Angular Correlation and Polarization Studies for Radiative Electron Capture into High-Z Ions

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in collaboration with

Experiment

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University of Cracow, Poland
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Theory

J. Eichler, S. Fritzsche, A. Ichihara,
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JAERI, Japan
TU-Dresden, Germany
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University of Kassel, Germany

Angular Correlation and Polarization Studies

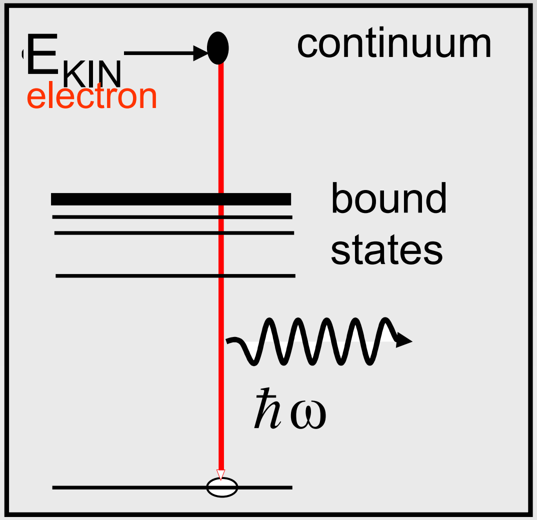
- **Introduction**
- **Relativistic Effects in Electron-Ion Recombination and Electron Capture**

  Population of Magnetic Sub-Levels

  Multipole-Mixing
- **Photon Angular Distributions**

  Capture into the Ground and Excited States
- **Photon Polarization Studies for Radiative Recombination**
- **Summary and Outlook**

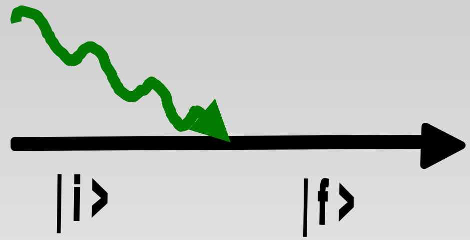
Radiative Recombination (RR) / Electron Capture (REC)



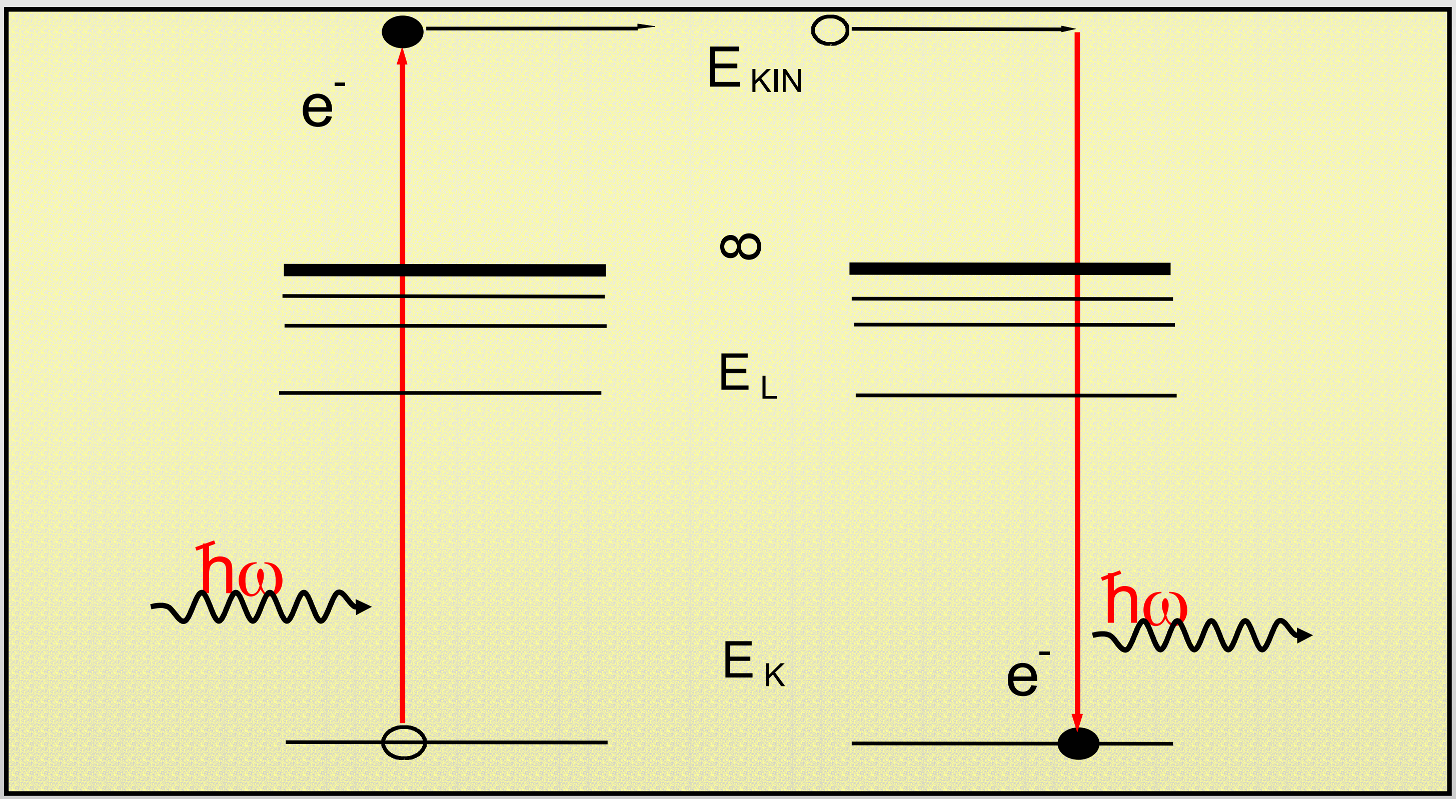
- *Electron capture into a bound ionic state by emission of a photon*

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

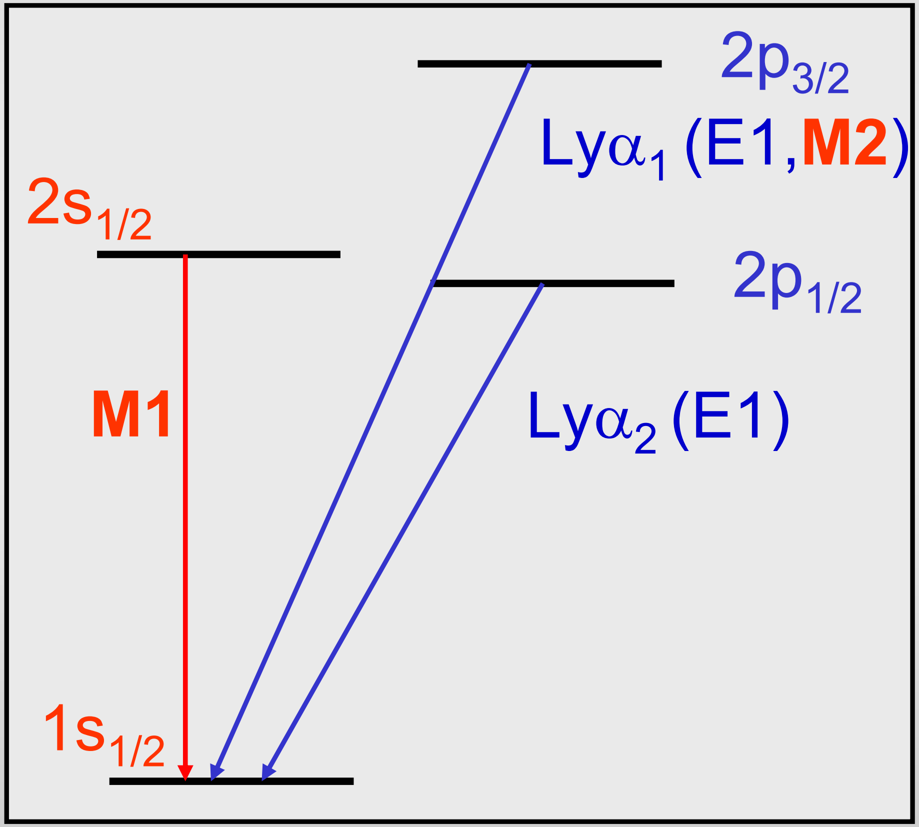
- *Time-reversed photionization*
- *Only possible capture/recombination process for bare ions colliding with electrons*



