Linear Polarization Properties of Radiative Electron Capture Revealed for Relativistic Projectiles

Thomas Stöhlker

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

in collaboration with

Experiment

D. Banas, H.F. Beyer, F. Bosch,
A. Gumberidze, S. Hagmann, C. Kozhuharov,
R. Reuschl, D. Sierpowski, X. Ma, U. Spillmann,
J. Rzadkiewicz, S. Tashenov and the ESR-Team

Atomic Physics Group, GSI-Darmstadt, Germany
IMP, Lanzhou, China
University of Cracow, Poland
University of Frankfurt, Germany

Theory

J. Eichler, S. Fritzsche, A. Ichihara,
T. Shirai, A. Surzhykov

Theoretische Physik, HMI-Berlin, Germany
JAERI, Japan
University of Kassel, Germany

Photoeffect, Radiative Electron Capture, and Polarization

Relativistic Quantum Dynamics

Polarization Studies of Radiative Capture Transitions: Experiment
A Diagnostic Tool to Identify Spin-Polarized Ion Beams

Detector Developments

Towards Polarization Studies of Inner Shell Transitions in Heavy Ions

Summary and Outlook

Motivation

Polarization Studies for Hard X-Rays

Relativistic Particle Dynamcis (free-bound and free-free transitions):

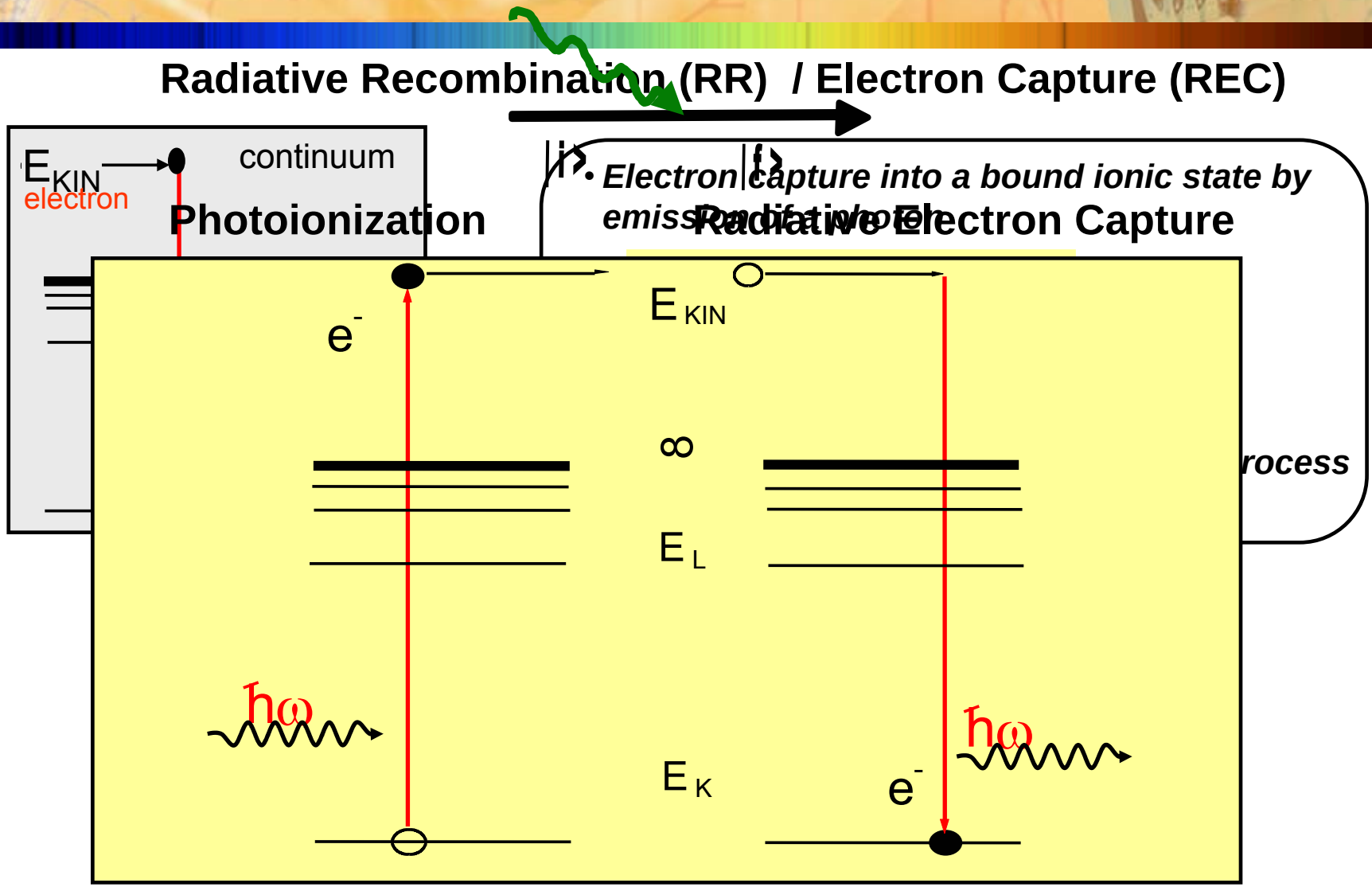
Synchrotron Radiation, *Inverse Compton* scattering *Bremsstrahlung*, and *Recombination* are the main photon processes in plasmas with distinct photon polarization features

- Diagnostic tool to indentify *spin polarized particle beams*
- Diagnostic tool to identify *Thomson scattered photons* from laser produced relativistic electron bunches

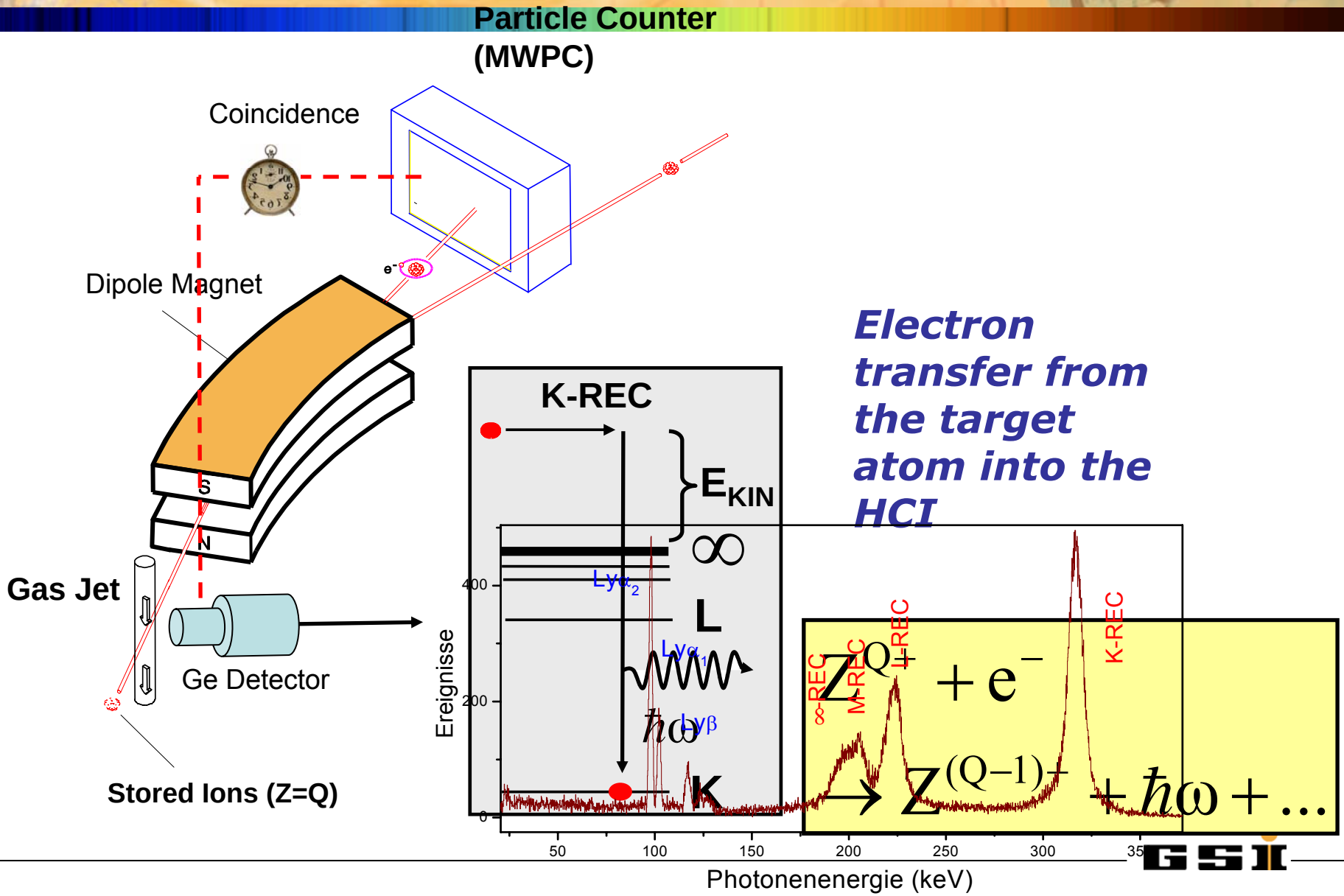
Atomic Structure (bound-bound transitions):

Excited states in heavy ions formed in atomic collisions are usually strongly aligned which translates in a *polarization of the emitted photons*

Relativistic Quantum Dynamics



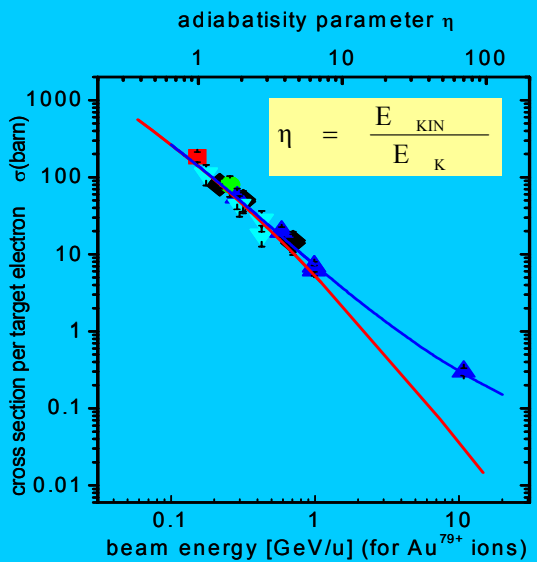
Experiments at the Jet-Target



Electron transfer from the target atom into the HCI

Experimental REC Studies

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

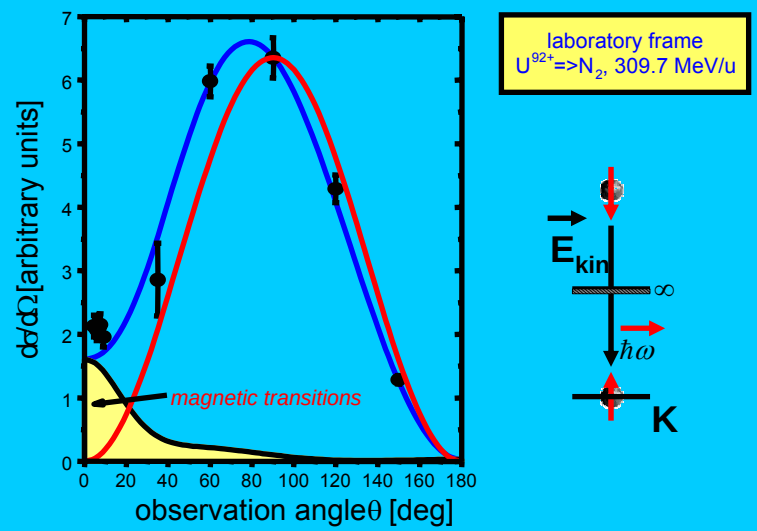


complete relativistic calculations for Au $^{79+}$ (Eichler et. al)

dipole approximation

photon angular distribution studies for REC

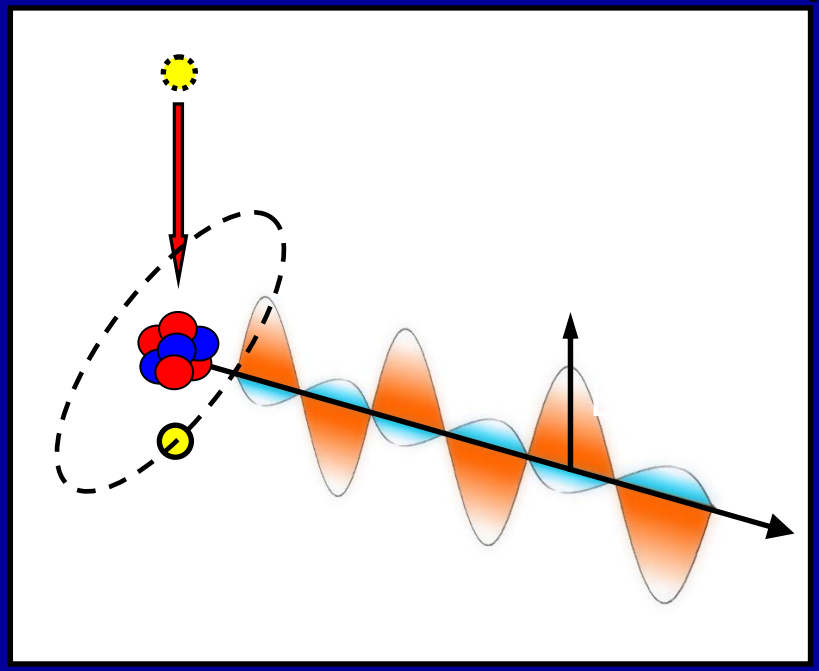
Kinematical Identification of Spin-Flip Transitions from Continuum States into the 1s-Ground State

