Relativistic Quantum Dynamics Explored in Atomic Collisions of High-Z Ions

Thomas Stöhlker

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

in collaboration with

Experiment

D. Banas, H.F. Beyer, G. Bednarz, F. Bosch,
A. Bräuning-Demian, R.W. Dunford, A. Gumberidze,
S. Hagmann, E. Kanter, O. Klepper, C. Kozhuharov,
D. Liesen, P.H. Mokler, X. Ma, A. Muthig, F. Nolden,
U. Spillmann, S. Tachenov, Z. Stachura,
A. Warczak and the ESR-Team

Atomic Physics Group, GSI-Darmstadt, Germany
Argonne National Laboratory, Argonne, USA
IMP, Lanzhou, China
Kansas State University, Kansas, USA
University of Cracow, Poland
University of Frankfurt, Germany

Theory

J. Eichler, S. Fritzsche, A. Ichihara,
D.C Ionescu, T. Shirai, A. Surzhykov

Theoretische Physik, HMI-Berlin, Germany
JAERI, Japan
TU-Dresden, Germany
GSI-Darmstadt, Germany
University of Kassel, Germany

Relativistic Quantum Dynamics

Introduction

Atomic structure at high-Z

Test of Bound-State QED for the Groundstate in H- and He-Like Ions

1s Lamb Shift
Two-Electron QED

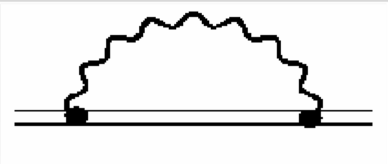
Relativistic Effects in Electron-Ion Recombination and Electron Capture

Photon correlation studies
Population of magnetic sub-levels
Multipole-Mixing
Photon polarization studies
3D x-ray/compton cameras

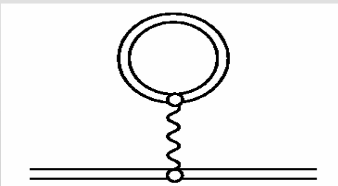
Summary and Outlook

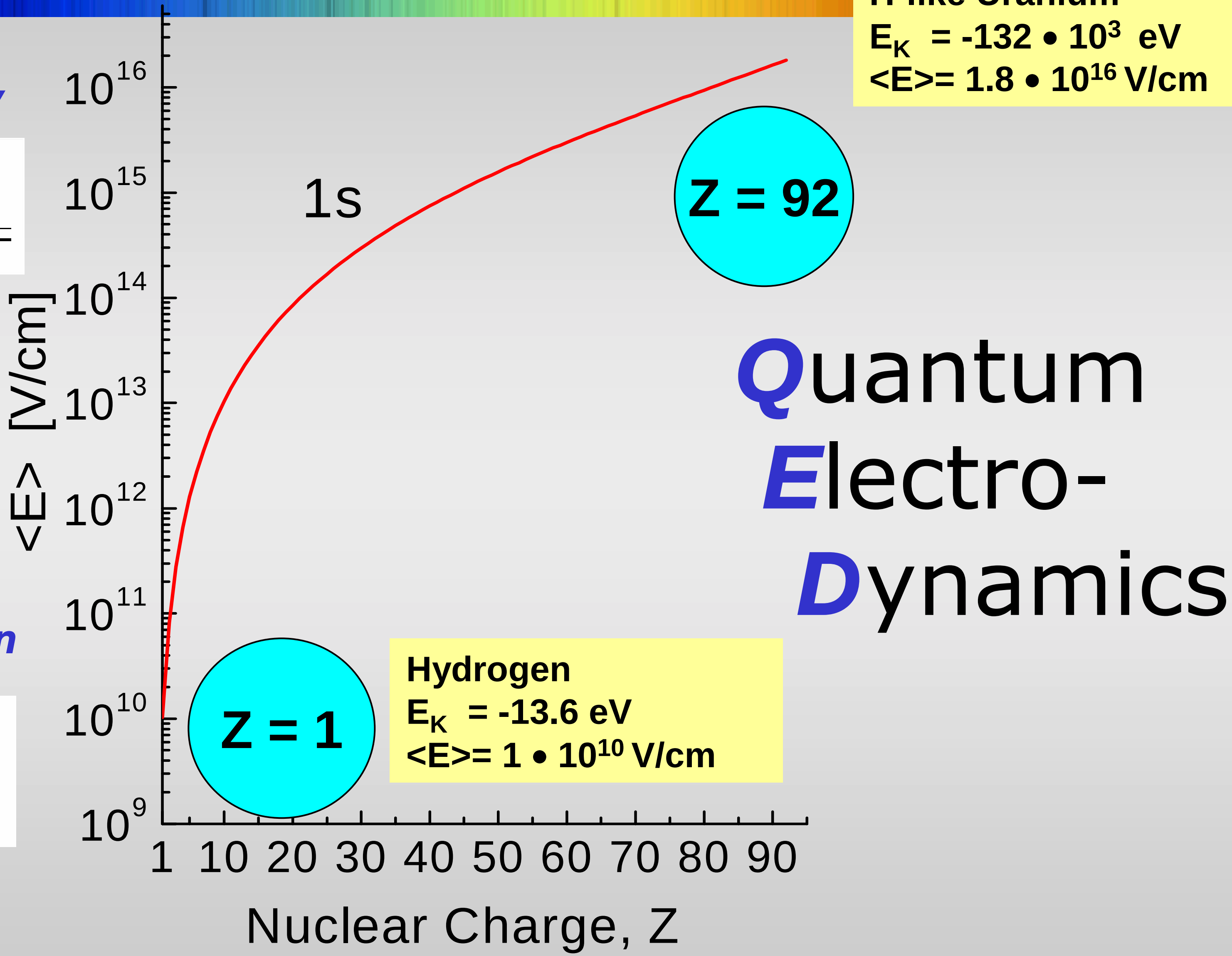
Atomic Physics in Extremly Strong Coulomb Fields

Self Energy



Vacuum Polarization



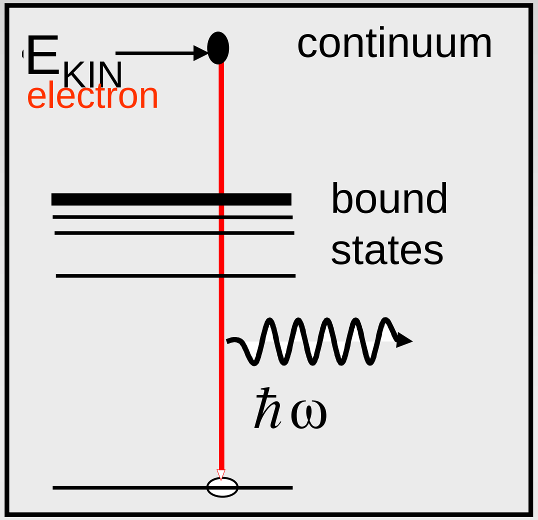


Quantum
Electro-
Dynamics

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

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

Radiative Recombination/Electron Capture

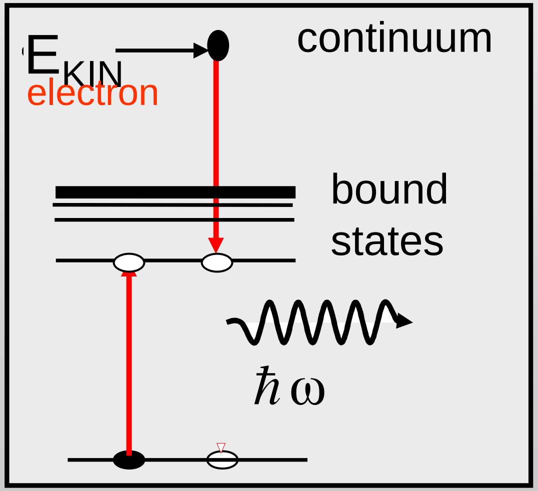


- ***Electron capture into a bound ionic state by emission of a photon***

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

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

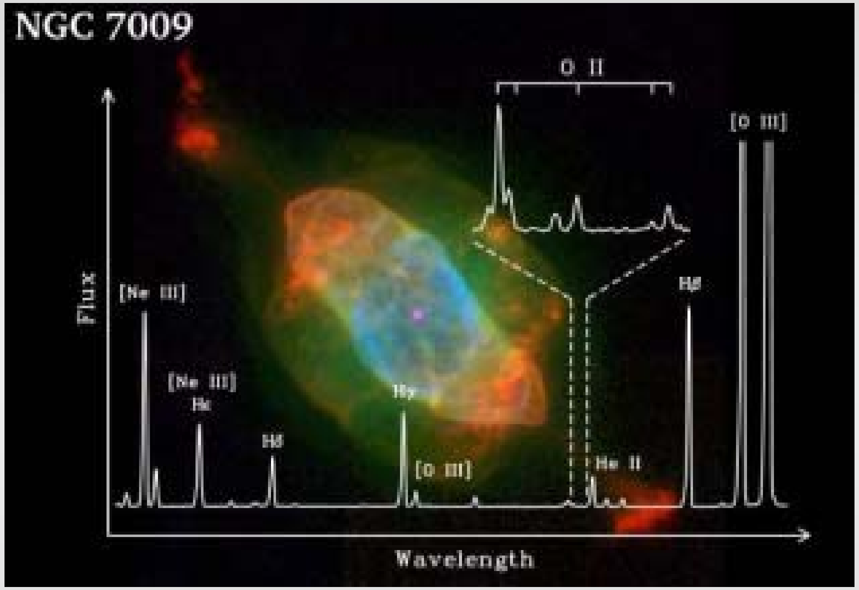
Dielectronic Recombination/Electron Capture



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

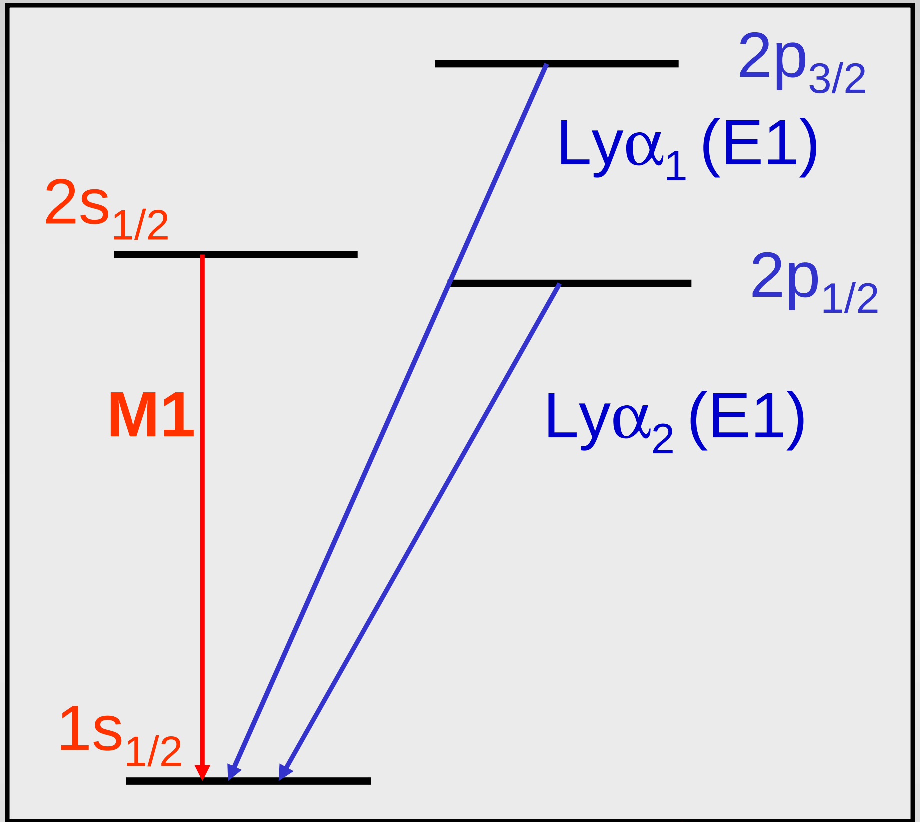
e.g.

- ***ion sources***
- ***accelerator***
- ***charge state 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 capture

The Structure of One-Electron Systems



QED corrections

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

Z: nuclear charge number
n: prinzipal quantum number

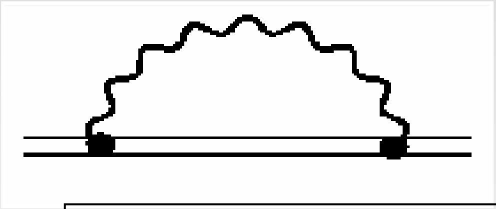
Atomic systems at high-Z

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

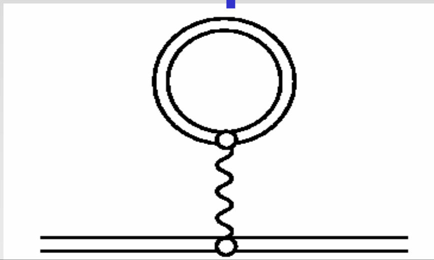
Bound-State QED: 1s Lamb Shift

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

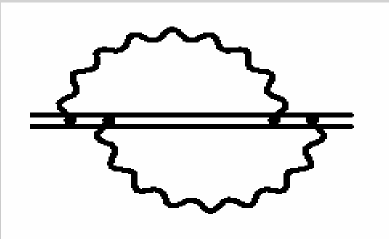
$\Delta E = \alpha/\pi\ (\alpha Z)^4\ F(\alpha Z)\ m_e c^2$

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

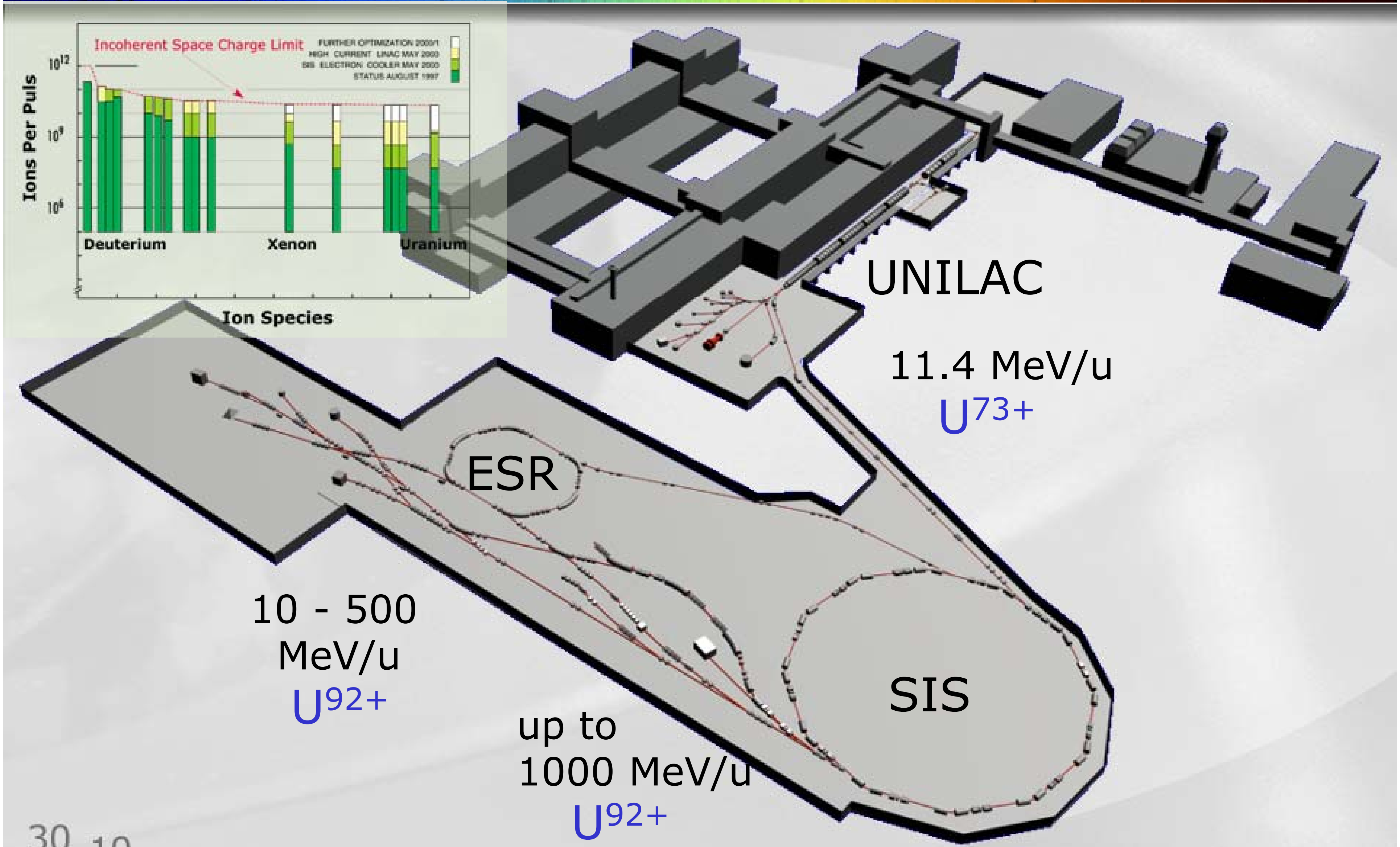
F(αZ): series expansion in αZ

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

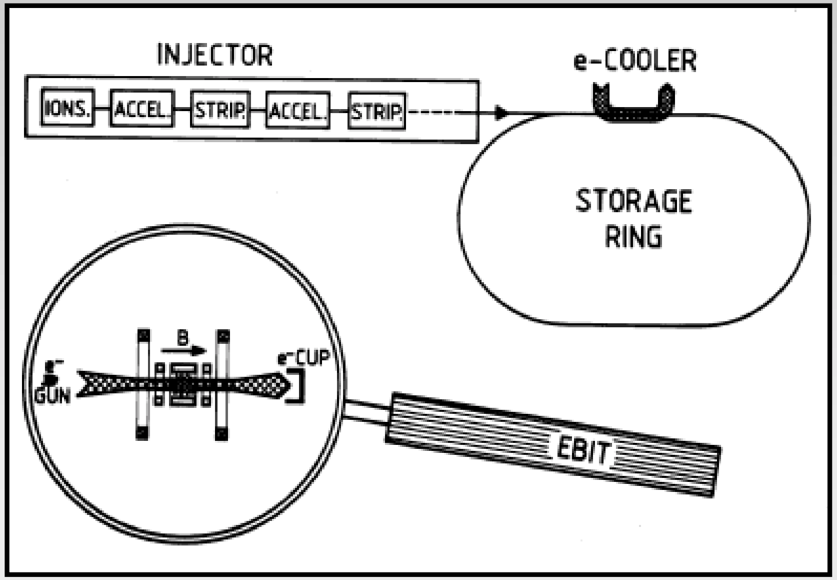
F(αZ): series expansion in αZ not appropriate