Photoionization **Radiative Electron Capture**



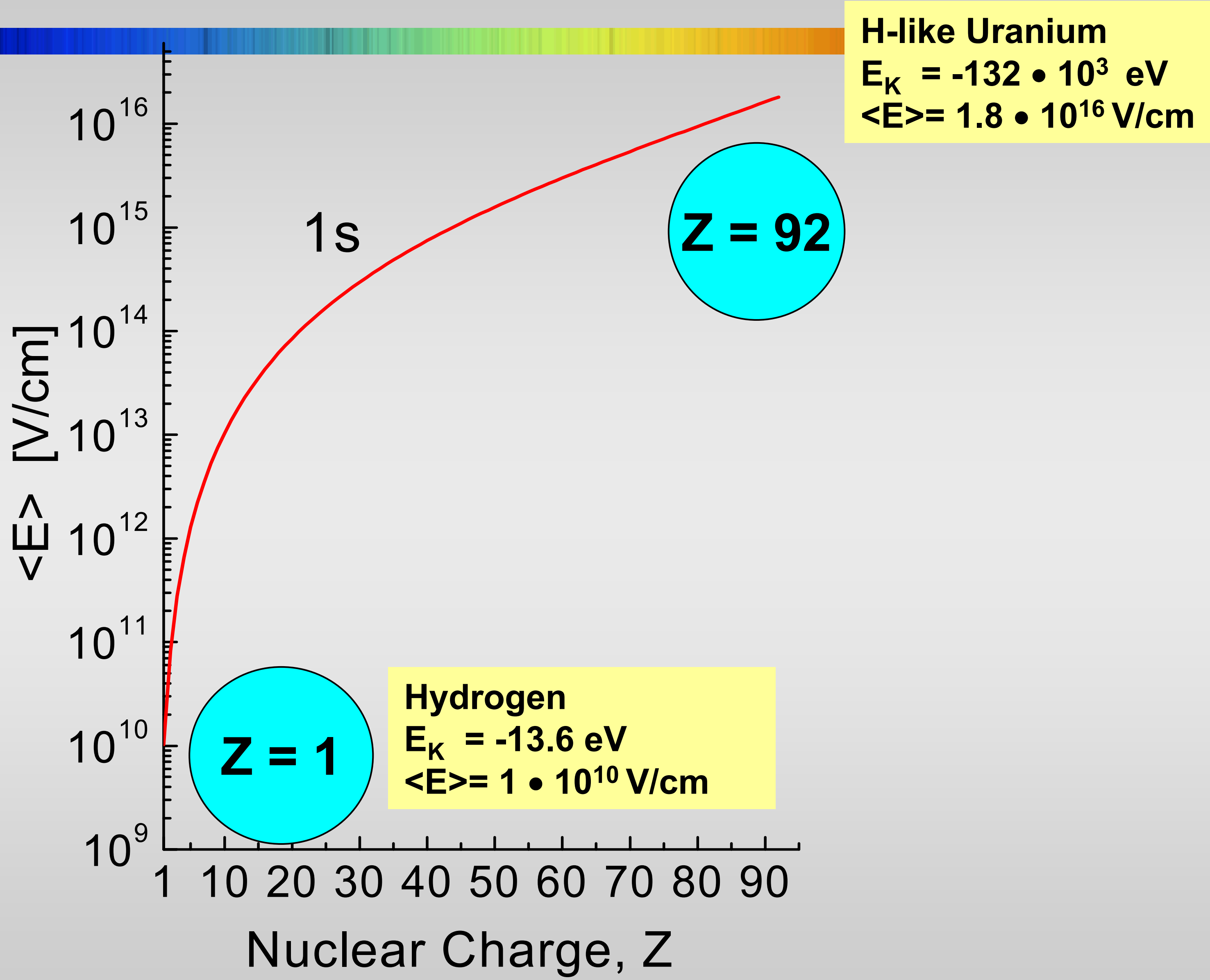
The Structure of One-Electron Systems



Atomic systems at high-Z

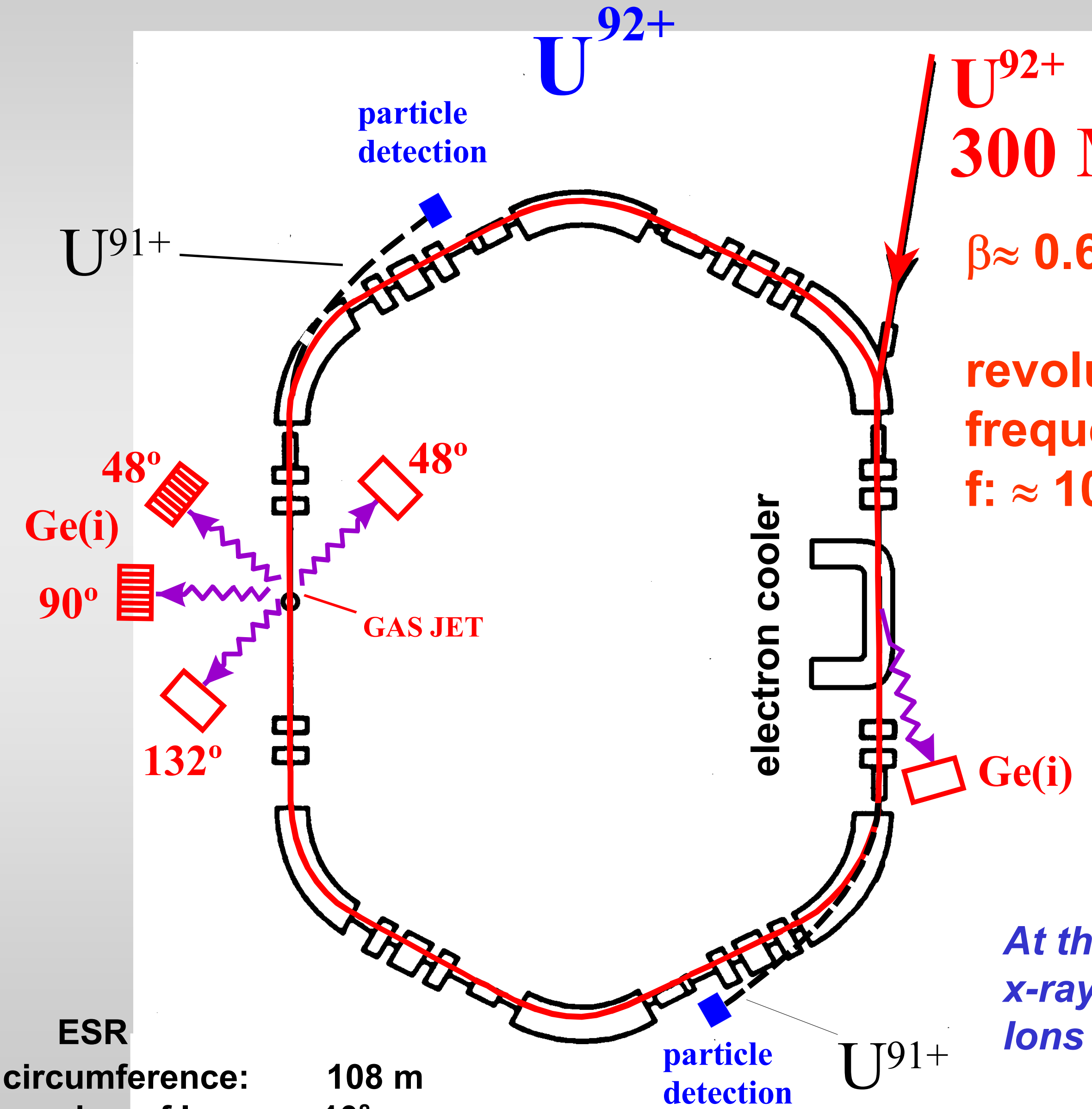
- Large relativistic effects on energy levels and transition rates (e.g. shell and subshell splitting)
- Transition energies close to 100 keV
- Higher order multipole transitions

Atomic Physics in Extremly Strong Coulomb Fields



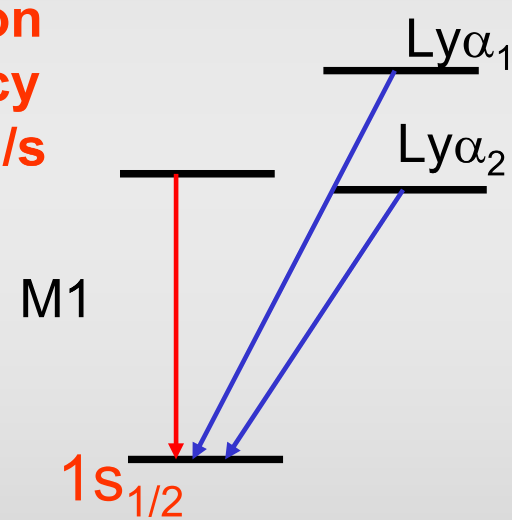
1s-ground state: increase of the electric field strength by six orders of magnitude