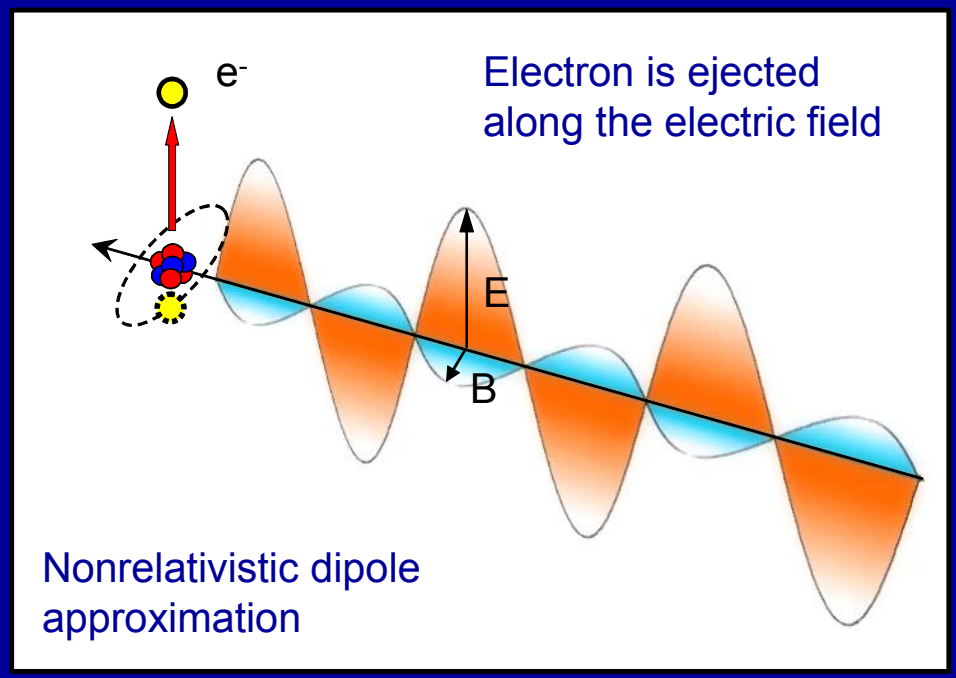


complete relativistic calculations (Eichler et al.)

nonrelativistic dipole distribution

Photon Polarization

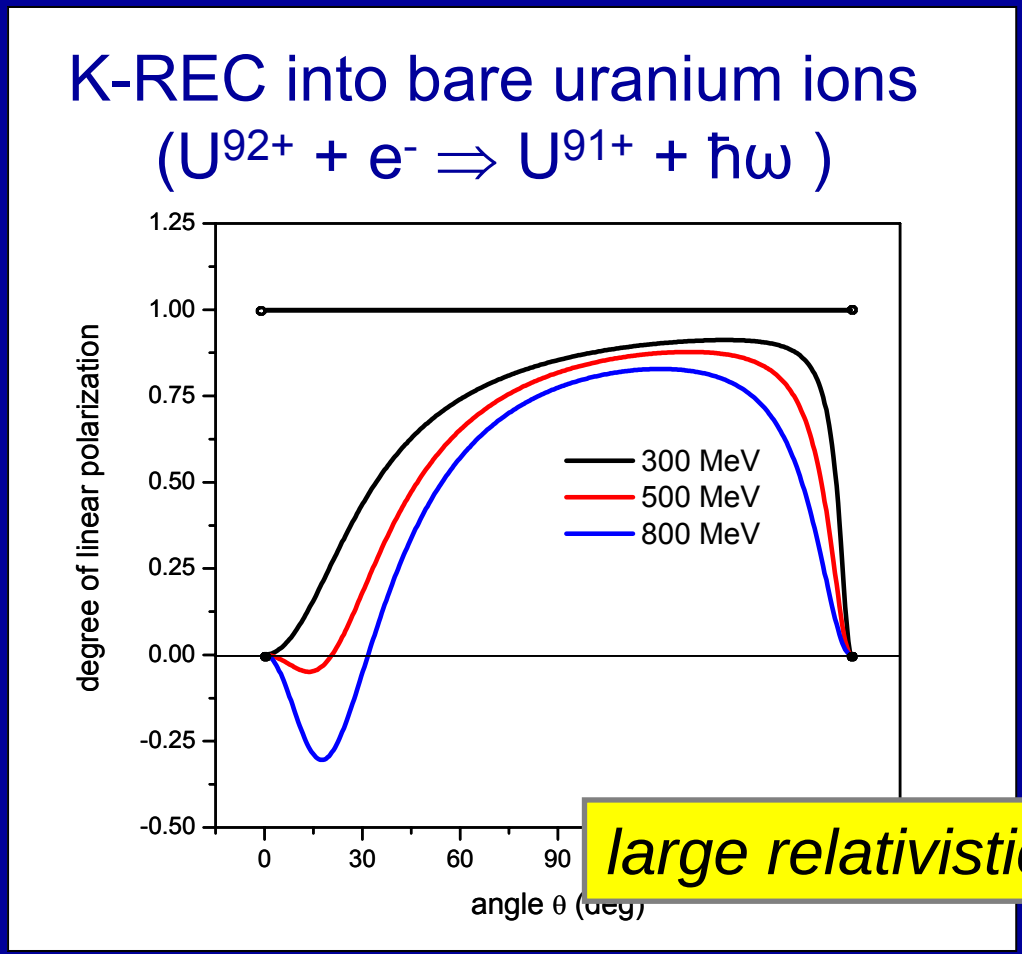




Radiative Electron Capture **Photoionization**

non-relativistic dipole approximation: 100 % polarization for all emission angles

K-REC Photon Polarization



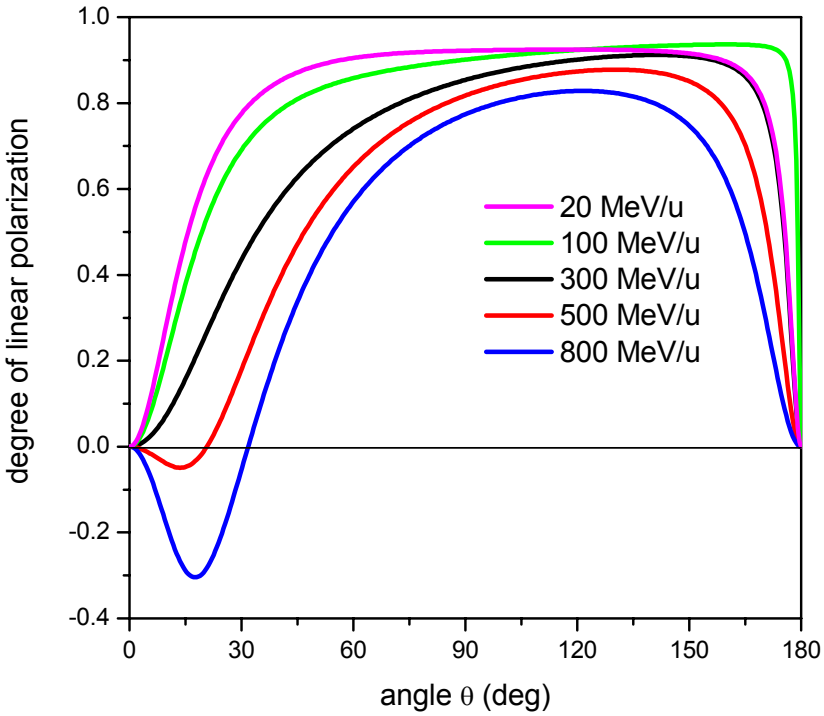
non-relativistic dipole approximation: 100 % polarization for all emission angles

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

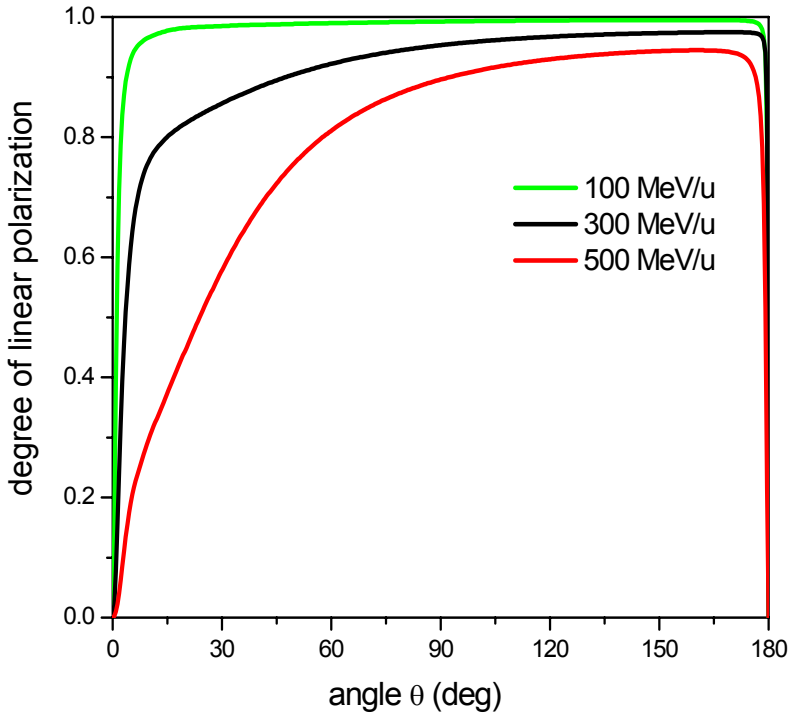
large relativistic contributions

Energy and Charge Dependence

Uranium (Z=92)



Argon (Z=18)



Photon Polarimetry

Lyquid crystals

Crystal optics

Bragg reflection

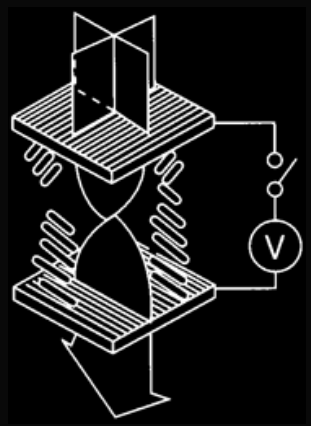
Photoabsorption

Thomson scattering

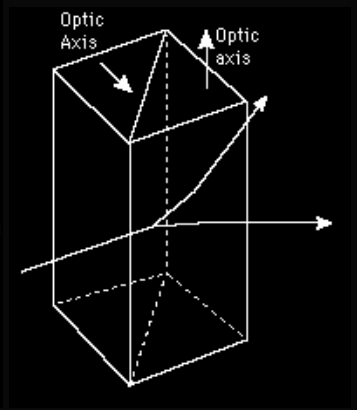
Compton scattering

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

energy (eV)



LCD

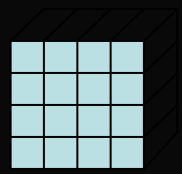


Wollaston prism

Micropattern gas counters

CCD cameras

x-ray optics

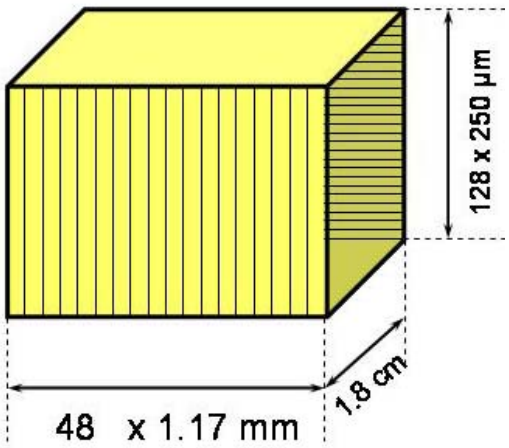


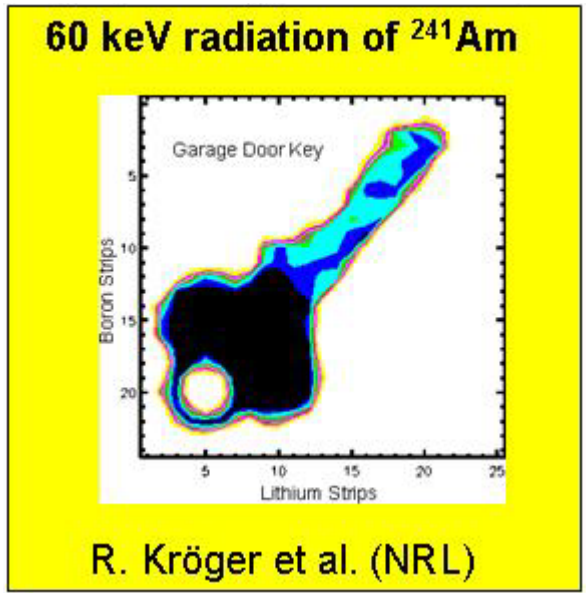
Segmented solid state detectors

2D Position Sensitive Ge(i) Detectors

Micro-Strip Germanium Detector Development:

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

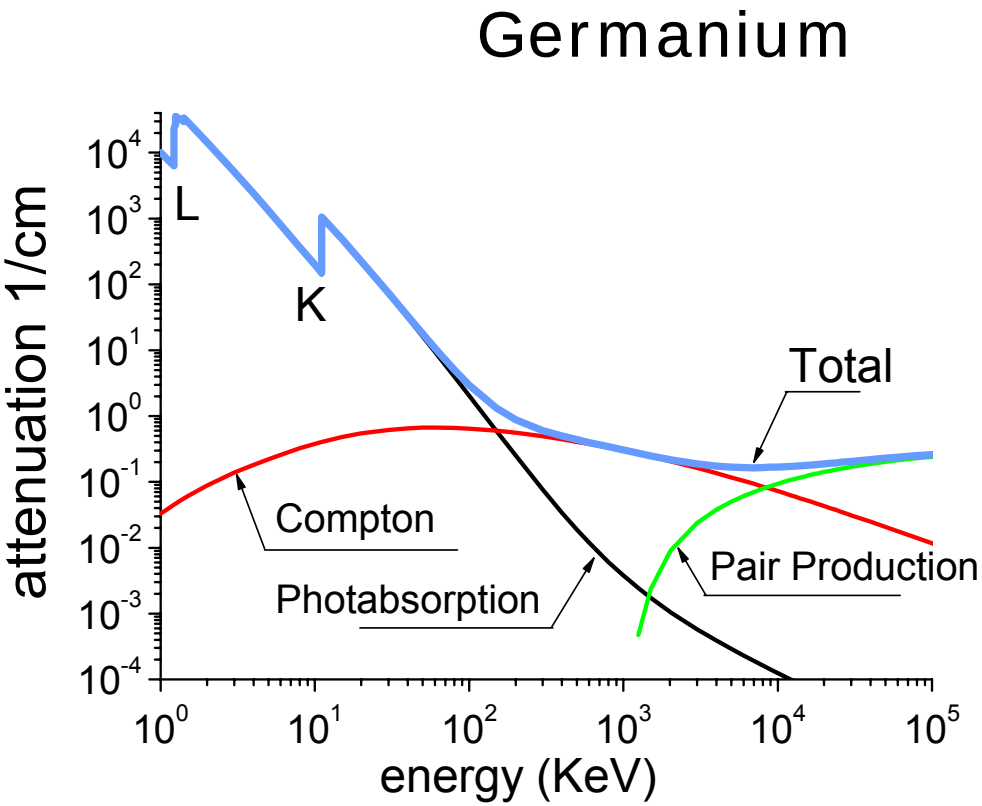




- polarization studies
- Compton cameras
- x-ray îmager
  e.g. medical applications

