Sparc Topical Workshop
12-15 February 2007

X-ray Spectroscopy of Highly Charged Ions at FAIR

An overview of the activities at GSI in preparation of the new facilities

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Darmstadt, Germany

Collaboration

Mainz

Paris

Frankfurt

Jülich

Grenoble

Darmstadt

Caen

Cracow

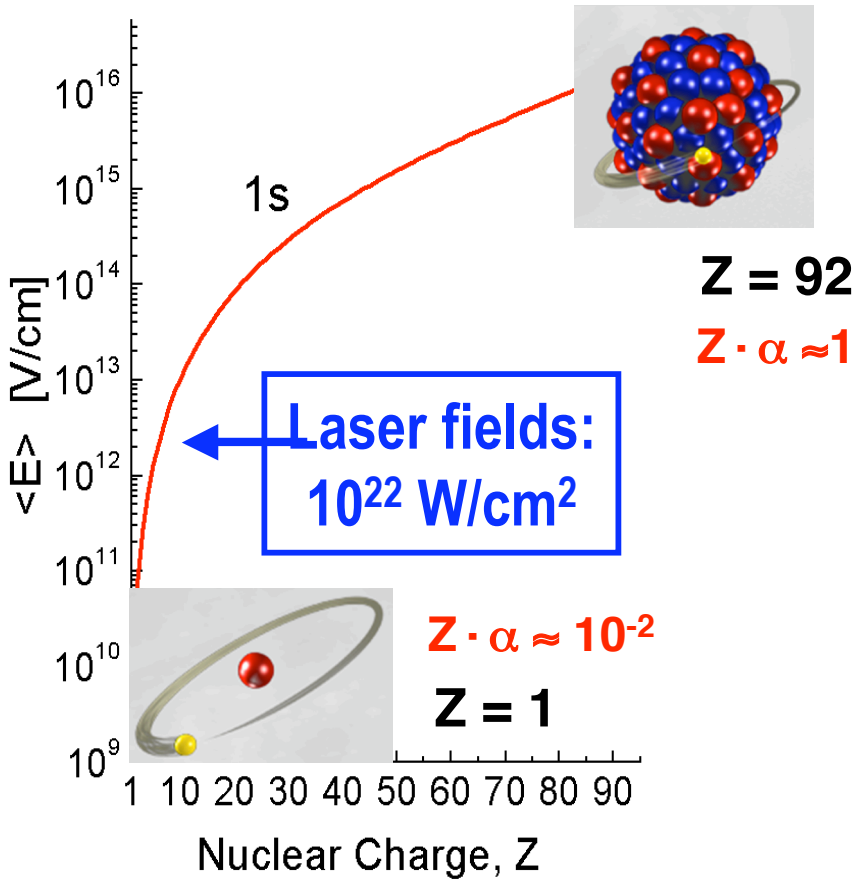
Madison

Jena

Greenbelt

Kielce

Atomic Physics in Extremely Strong Coulomb Fields



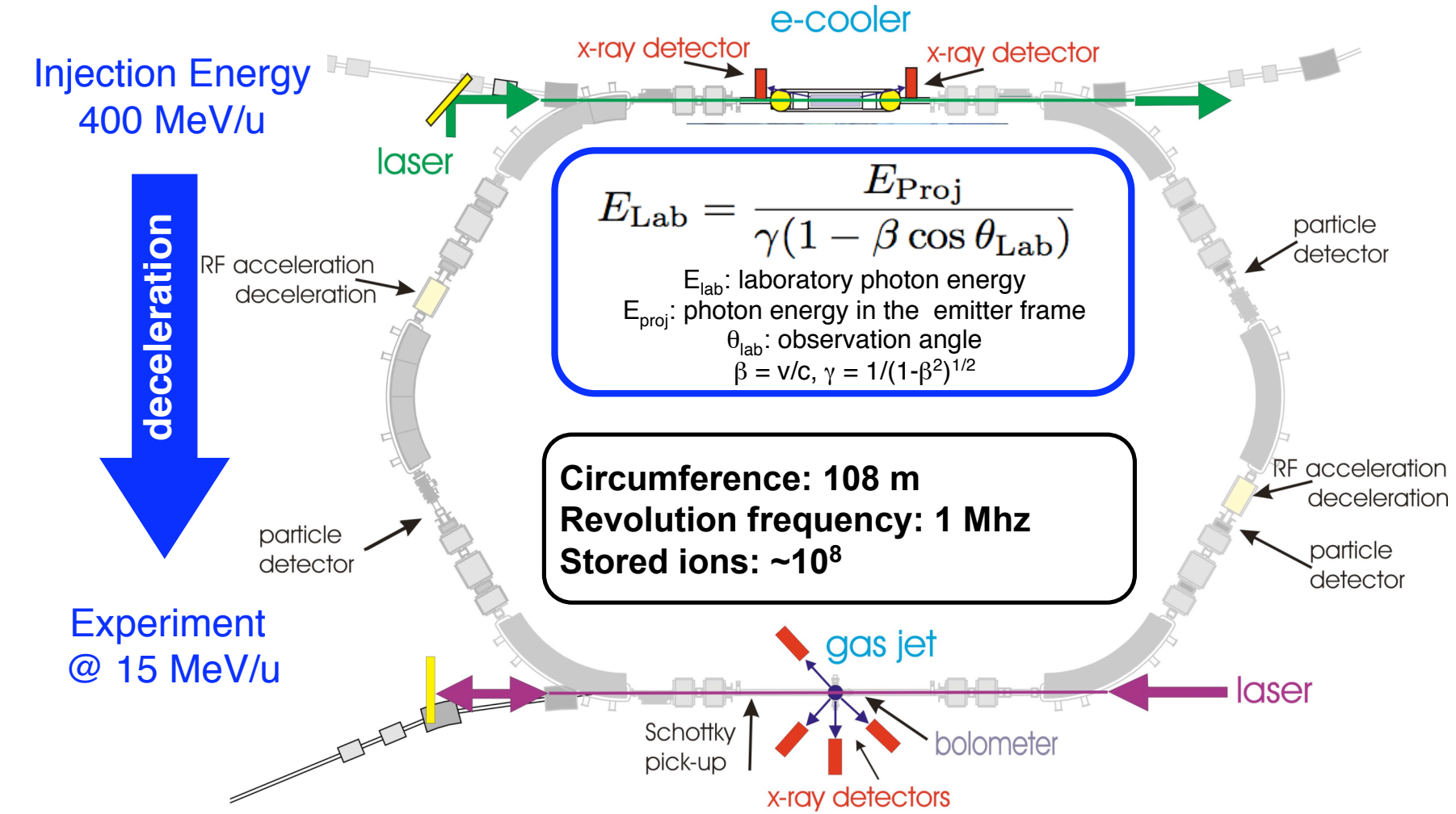
Atomic Structure at High-Z

- Bound state quantum electrodynamics (QED)
- Effects of relativity on the atomic structure
- Electron correlation in the presence of strong fields

Atomic Collision at High-Z

- Correlated many-body dynamics
- Photon matter interaction: e.g., photon polarization effects
- Dynamically induced strong field effects

X-ray spectroscopy at the ESR storage ring



Excited states are produced by electron capture (jet target) / recombination (electron target)