Recombination and Electron Capture Studies at the ESR Storage Ring



$\beta \approx 0.65$

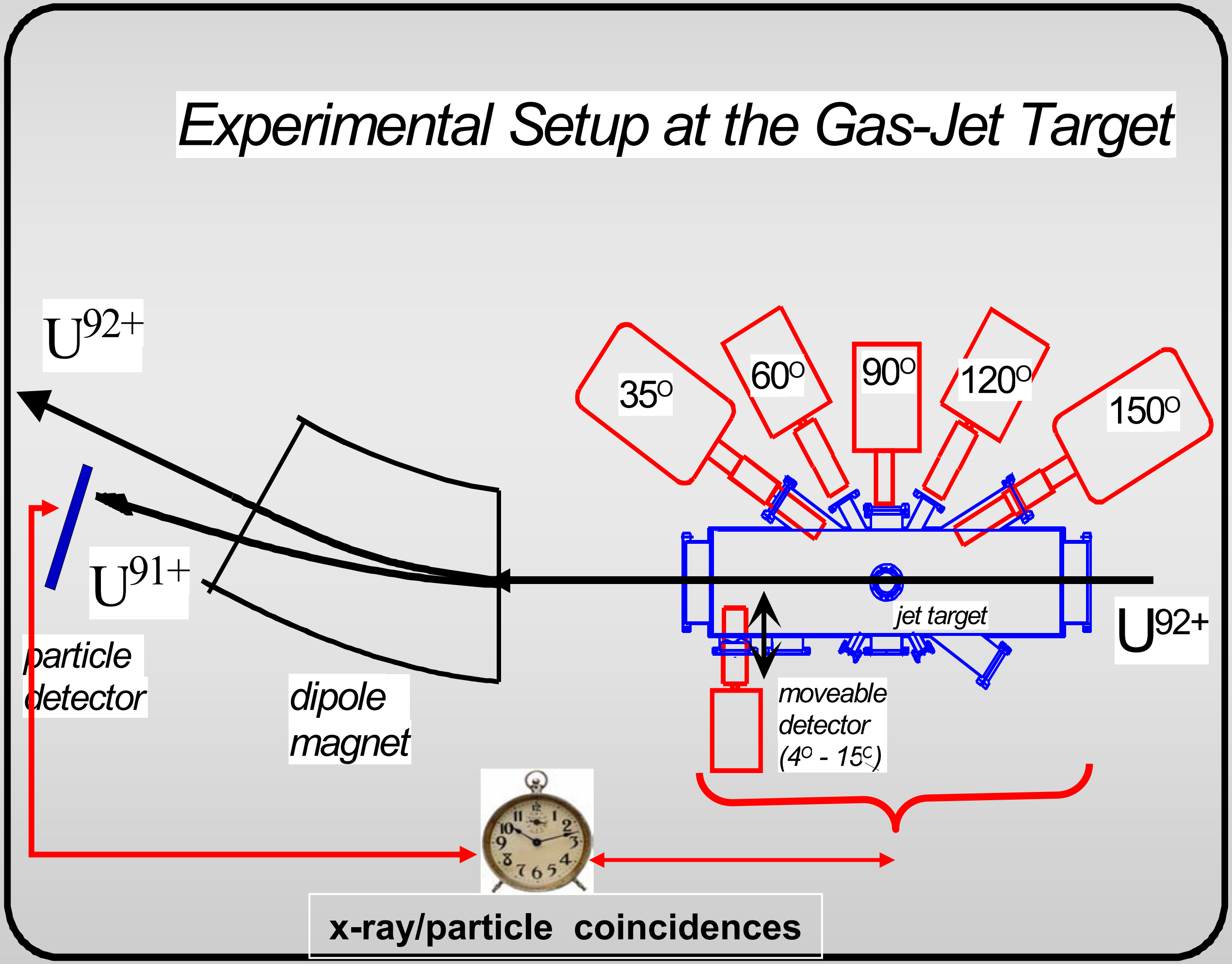
revolution frequency
f: ≈ 10^6 1/s



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

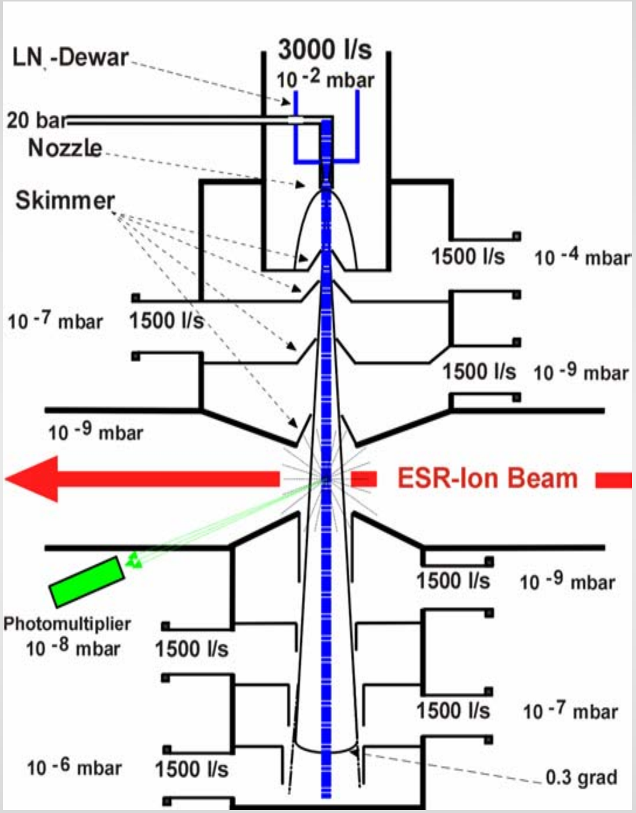
Experiments at the Jet-Target



The Jet-Target

Target species

H_2
CH_4
N_2
Ne
Ar
Kr
Xe



Target densities

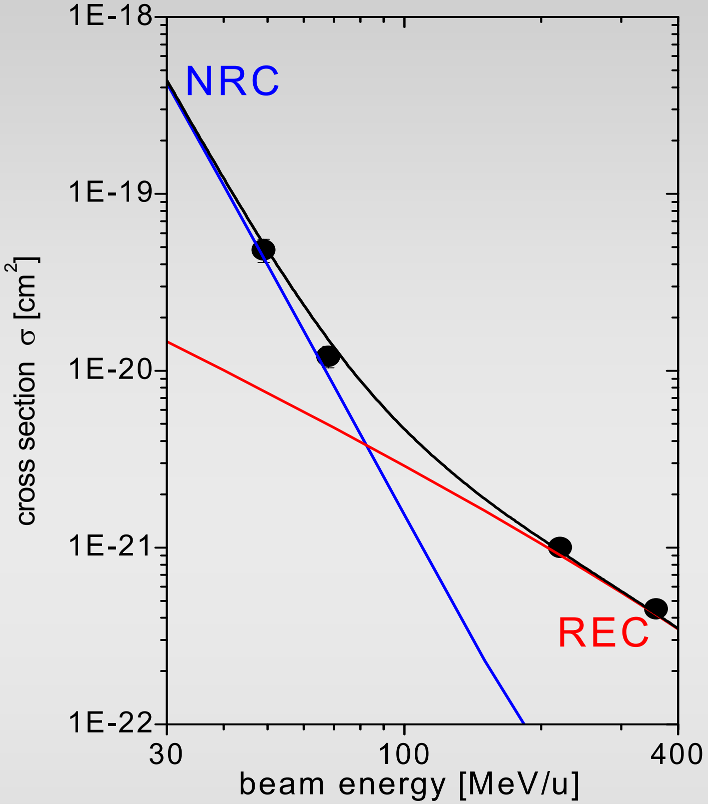
$10^{12} – 10^{14}$ p/cm^3

Single collision conditions

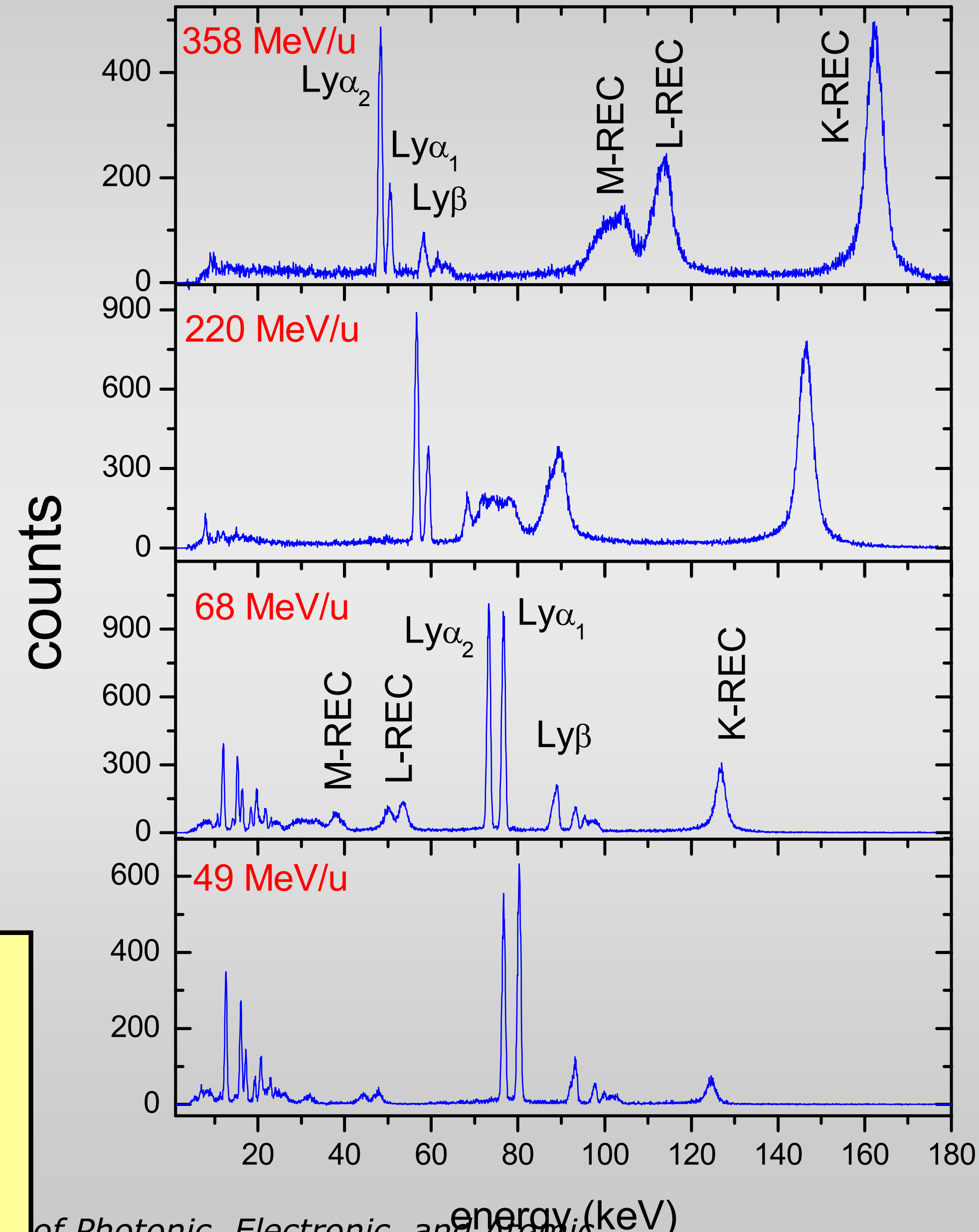
Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)

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

REC Cross Sections/U^{92+} => N_2



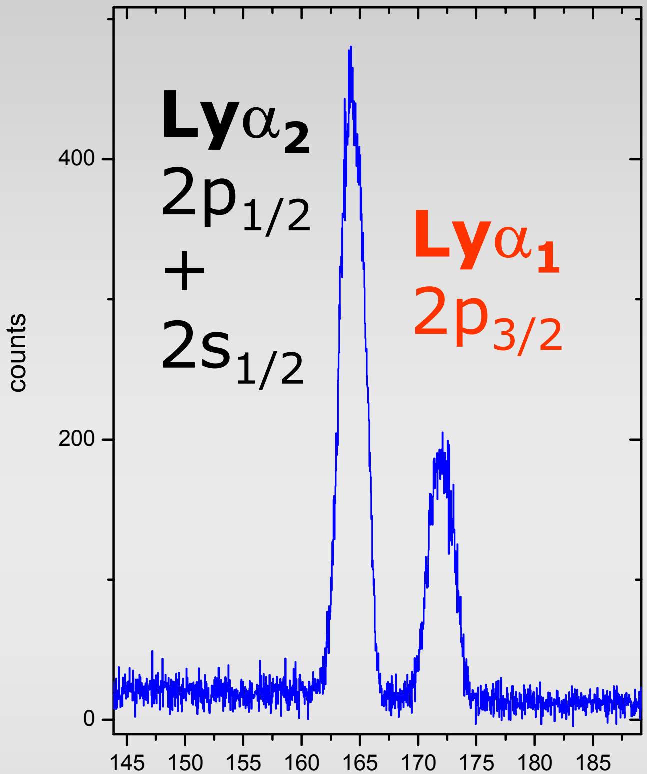
REC: dipole approximation
NRC: eikonal approach

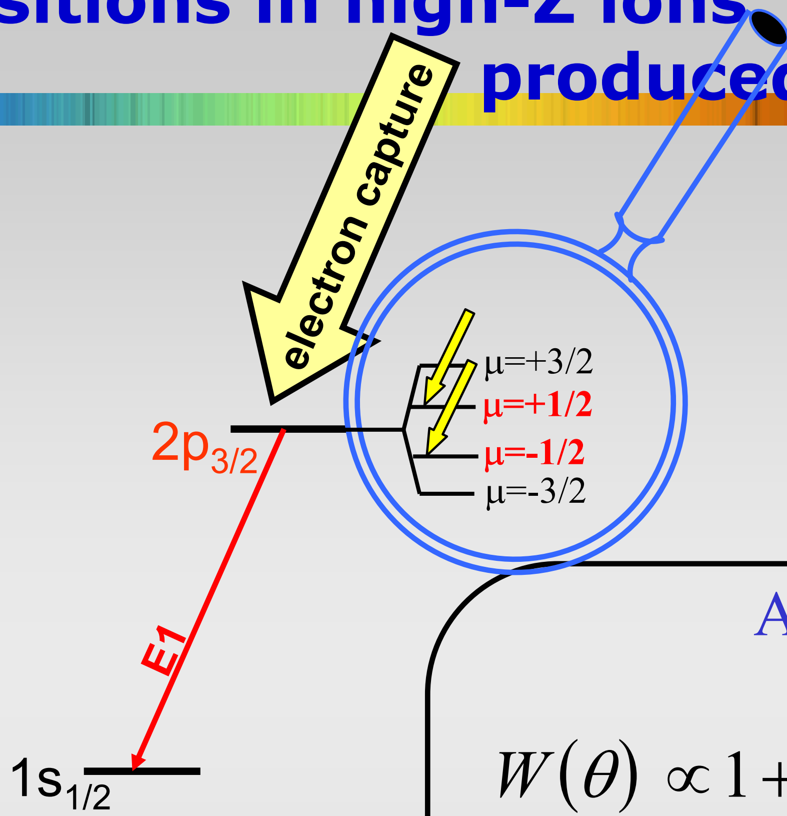


For high-Z ions and high energies REC is the most important charge exchange process for collisions with low-Z targets

REC populates predominately s-states and in particular the 1s ground state (80%)

