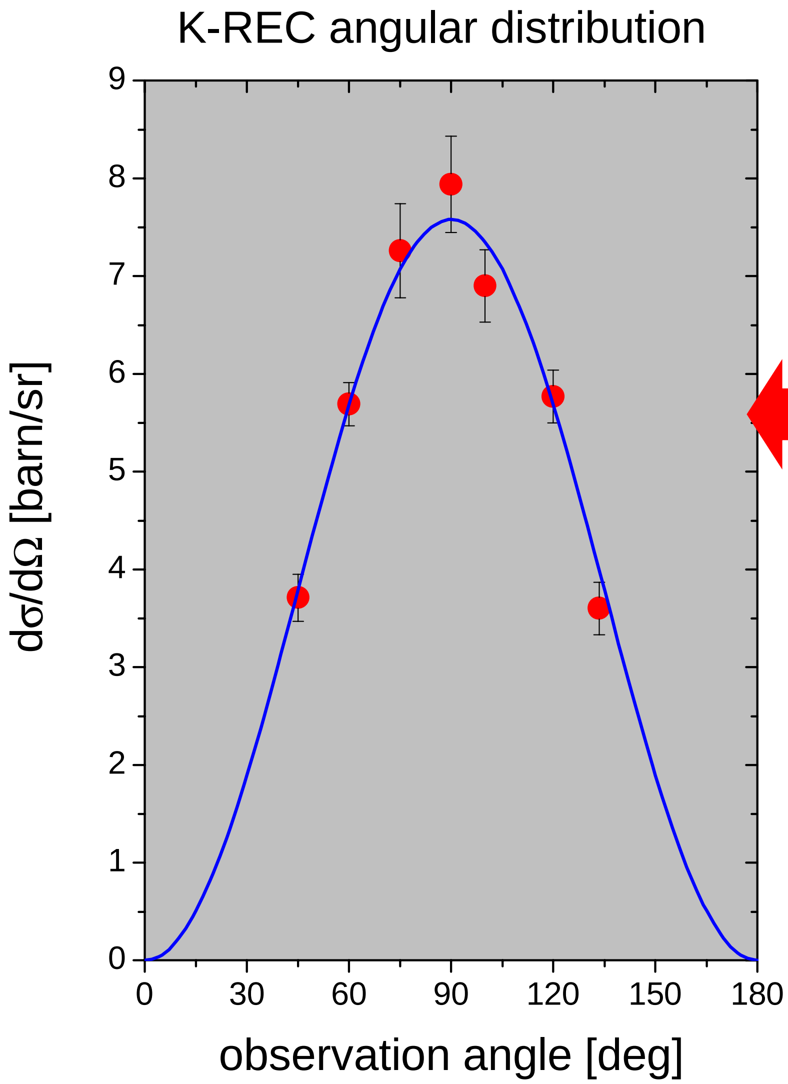
(BEVALAC, SIS/FRS/ESR, BROOKHAVEN)

complete relativistic calculations for Au^{79+} (Eichler et. al)

dipole approximation

The simple non-relativistic dipole approximation provides an accurate tool for cross section preditions (below 1 GeV/u)

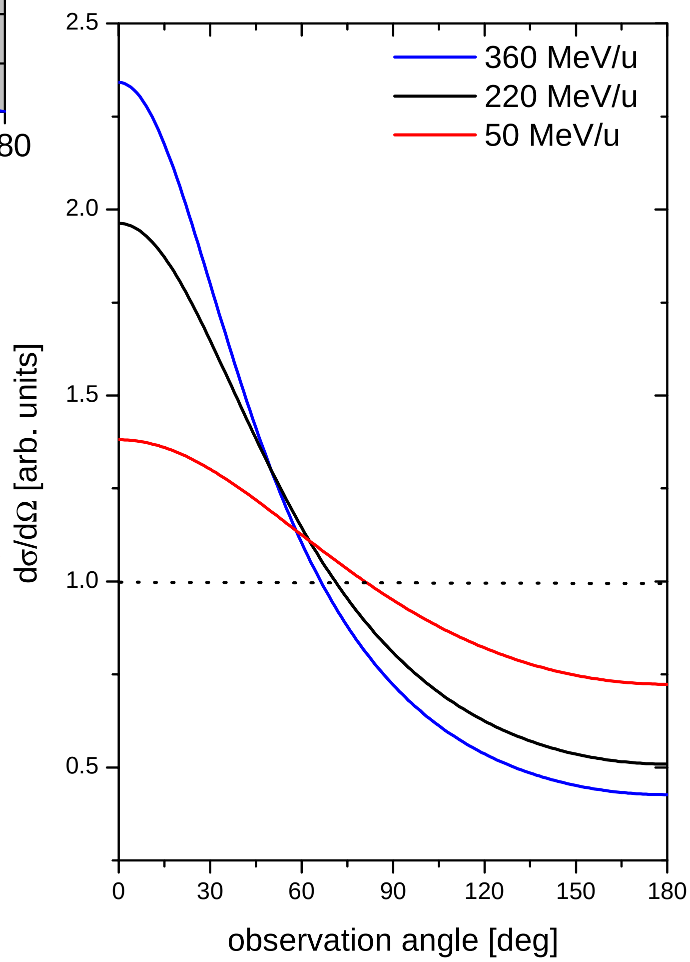
K-REC Distribution for Xe^{54+} (200 MeV/u)