Goal:  **±1 eV**

GSI-Accelerator Facility



Production of Highly Charged Heavy Ions

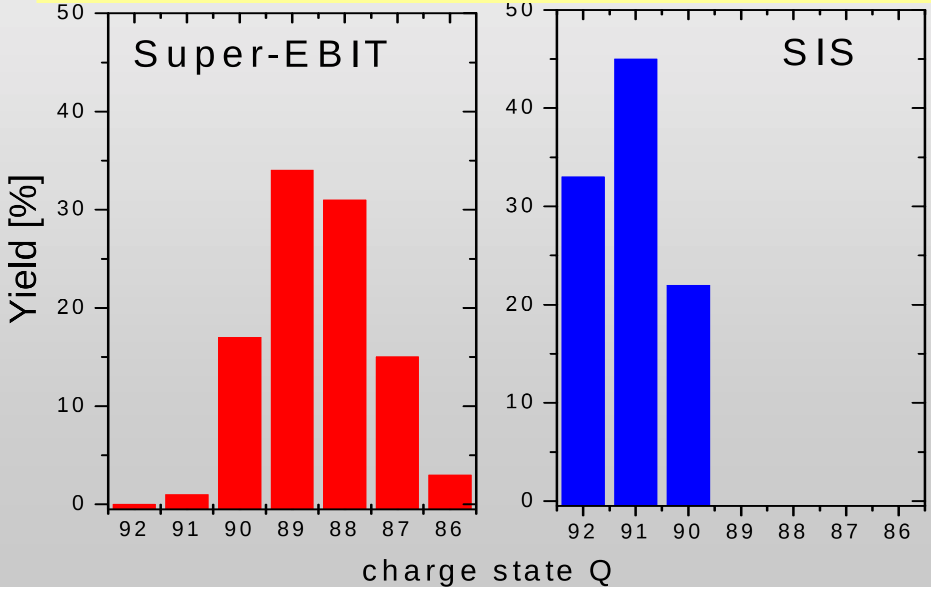


EBIT: Trapped, stationary ions; charge state production by electron bombardment

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

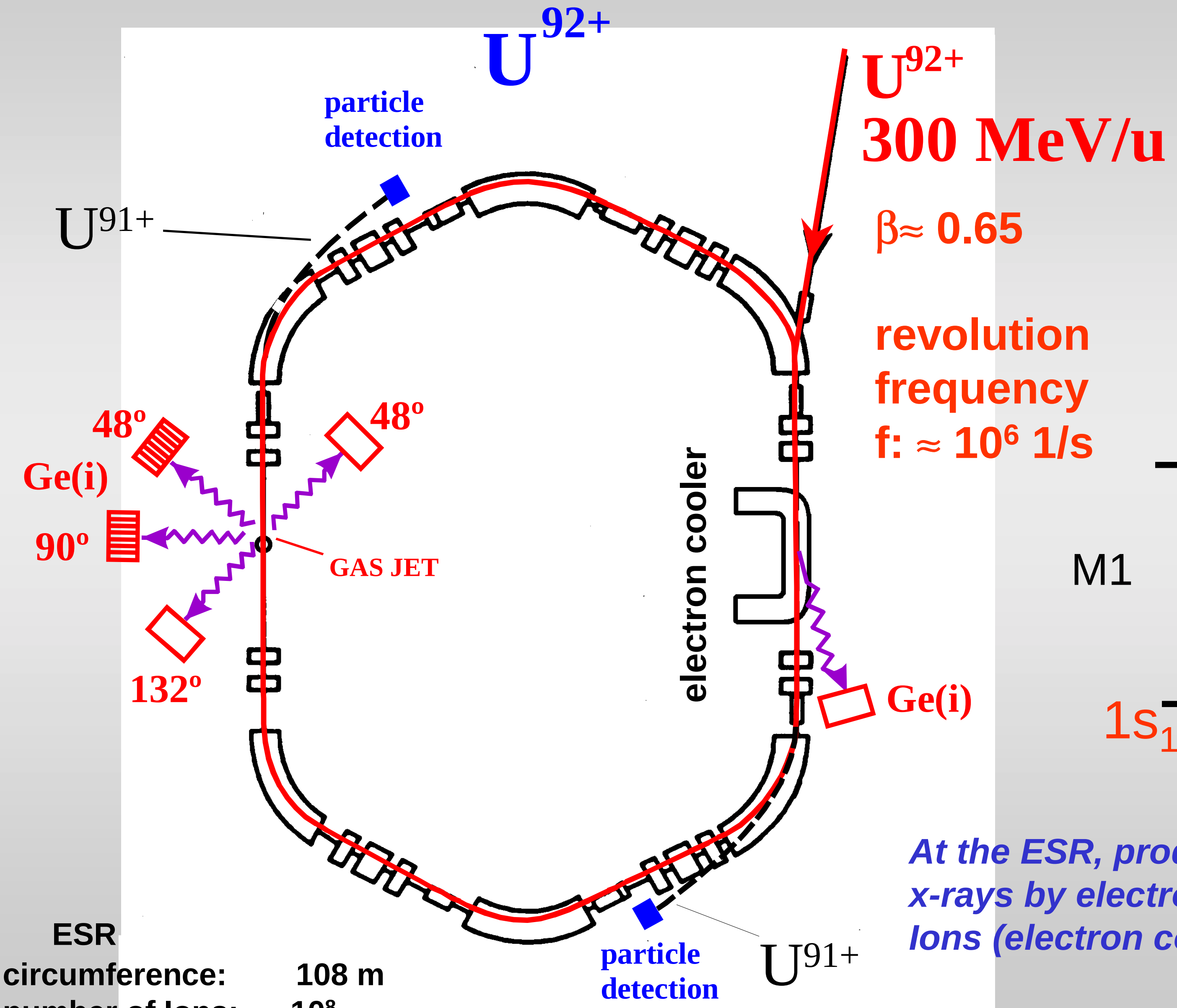
Charge State Distributions for Uranium

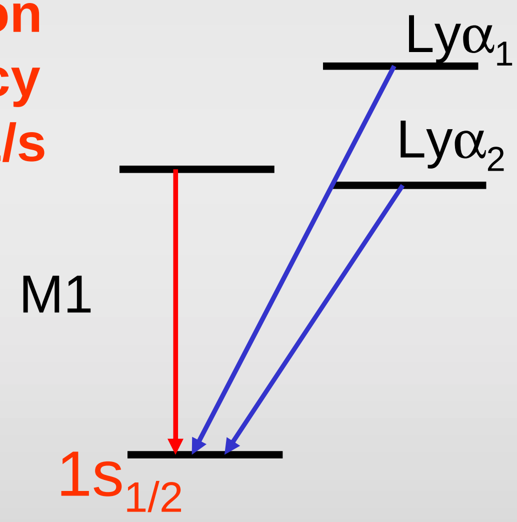
200 keV electron energy (ion at rest)



300 MeV/u ($\beta \approx$ 0.65)

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)

ESR

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

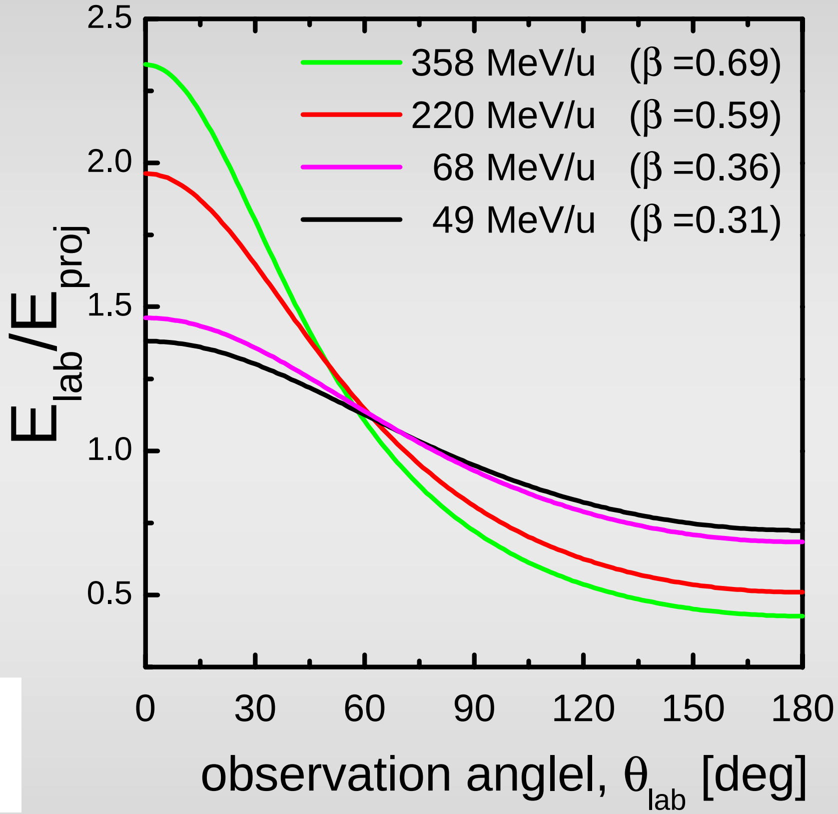
The Experimental Challenge

Relativistic Doppler-Transformation

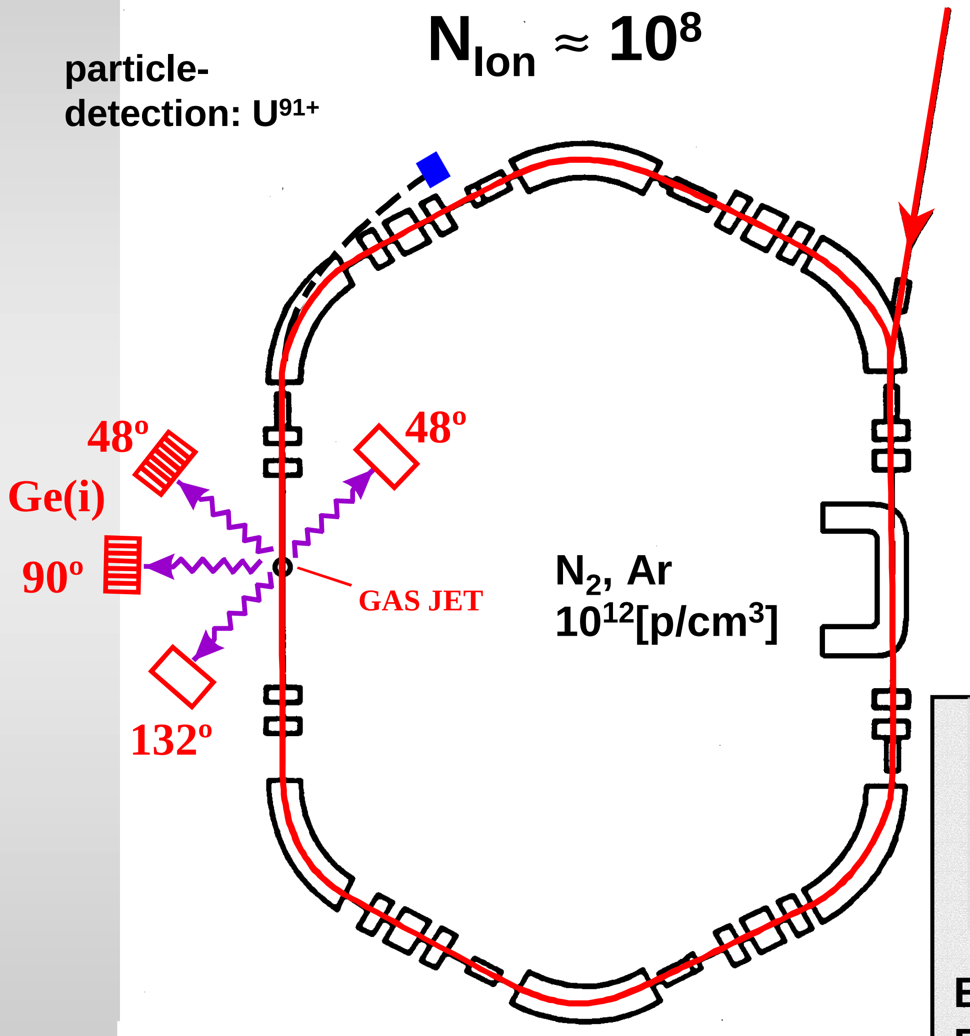
$$E_{lab} = \frac{E_{proj}}{\gamma \cdot (1 - \beta \cdot \cos\theta_{lab})}$$

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}



X-Ray Spectroscopy at the Jet-Target



U^{92+} 300 MeV/u

deceleration

U^{92+} 49 MeV/u

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

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

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

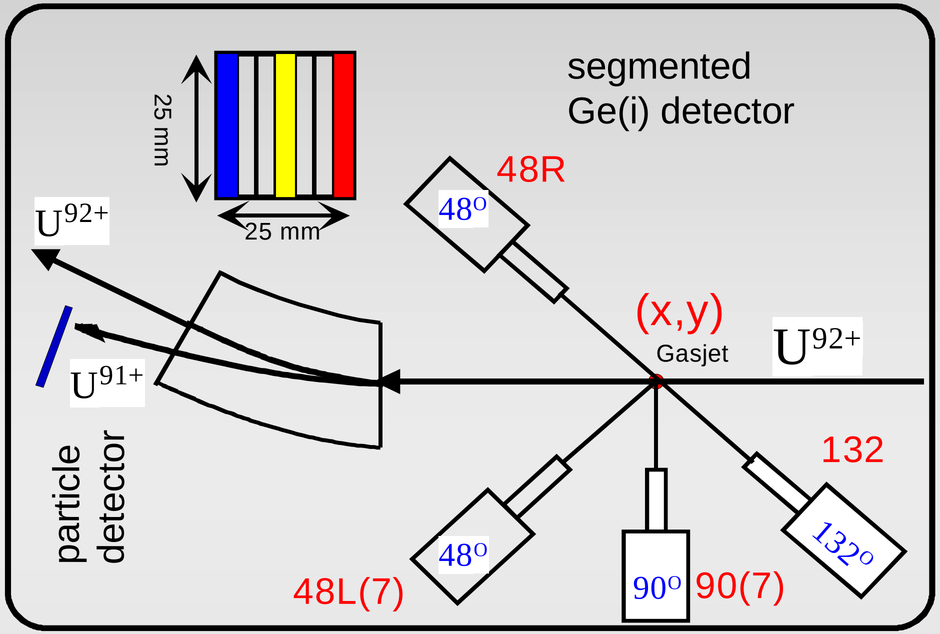
5. Doppler correction

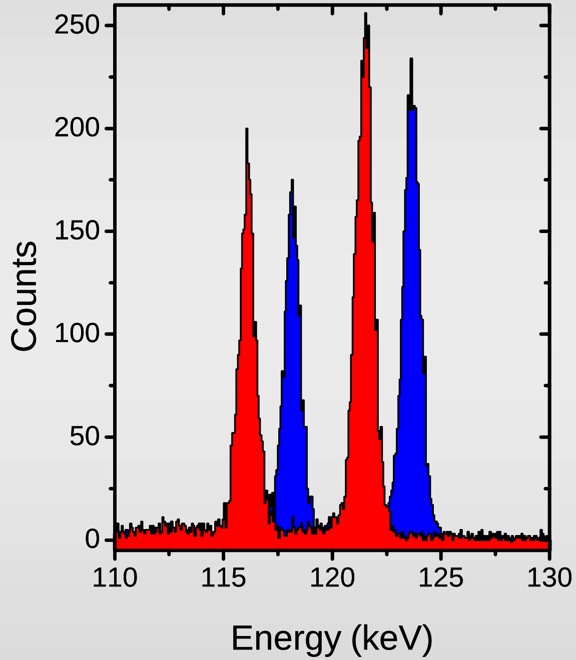
6. Comparison with Dirac theory

→ **1s Lamb Shift**

Lamb Shift-Experiment at the Jet-Target

$Ly\alpha_1$ ($2p_{3/2} \rightarrow 1s_{1/2}$)
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*

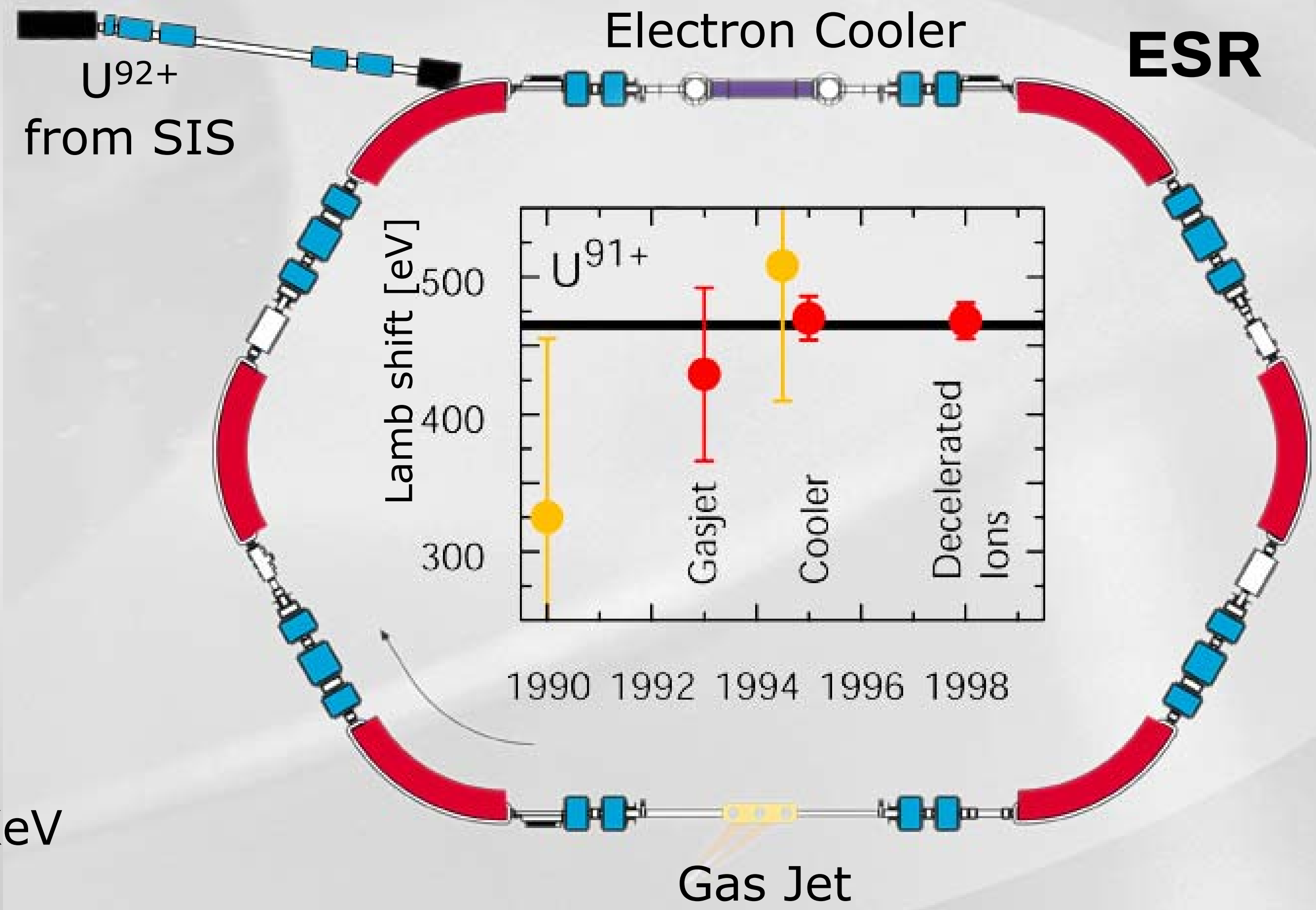
Test of Quantum Electrodynamics (1s-LS)