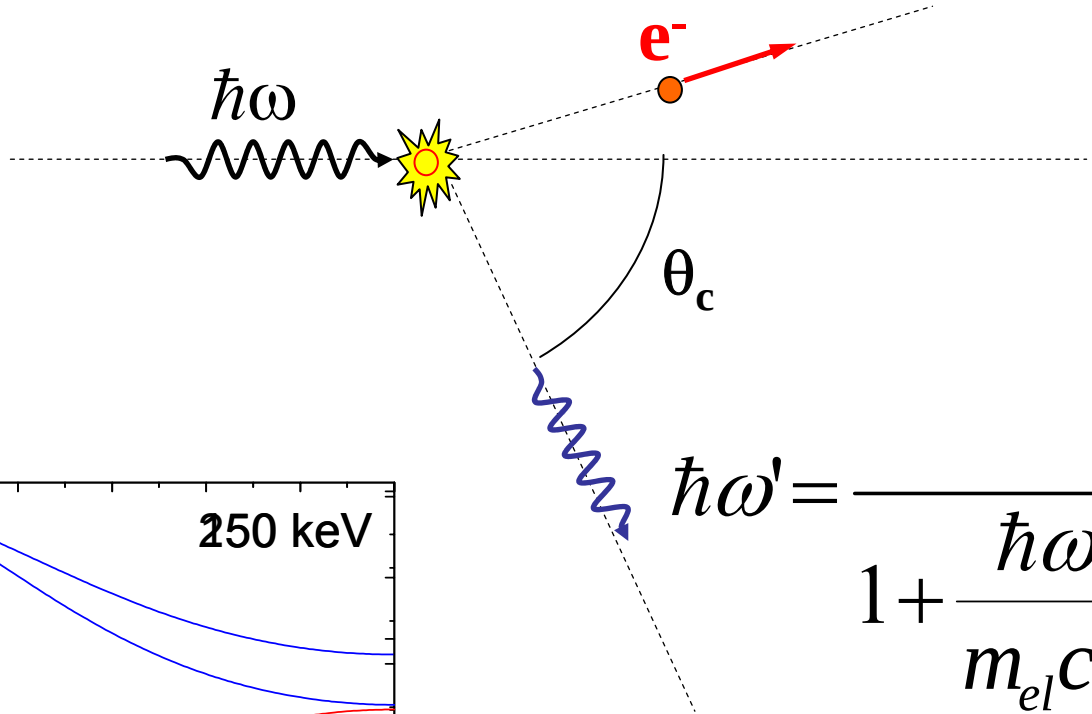
- precision spectroscopy
- Doppler tuned spectroscopy
- atomic lifetime studies

Interaction of electro-magnetic radiation with matter

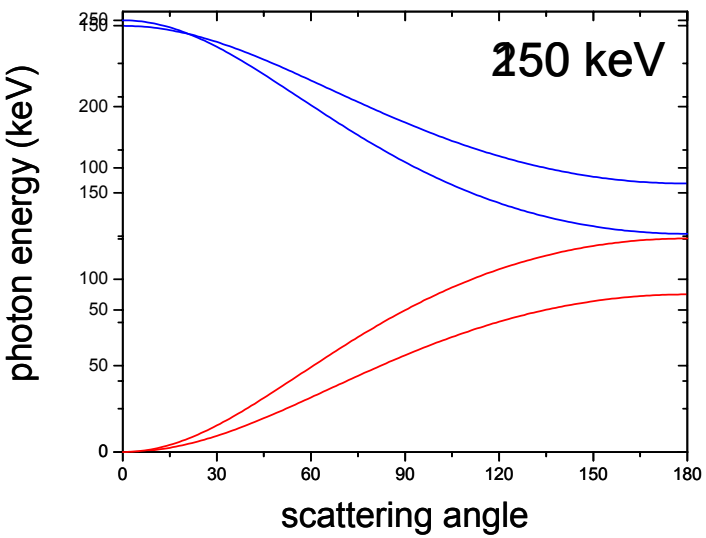


- **photoelectric effect**
- ***Compton scattering***
- **pair production**

Compton Scattering



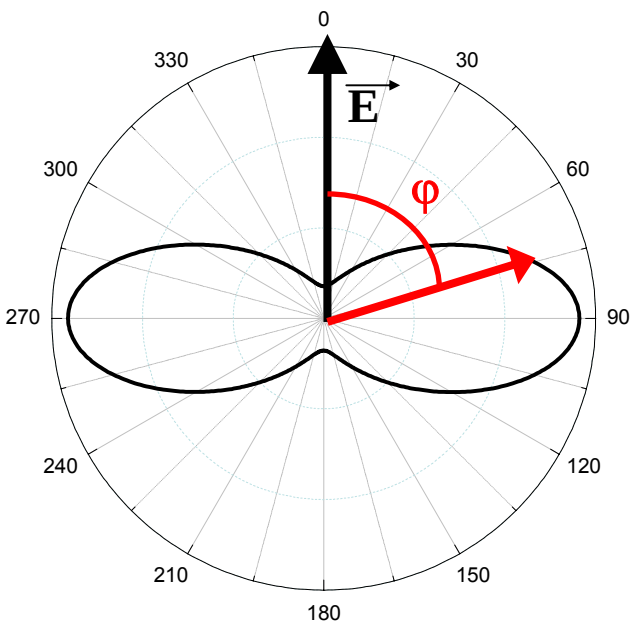
$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_{el}c^2}(1 - \cos\theta_c)}$$

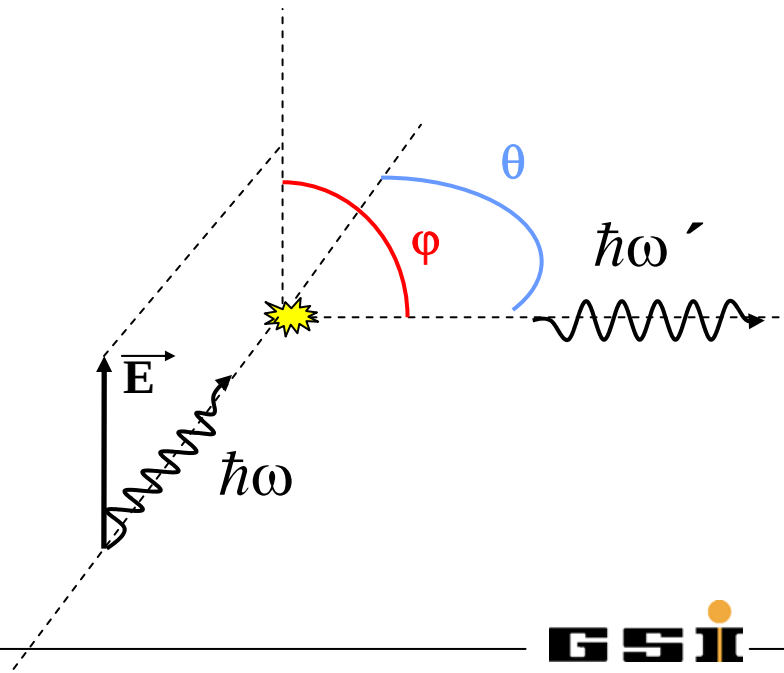


Polarization Measurement by Means of Compton scattering

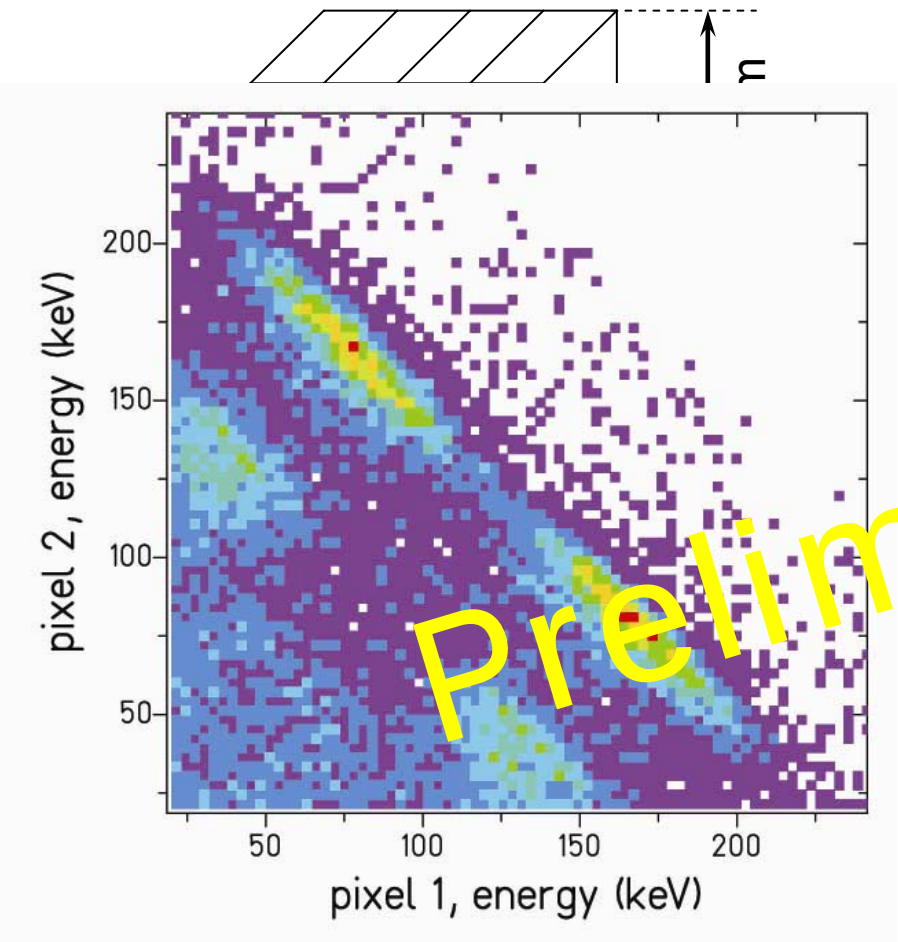
Klein-Nishina equation

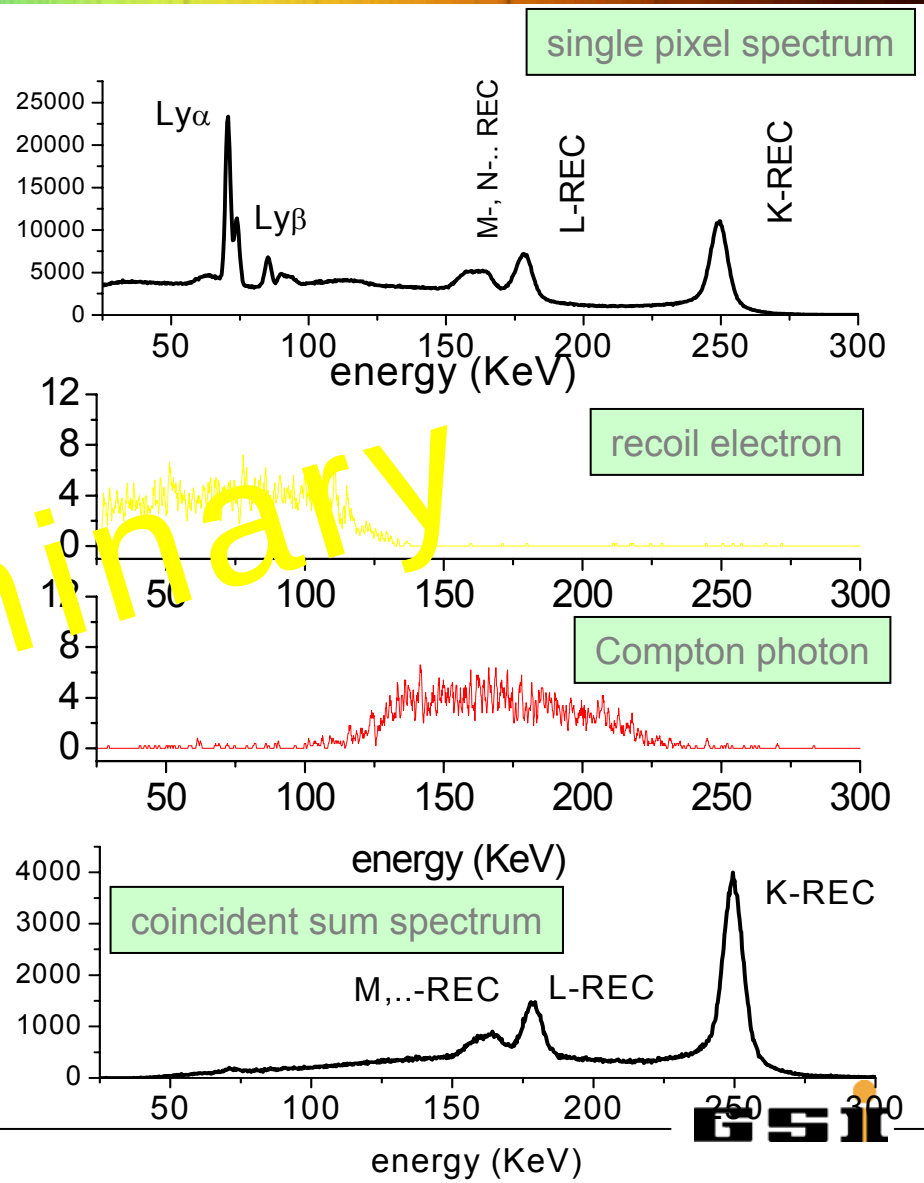
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta\cos^2\varphi\right)$$