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





1st photon: resonant excitation to the $2p_{3/2}$ state
+
2nd photon: ionization

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

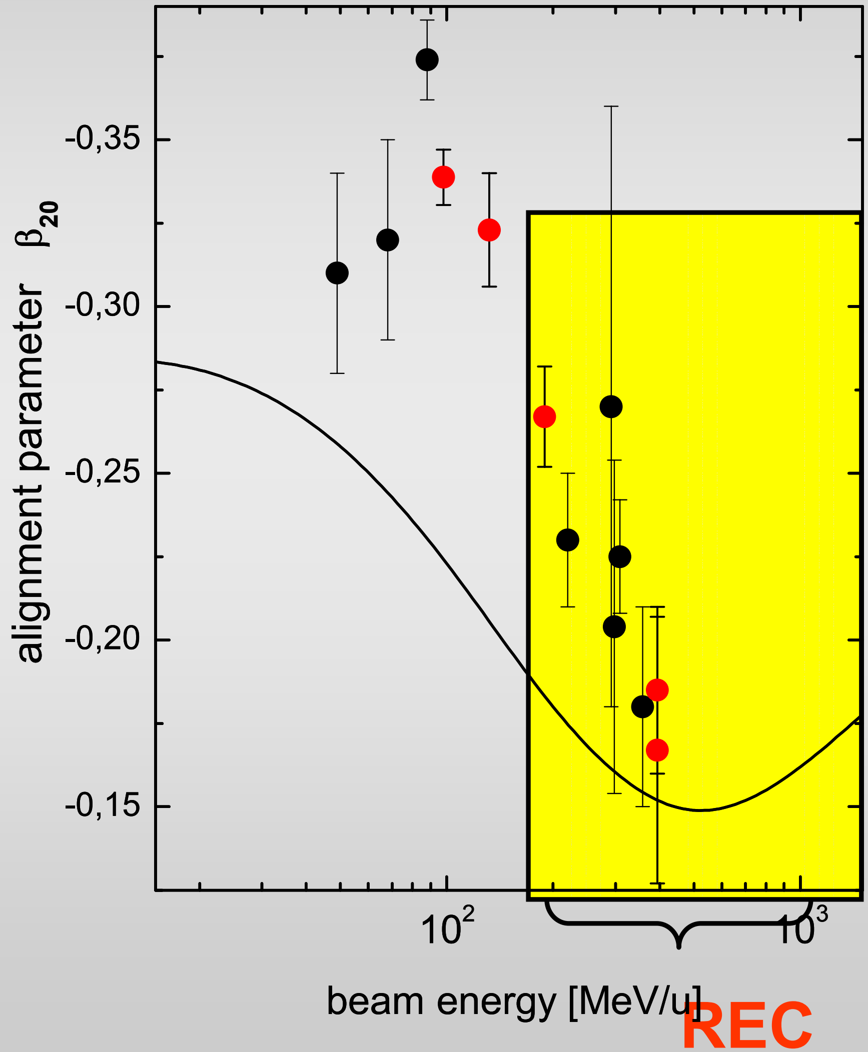
Alignment

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

Alignment Parameter

$$\beta_A = \frac{1}{2}\frac{\sigma\left(\frac{3}{2}\frac{3}{2}\right) - \sigma\left(\frac{3}{2}\frac{1}{2}\right)}{\sigma\left(\frac{3}{2}\frac{3}{2}\right) + \sigma\left(\frac{3}{2}\frac{1}{2}\right)}$$

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



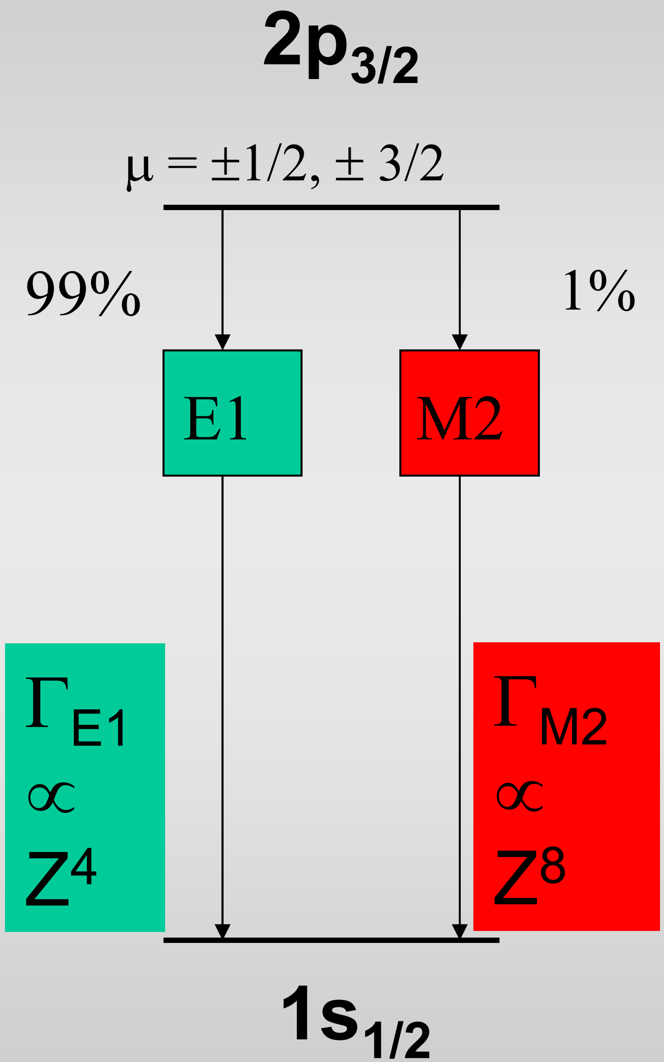
Theory by J. Eichler et al.

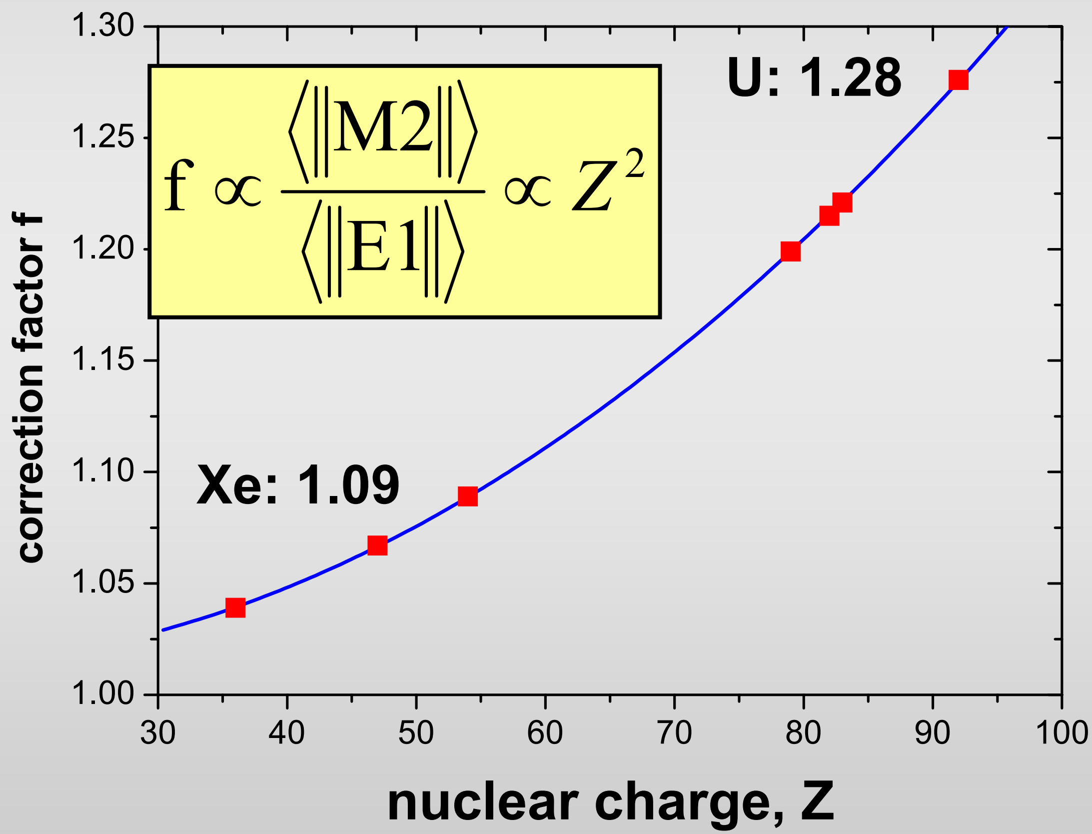
Disagreement with theory ?

Th. Stöhlker et al., PRL 79, 3270 (1997)

E1/M2 Multipol Mixing (Interference between the E1 and M2 transition amplitudes)

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

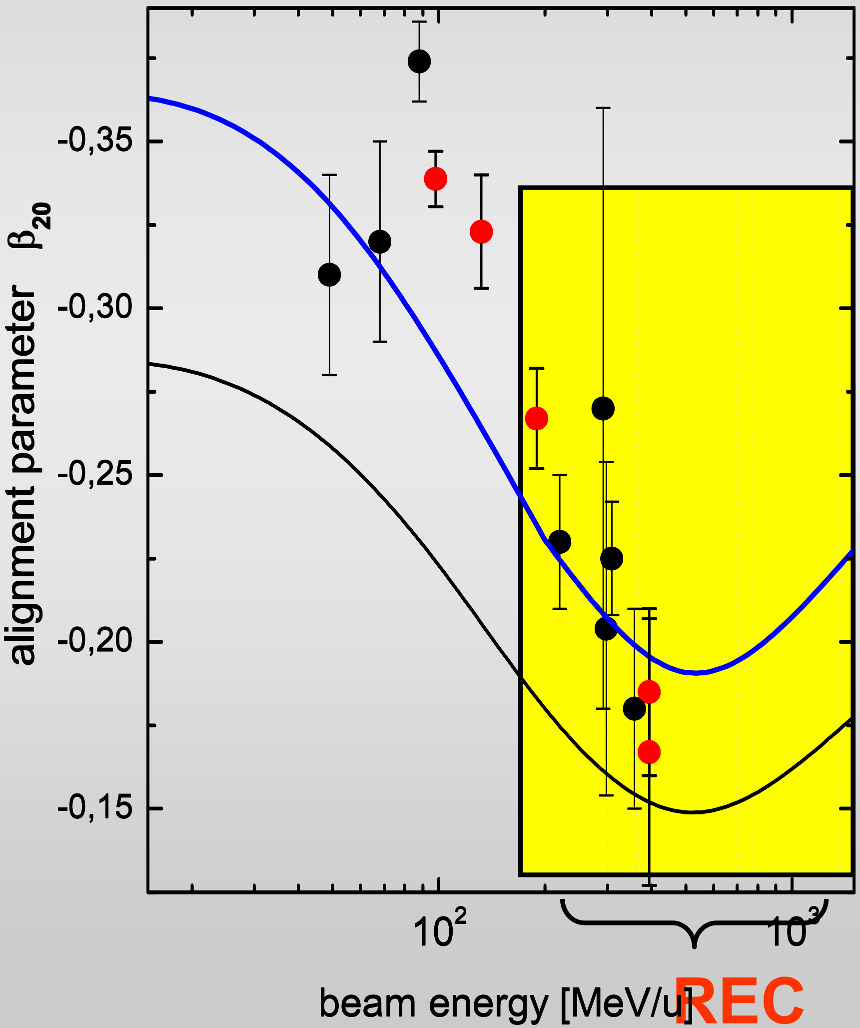




Surzhykov et al., PRL 88, 153001 (2002)