Hydrogen-Atom

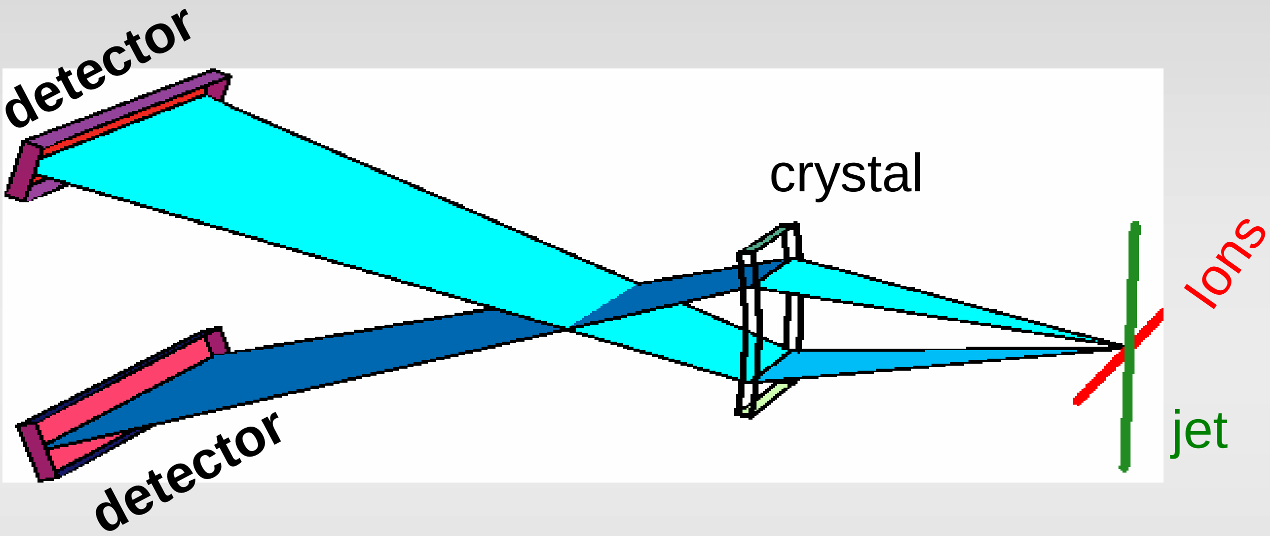
Z=1; E_b = 13.6 eV
$Z \cdot \alpha \ll 1$

Uranium-Ion

Z=92; E_b = 132 KeV
$Z \cdot \alpha \approx 1$



Transmission crystal spectrometer:
towards an accuracy of 1 eV



Bragg-Laue relation

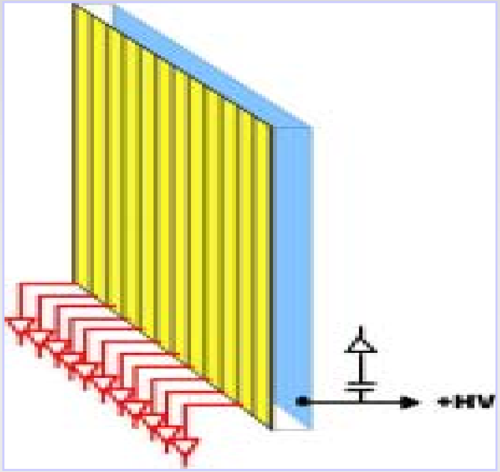
$$n \cdot \lambda = 2 \cdot d \cdot \sin\theta$$

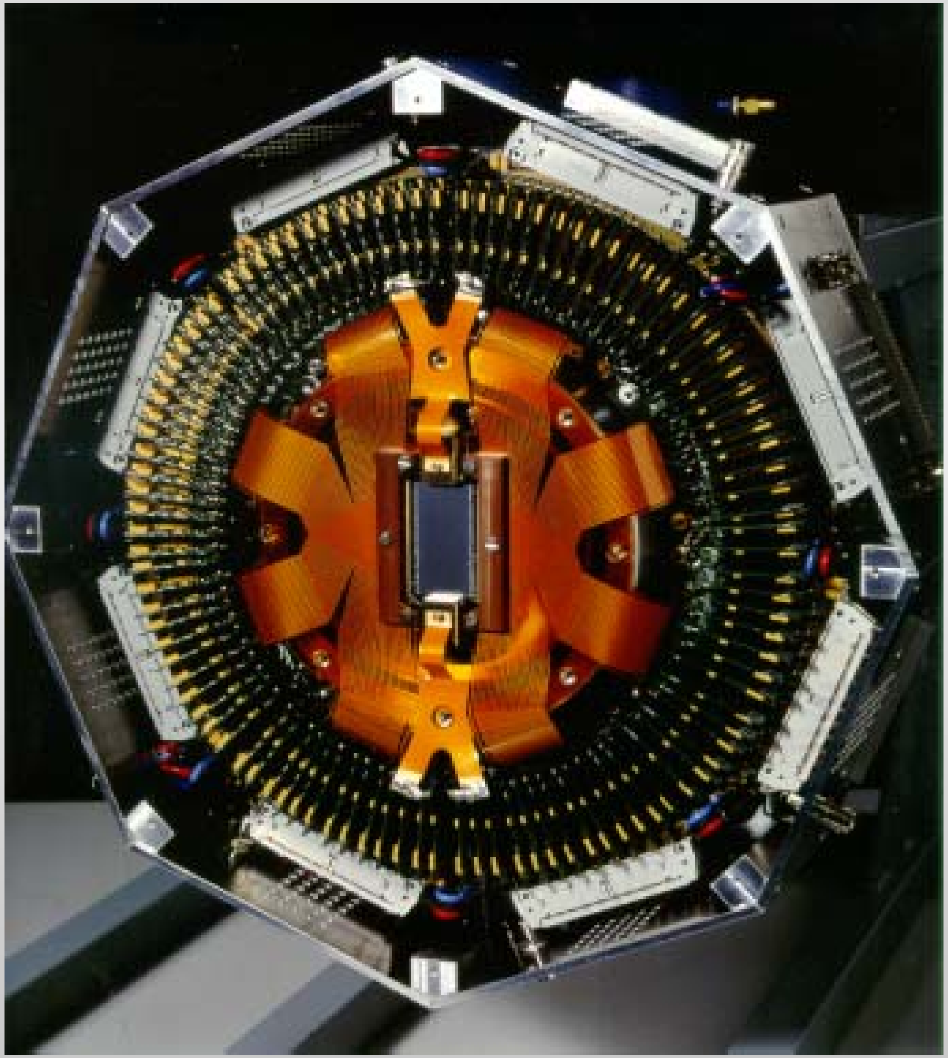
H.F. Beyer et al., GSI Report 2000

Position Sensitive Ge(i) Detectors

Micro-Strip Germanium Detector Development:

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





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

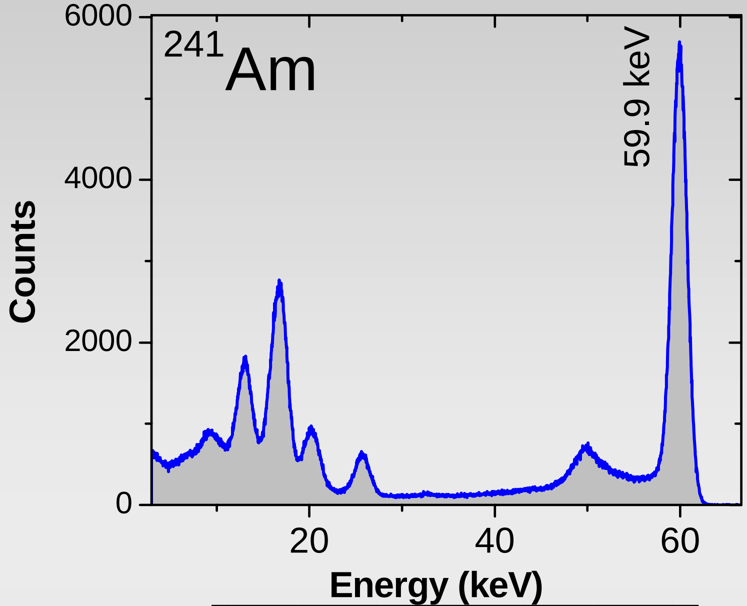
D. Protic et al., IEEE in print (2001)

Micro-Strip Germanium Detectors:
Position Sensitive X-ray Spectroscopy

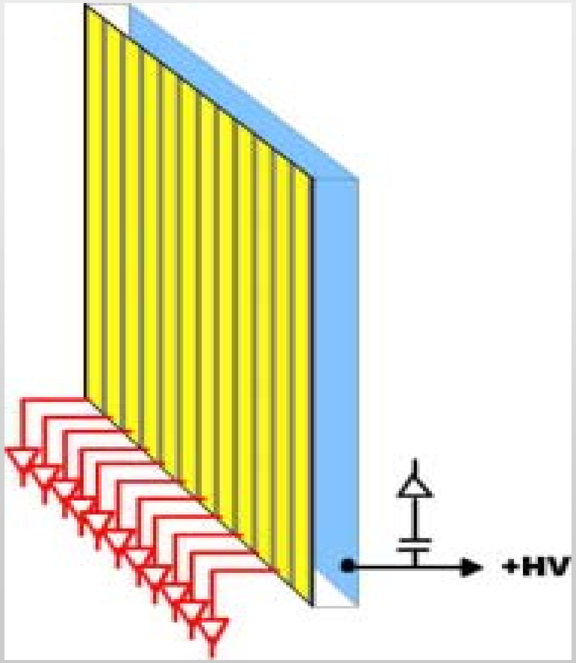
Energy resolution
1.6 keV @ 60 keV

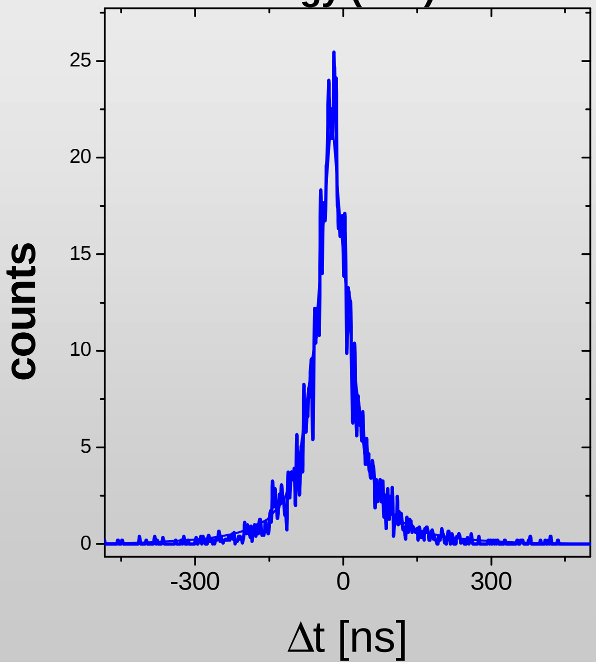
Position resolution
200 μm

Time resolution
50 ns



Energy

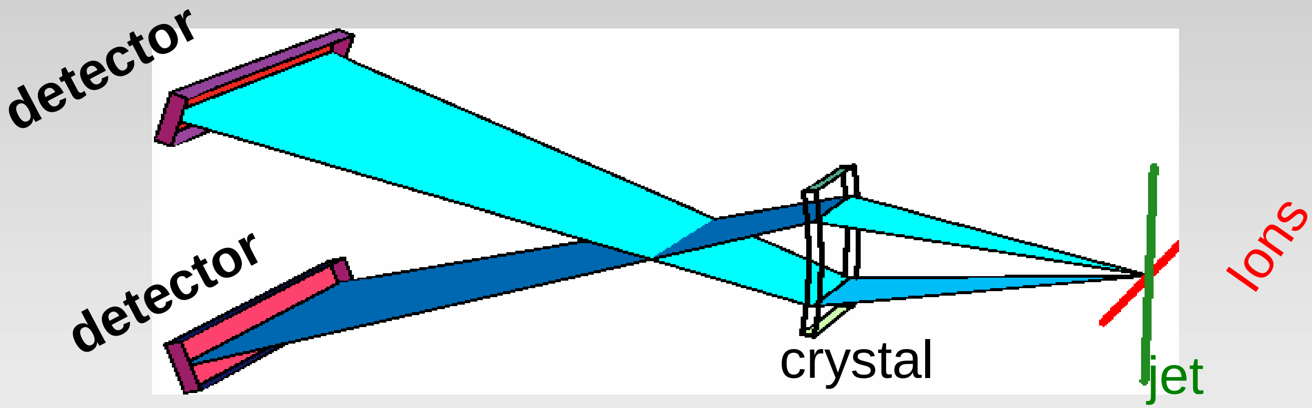


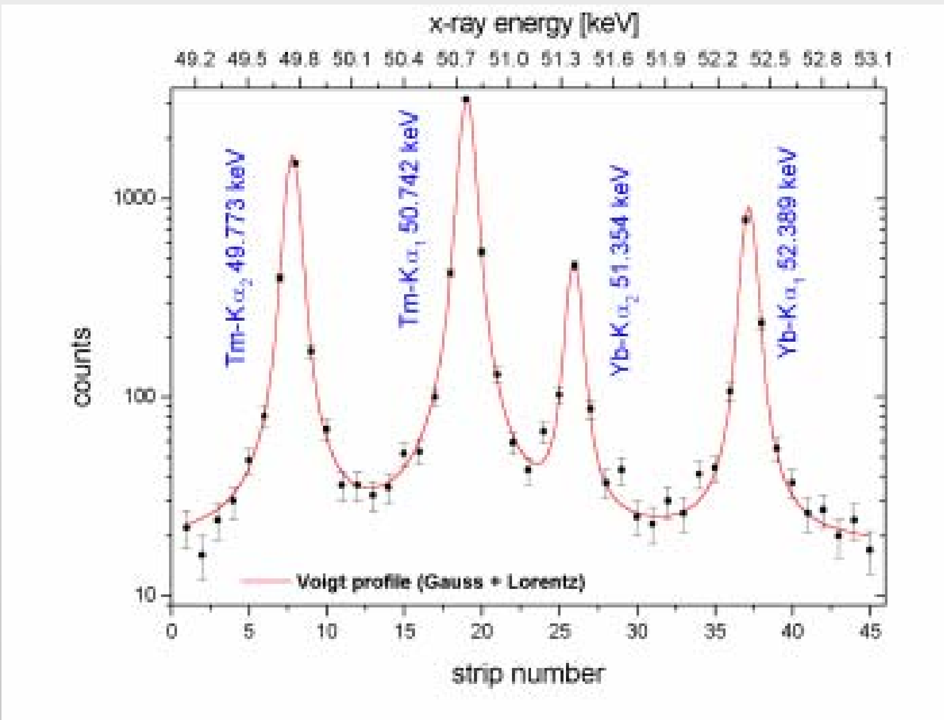


Timing

Transmission crystal spectrometer

towards an accuracy of 1 eV



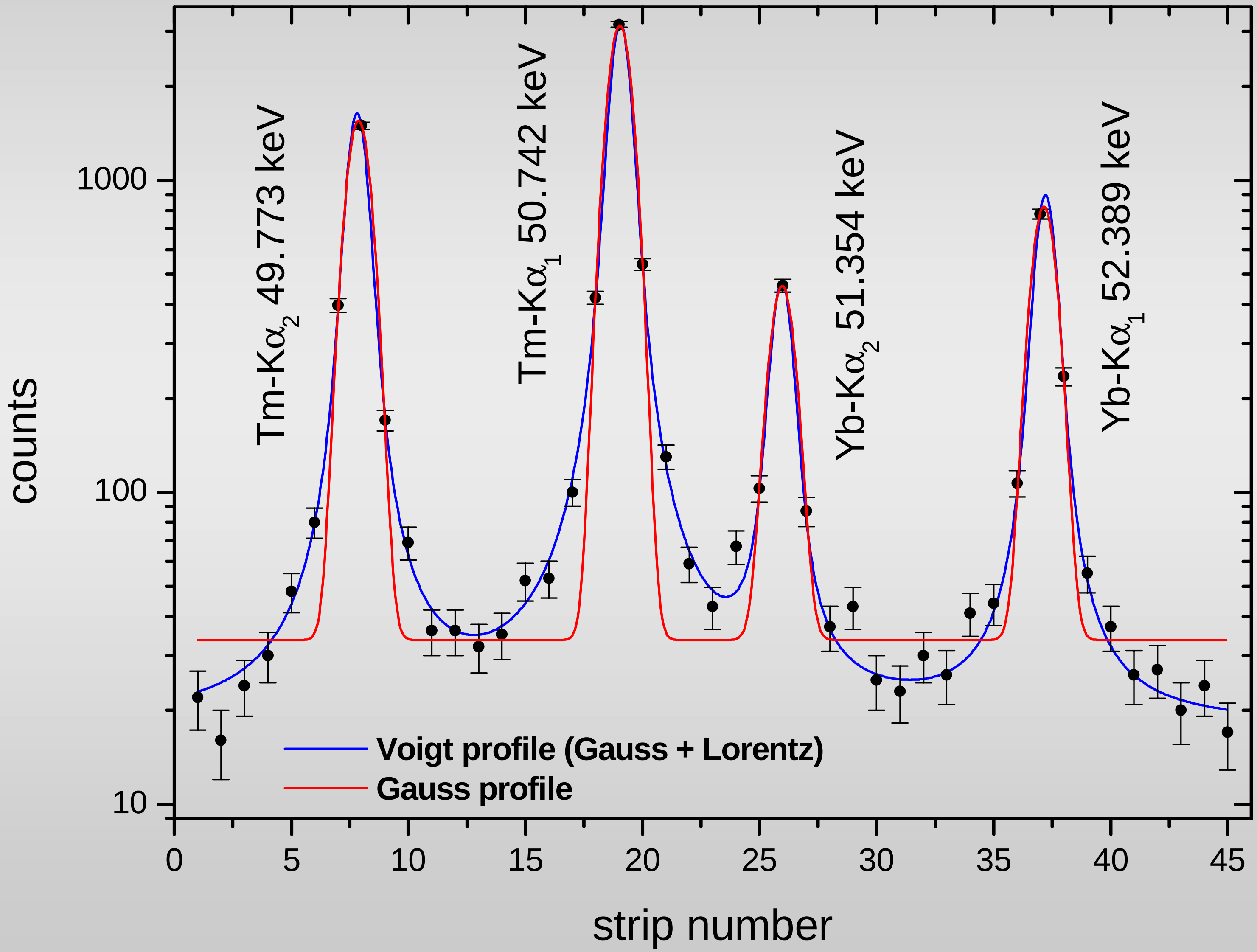


H.F. Beyer et al., GSI Report 2000

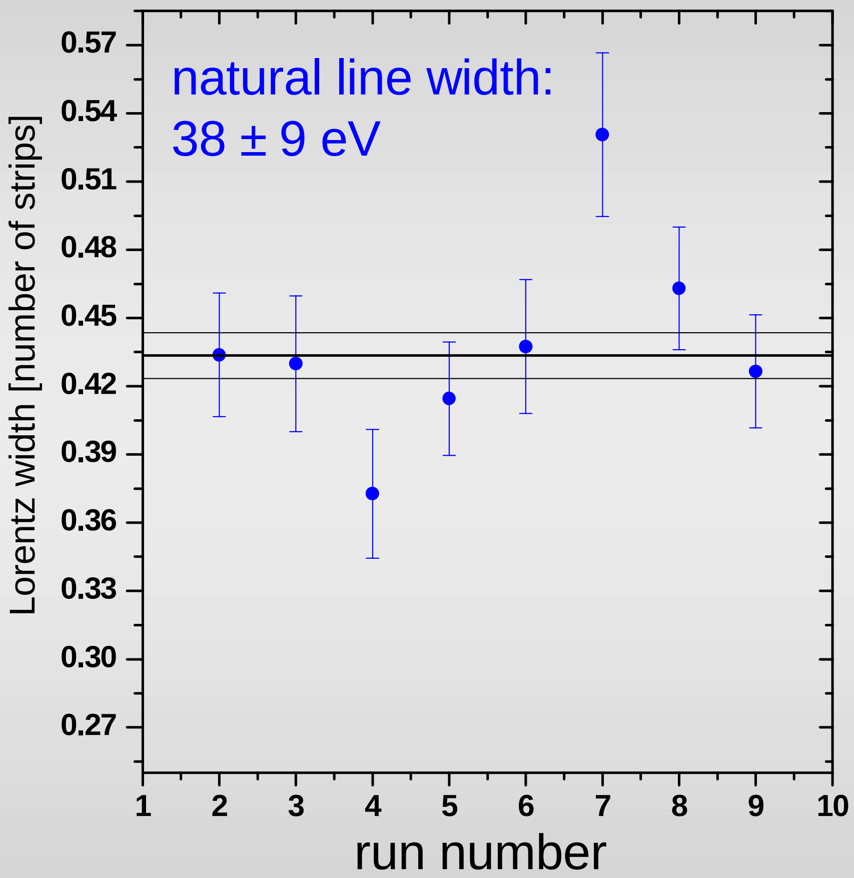
Bragg-Laue relation

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

Transmission crystal spectrometer
towards an accuracy of 1 eV



using micro-strip detectors, lifetimes of atomic statest are accessible (natural line width)