New Experimental Storage Ring

Instrumentation

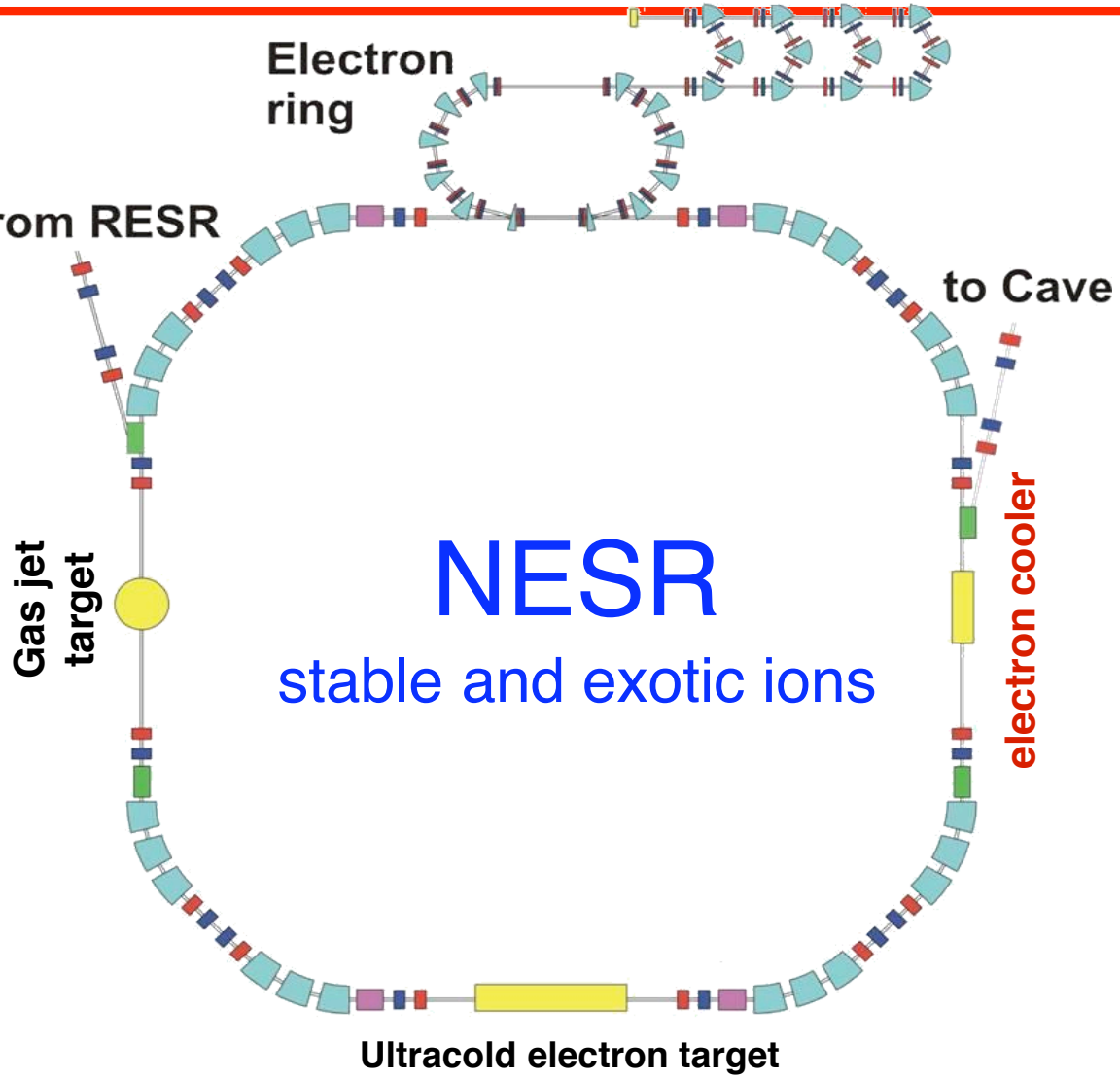
Ultracold electron target

Internal Target (atomic, cluster, micro-cluster)