Theory for Z=92: $f = 1.28$

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



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

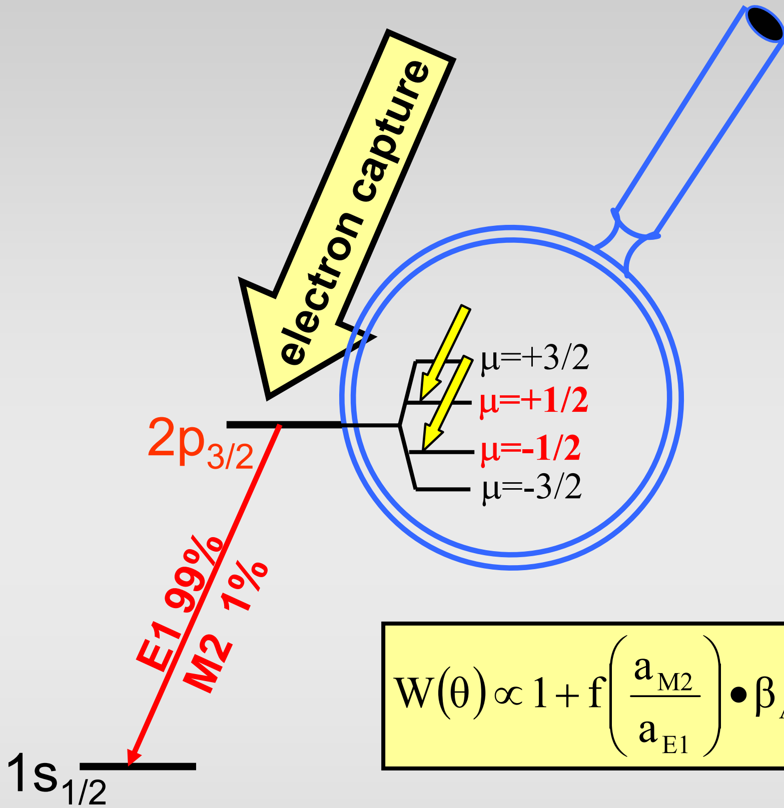
$$f\left(\frac{a_{M2}}{a_{E1}}\right) \propto \left[1 + 2\sqrt{3}\,\frac{\langle \| M2 \| \rangle}{\langle \| E1 \| \rangle}\right]$$

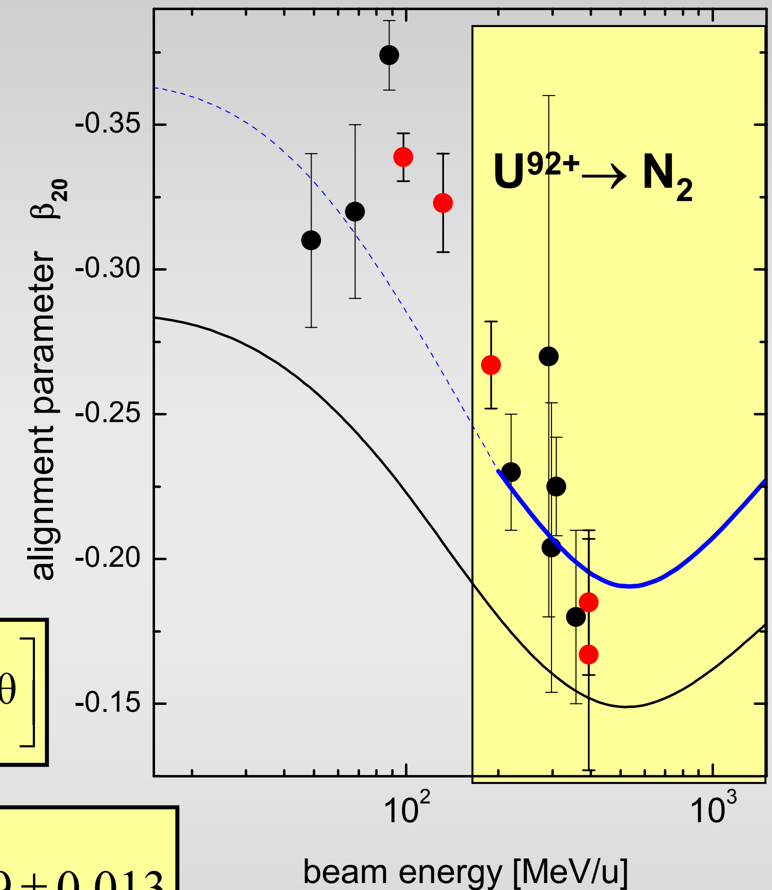
Theory for Z=92: $f = 1.28$

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

Poster contribution:
A. Orsic Muthig et al., TU100

M2 contribution to the $2p_{3/2}$ decay in H-like uranium





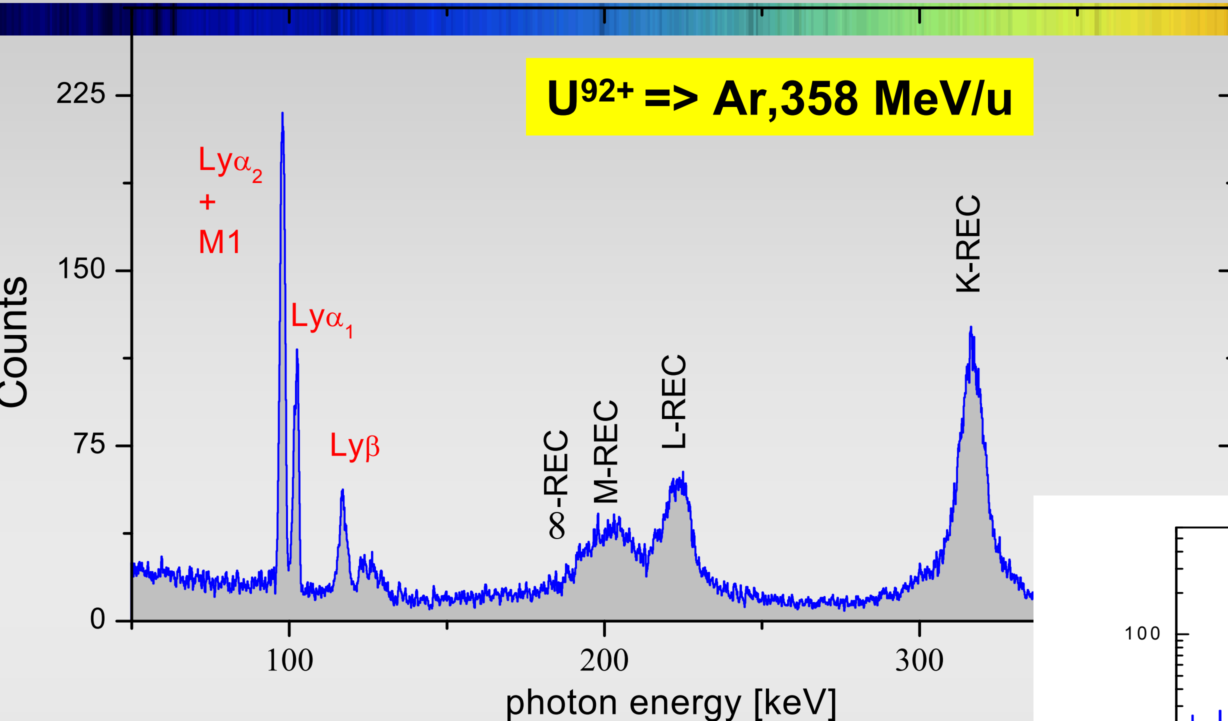
$$W(\theta) \propto 1 + f\left(\frac{a_{M2}}{a_{E1}}\right) \bullet \beta_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$

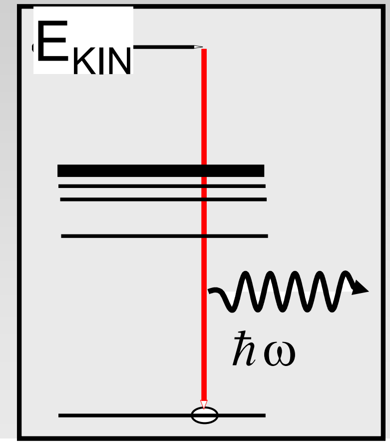
$$f\left(\frac{a_{M2}}{a_{E1}}\right) = 1.27 \pm 0.05 \Rightarrow \frac{\langle\|M2\|\rangle}{\langle\|E1\|\rangle} = 0.079 \pm 0.013$$

M2 contribution

$$\frac{\Gamma_{M2}}{\Gamma_{E1}} = 0.0062 \pm 0.002$$

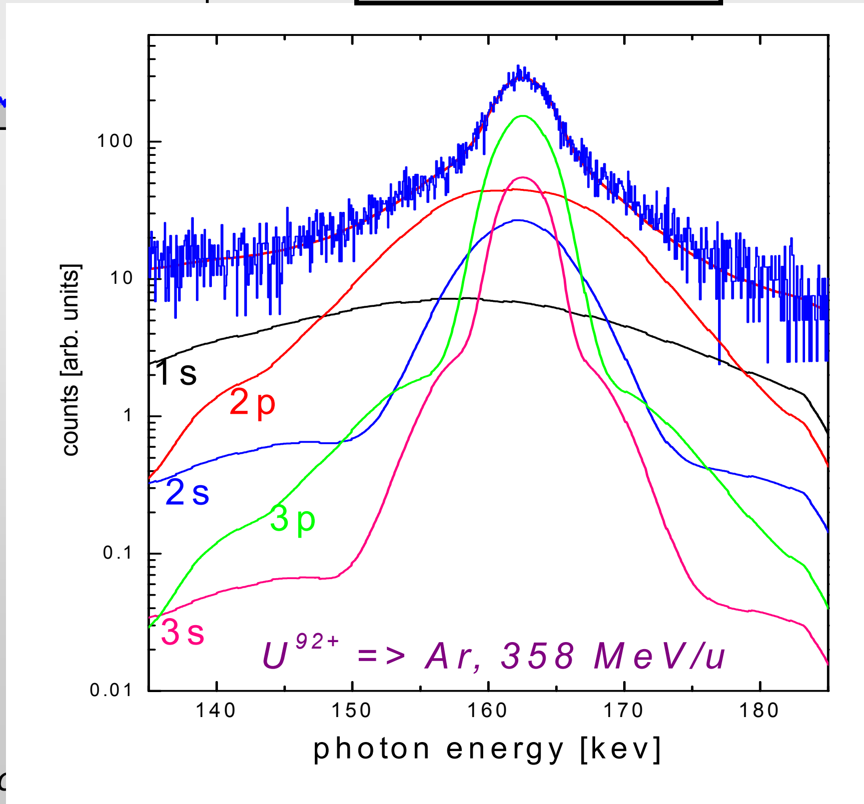
Radiative Electron Capture
Capture of Quasifree Targetelectrons





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

Photon Angular Distribution (310 MeV/u)