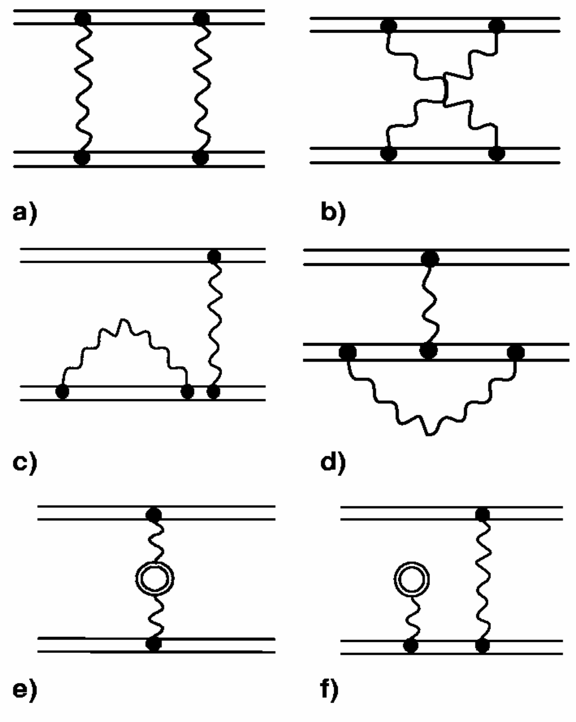
natural line width
theory: 30 eV

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

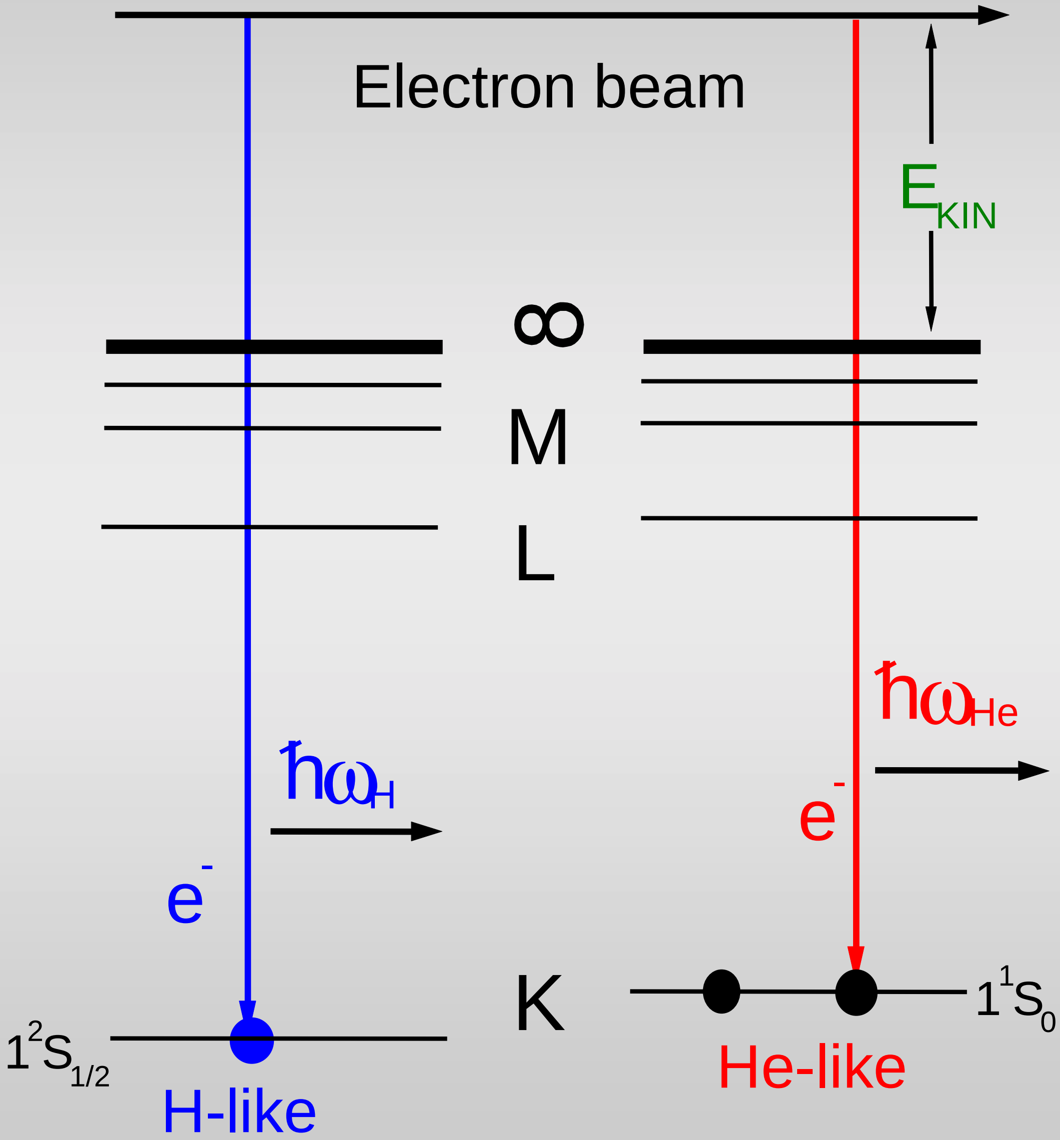


a,b) Non-Radiative QED
+1.3 eV [U^{90+}]
0.06%

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:

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

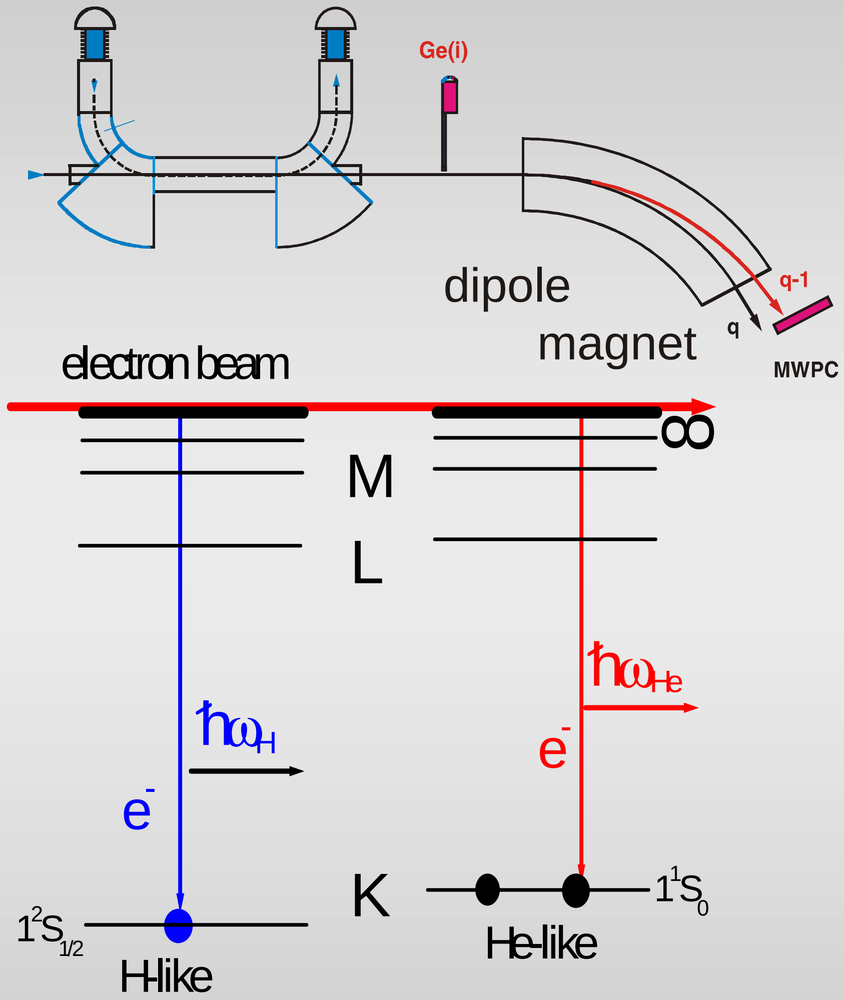
$$E(\hbar\omega_H - \hbar\omega_{He}) = I_H - I_{He}$$

Advantage of relative measurement:

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

2eQED Studies for the Ground State

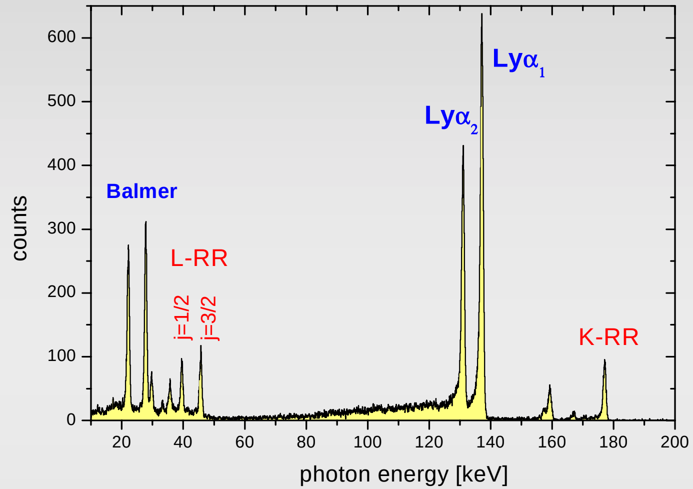
0 deg spectroscopy at the electron cooler



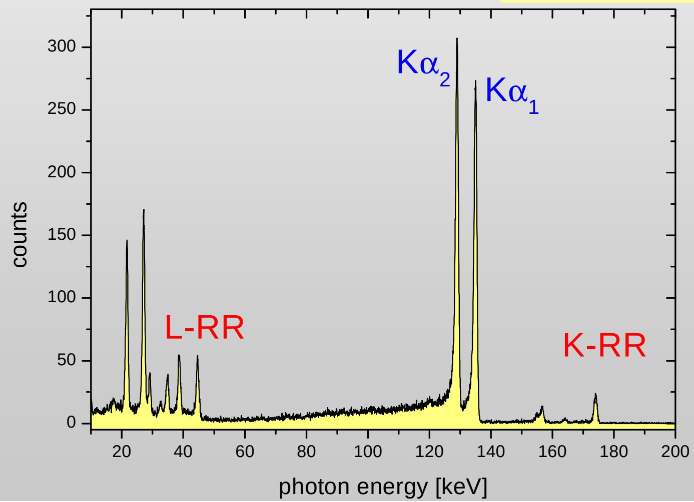
$$E_{KIN} + I_H = \hbar\omega \qquad E_{KIN} + I_{He} = \hbar\omega$$