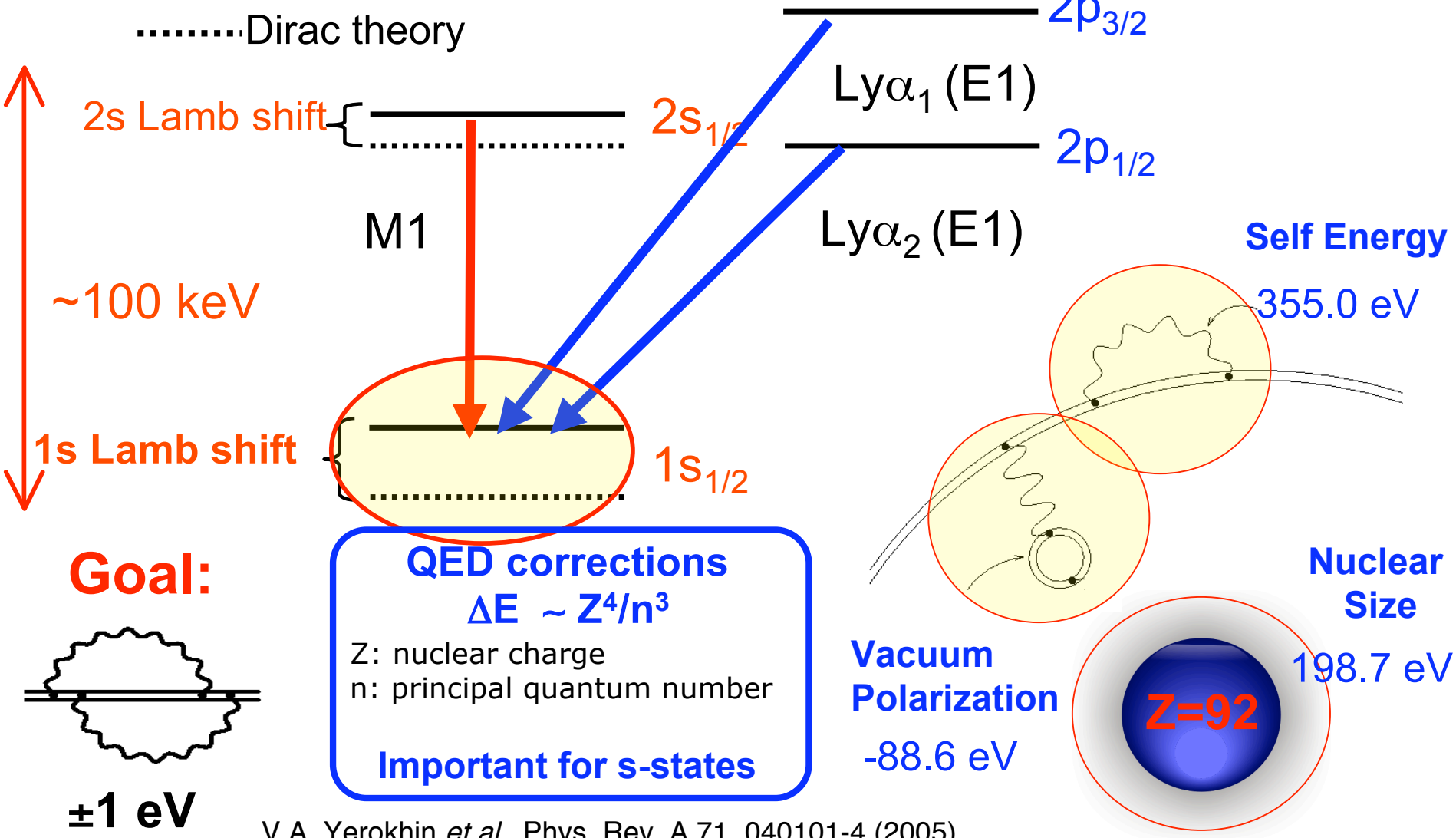
In-Ring Recoil Momentum Microscope

High Resolution X-Ray and Electron Spectrometers

Highly Intense Laser Beams

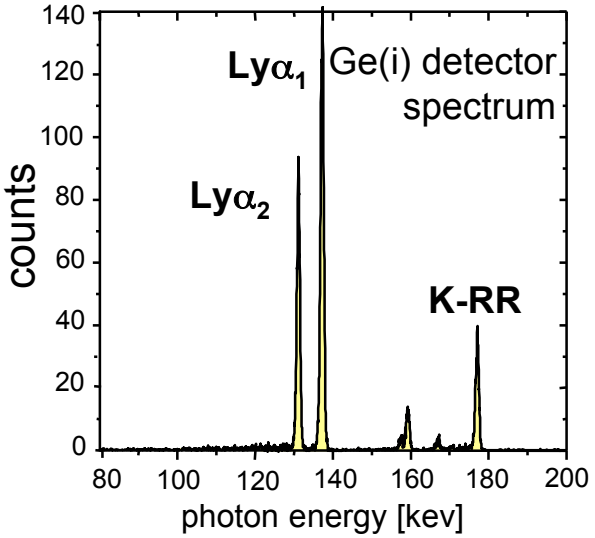


Atomic structure: 1s Lamb shift



V.A. Yerokhin *et al.*, Phys. Rev. A 71, 040101-4 (2005).