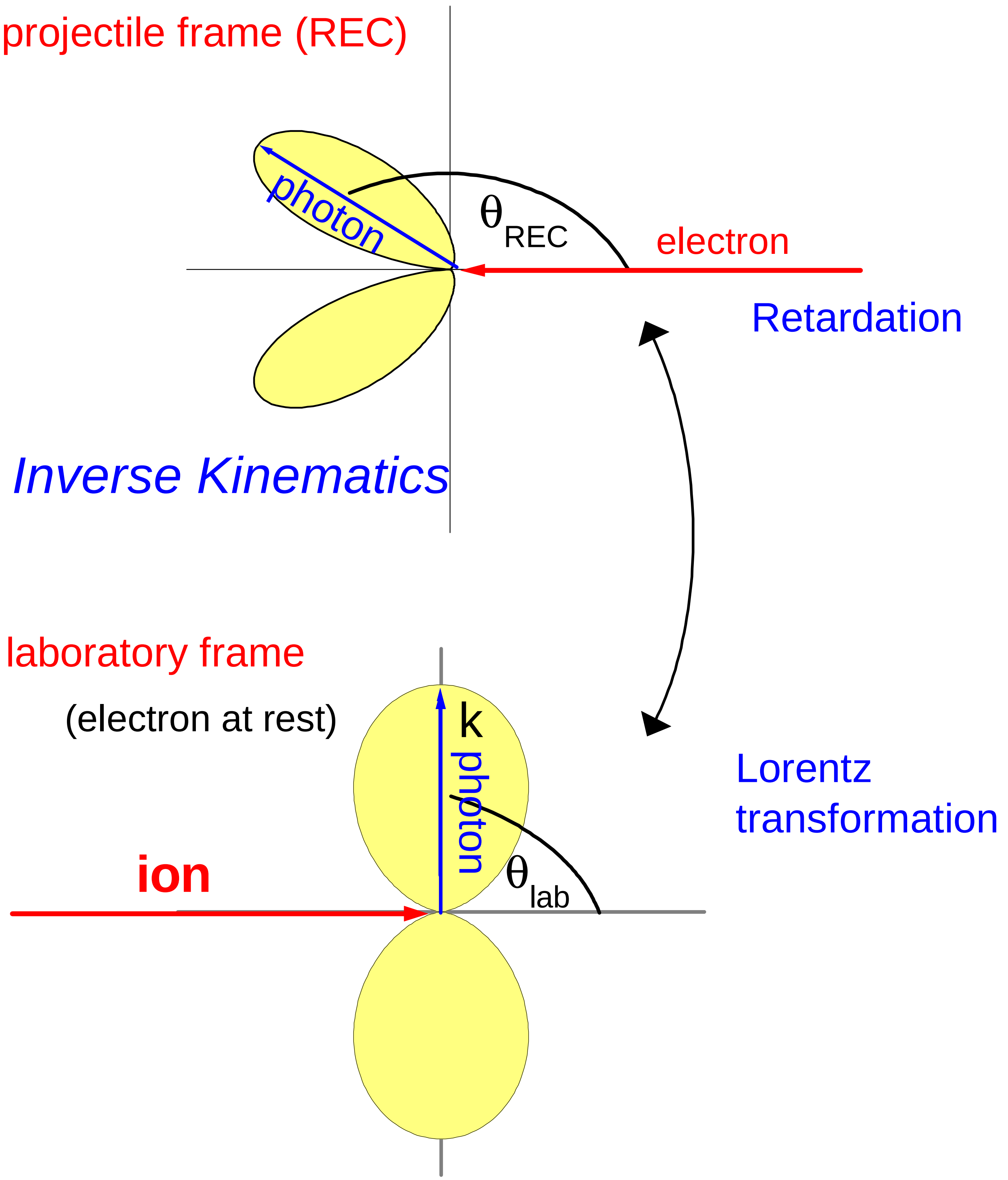
R. Anholt (1984)
BEVALAC experiment

$$\left.\frac{d\sigma}{d\Omega}\right|_{LAB} \propto \sin^2 \vartheta_{lab}$$