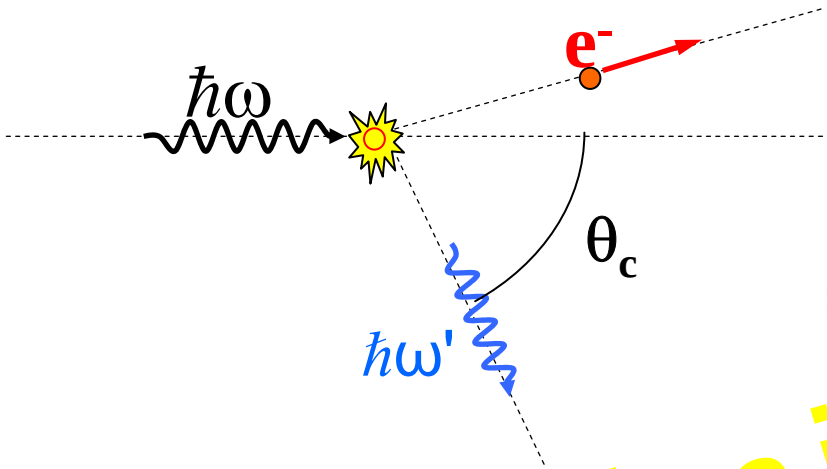


Pixel Detector -Coincidence Technique

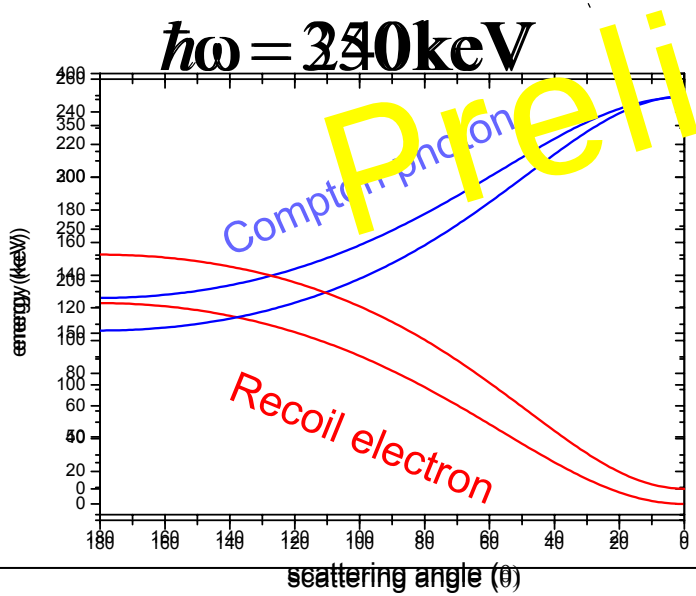


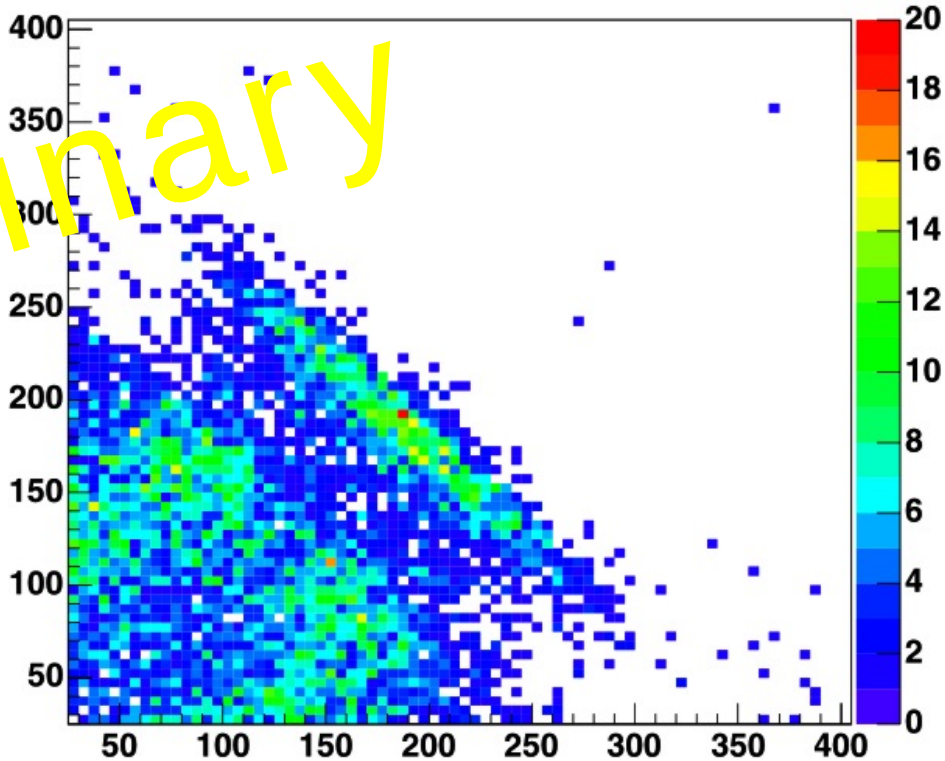


Compton Kinematics



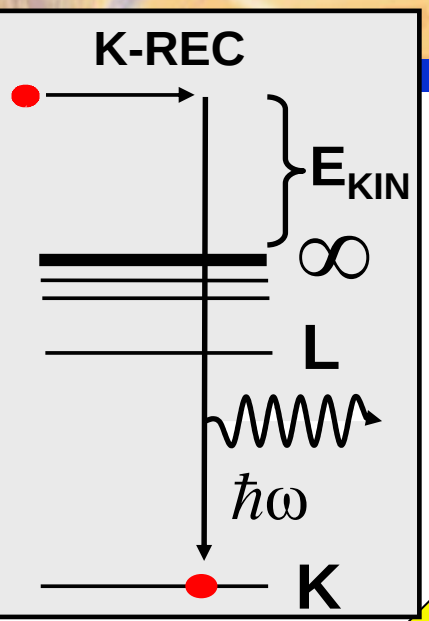
$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_{el}c^2}(1-\cos\theta_c)}$$

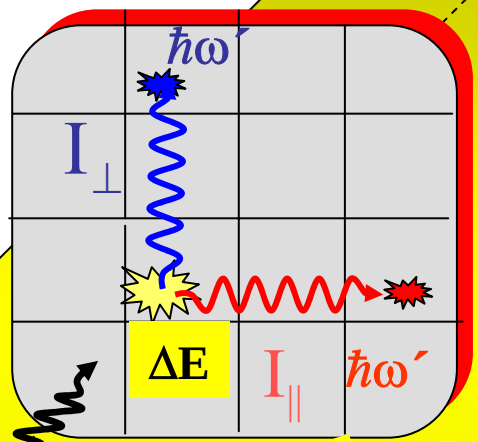




Preliminary

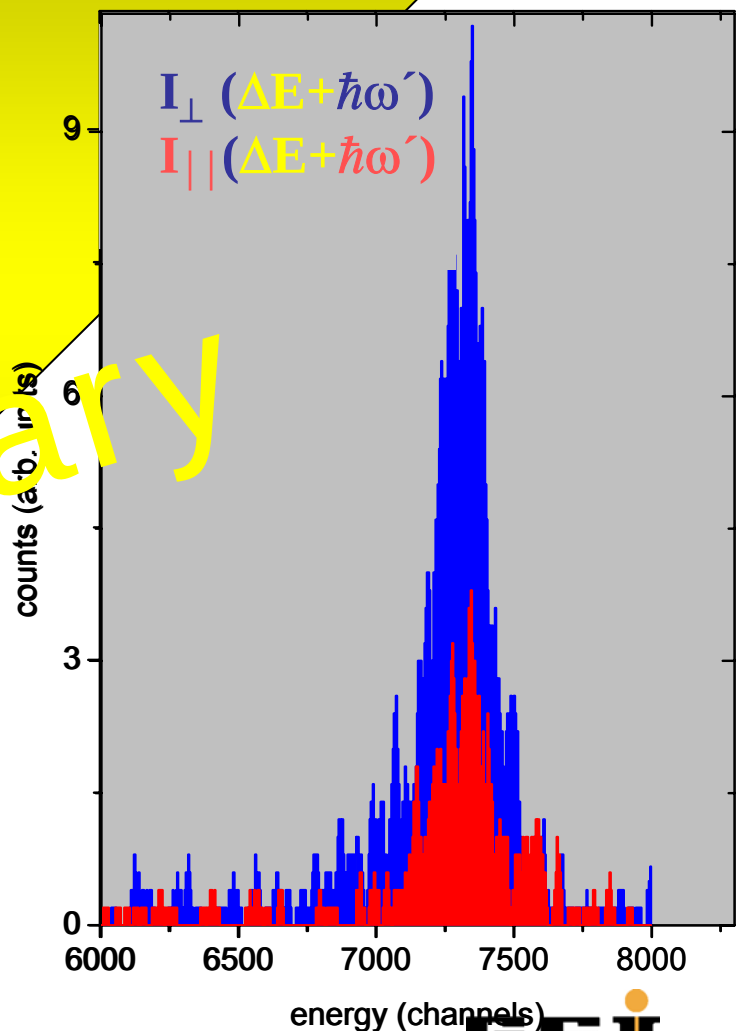
Polarization Experiment
($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)





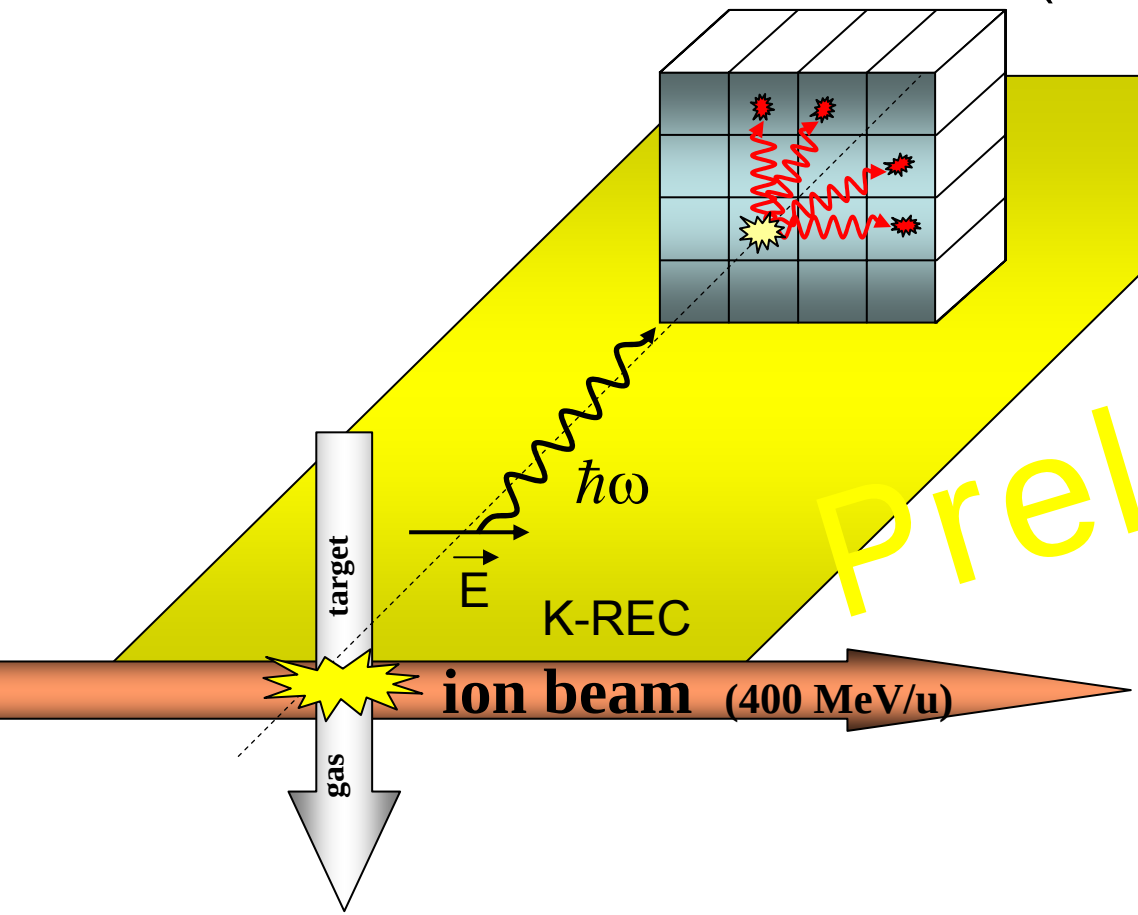
target

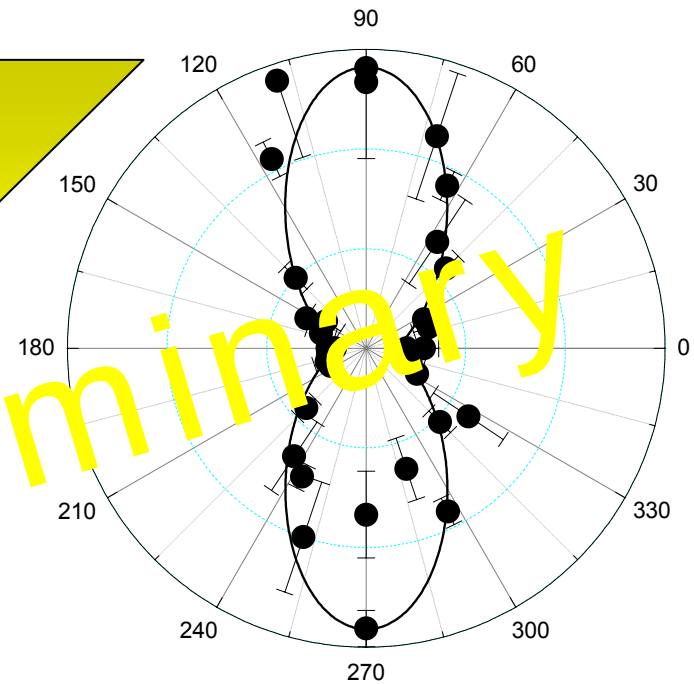
ion beam (400 MeV/u)