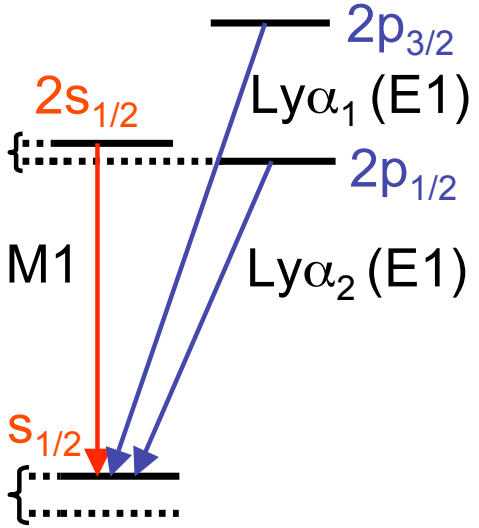
Test of QED in hydrogenlike Uranium

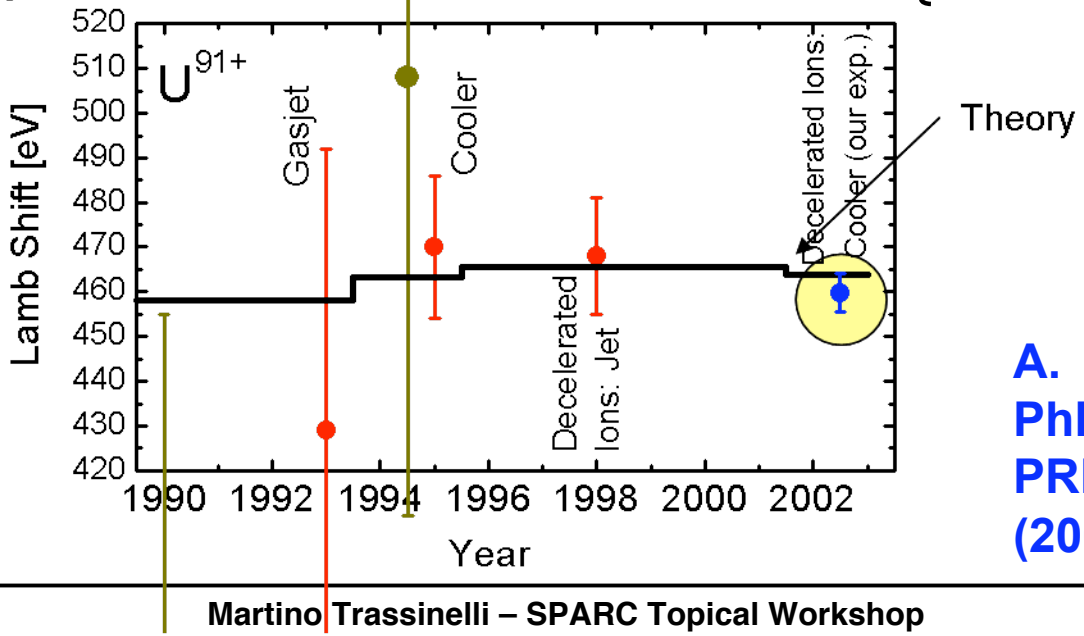


1