Lab. angular distribution of an isotropic transition in the projectile frame

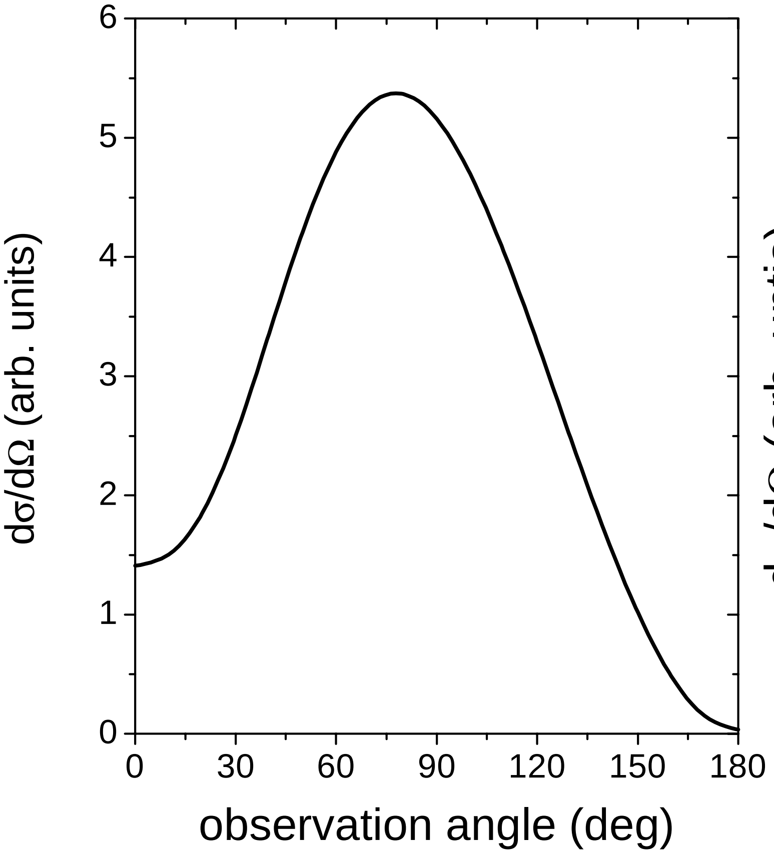


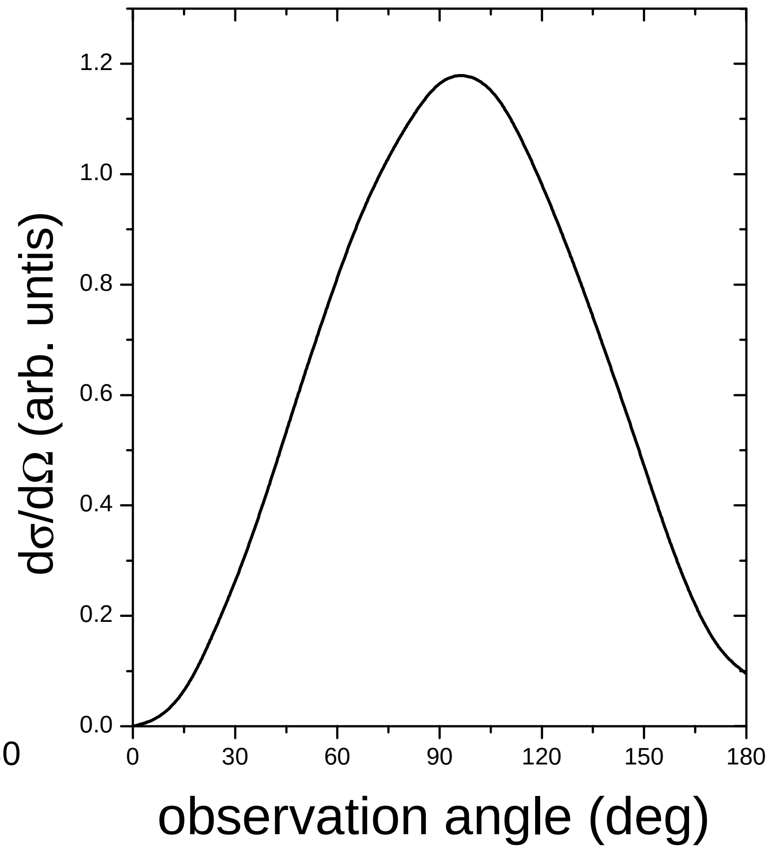
Recombination and Photoionisation of s-States