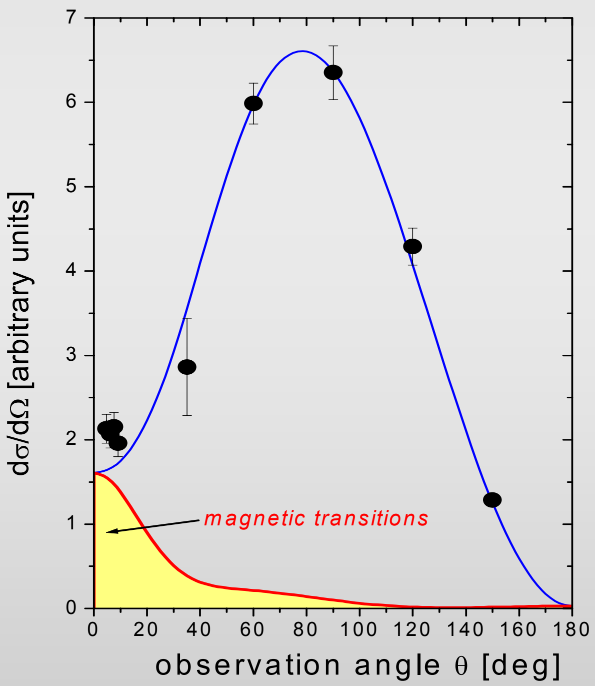
radiative capture into U^{92+}

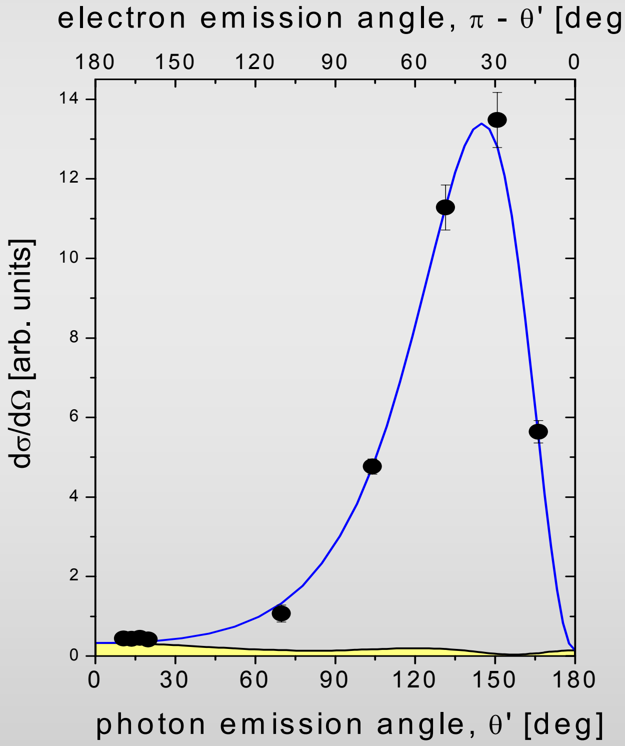
photoionization of U^{91+}

laboratory frame

Time reversal

emitter frame





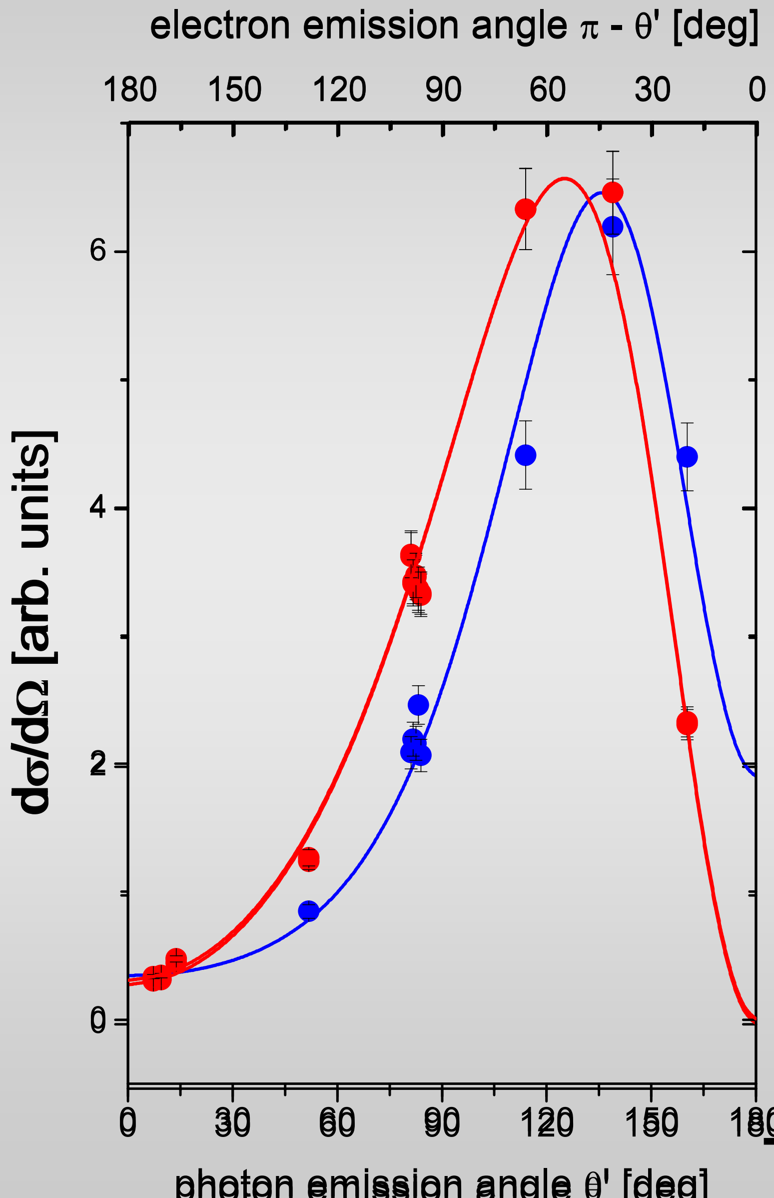
Angle and solid angle transformation

Theory: J. Eichler

Capture into bare, decelerated uranium

U^{92+} at 88 MeV/u

Photoelectron energy 48 keV



K-shell

$2p_{3/2}$

Th. Stöhlker
PRL 86, 983 (2001)

Theory: J. Eichler

Experimental REC studies performed up to now

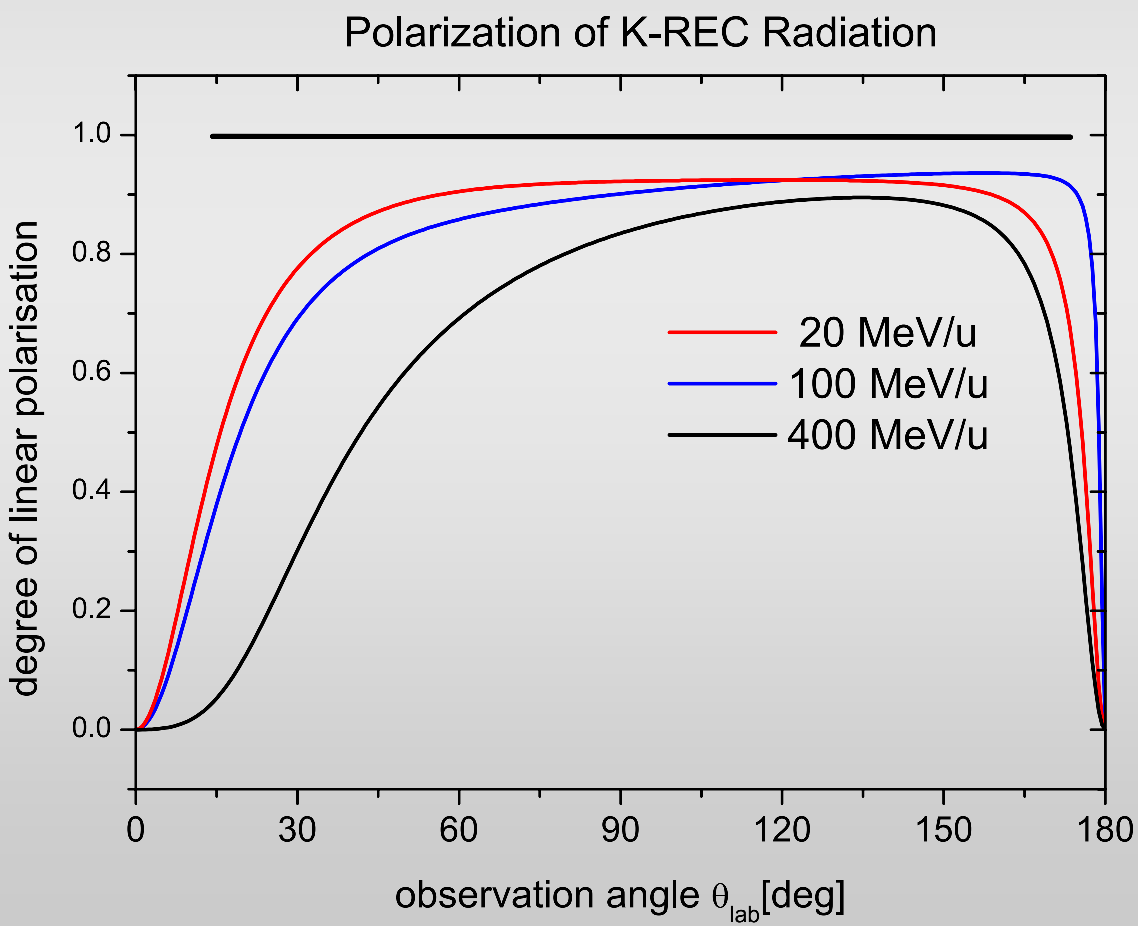
total REC cross sections for bare ions up to uranium (20 MeV/u – 170 GeV/u) ✓

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

Open Questions

Angular distributions for few-electron ions close to the threshold (decelerated ions)

Polarization of the emitted photons (no experimental information available)



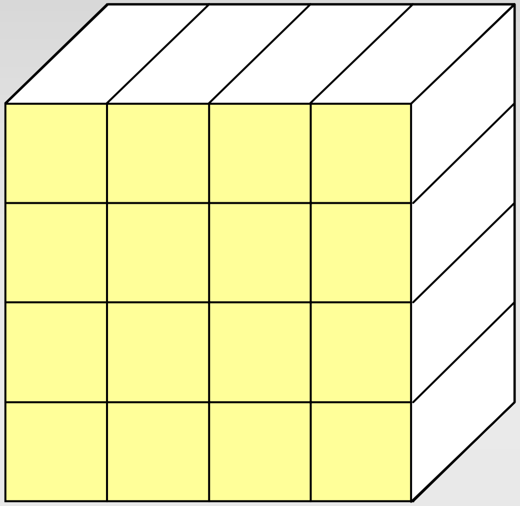
non-relativistic dipole approximation

Exact relativistic Treatment

Eichler et al., PRA, 2001
Surzykov et al., PRA, 2001

Polarization Studies via 2D Compton Imagine

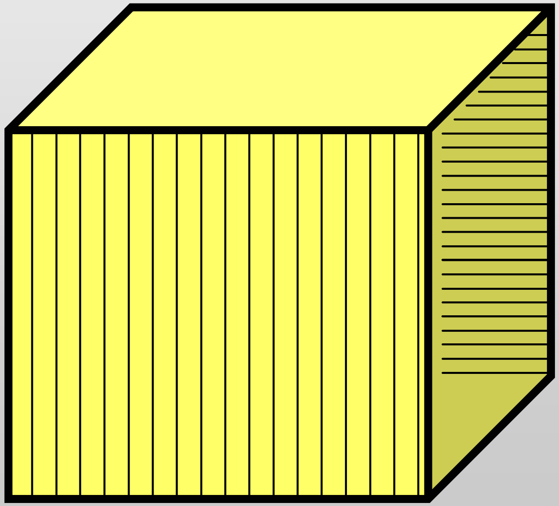
Pixel and/or Micro-Strip Germanium Detectors