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



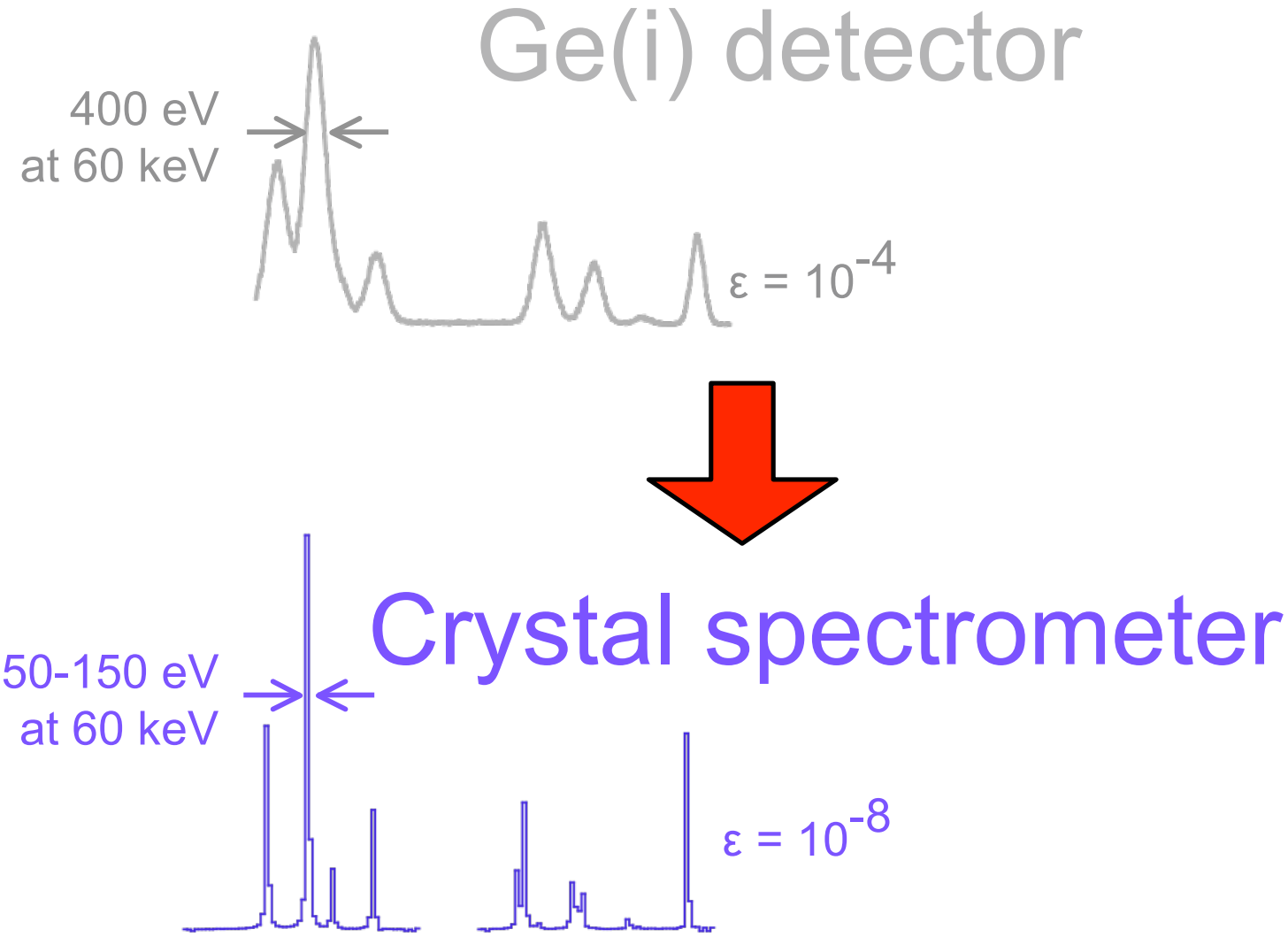


nature

Research Highlights
Nature **435**, 858-859
(16 June 2005)