Using non-relativistic wave functions, complete cancellation between retardation and Lorentz transformation occurs (verified by Anholt for 197 MeV/u $Xe^{54+} \Rightarrow Be$)

K-Shell Angular Distribution Studies for U^{92+} close to 500 MeV/u

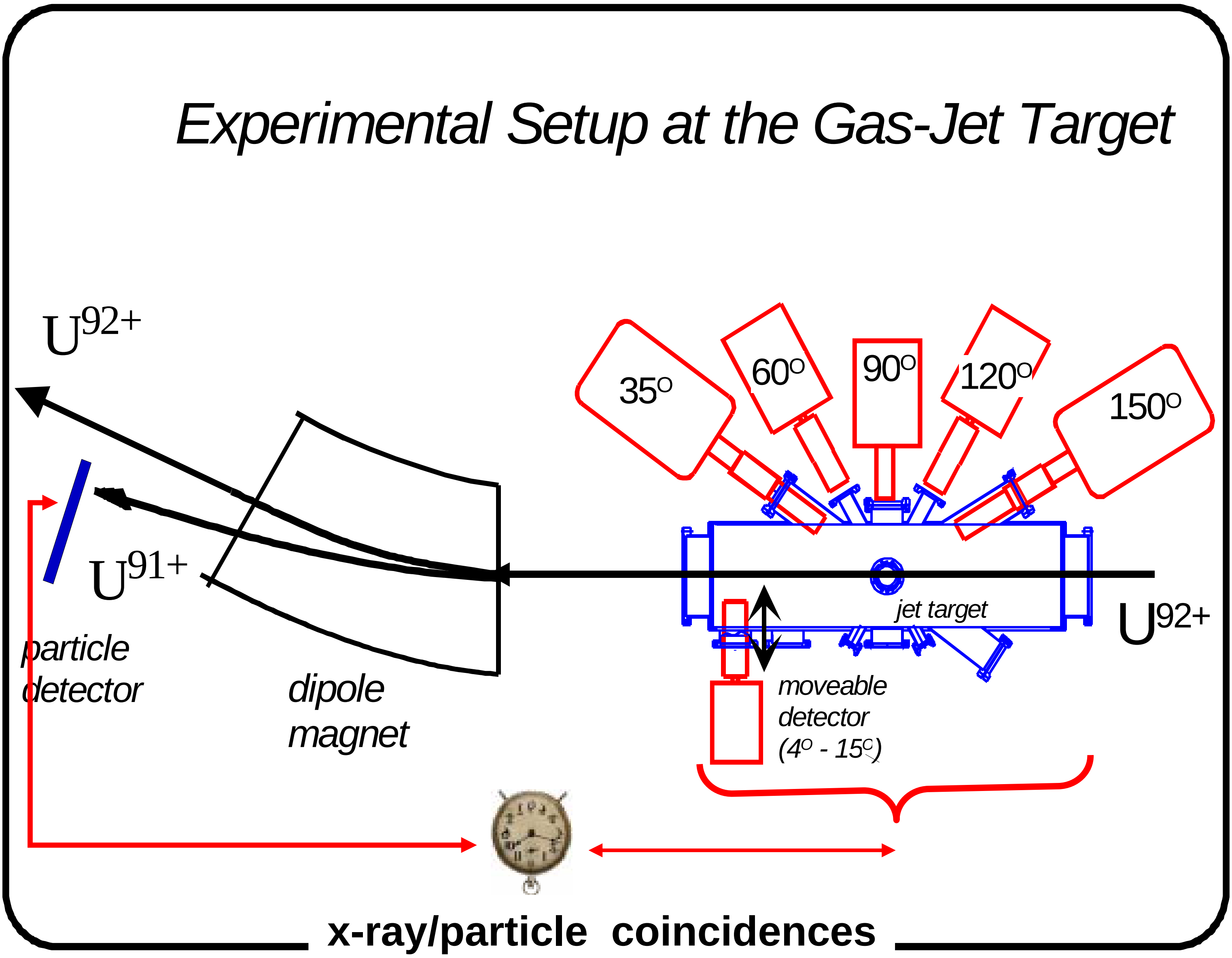




Eichler, PRA (1995)
rigorous all order relativistic calculations

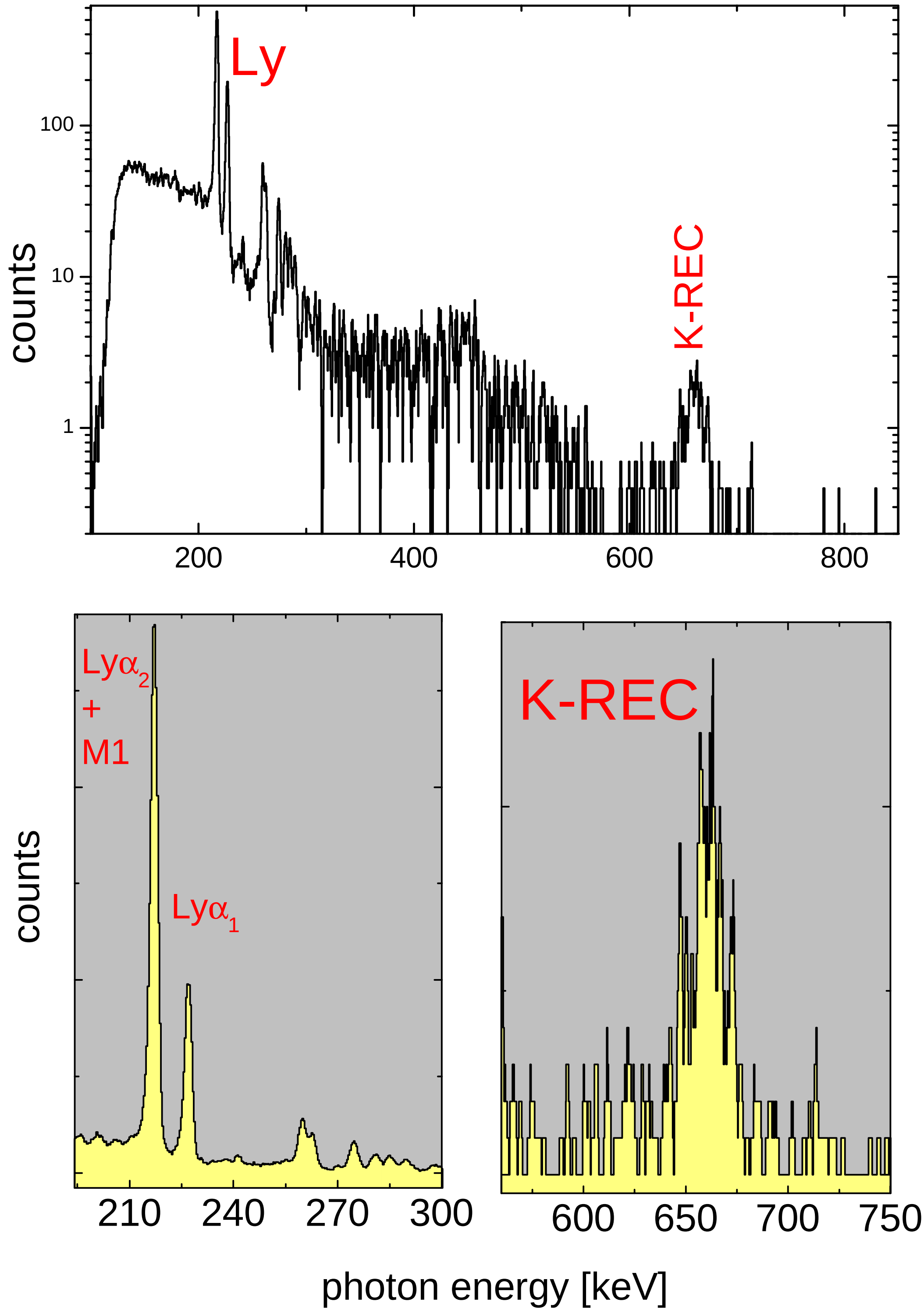
Hino and Watanabe, PRA (1989)
Relativistic Born approximation