Experiment

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





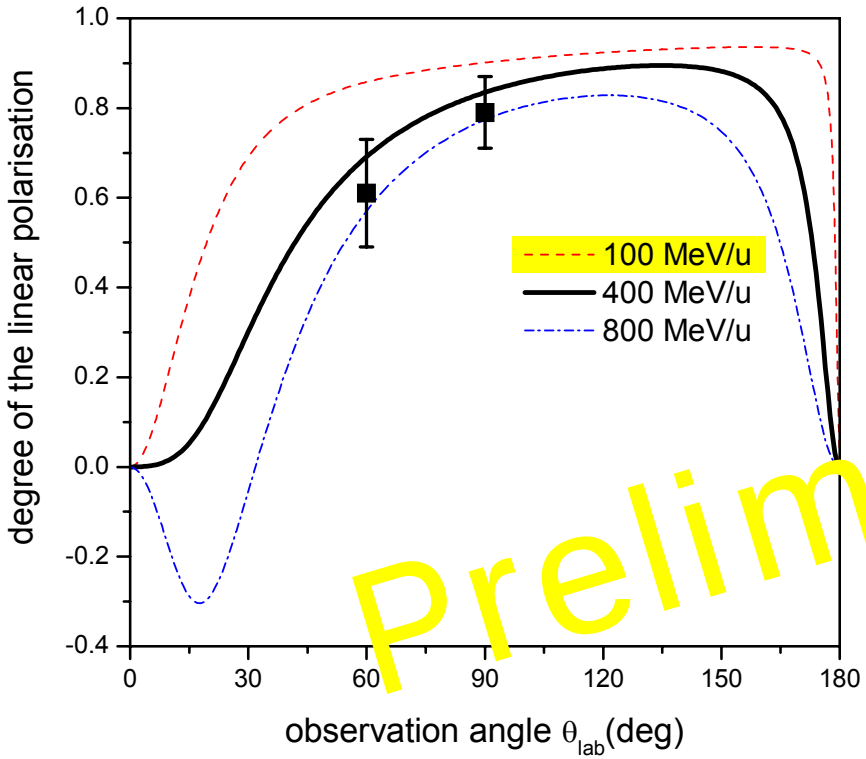
Preliminary

- ✓ K-REC radiation is strongly polarized
- ✓ polarization is within the scattering plane

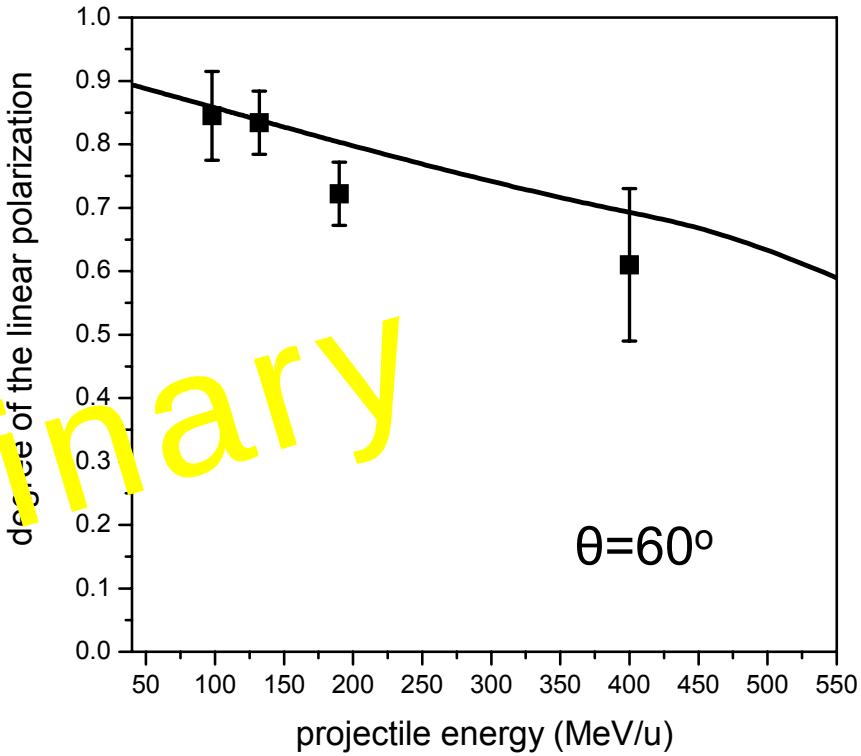
GSI ESR Storage Ring

Preliminary Results

Angular dependence



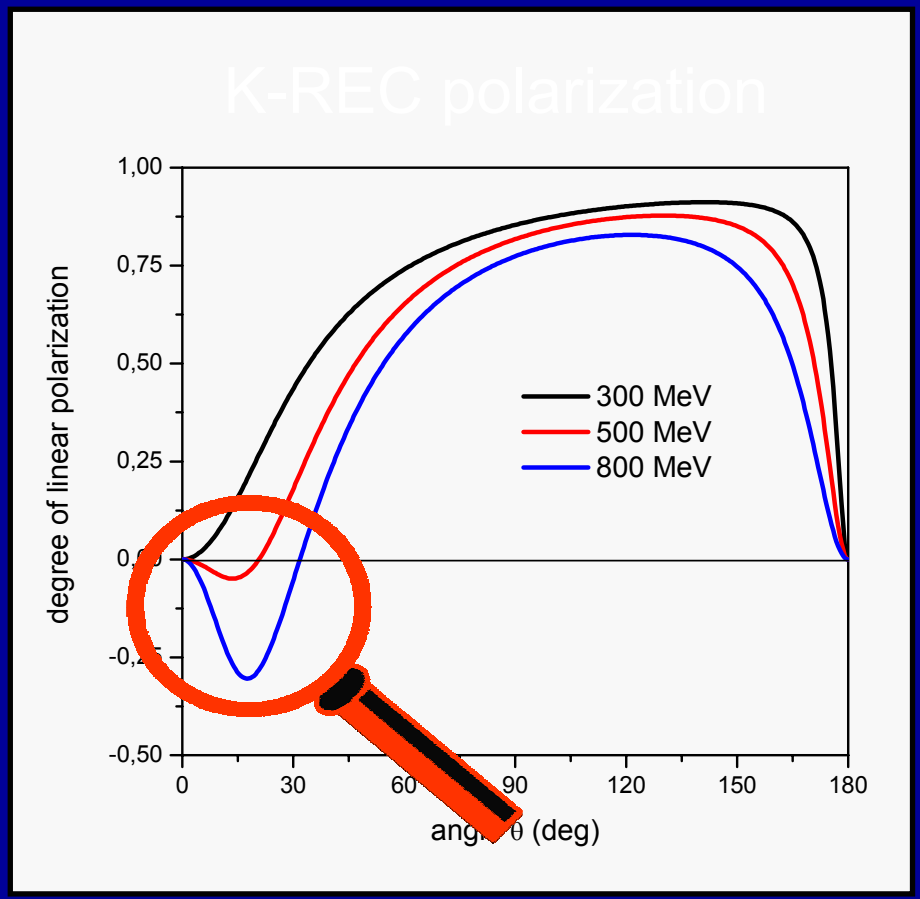
Energy dependence



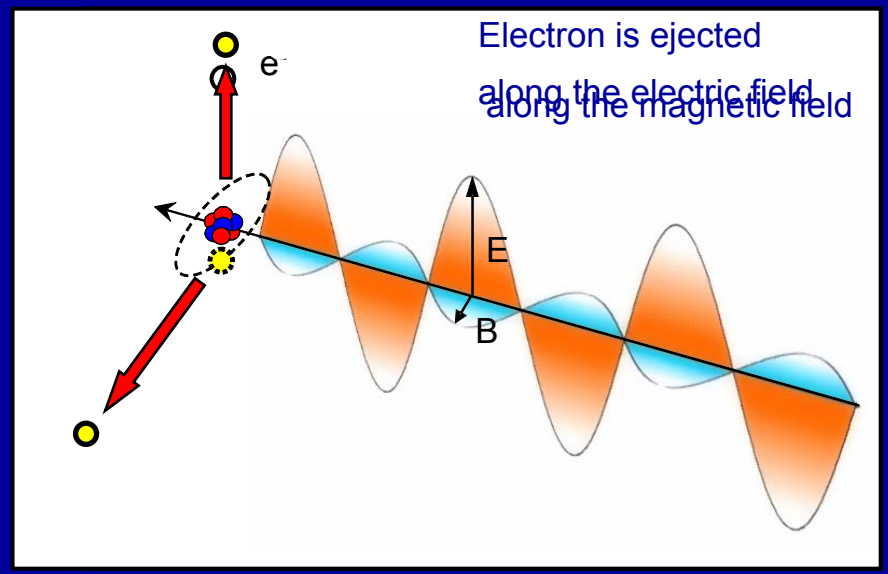
Experiment:
Tachenov et al.,
PHD Thesis 2005

Exact Relativistic Treatment
Eichler et al., PRA, 2001
Surzykov et al., PRA, 2001

Crossover Phenomenon



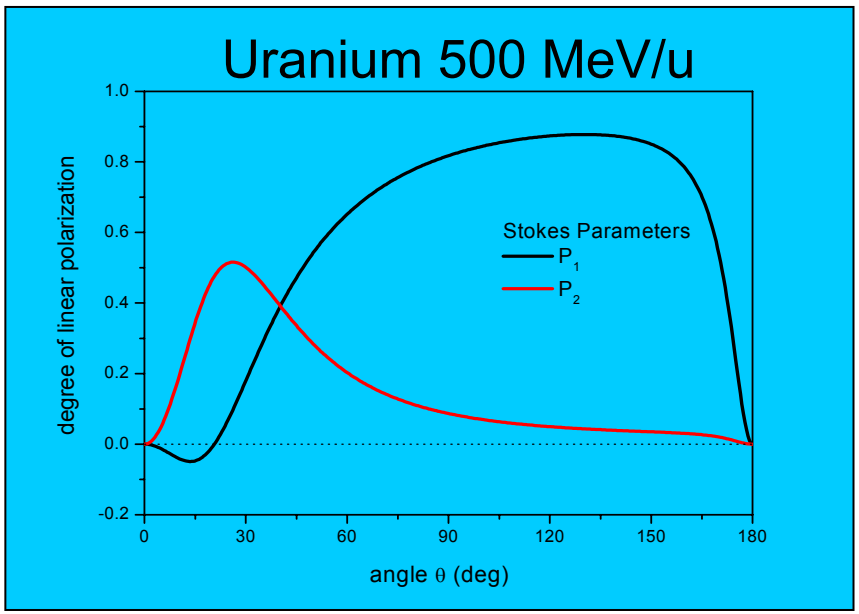
Photoionization



$$\vec{F} \propto \vec{E} + [\vec{v} \times \vec{B}]$$

Ion Beam Spin Polarization

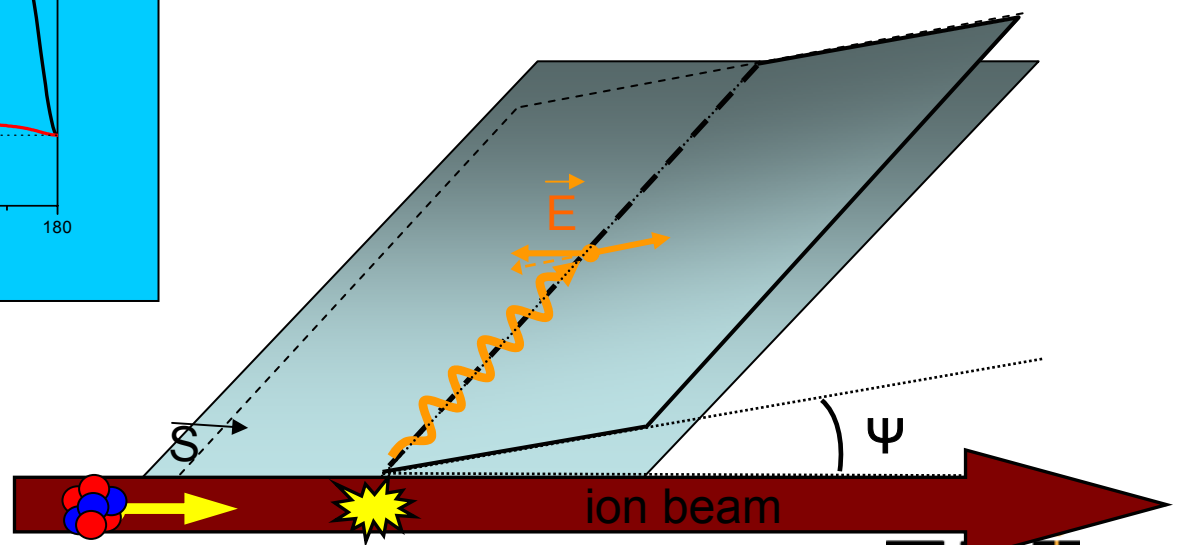
for spin polarized particles, the Stokes parameter P_2 is non-zero => ***polarization plane and scattering plane are not equal***



$$P_1 = \frac{I_0 - I_{90}}{I_0 + I_{90}} \qquad P_2 = \frac{I_{45} - I_{135}}{I_{45} + I_{135}}$$