Energy Resolved X-Ray Imager

Timing

Multi-Hit Capability

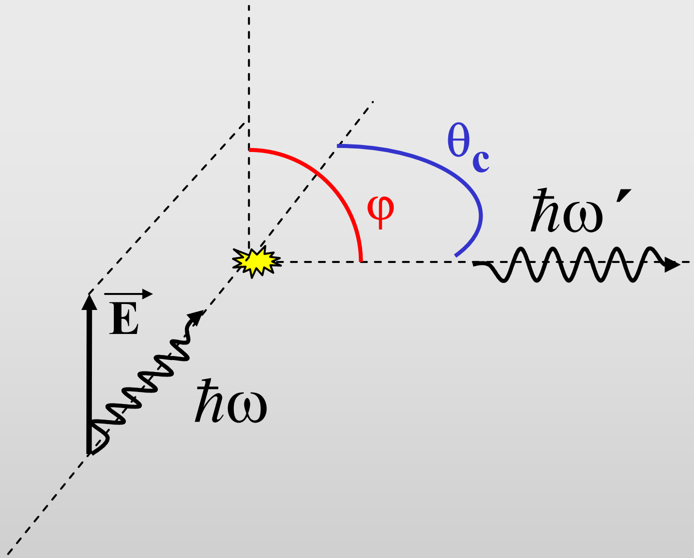


In collaboration with FZ-Jülich

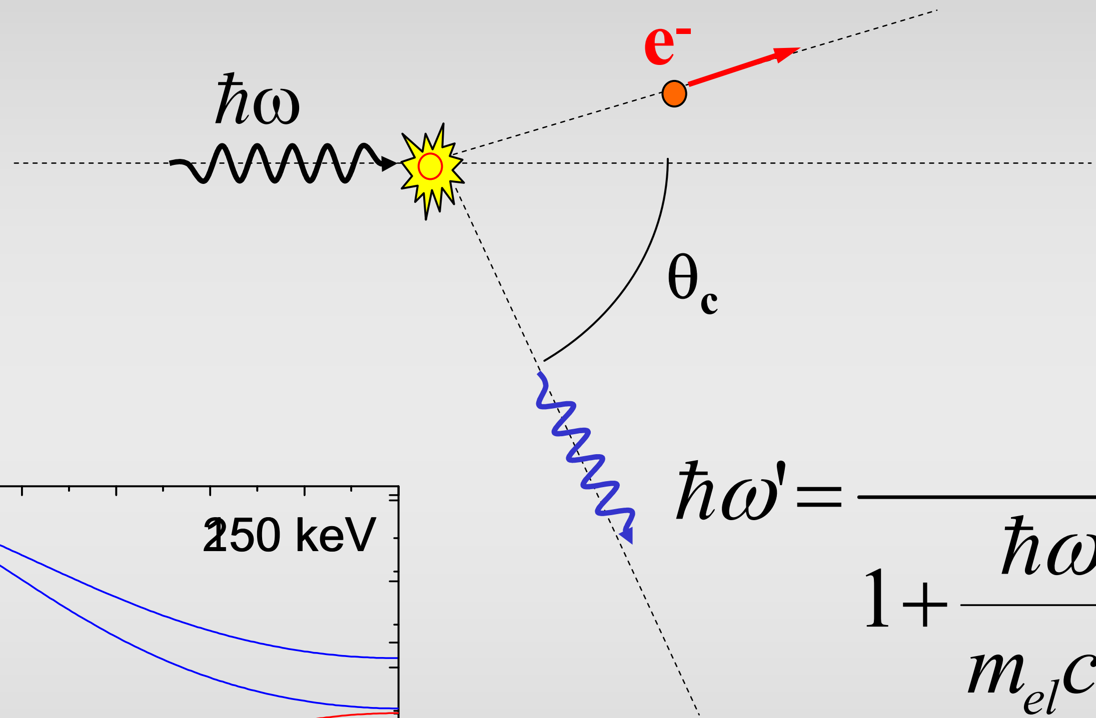
Polarization Measurements by Means of Compton Scattering

Klein-Nishina formula

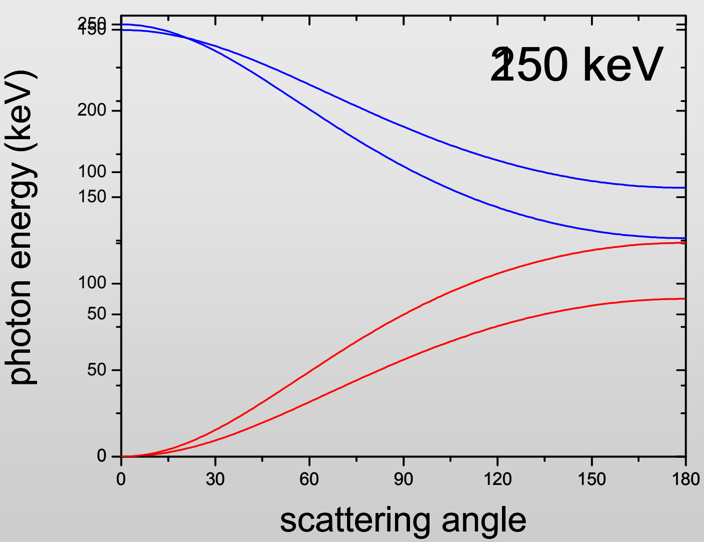
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta_c \cos^2\varphi\right)$$



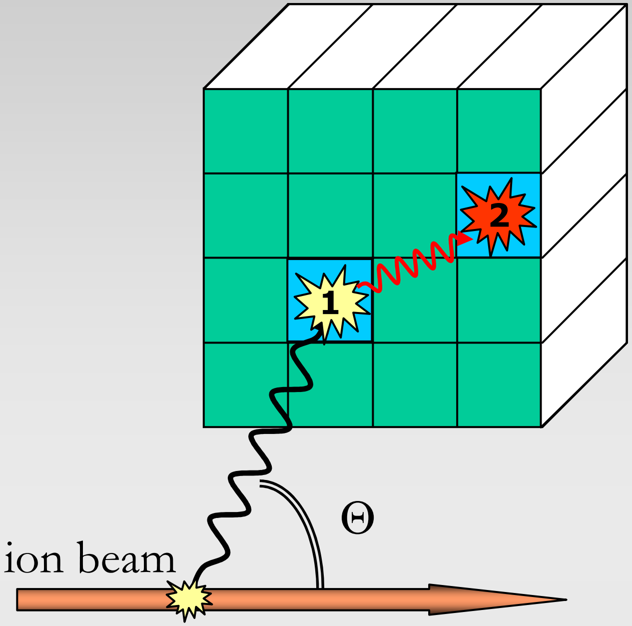
Compton scattering

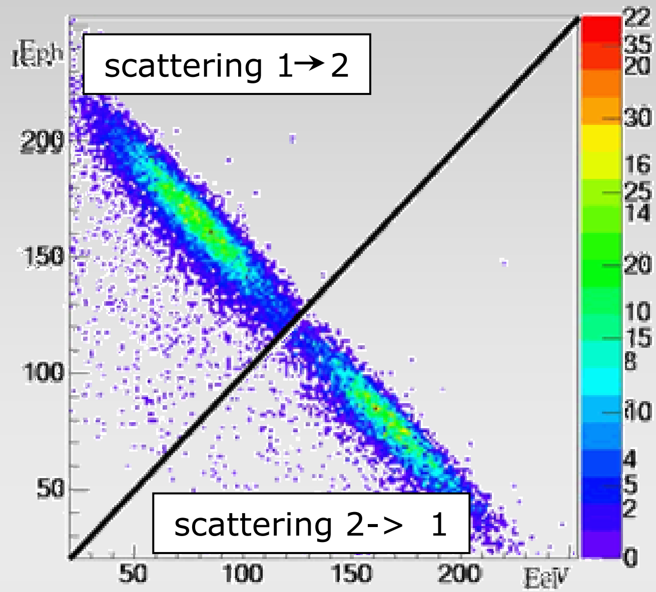


$$\hbar\omega' = \frac{\hbar\omega}{1+\frac{\hbar\omega}{m_{el}c^2}(1-\cos\theta_c)}$$