Photon Angular Distribution Studies



Photon Emission Close to Zero Degree

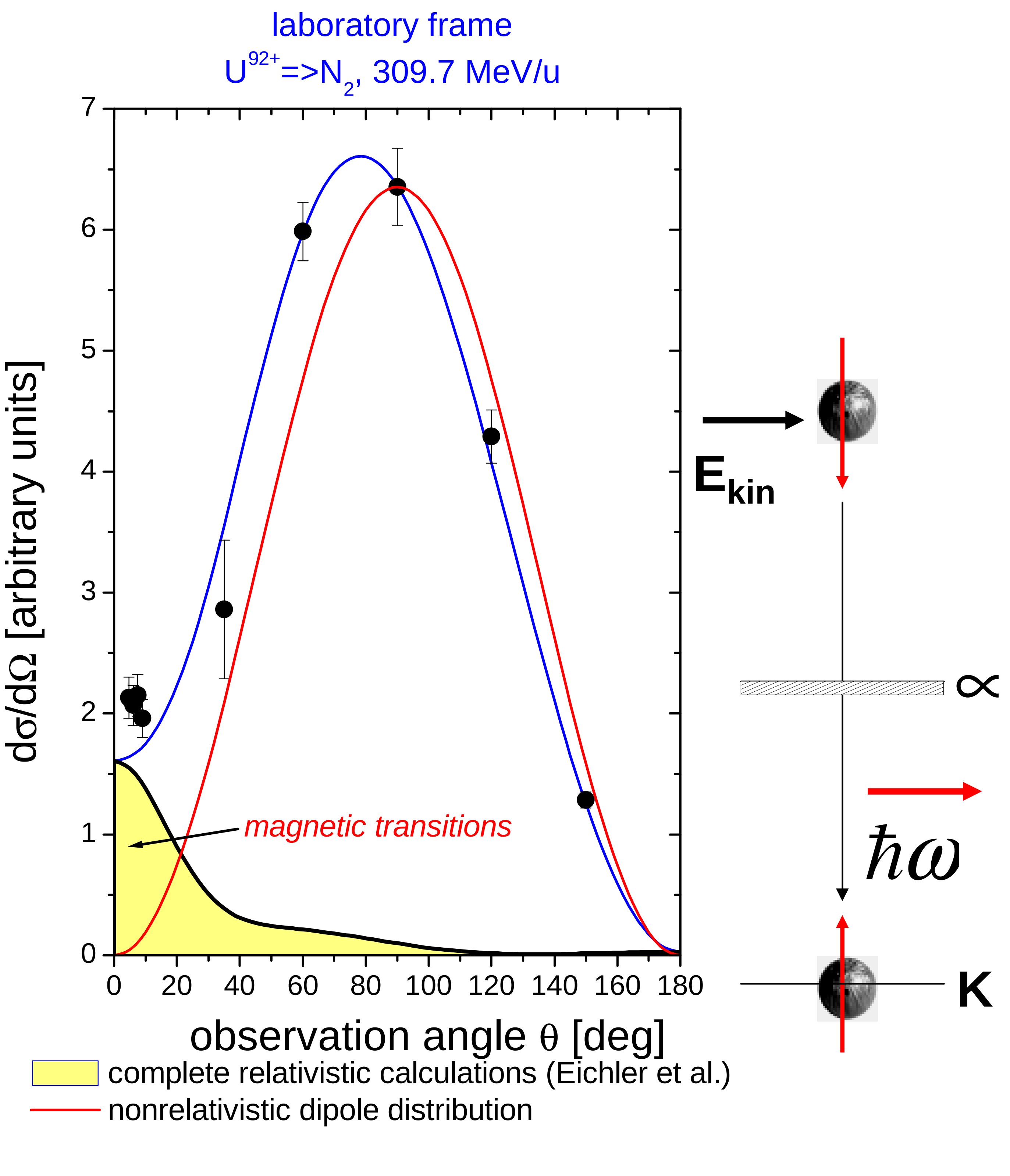
$U^{92+} \Rightarrow N_2$, 310 MeV/u $\theta_{LAB} = 4$ deg



normalization to the $Ly\alpha_2$+M1 intensity:

a) angular distribution of the REC radiation in the emitter frame
b) almost all systematic uncertainties cancel out completely