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

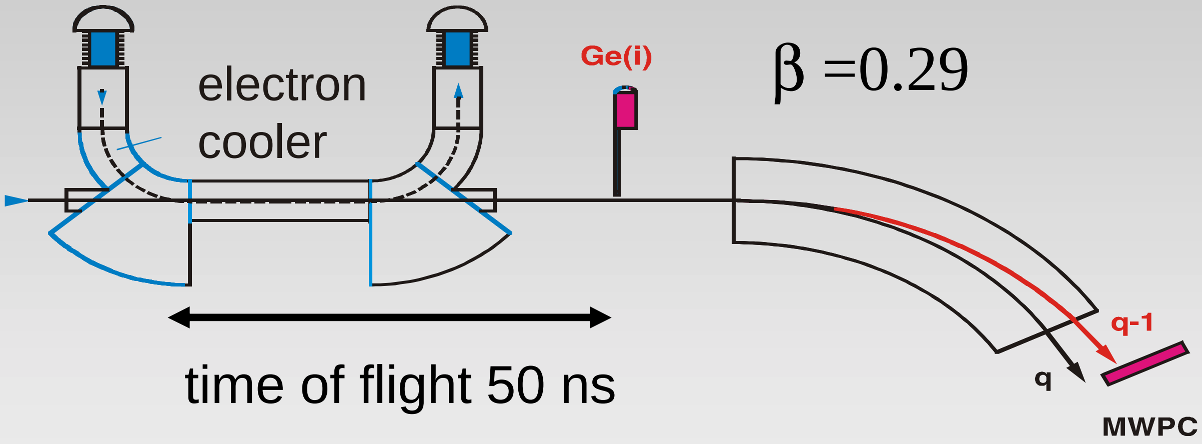
H-like uranium

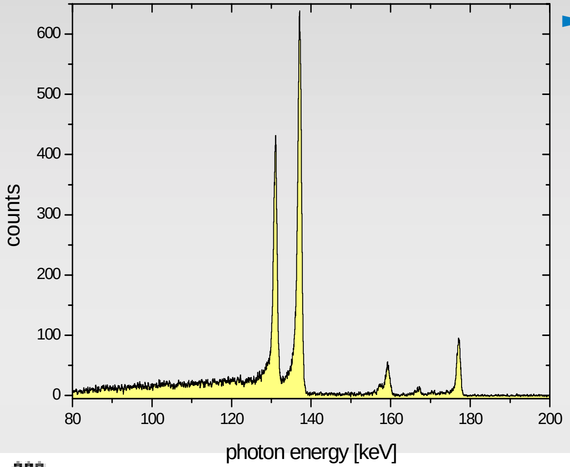


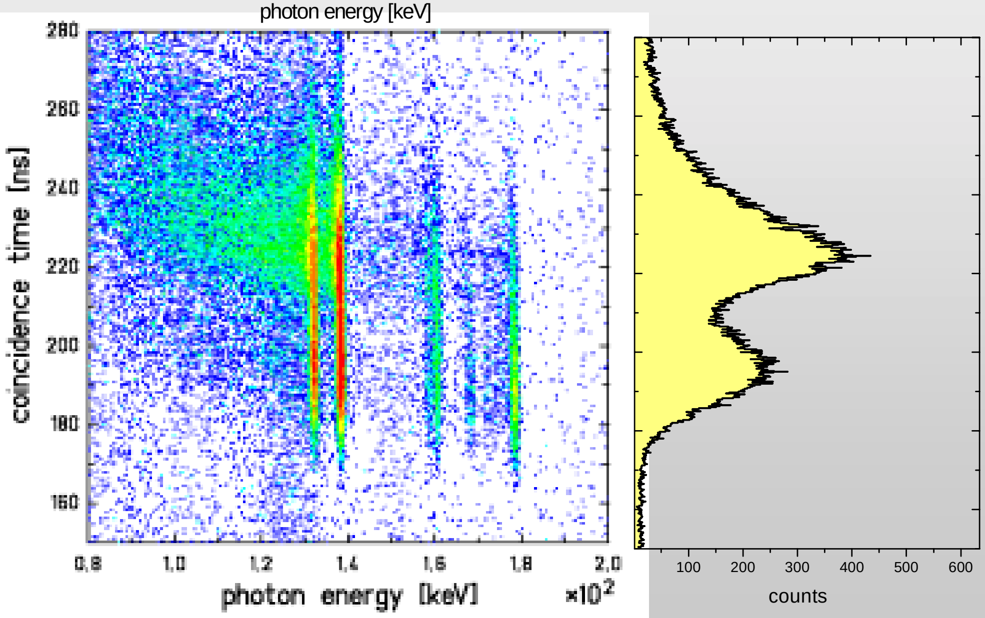
He-like uranium

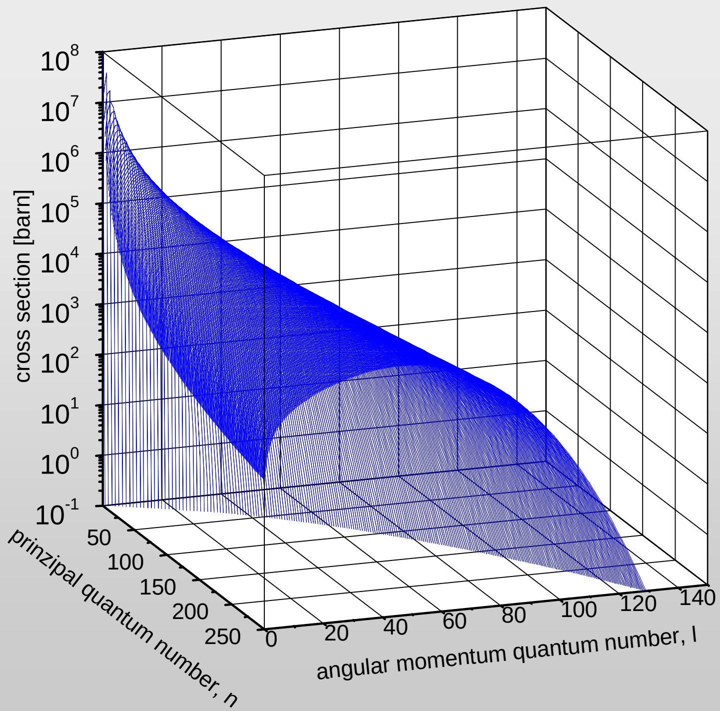


0 deg spectroscopy at the electron cooler

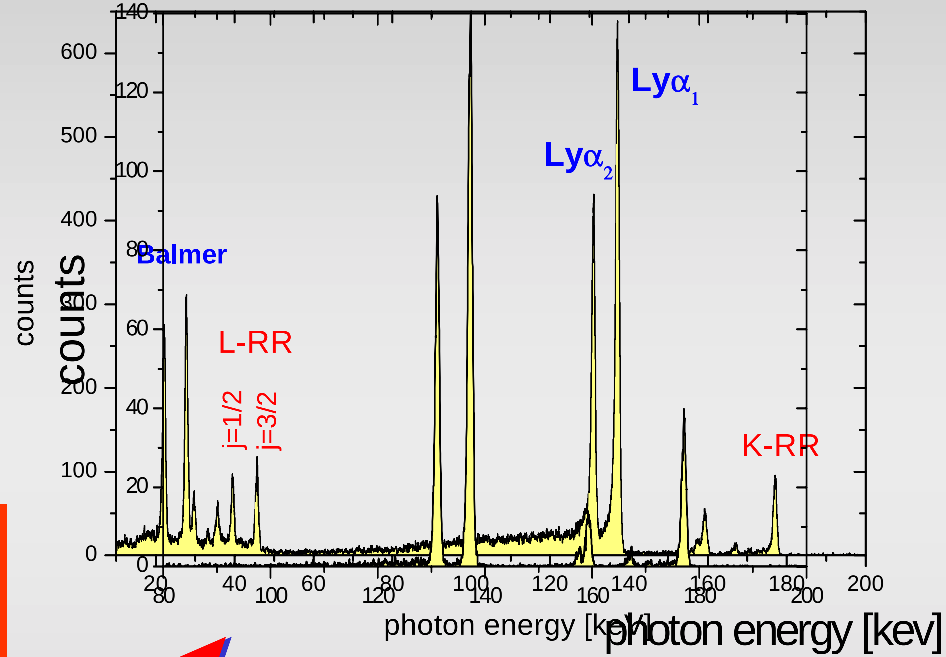


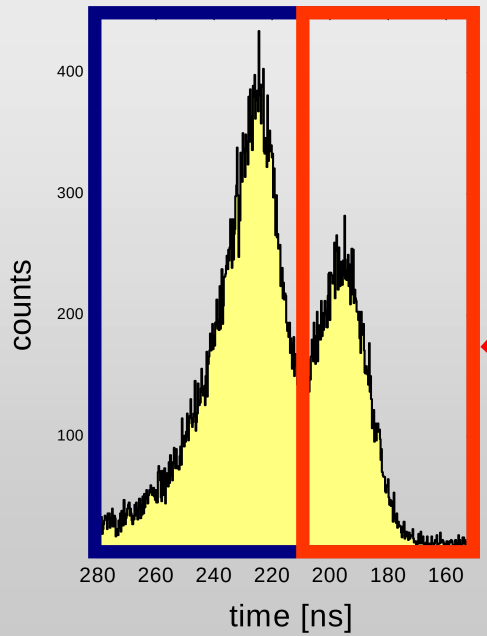






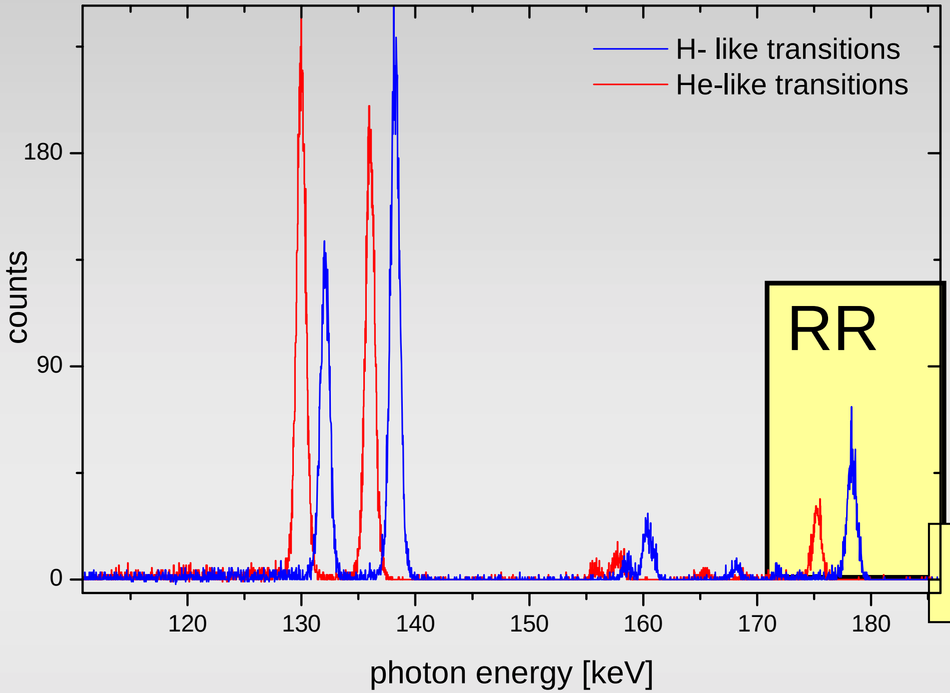
0 deg spectroscopy at the electron cooler





time condition

Relative measurement at the electron cooler



Prel. Result

2.248keV ± 9 eV

A. Gumberidze

Estimated statistical uncertainty for RR into H- and He-like uranium: ≈ 9 eV

Uncertainty caused by doppler shift:

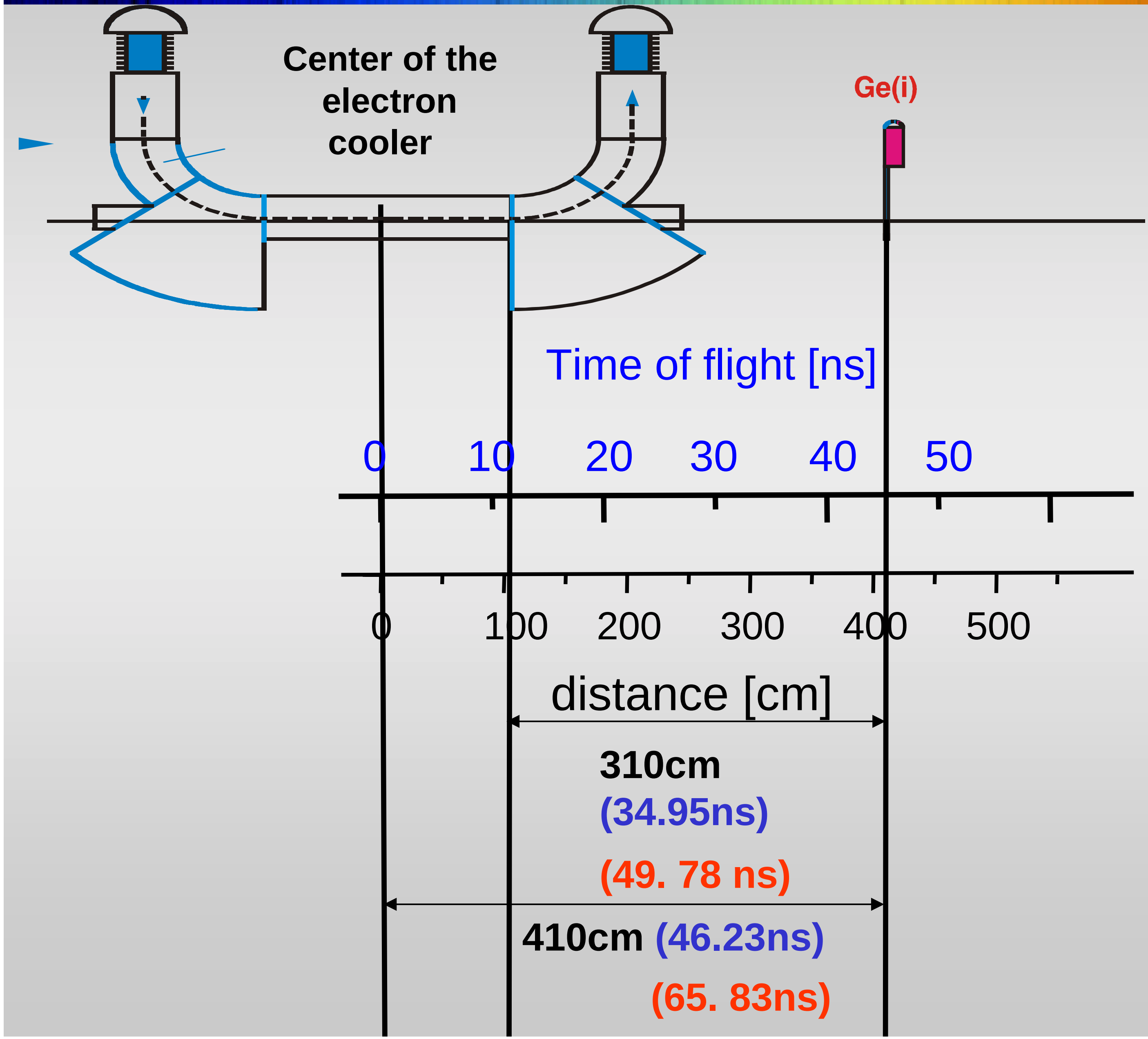
Additional systematic errors: ?

Two Electron

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

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

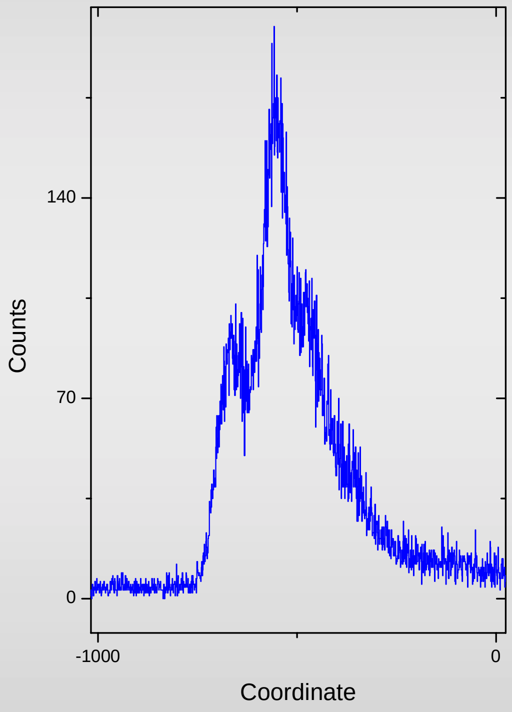
0 deg spectroscopy at the electron cooler



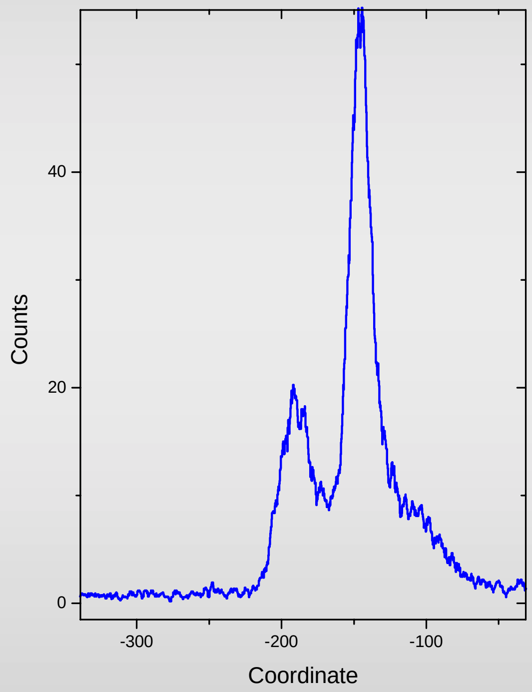
E=43.5904 MeV/u
β =0.29565
γ=1.0468

E=20.74 MeV/u
β=0.20761
γ=1.0223

0 deg spectroscopy at the electron cooler



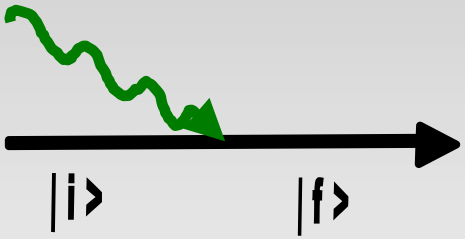
43 MeV/u



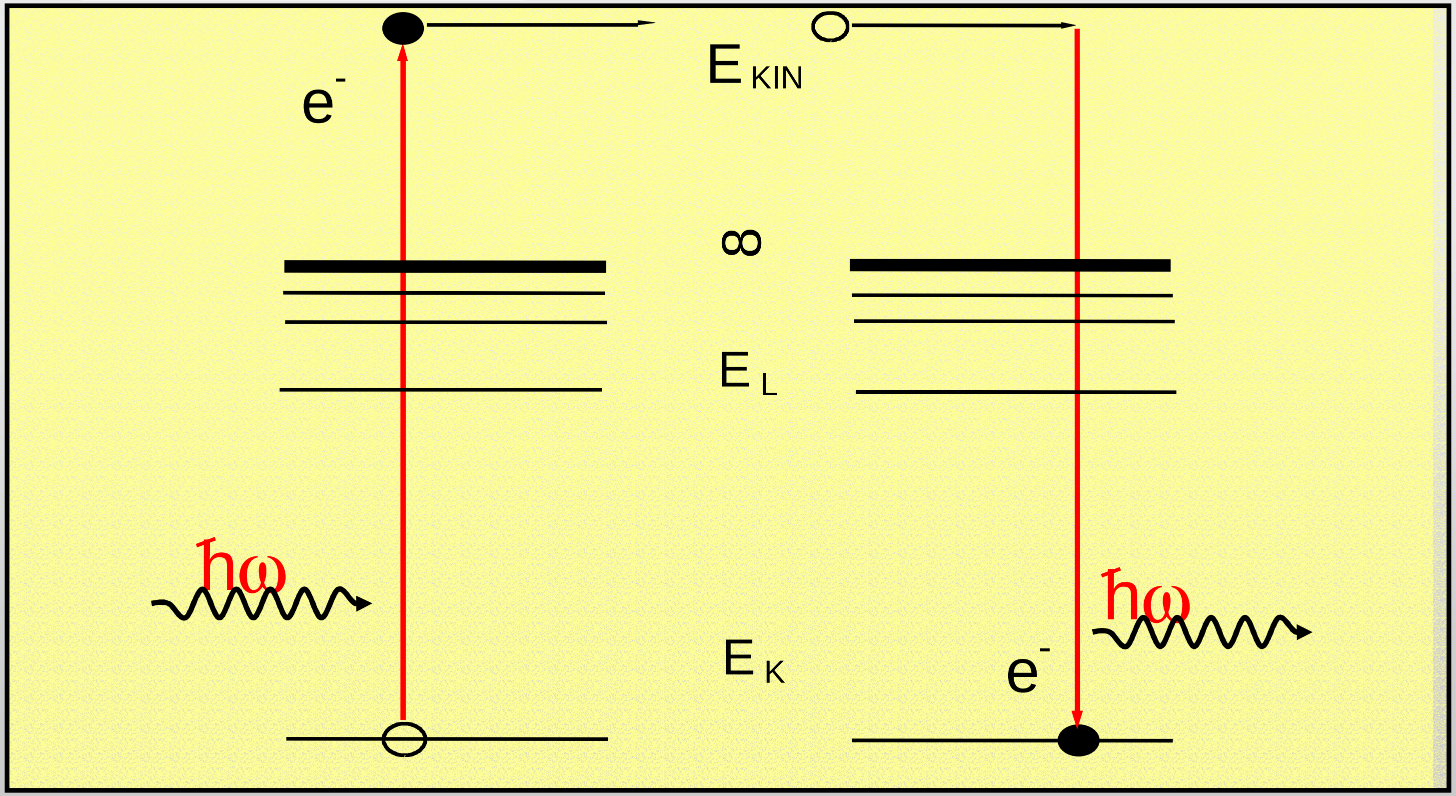
21 MeV/u

Photon-Matter Interaction in the Relativistic Regime

Radiative Electron Capture

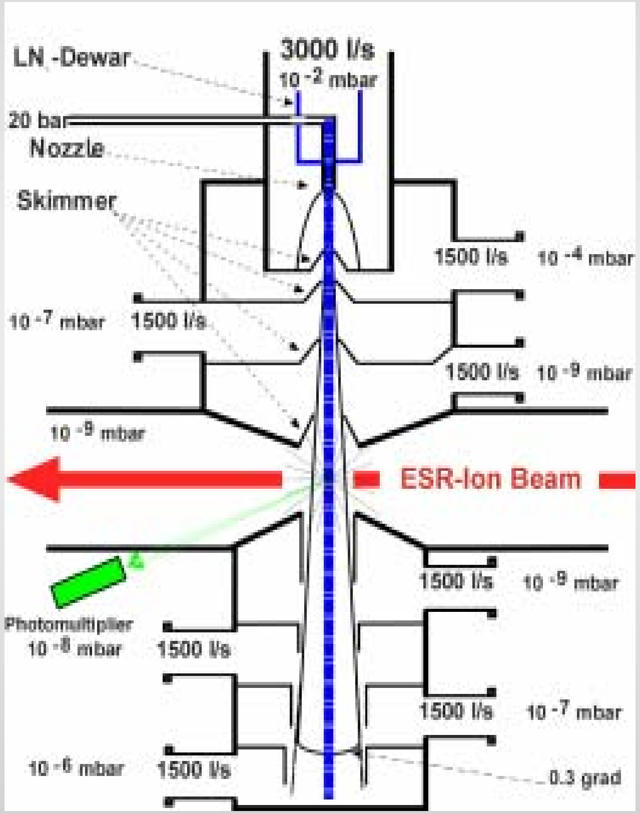


Photoionization **Radiative Electron Capture**



Experiments at the Jet-Target

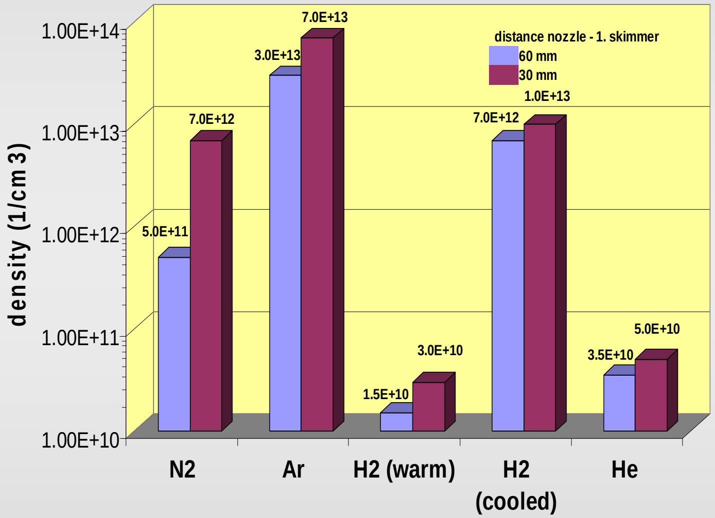
The Jet-Target



Target densities

$10^{12} – 10^{14}$ p/cm³

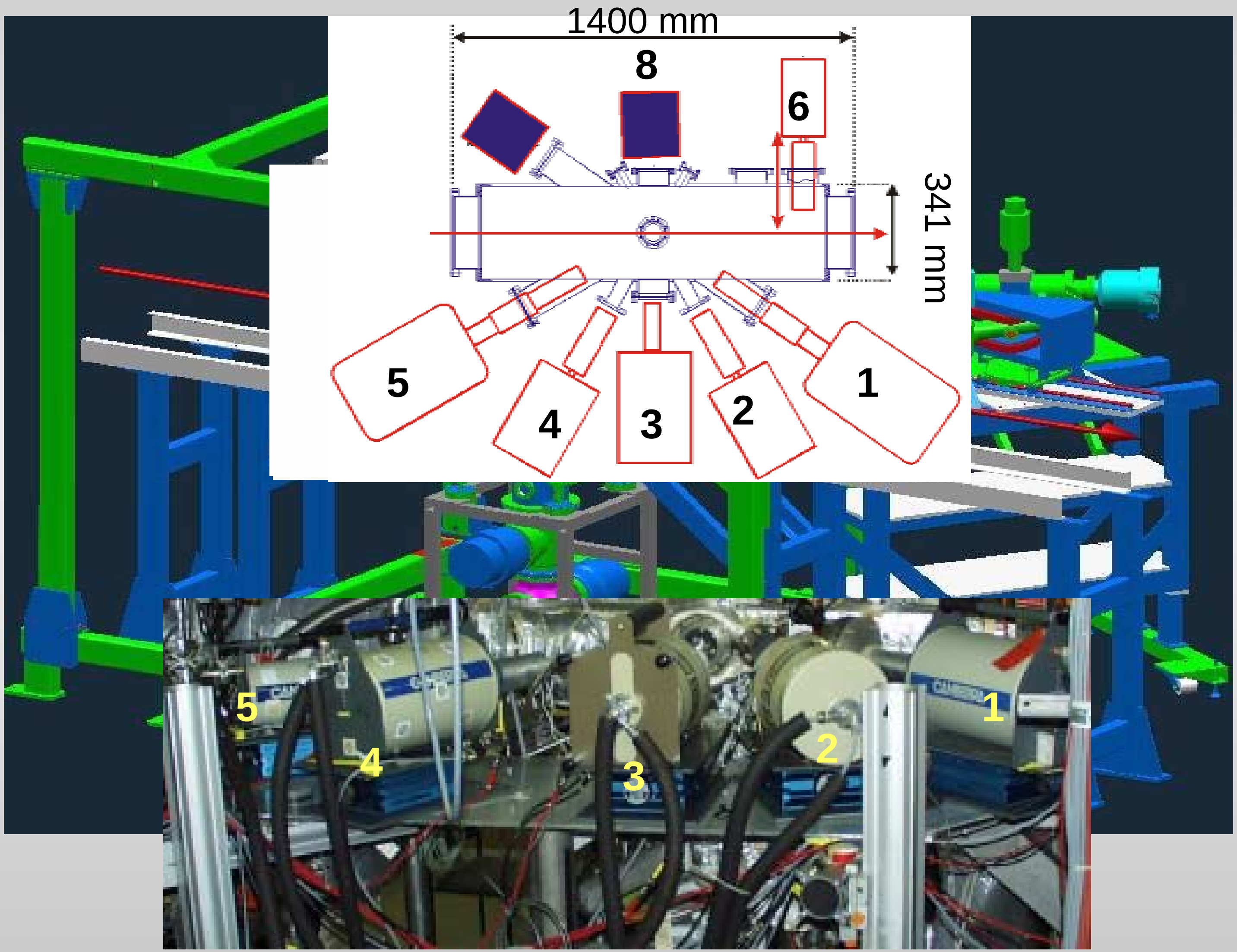
Single collision conditions



Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)