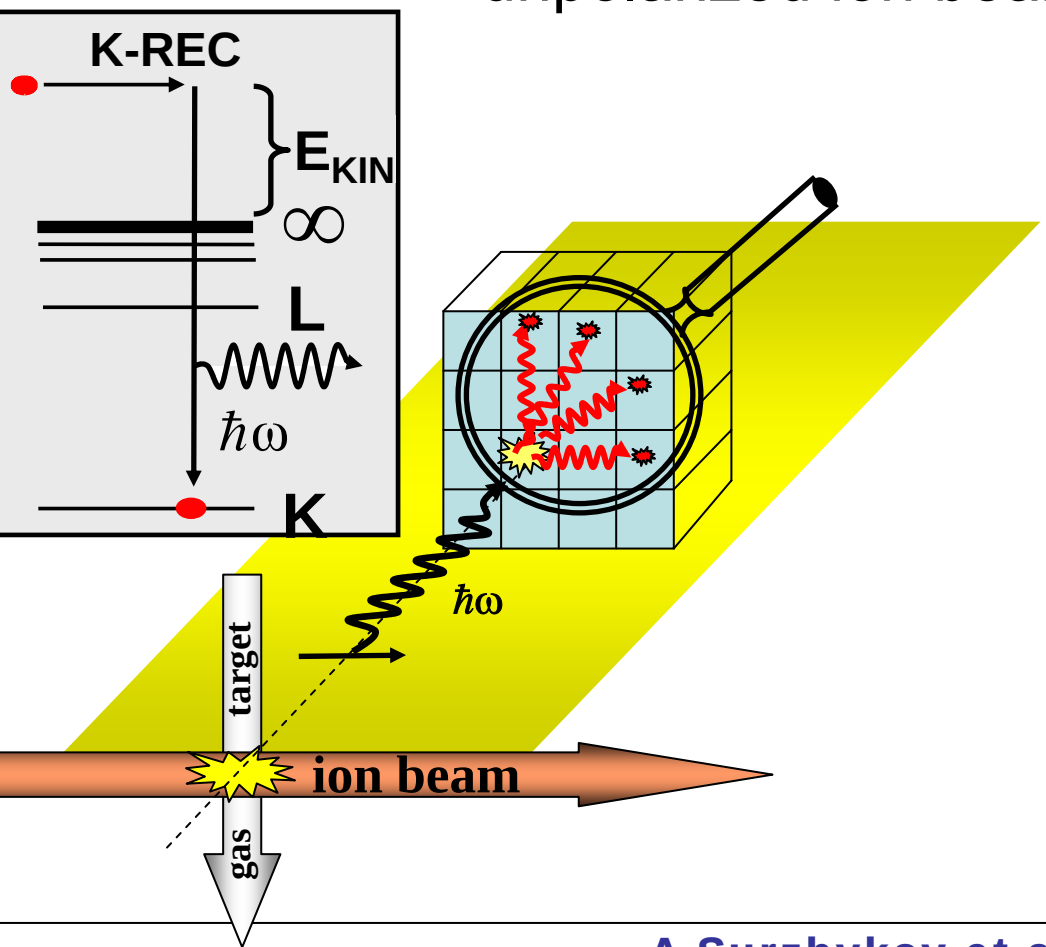
$$\tan 2\Psi = \frac{P_2}{P_1}$$

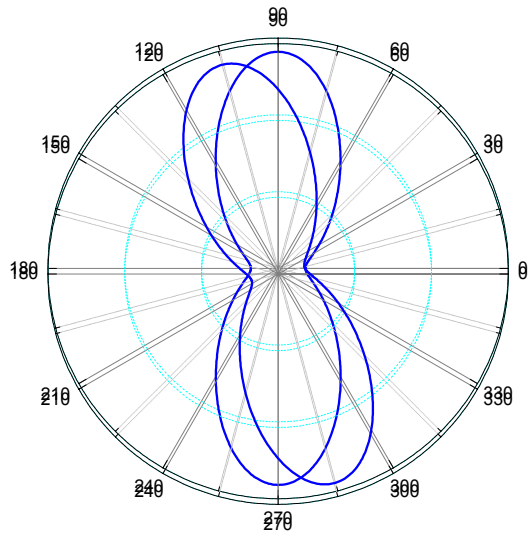
$\Psi \Rightarrow$ degree of ion beam spin polarization



Detection of spin polarized ion beams

spin polarized ion beams
unpolarized ion beams





A.Surzhykov et al., PRL 94, 203202 (2005)

Energy Resolution

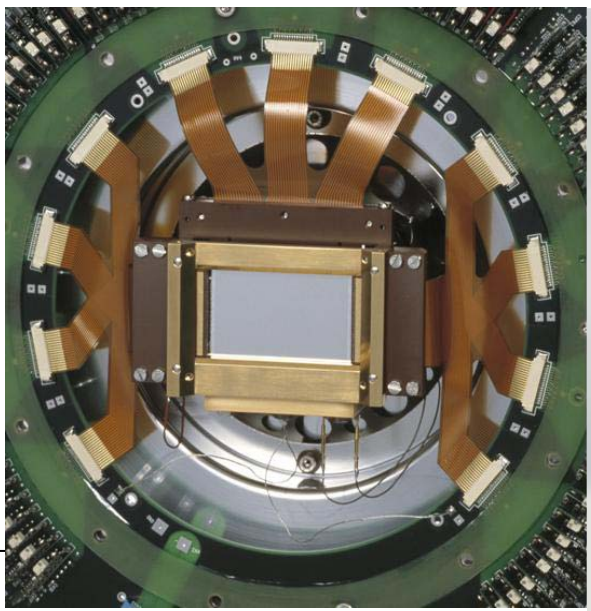
Position Resolution (2D/3D)

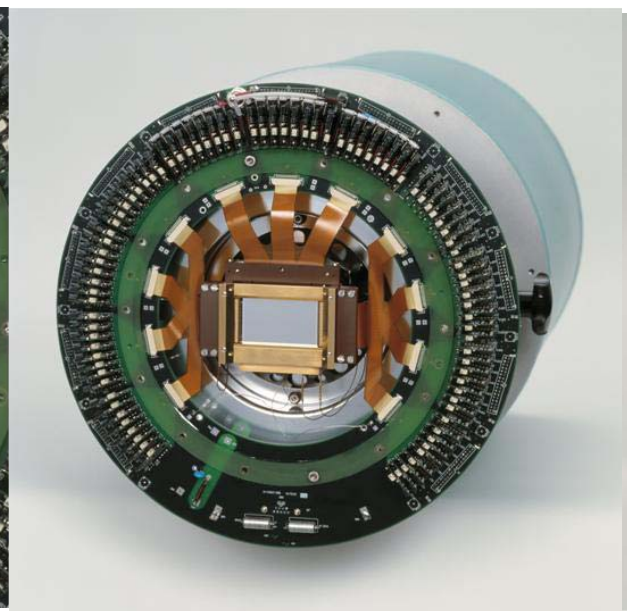
Timing

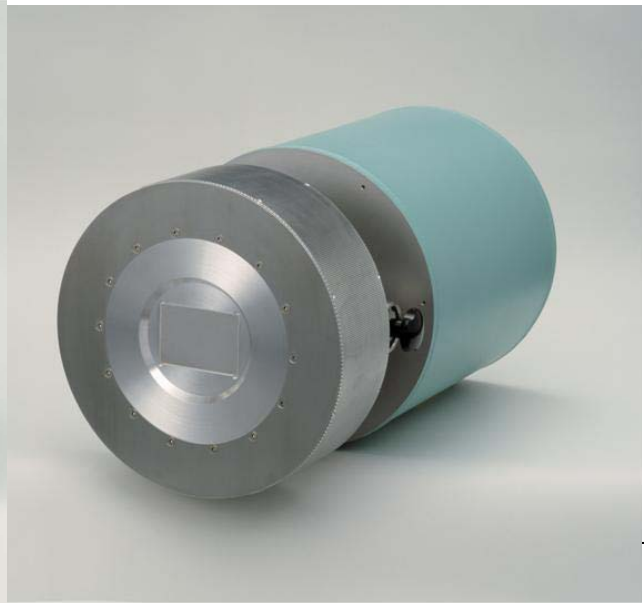
2D μSTRIP

germanium detector

J – GSI





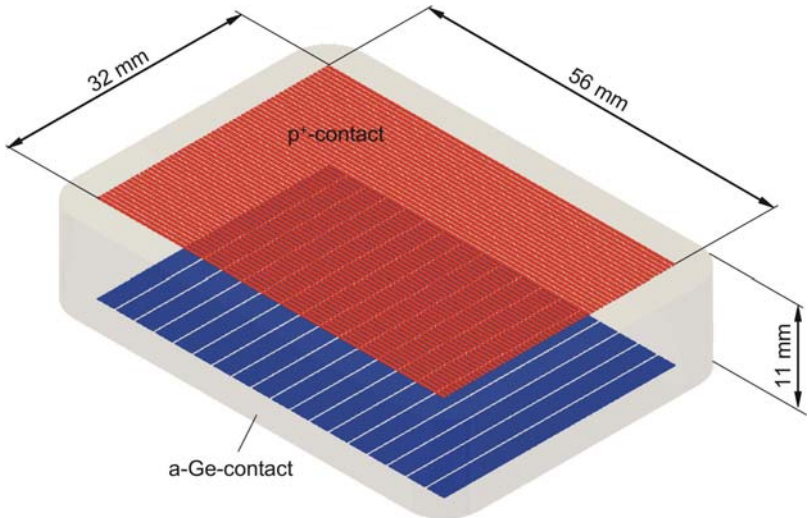


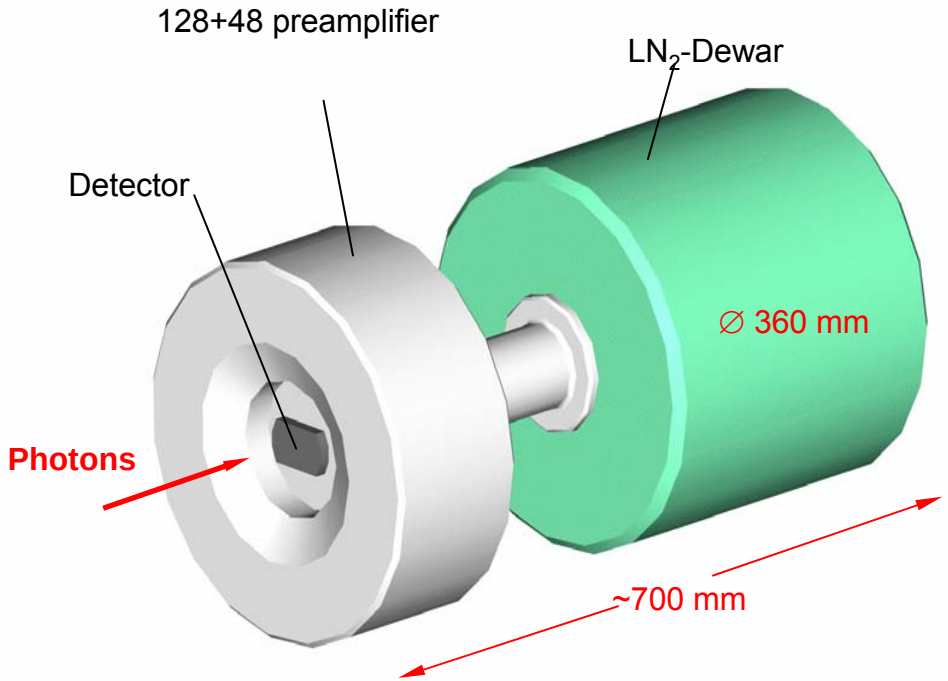
ESRF

at ESRF: systematic studies of the detector responce for the 2D polarimeter (e.g. polarization sensitivity)