A. Gumberidze PhD thesis 2003, PRL 94, 223001 (2005)

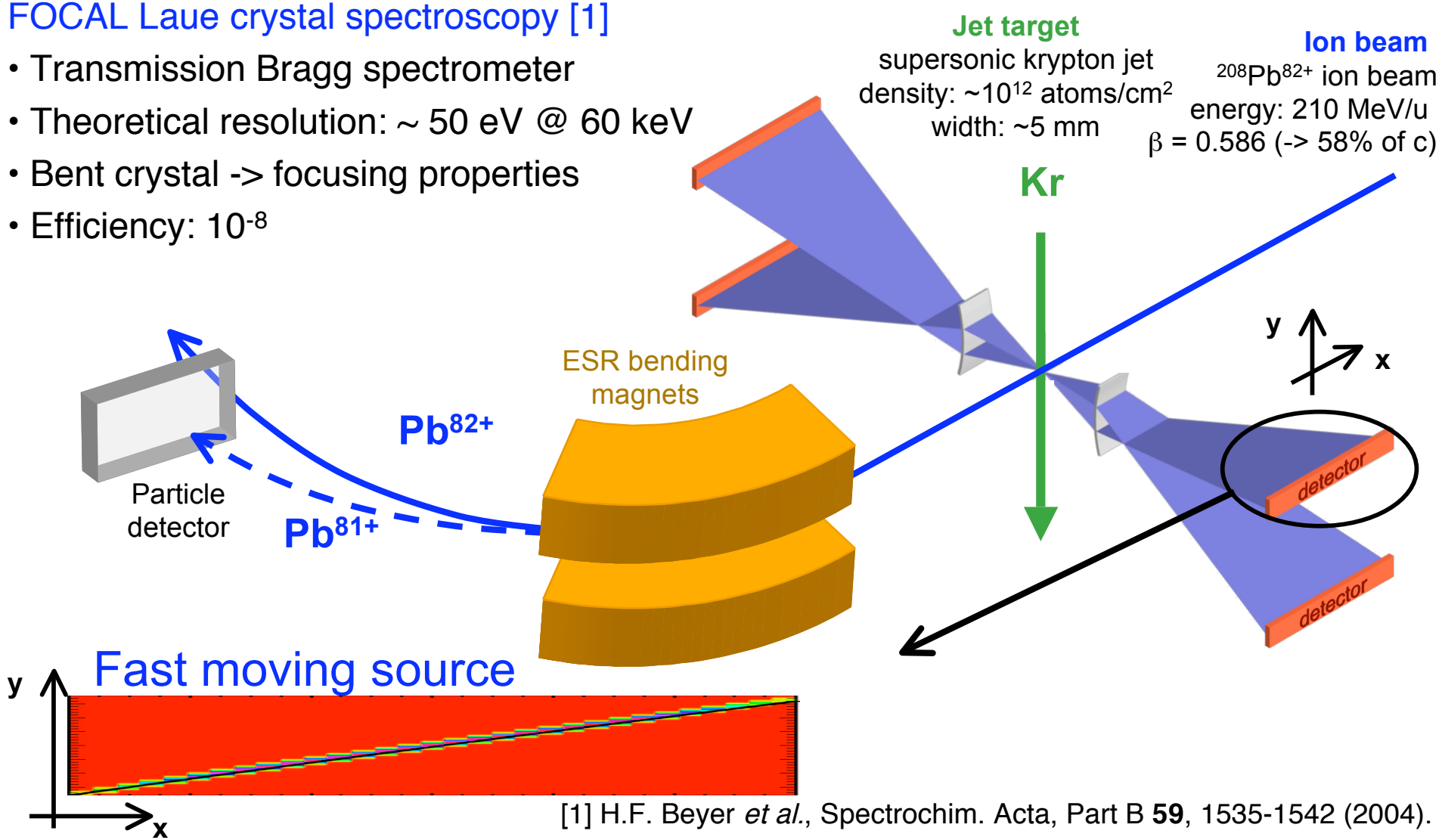
Towards an accuracy of 1 eV



Lead 1s Lamb shift measurement (March 2006)

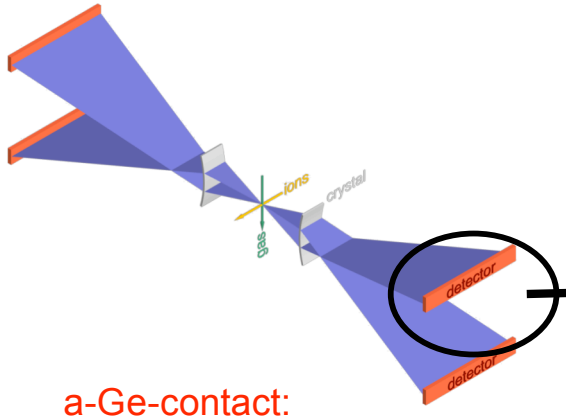
FOCAL Laue crystal spectroscopy [1]

- Transmission Bragg spectrometer
- Theoretical resolution: ~ 50 eV @ 60 keV
- Bent crystal -> focusing properties
- Efficiency: 10^{-8}