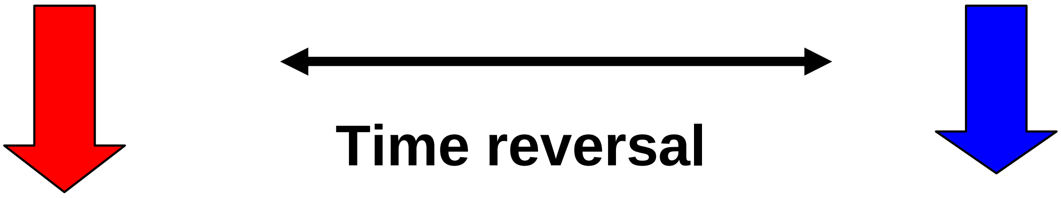
Kinematical Identification of Spin-Flip Transitions from Continuum States into the 1s-Ground State

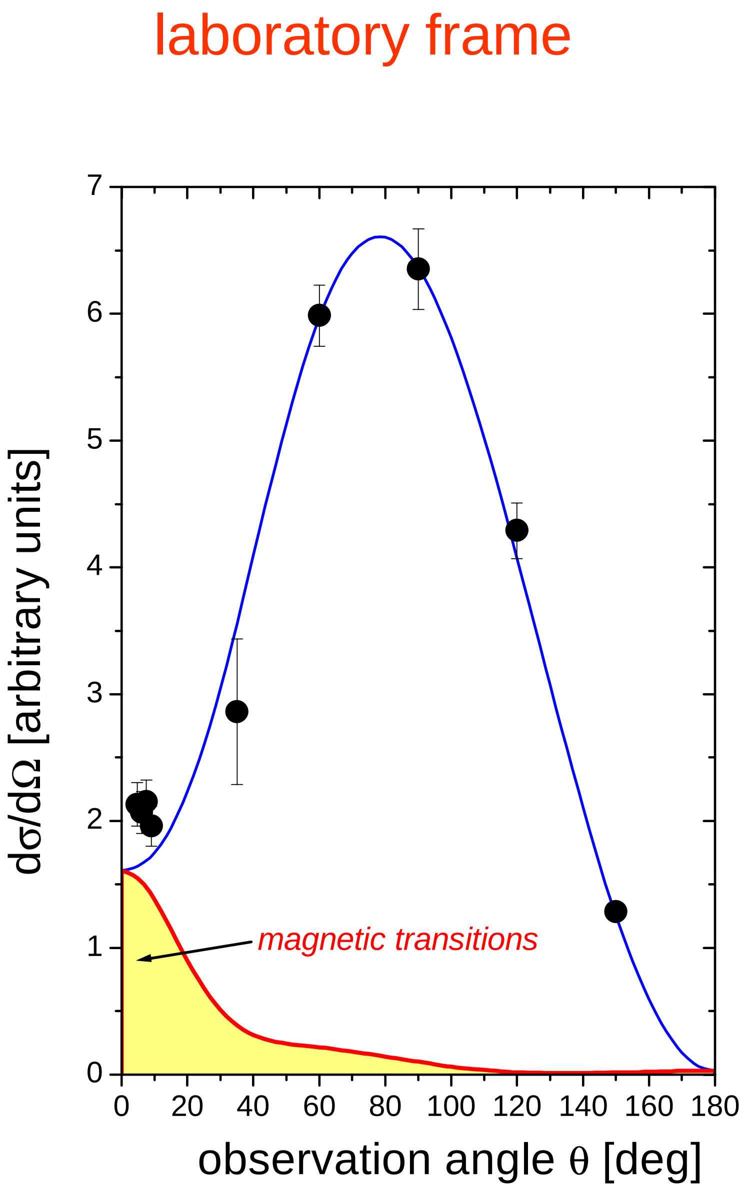


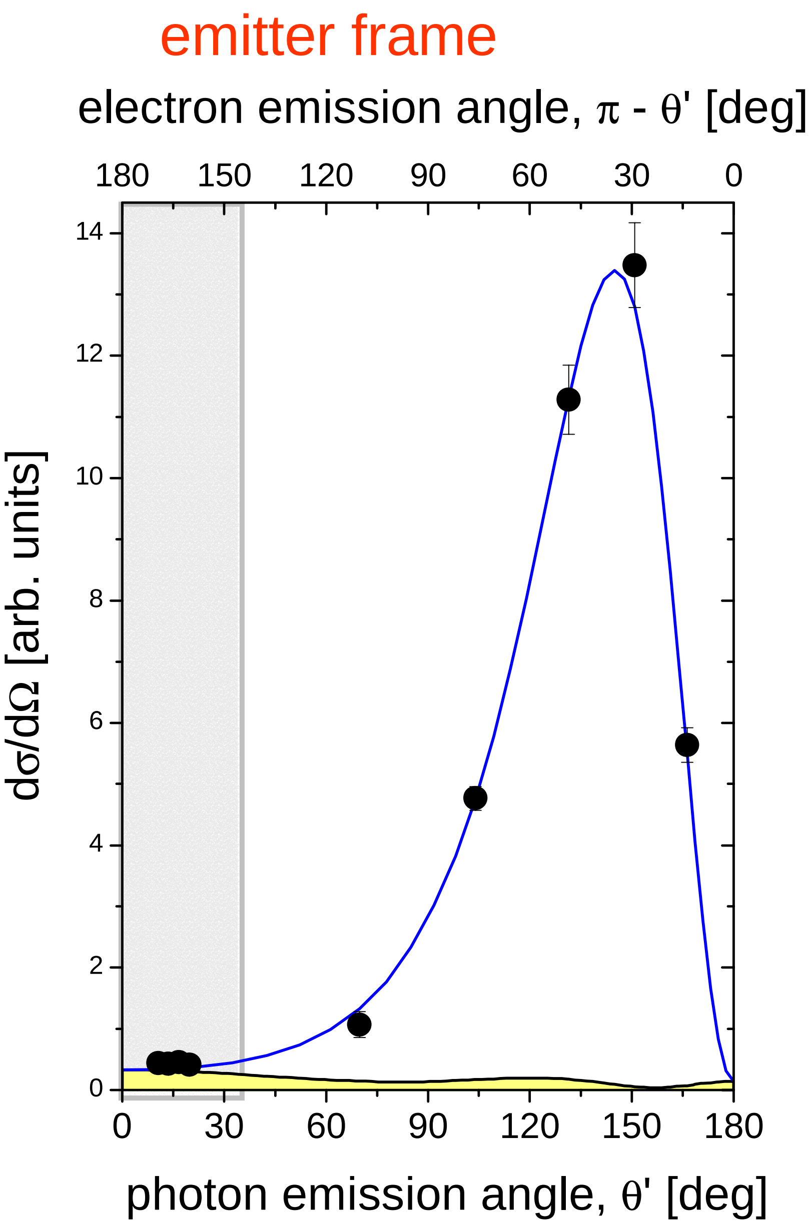
zero degree emission: $(\alpha Z)^2$ correction to the magnetic emission

Angular Distribution

radiative capture into U^{92+} and photoionization of U^{91+}







Angle and solid angle transformation

Open Questions

Angular distributions for few-electron ions close to the threshold (decelerated ions) (no appropriate theories available)

Polarization of the emitted photons (no experimental information available)

Almost 100% linear polarization predicted

Summary

- **Storing and cooling of highly charged ions delivers brilliant beams for experiments**

- **The ESR provides ideal conditions for accurate atomic structure studies**

- **1s-LS experiments at the ESR allowed to improve the experimental accuracy by an order of magnitude**

- **Study of 2eQED provides a test of QED in the strong field limit which is not blended by nuclear effects**

- **The study of elementary atomic processes for highly-charged heavy ions via their time-reversal**

Outlook

- **Implementation of new spectroscopic tools and techniques which are currently in preperation may provide a further gain of accuray towards the 1 eV limit**

- **Expansion of collision studies to few-electron ions**

- **Polarisation and x-x correlation studies**

- **Combined photon, electron and recoil ion momentum spectroscopy**

- **Structure and Collision Studies at High-γ**