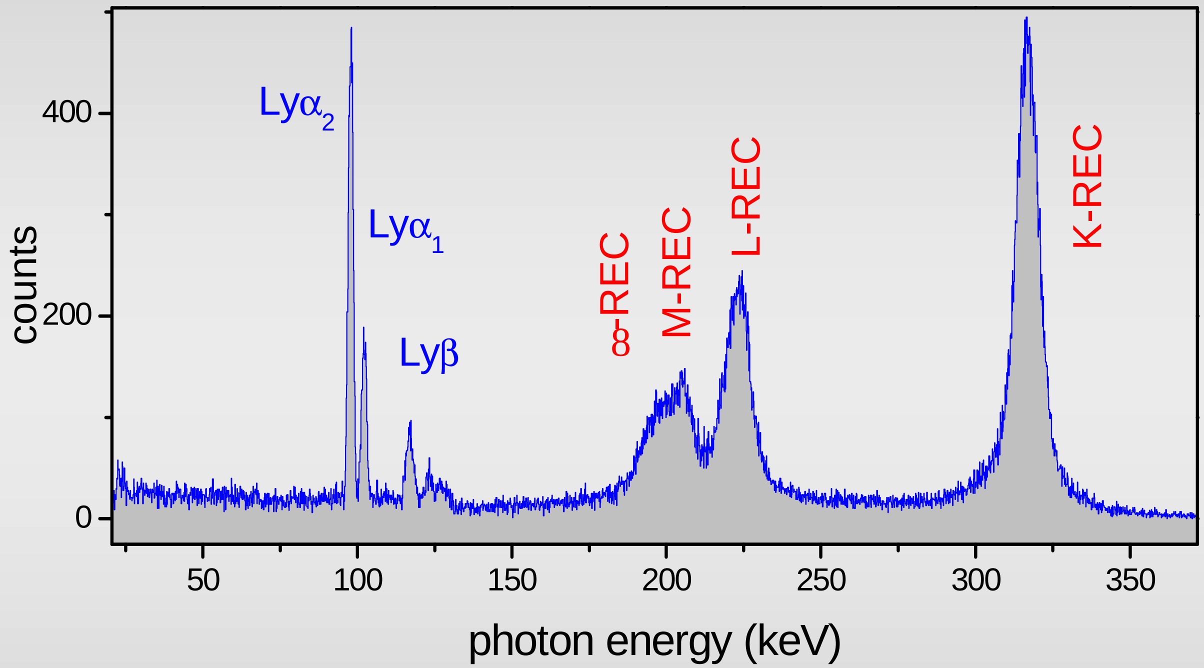
A. Krämer et al, NIM B 174. 205 (2001)

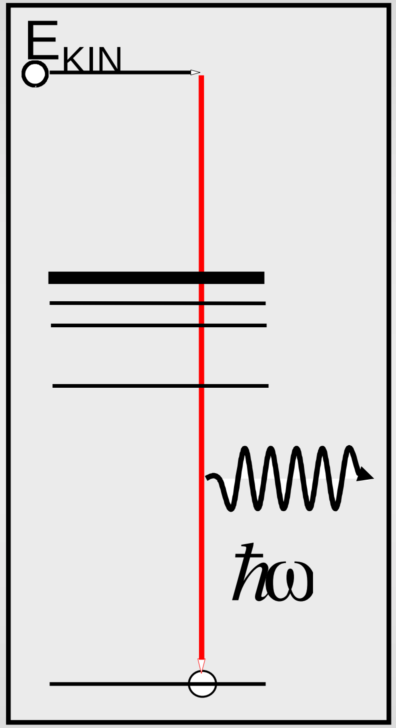
Experiments at the Jet-Target



Radiative Electron Capture Capture of Quasifree Targetelectrons

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





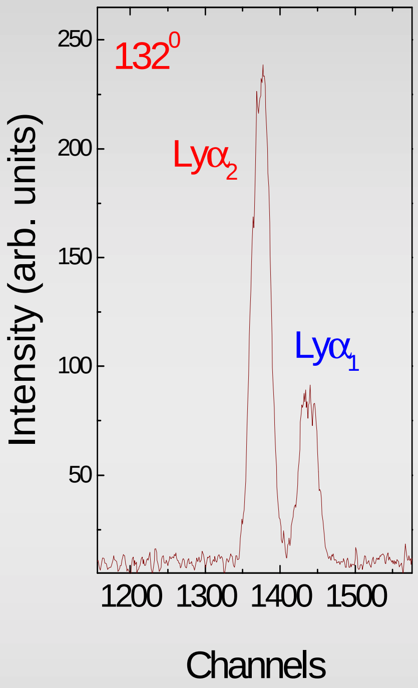
REC photon energy

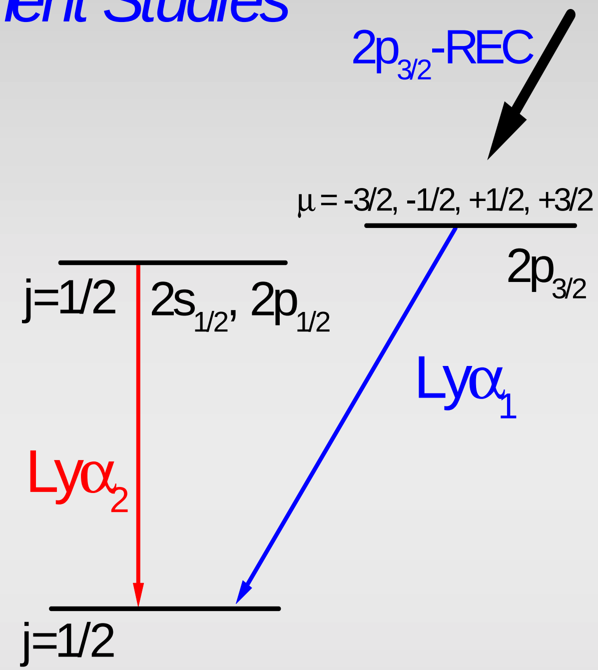
$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$

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

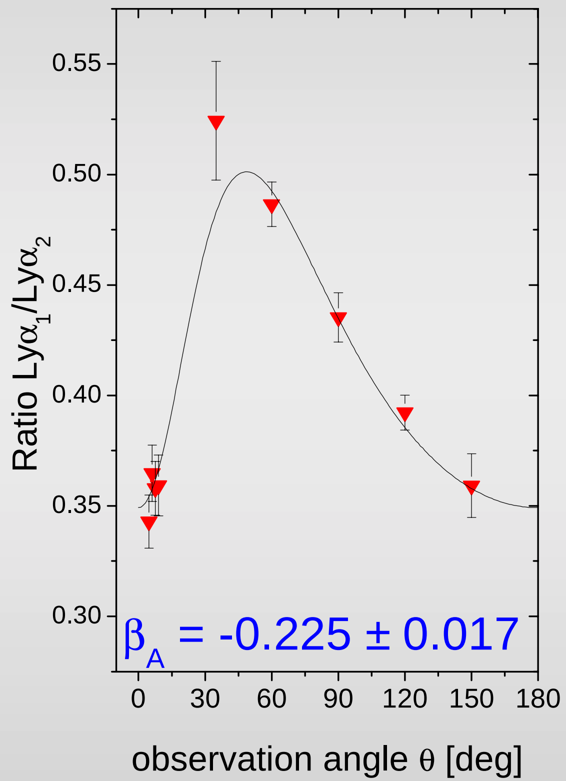
$2p_{3/2}$ transitions in high-Z ions produced by REC

Alignment Studies





$Ly\alpha_1$ transitions at 310 MeV/u



1st photon: resonant excitiation to the $2p_{3/2}$ state

+

2nd photon: ionization

$$W(\theta) \propto 1 + \beta_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$

$$\Delta t \approx 10^{-17}\ s$$

Alignment Studies

non-statistical population of the magnetic sublevels of the $2p_{3/2}$ state leads to an anisotrope photon emission

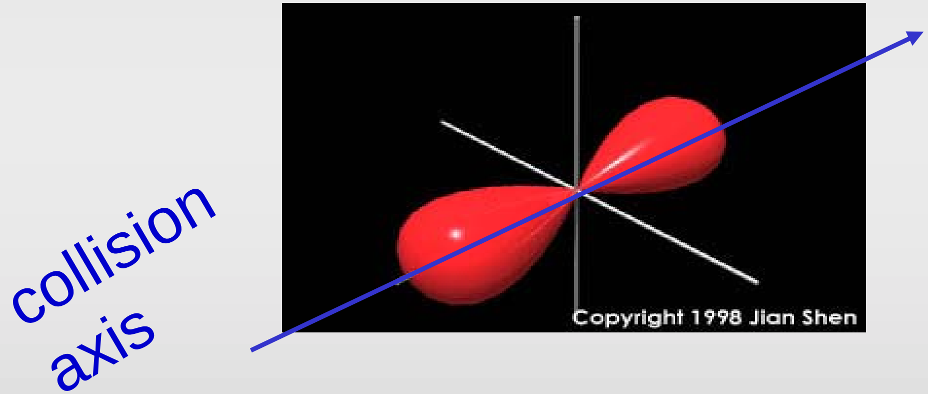
$$W(\theta) \propto 1 + \beta_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$

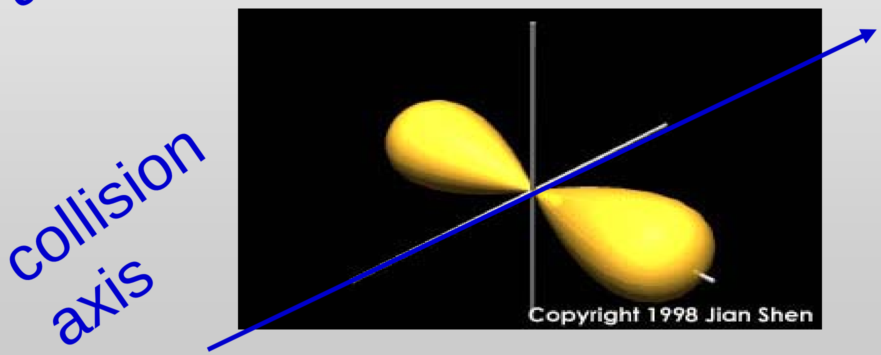
alignment parameter
$\beta_A < 0$

prefered population
of **$m_j = \pm 1/2$**

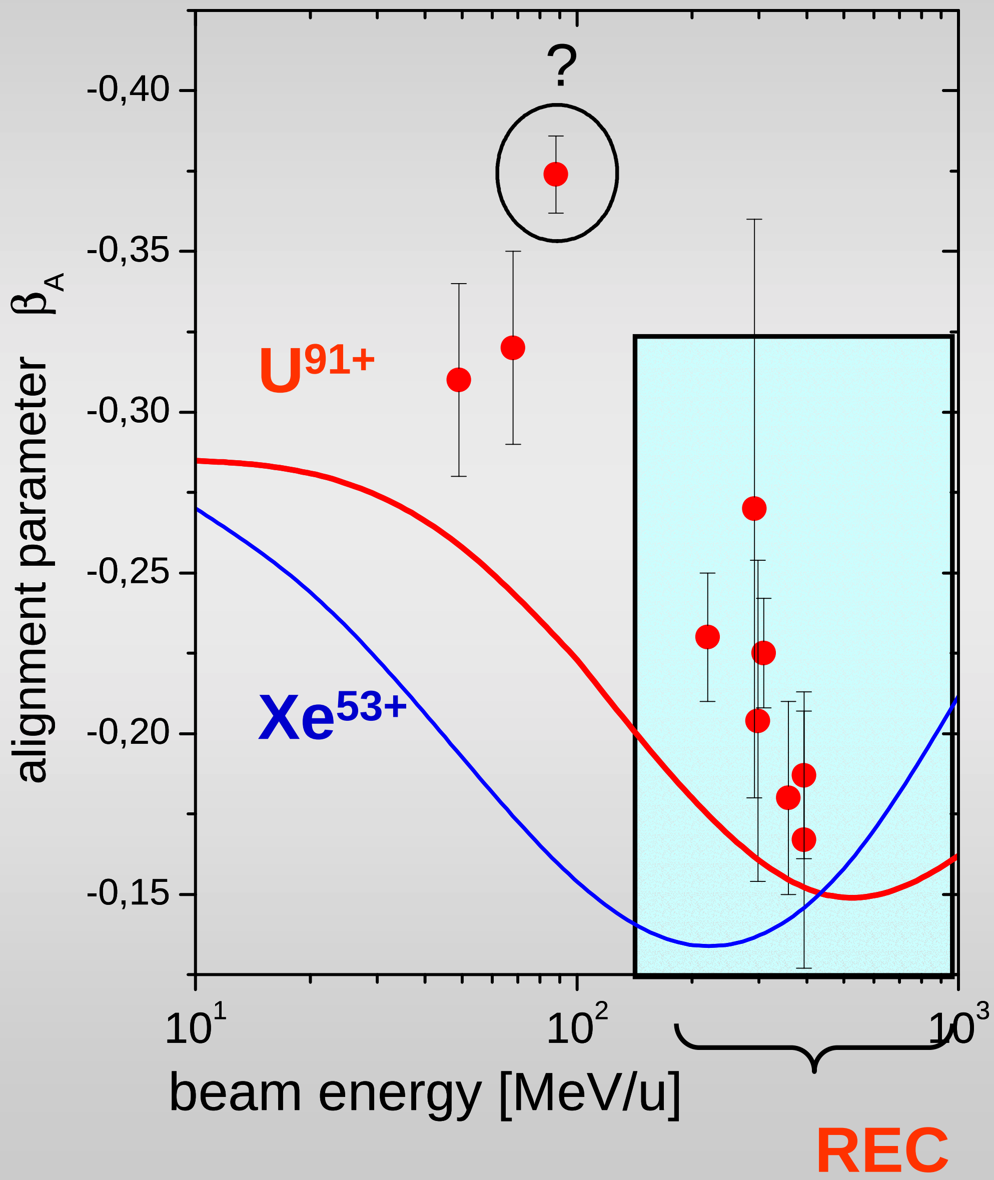
alignment parameter
$\beta_A > 0$

prefered population
of **$m_j = \pm 3/2$**





Strong Alignment Observed for REC into the $2p_{3/2}$ State



Theory by J. Eichler et al.

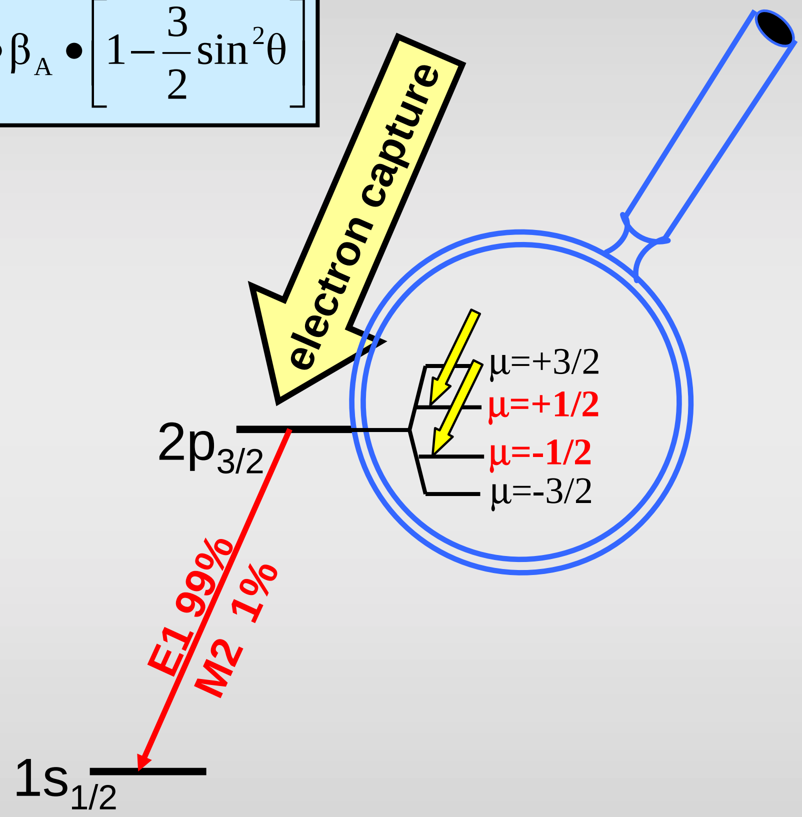
Disagreement with theory ?