Reconstruction of compton events

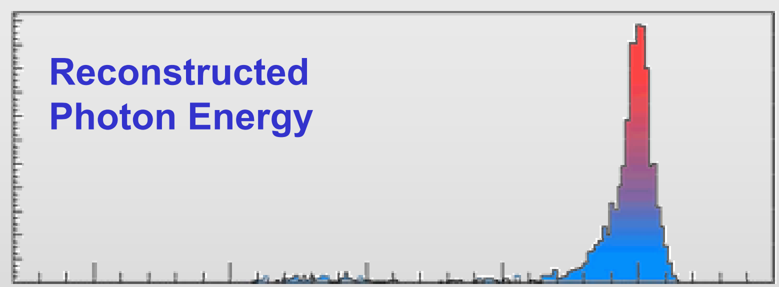


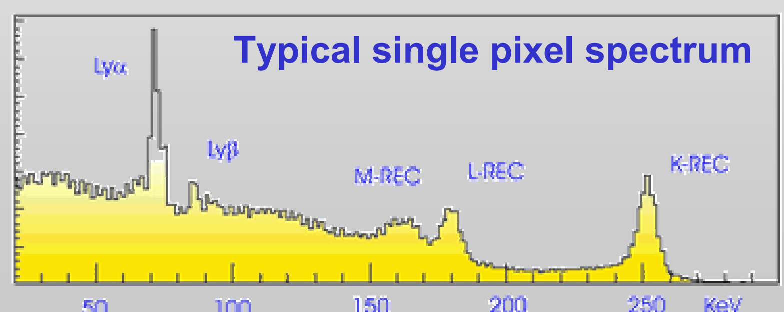


Two pixel coincidence registration

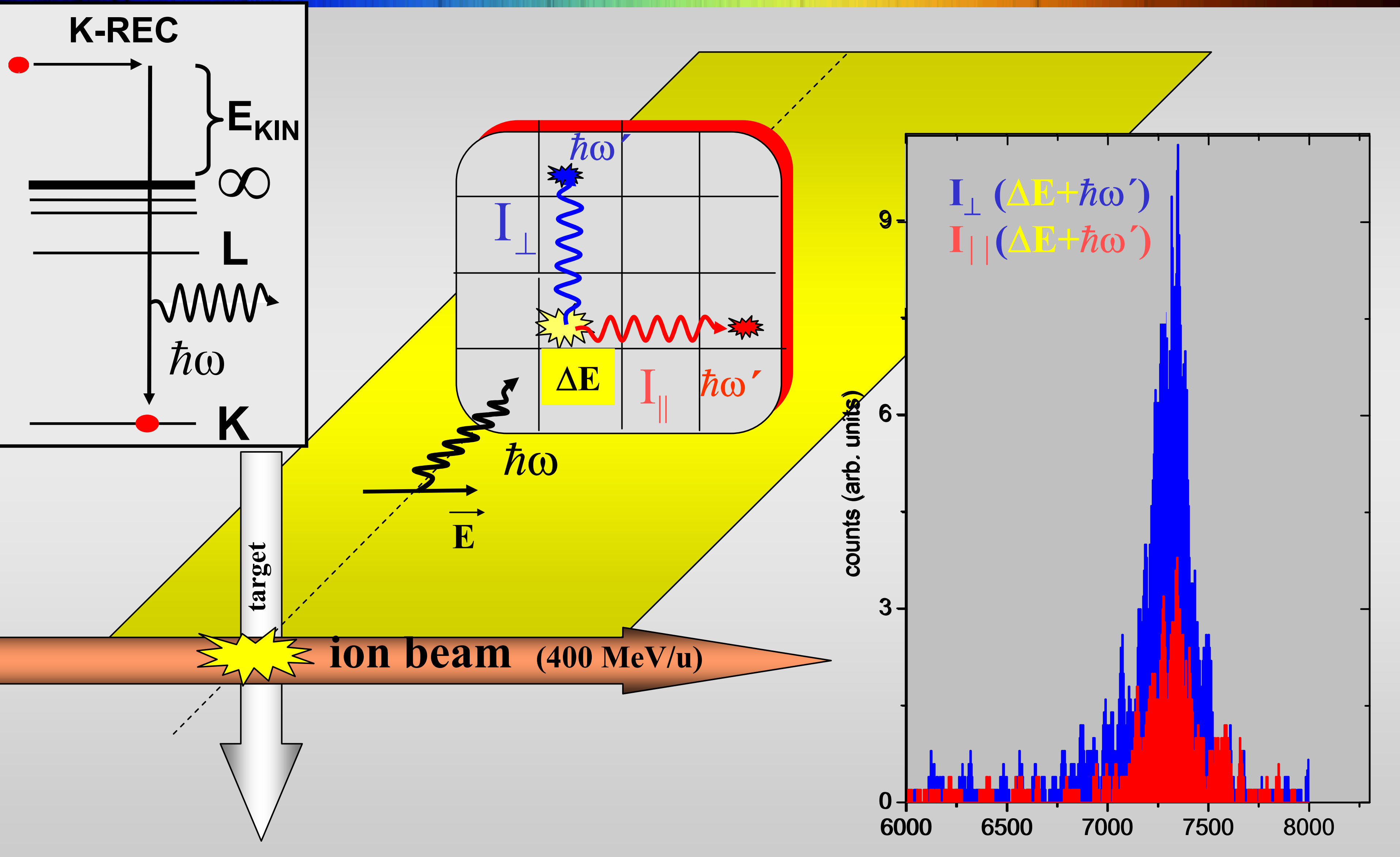
Energy condition $E_{ph} > E_{el}$

Reconstruction of compton events





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



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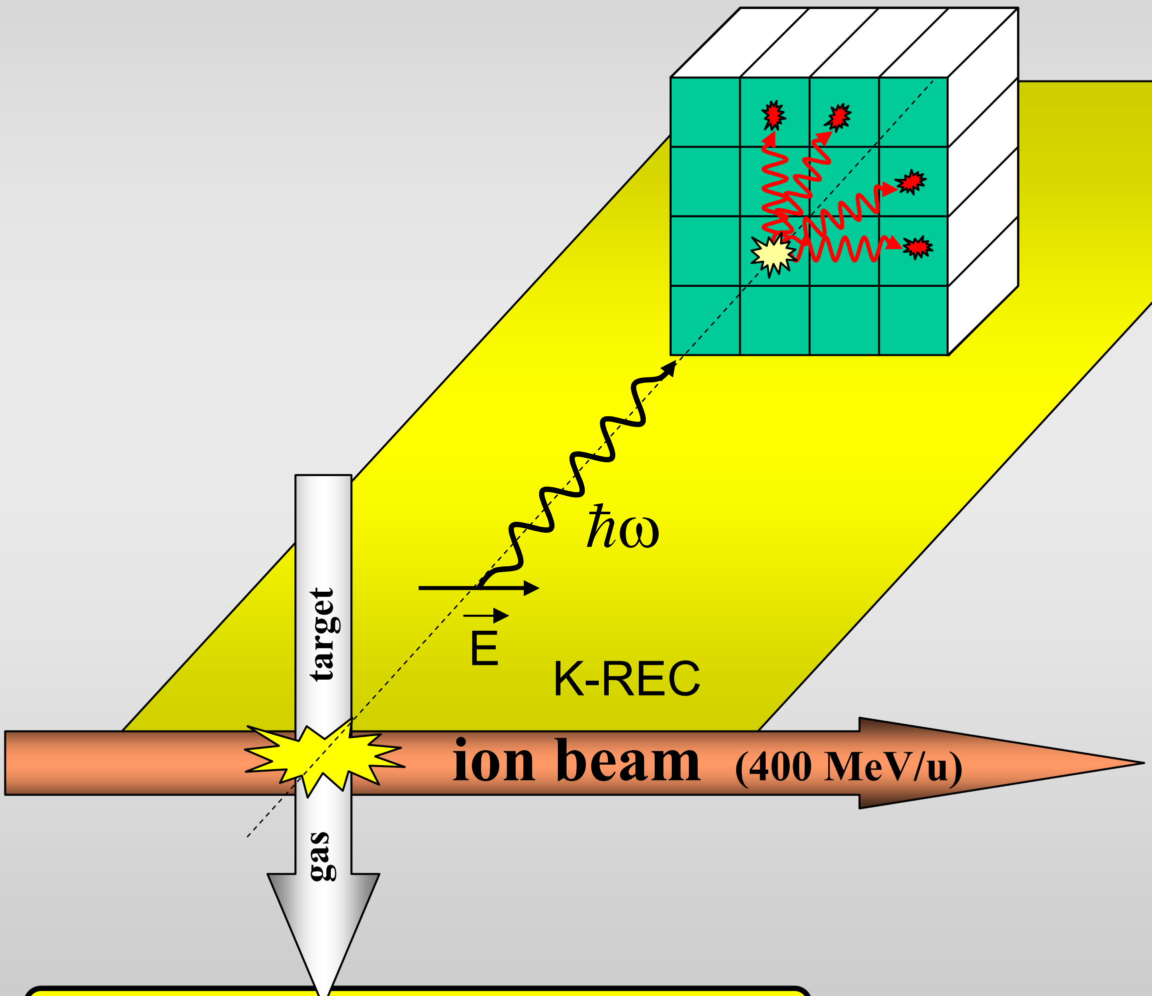
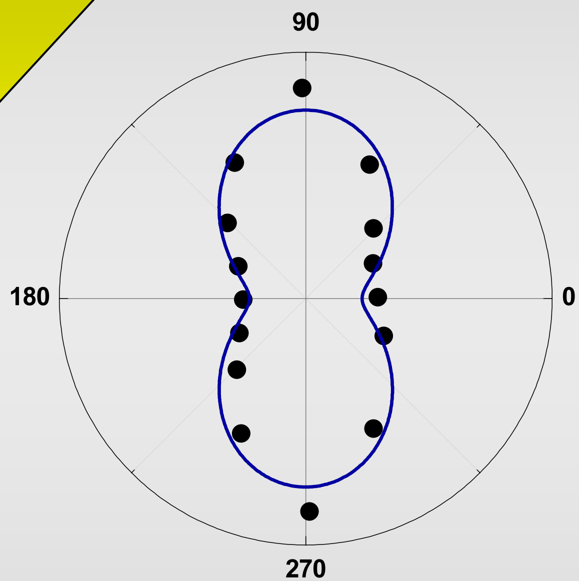
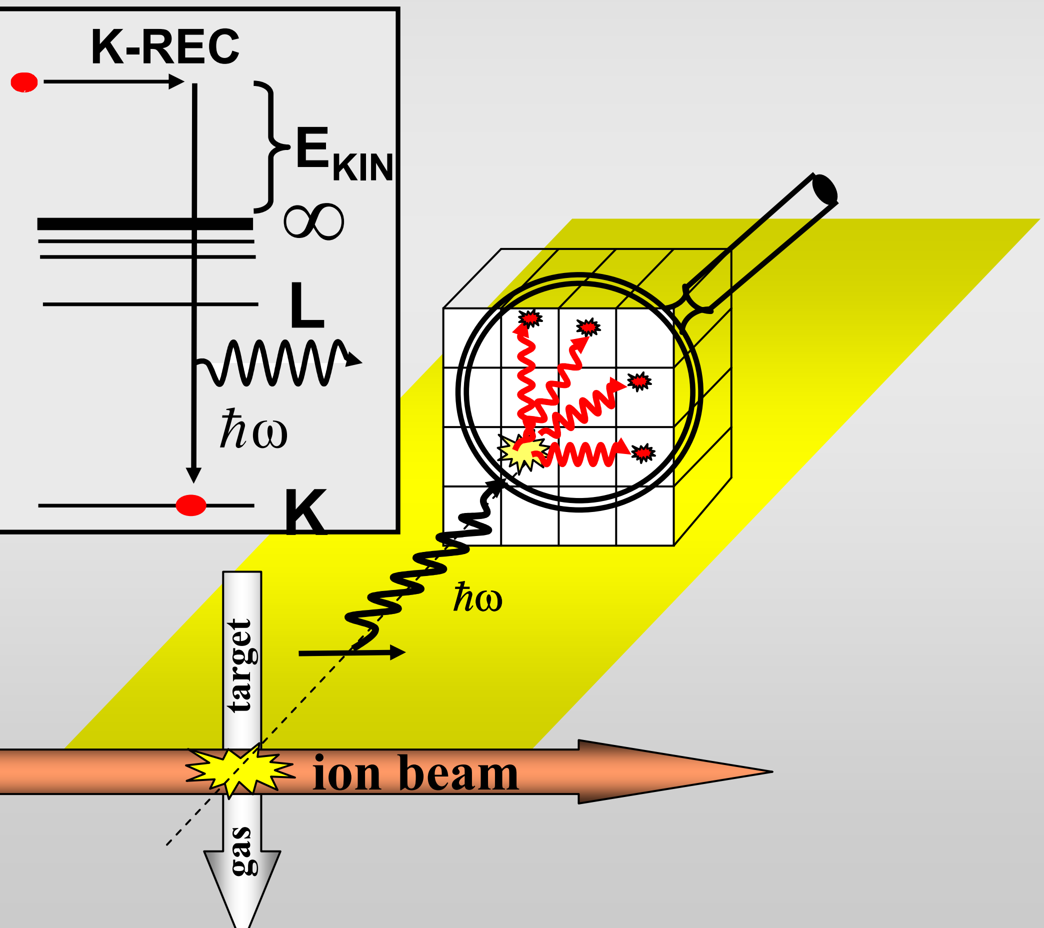


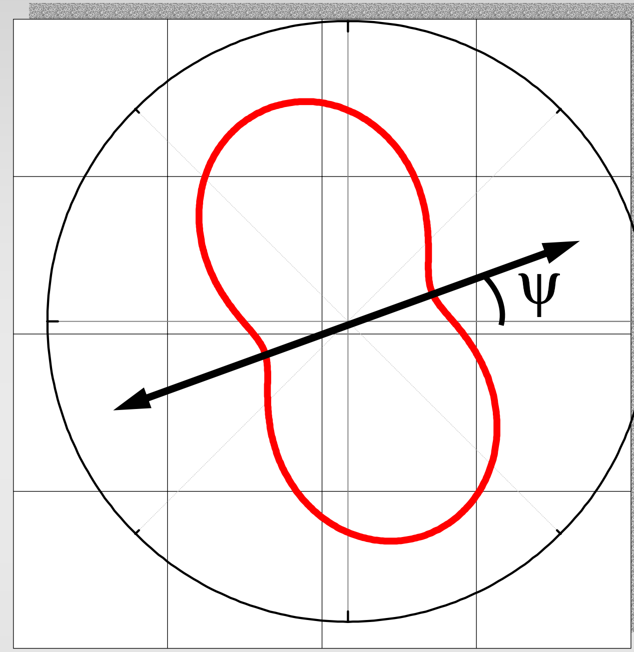


- ✓ K-REC radiation is strongly polarized
- ✓ Polarization is in the reaction plane

S. Tachenov et al., Poster Mo143

Application to Spin Polarized Ion Beams





<Spin polarized ion beam>

ψ ⇒ degree of ion beam polarization

Surzhykov et al., in print PRA (2003)
(Poster Th130)

Summary and Outlook

- The study of elementary atomic processes for highly- charged heavy ions via their time-reversal in ion-atom collisions
- Observation of multipol mixing for atomic transitions
- Polarization measurement of recombination radiation
- RR/REC a unique tool for the diagnostic for spin polarized ion beams

- Enhanced 2D and 3D resolution (100 x 100 µm)
- Polarization studies for x-rays in the Regime between 50 and 1000 keV
- Compton camera for atomic collisions Studies
- State selective recombination studies at electron cooler devices