50 keV to 500 keV

2D μstrip detector system



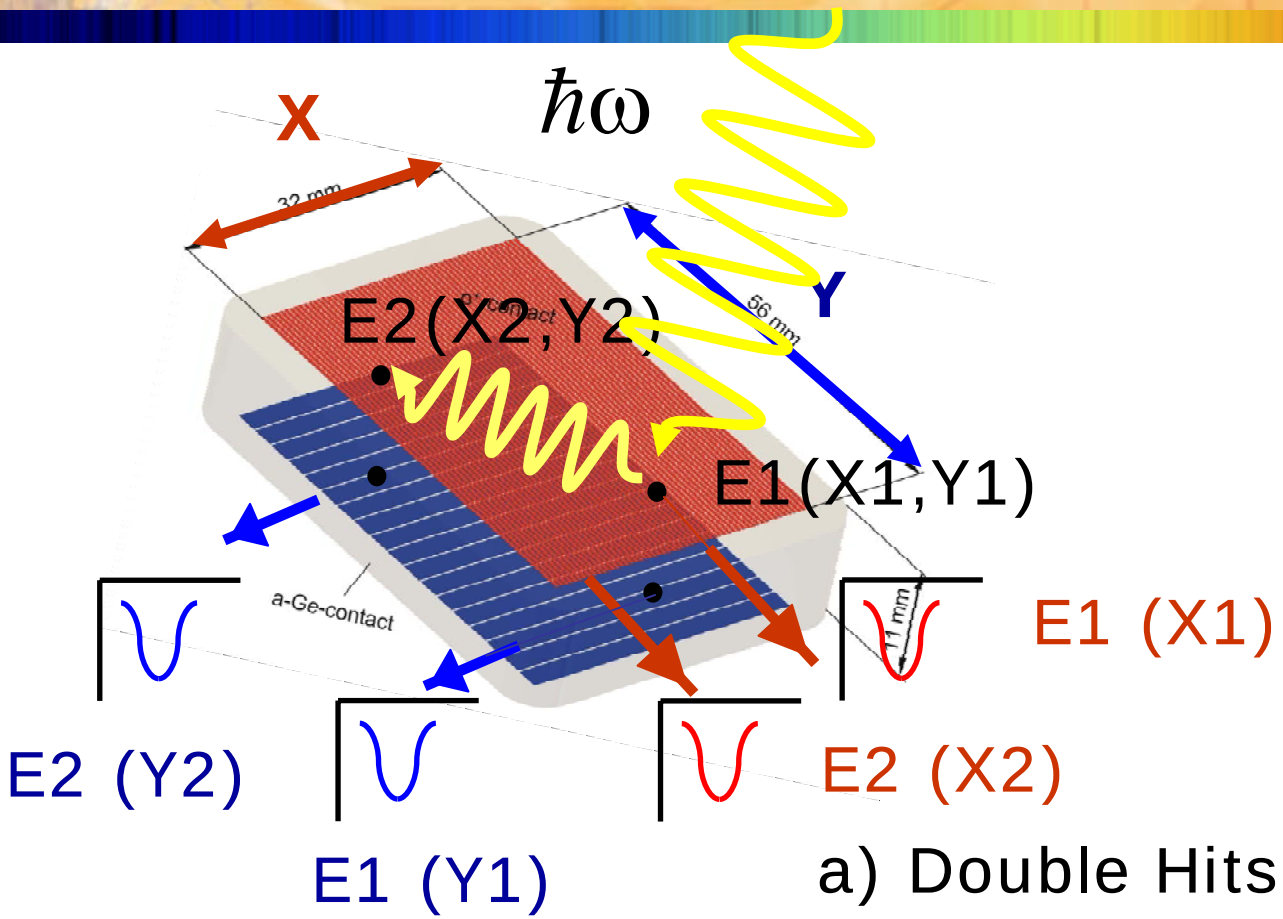


Crystal size
heigth: 32 mm
width: 56 mm
thickness: 11 mm

Front: 128 strips pitch ~250µm

Back: 48 strips pitch ~1167µm

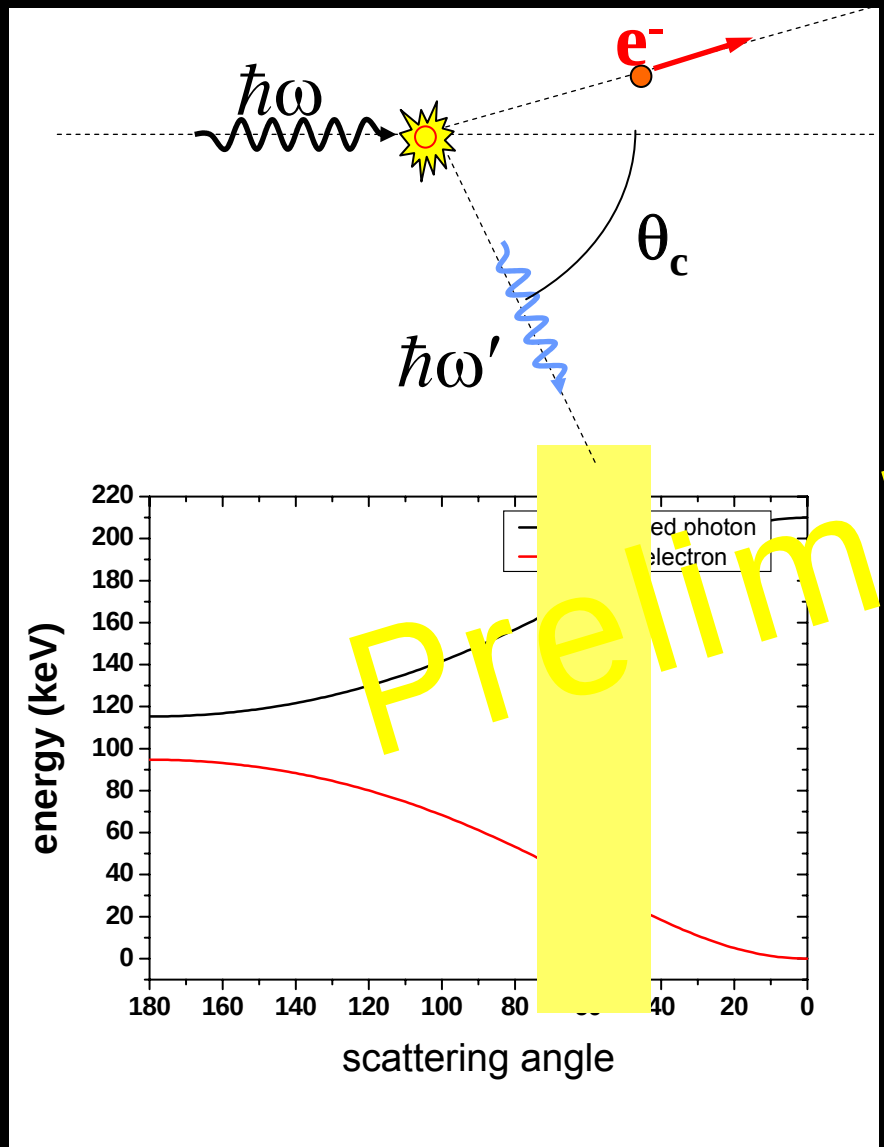
Strip Detector: Analysis of Compton Events => Use Multihit Sensitivity

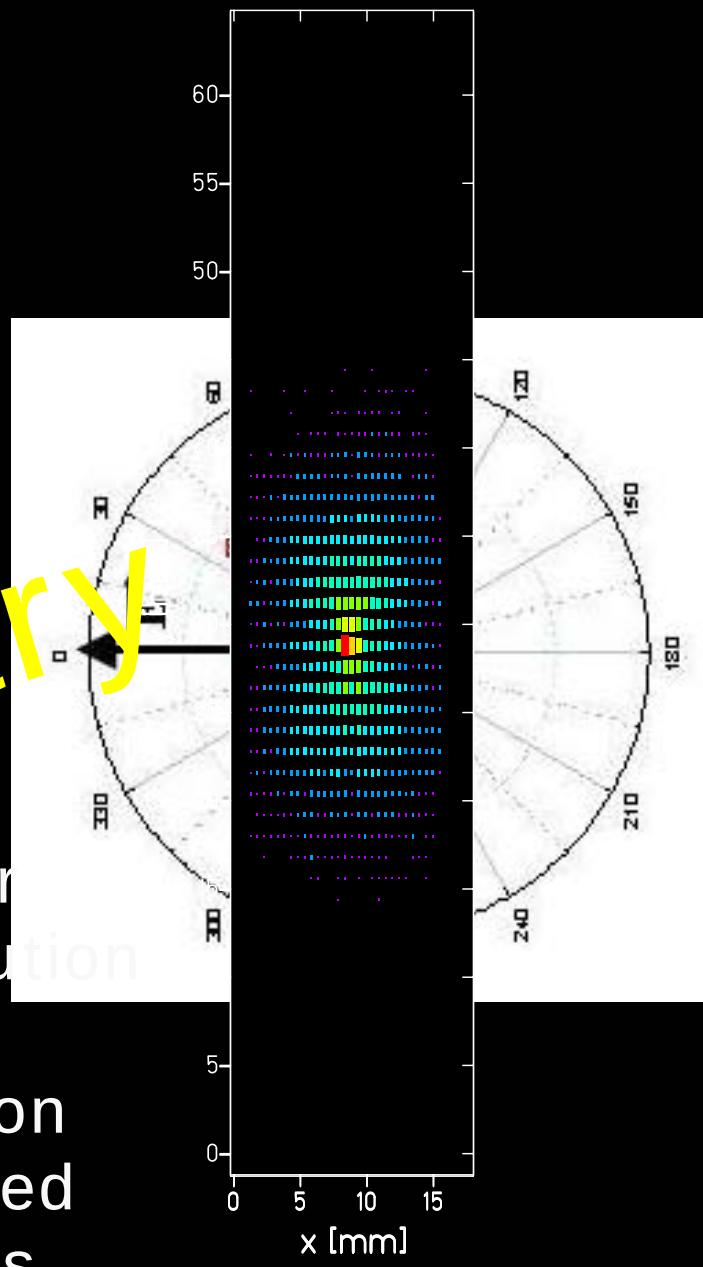


a) Double Hits on Front Side
b) Double Hits on Back Side
c) Compare Energy Information to fix (X1,Y1) and (X2,Y2)

2D images of the Compton scattering distribution in germanium as function of the scattering angle

The data were recored at the ESRF using 98% linearly polarized photons with en energy of 210 keV.





Preliminary

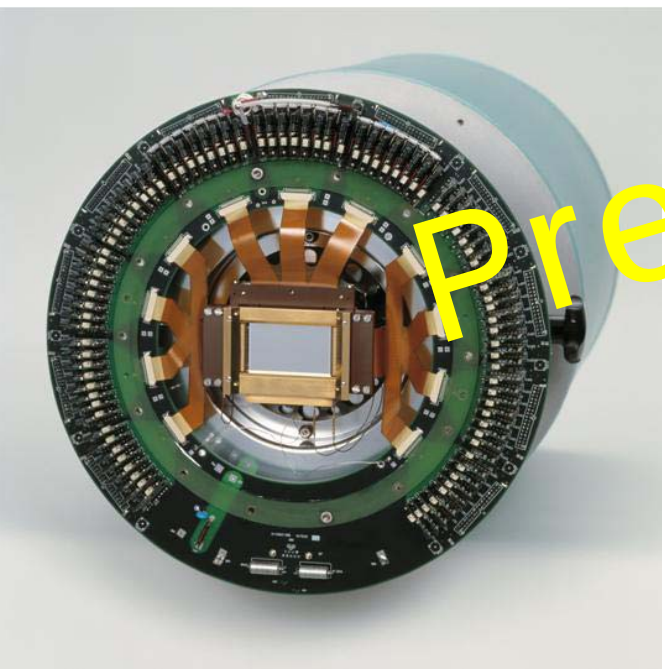
angular distribution of the Compton scattered photons

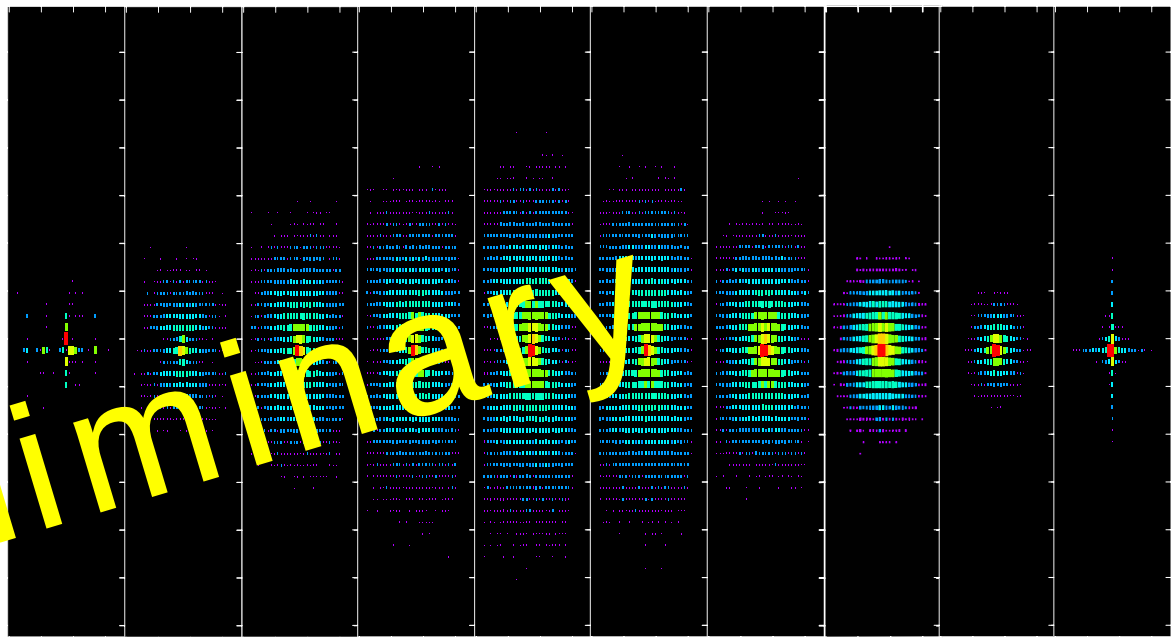
Compton Imager and Polarimeter for Hard X-Rays @ ESR

Polarization Spectroscopy of Photon-Matter Interaction

2D μSTRIP germanium detector

J-GSI





2D images of the Compton scattering distribution in germanium as function of the scattering angle

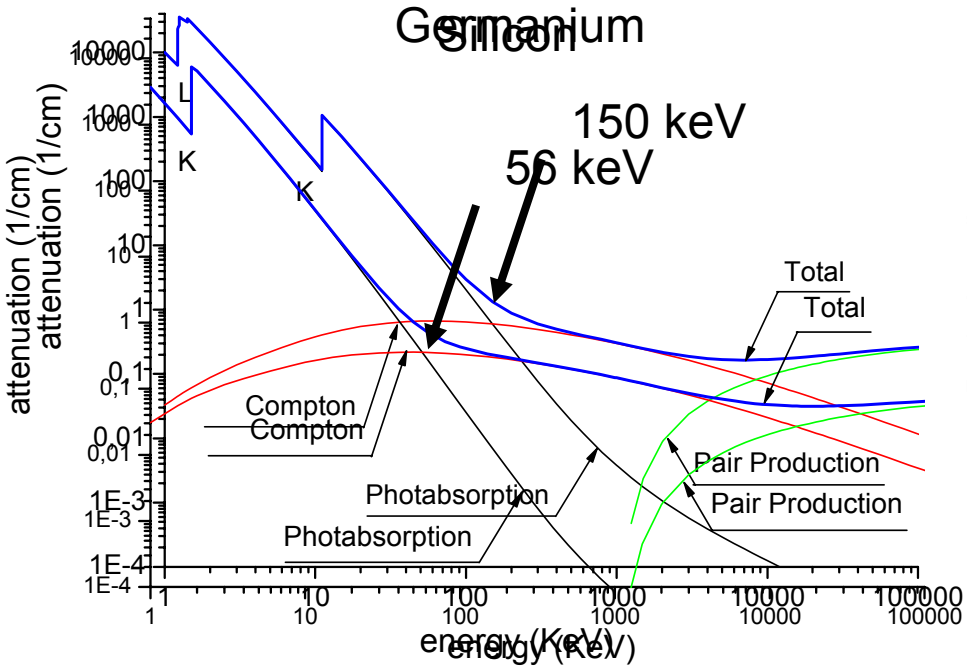
The data were recored at the ESRF using 98% linearly polarized photons with an energy of 210 keV.