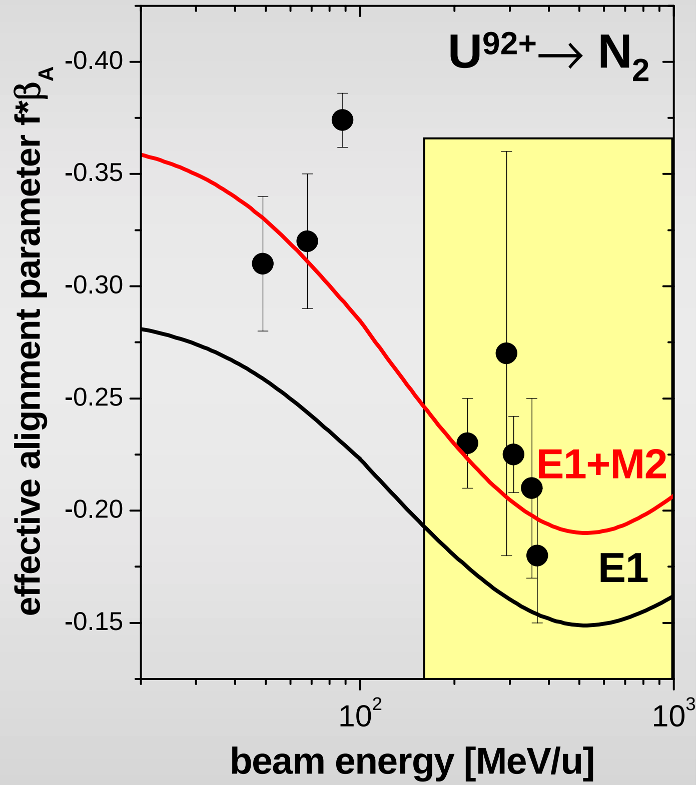
PRL 79, 3270 (1997)

Multipolmixing (E1/M2) observed for atomic transitions

[$2p_{3/2} \rightarrow 1s_{1/2}$ Transition in High-Z H-Like Ions]

$$W(\theta) \propto 1 + f\left(\frac{a_{M2}}{a_{E1}}\right) \bullet \beta_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$

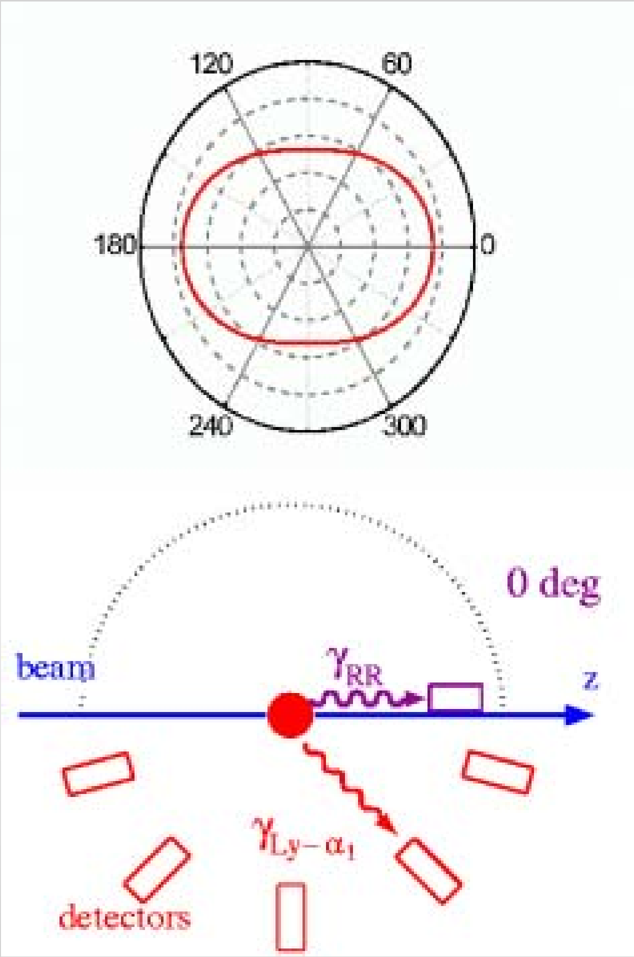


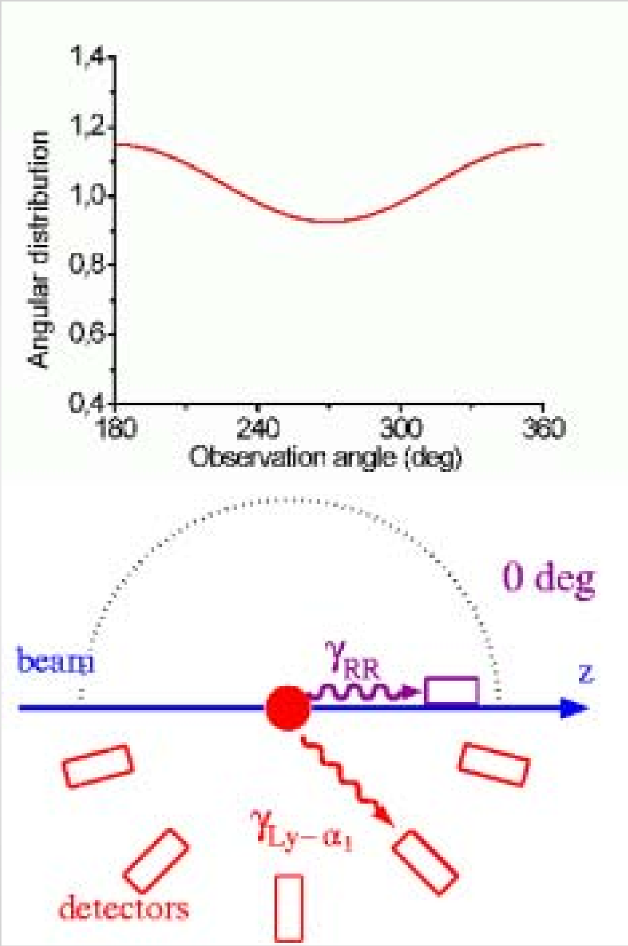


$$f\left(\frac{a_{M2}}{a_{E1}}\right) = 1.38 \pm 0.07 \Rightarrow \frac{\langle\|M2\|\rangle}{\langle\|E1\|\rangle} = 0.11 \pm 0.02 \Rightarrow \frac{\Gamma_{M2}}{\Gamma_{E1}} = 0.012 \pm 0.004$$

Surzhykov et al., PRL 88, 153001 (2002)

Differential Alignment Distribution





X-X angular correlations

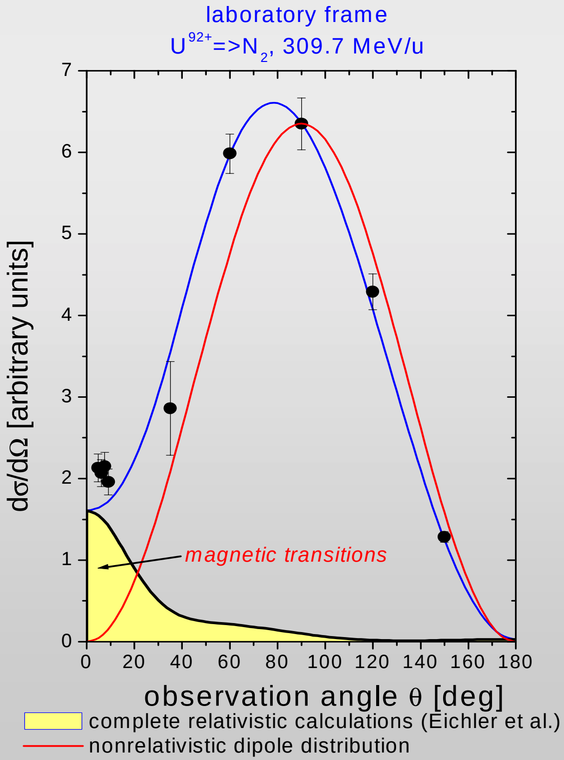
A. Surzhykov and S. Fritzsche, 2002

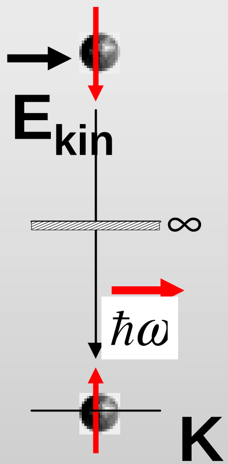
Experimental REC studies performed up to now

total REC cross sections for bare ions up to uranium (20 MeV/u – 170 GeV/u) ✓

photon angular distribution studies for REC into the ground and excited states ✓

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

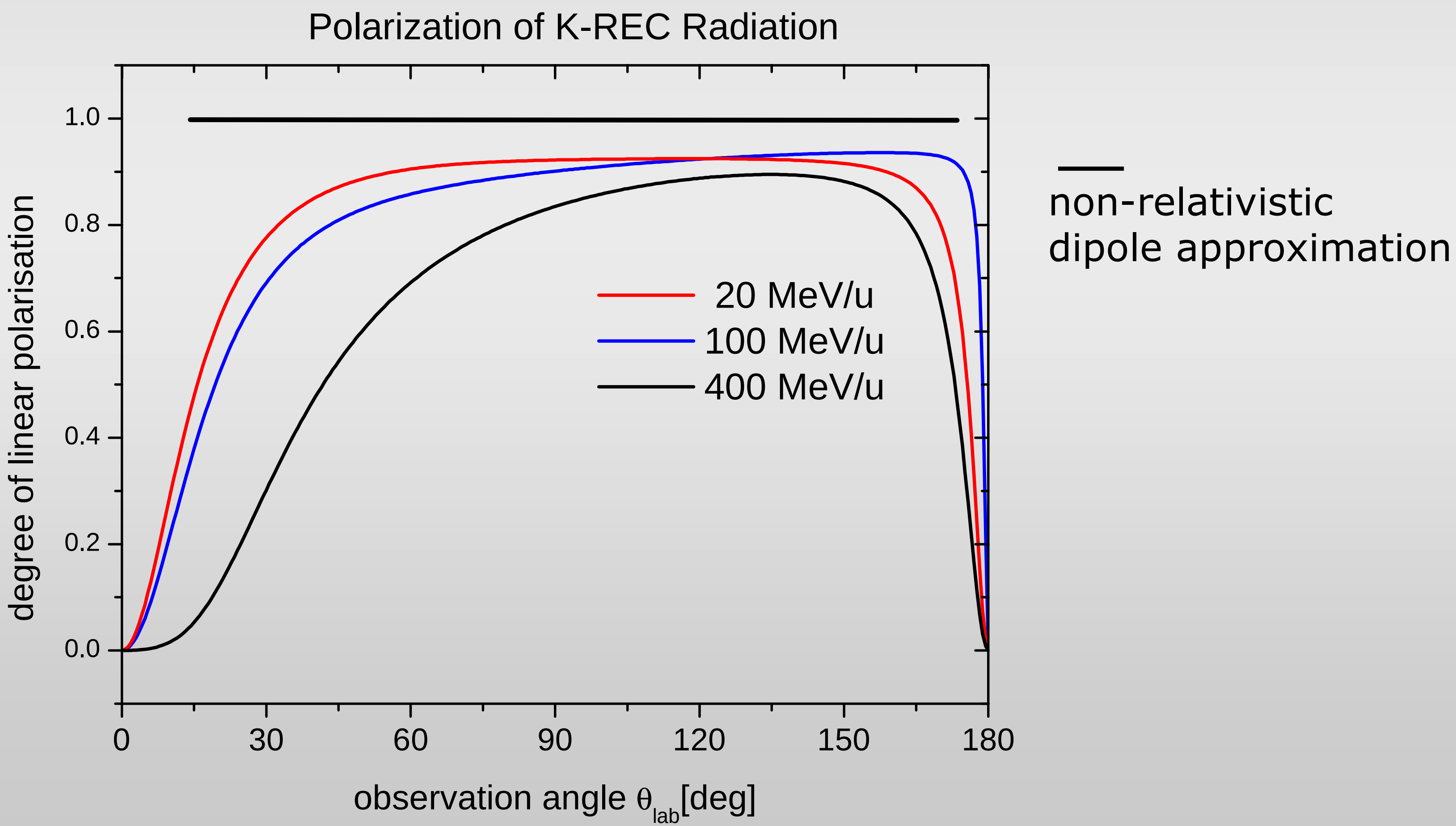




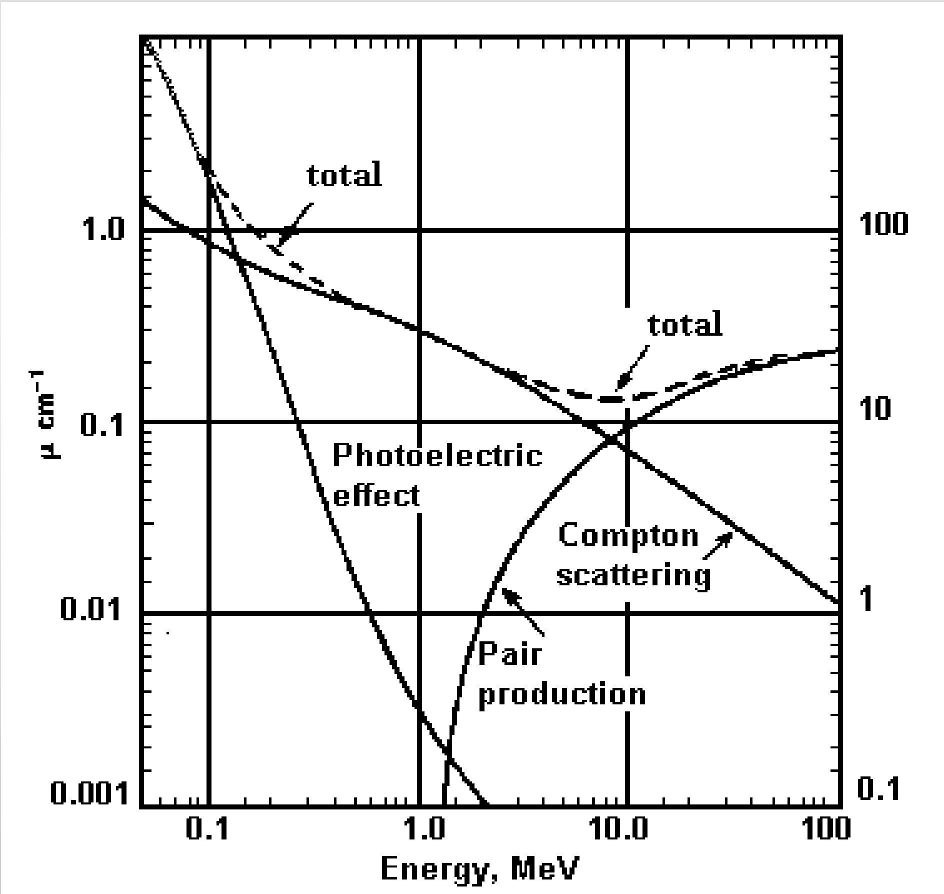
Open Questions

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)

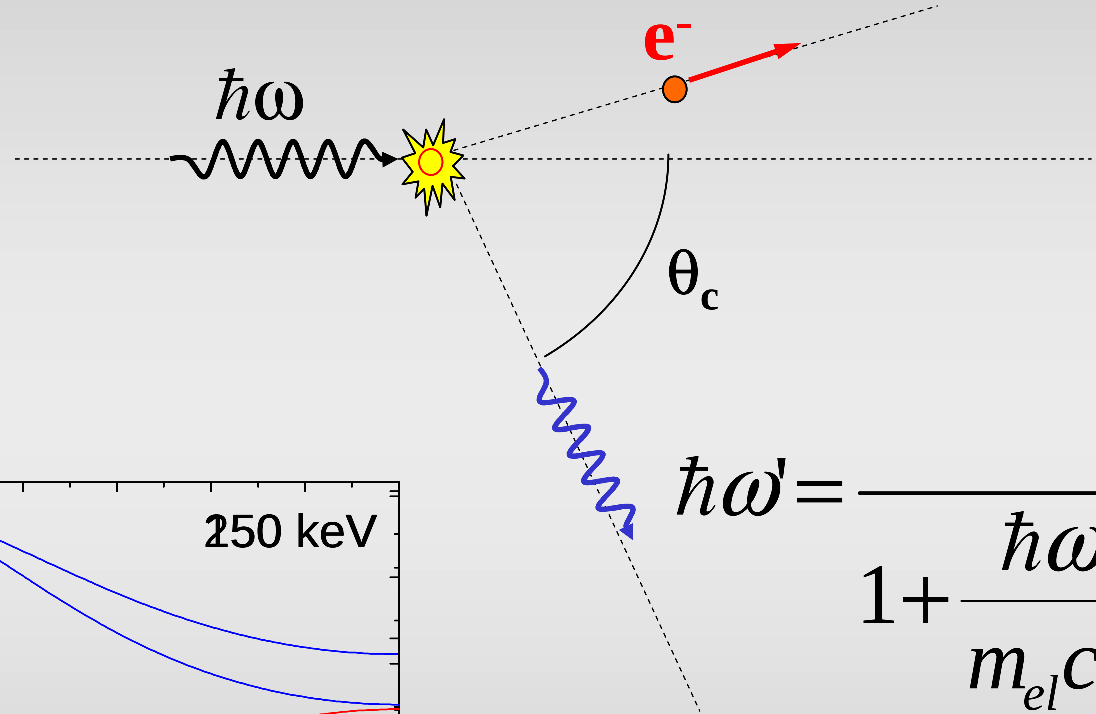


Interaction of electro-magnetic radiation with matter

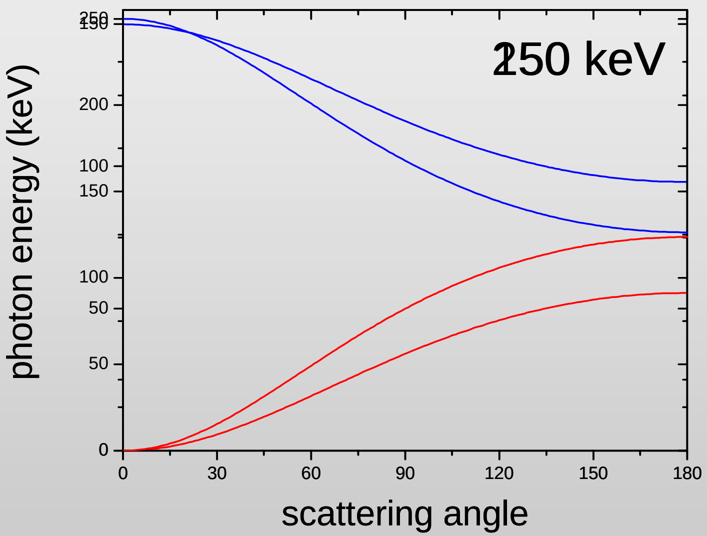


- photoelectric effect
- *Compton scattering*
- pair production

Compton scattering



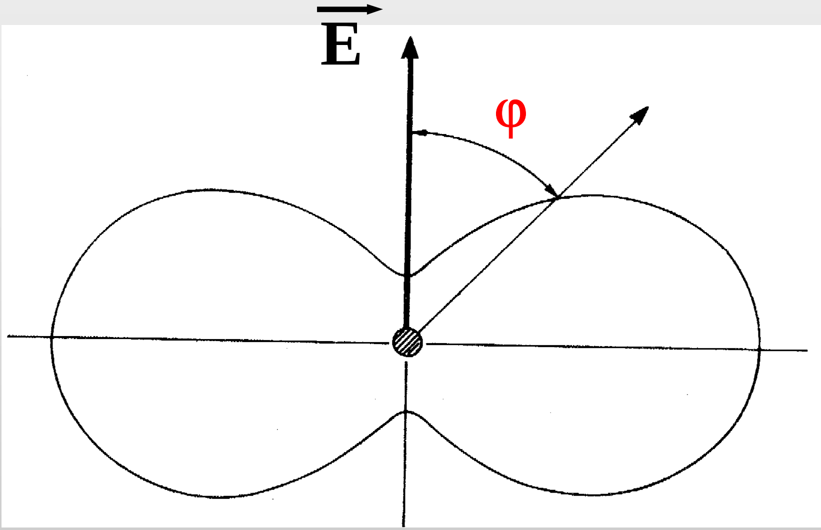
$$\hbar\omega' = \frac{\hbar\omega}{1+\frac{\hbar\omega}{m_{el}c^2}(1-\cos\theta_c)}$$

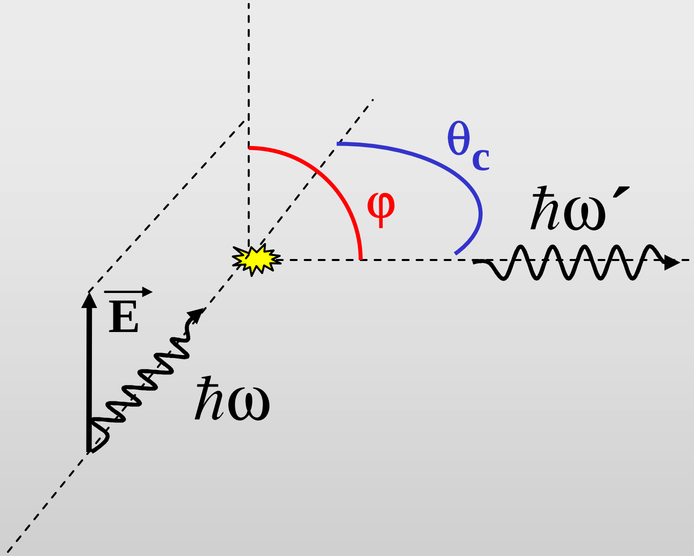


Polarization Measurements by Means of Compton Scattering

Klein-Nishina formula

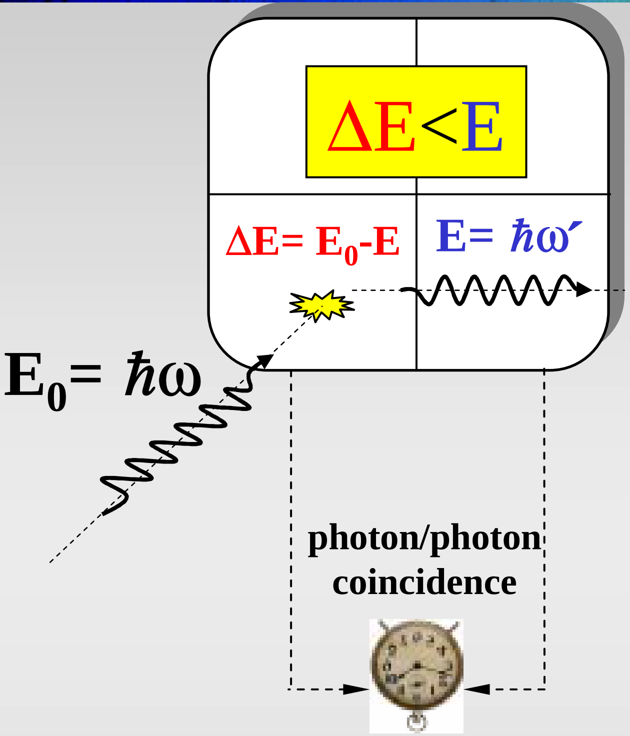
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta_c \cos^2\varphi\right)$$

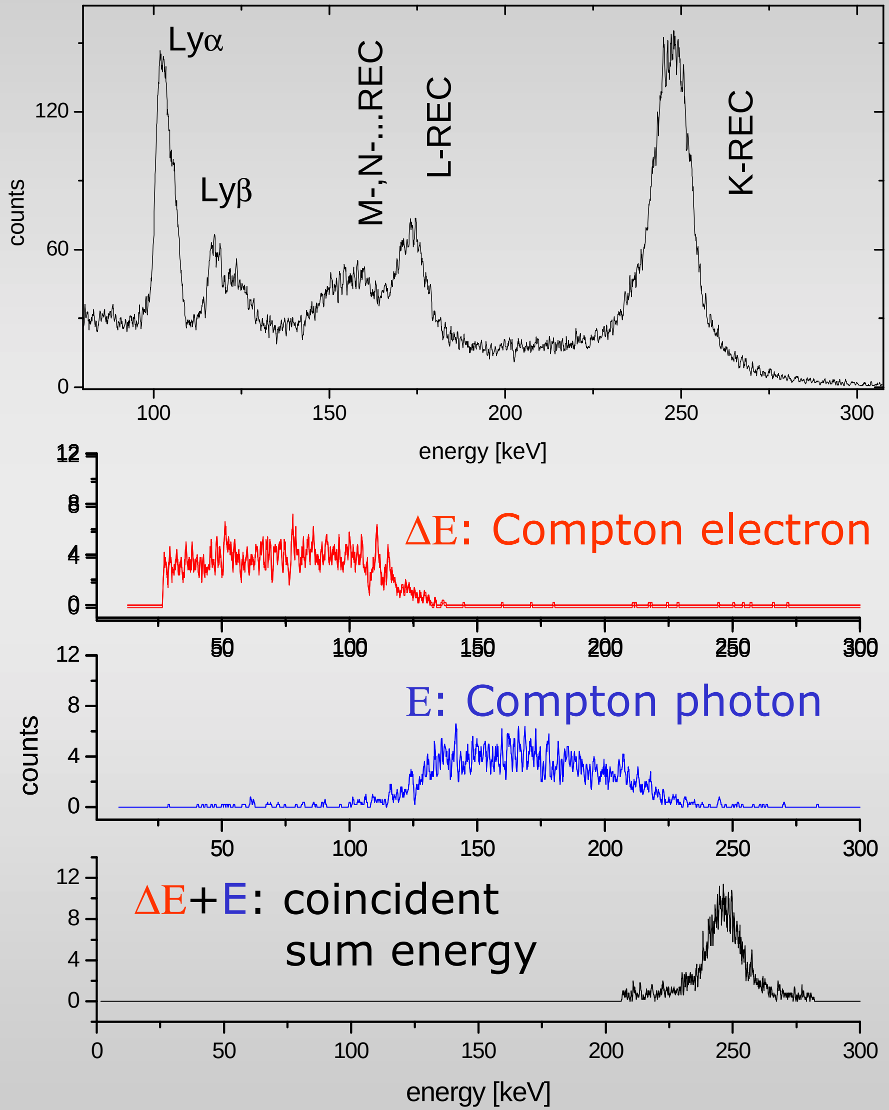




angular distribution of scattered photons

Compton scattered photons

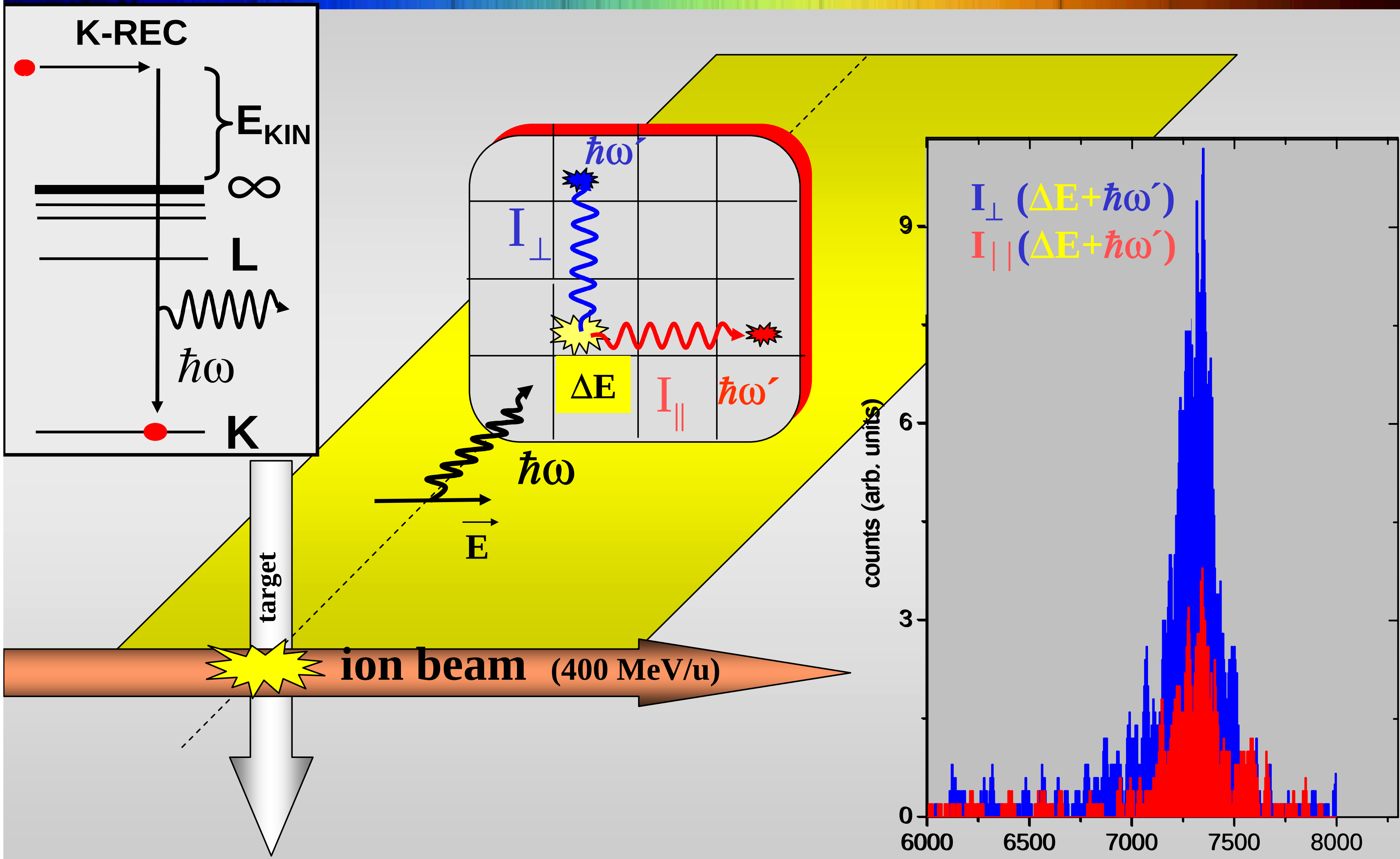




energy deposition in two independent parts of the detector

reconstruction of compton events

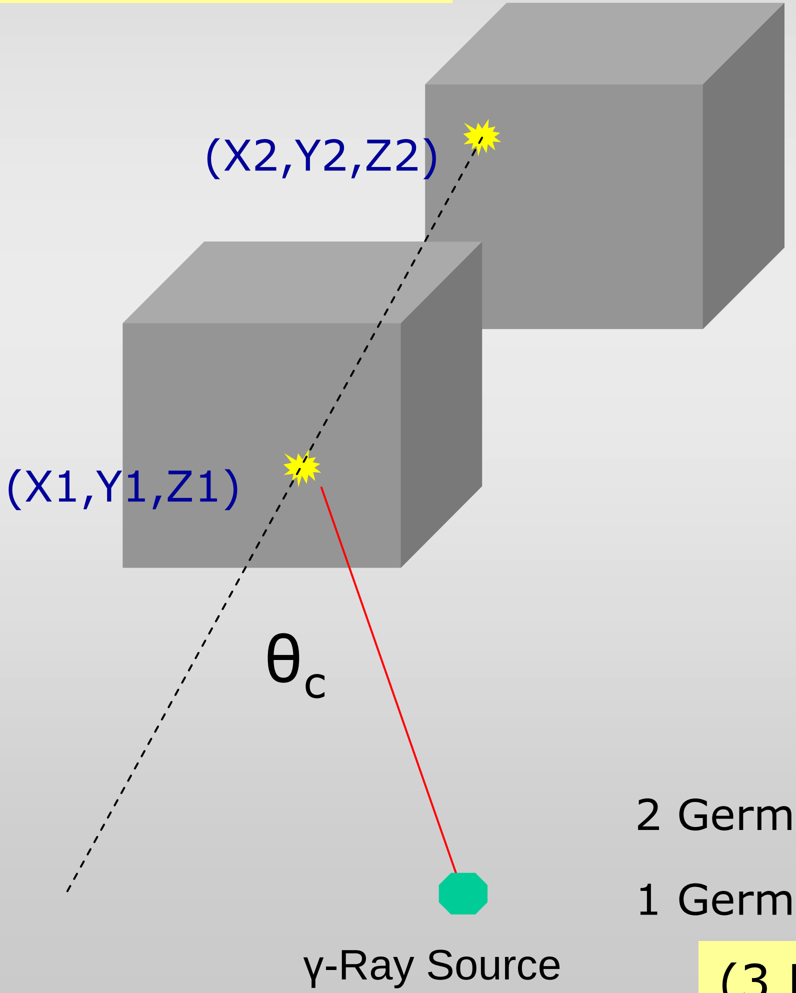
First Polarization Measurement for Radiative Recombination Transitions ($U^{92+} + e^{-} \Rightarrow U^{91+} + \hbar\omega$)



preliminary data from the ESR beam time May 2002

Compton/Gamma Camera

$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_{el}c^2}(1-\cos\theta_c)}$$



Imaging Quality depends on

- energy resolution
- spatial resolution
- Compton profile

(LBL, Burke et al. NRL; Kroeger et al.)

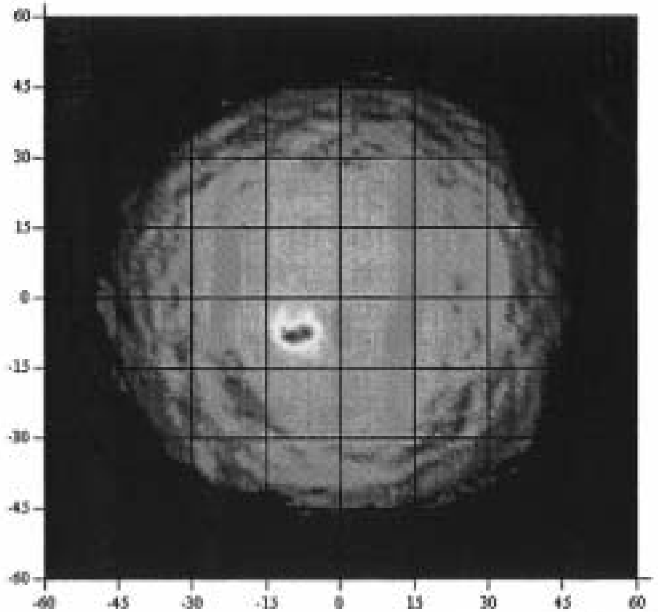
2 Germanium Detectors for $\hbar\omega$ > 1 MeV

1 Germanium Detector for $\hbar\omega$ ≈ 300 keV

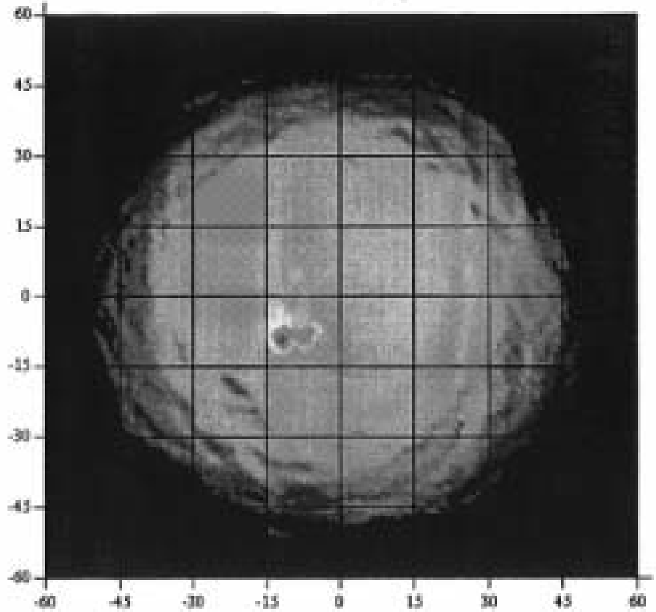
(3 D position sensitive)

Compton Telescope

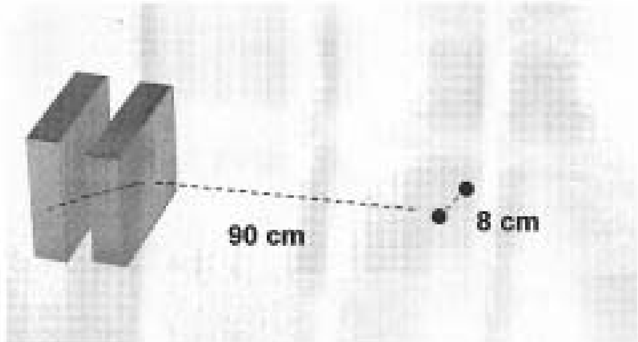
Resolving between two point sources (each 662 keV)



3.8° separation

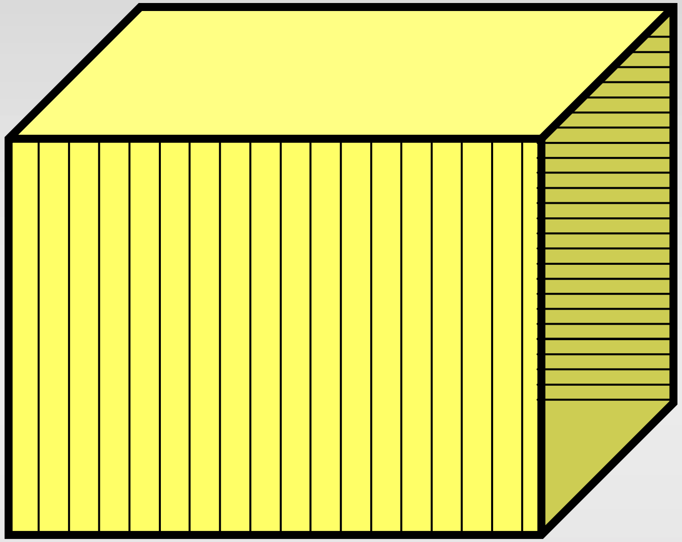


5° separation



Source size ~1.3°

Compton/Gamma Camera



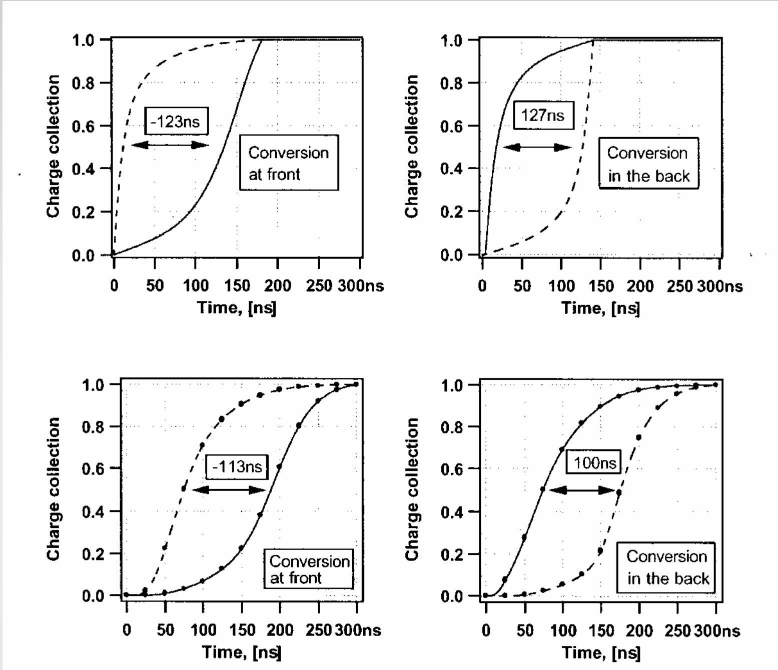
double sided Ge(i)
strip detector
(3D position sensitive)

128 x 320 µm
24   x 1.3 mm

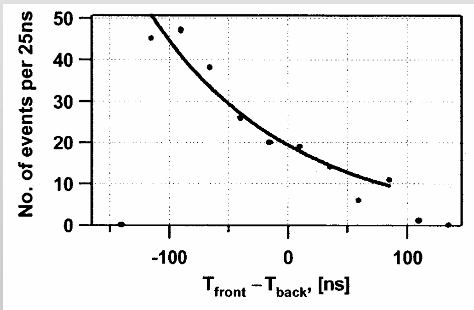
Thickness: 2 cm

D. Protic, FZ-Jülich

3D read out: z direction



M. Momayezi et al. 1999



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

Development of 3D x-ray detectors

Experiments with polarized targets and ions

Combined photon, electron and recoil ion momentum spectroscopy

Structure and Collision Studies at High-γ