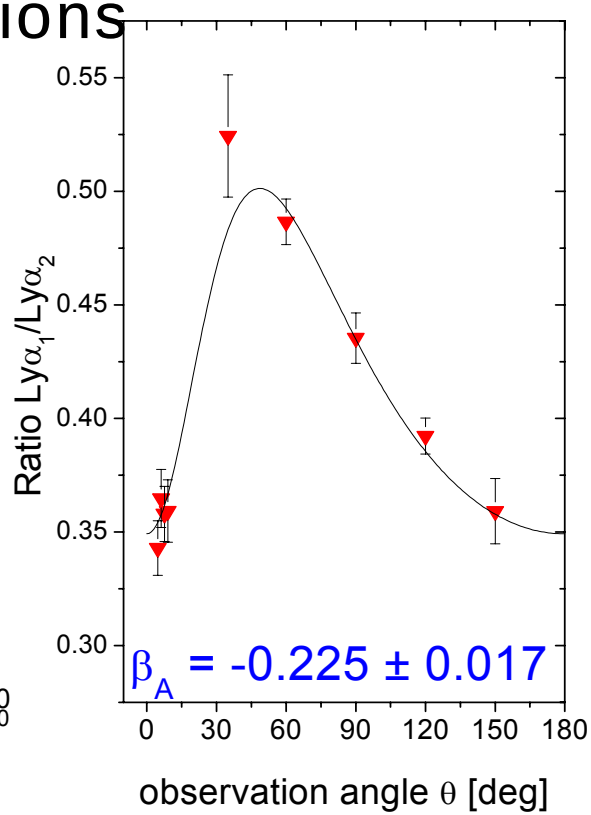
GSI

What About Inner Shell Transitions with Energies Below 100 keV ?

bound-bound transitions

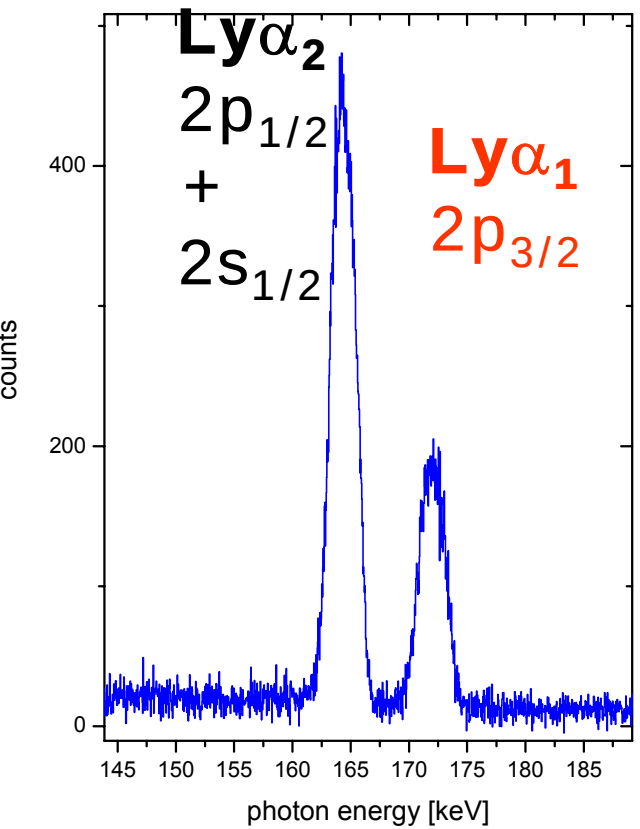
bound-free, free-free transitions

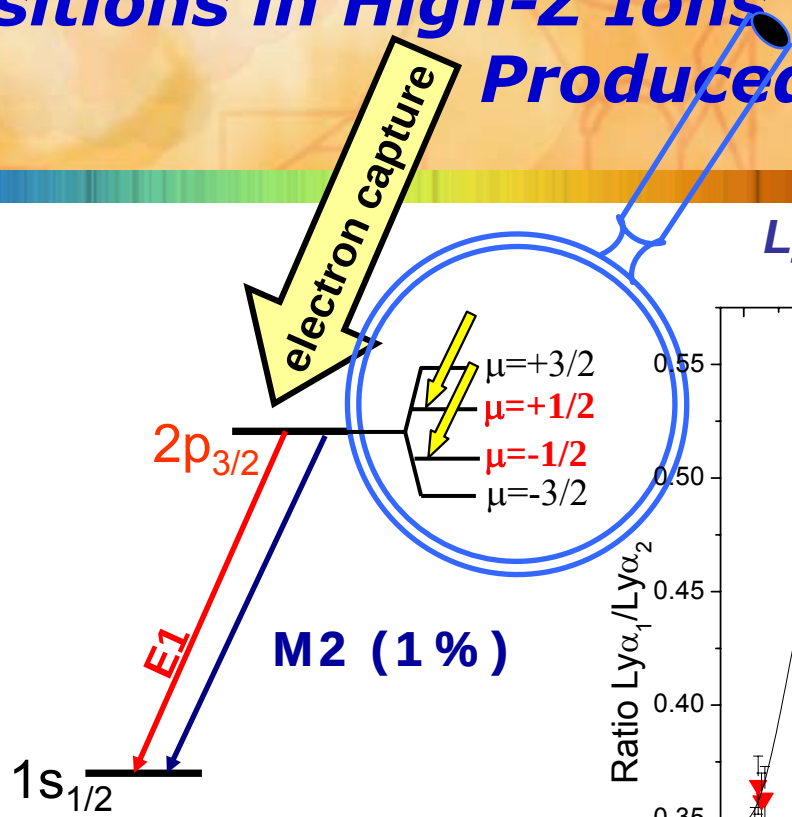


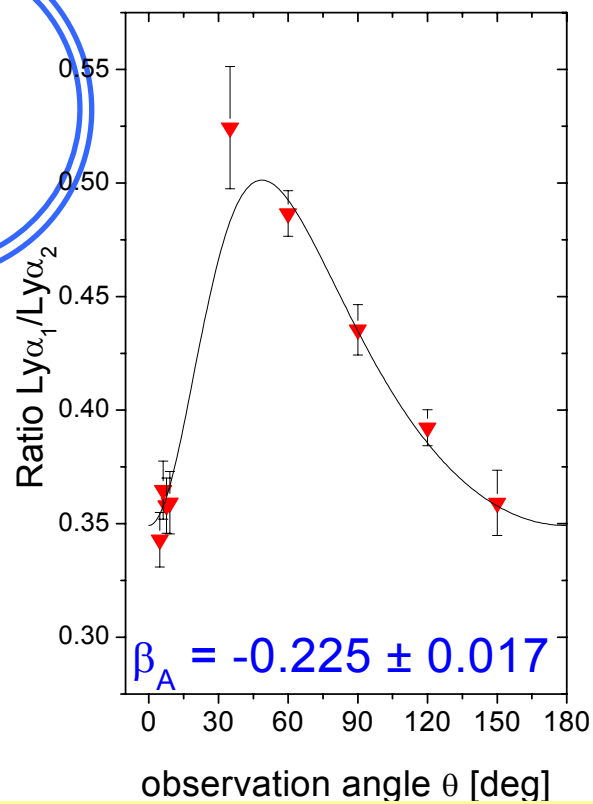


$2p_{3/2}$ transitions in high-Z ions populated by electron capture

$2p_{3/2}$ Transitions in High-Z Ions Produced by REC







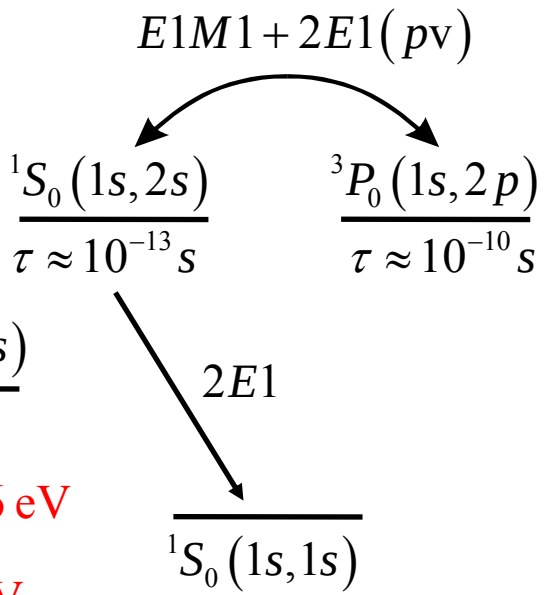
Strong Alignment
PRL 79, 3270 (1997)
Multipolmixing E1 / M2
PRL 88 153001 (2002)

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

Helium-like Uranium: Parity Violation in Heavy Ions

Parity admixture

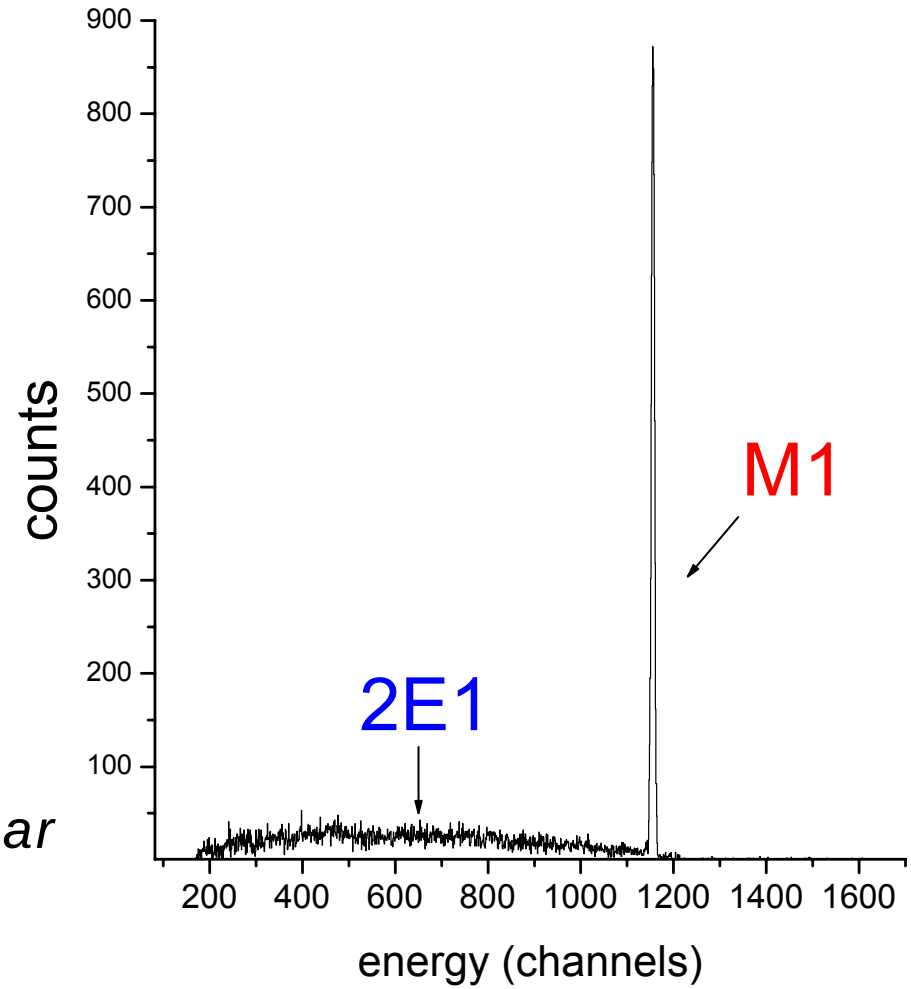
$|\eta| = 5 \cdot 10^{-6}$



$E(^1S_0) = -165\,114.406$ eV

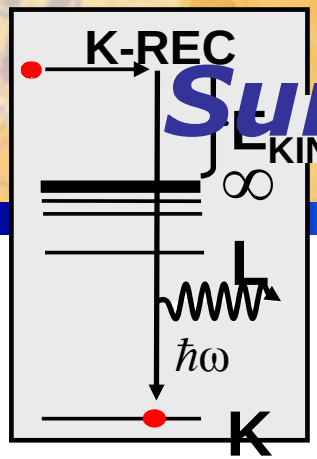
$E(^3P_0) = -165\,113.5$ eV

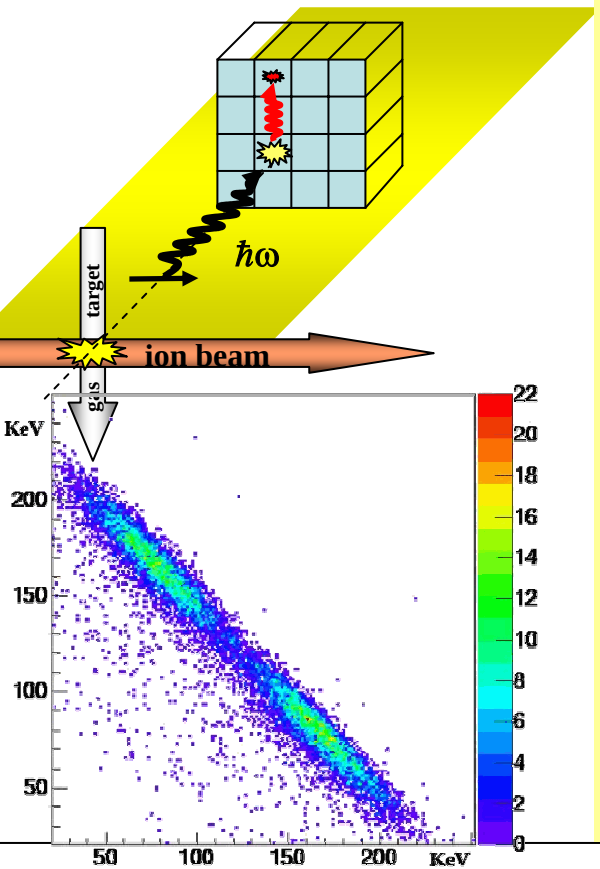
$\Delta E = -0.906$ eV



Check for the Asymmetry in the Linear or Circular Polarization of the 2E1 Transitions

Summary and Outlook





- segmented solid state detectors an excellent tool for polarization studies in the hard X-Ray regime
- for REC: first polarization studies for hard x-rays
- diagnostic tool for spin polarized ion beams
- using Si(Li) strip detectors, such studies can be extended to inner-shell transitions
- towards a study of parity violation experiments in atomic systems at high-Z
- further sensitivity enhancement via 3D readout
- a lots of applications