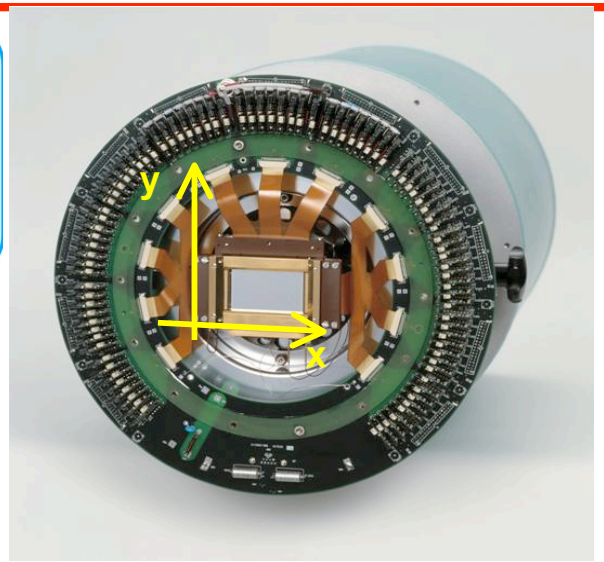


[1] H.F. Beyer *et al.*, Spectrochim. Acta, Part B **59**, 1535-1542 (2004).

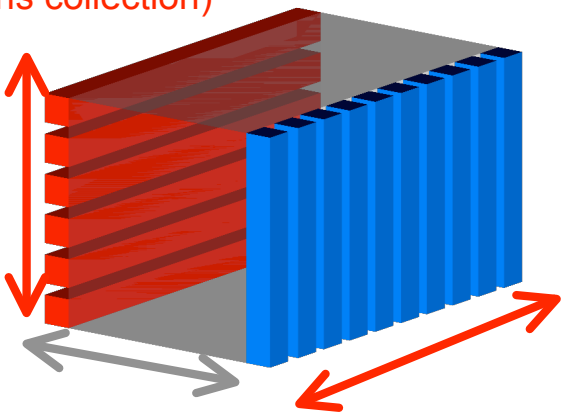
Position-sensitive detector



2D µSTRIP germanium detector



a-Ge-contact:
48 strips in the back side
(electrons collection)



Ge(i) crystal
11 mm thick

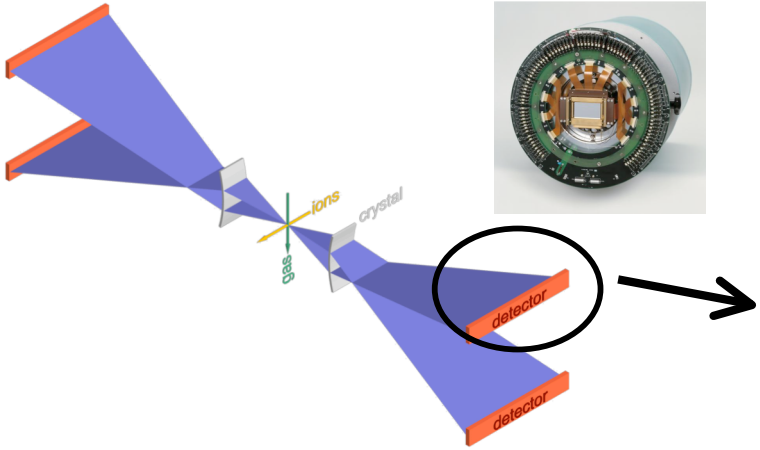
p⁺-contact:
128 strips in the front side
("holes" collection)

2D detector [1,2]
Ge(i) crystal
128 X 48 Strips
$\Delta x \sim 1167$ µm
$\Delta y \sim 250$ µm (< 150 eV)
$\Delta E \sim 2.1$ keV
$\Delta t \sim 50$ ns

2D/3D position-sensitivity, energy resolution, timing

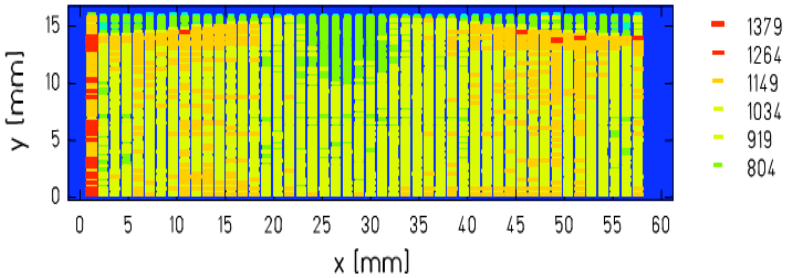
[1] D. Protic *et al.*, IEEE Trans. Nucl. Sci. **52**, 3194-3198 (2005)
[2] U. Spillmann Ph.D. Thesis, University of Frankfurt, 2006 (to be finished)

Preliminary data: March 2006

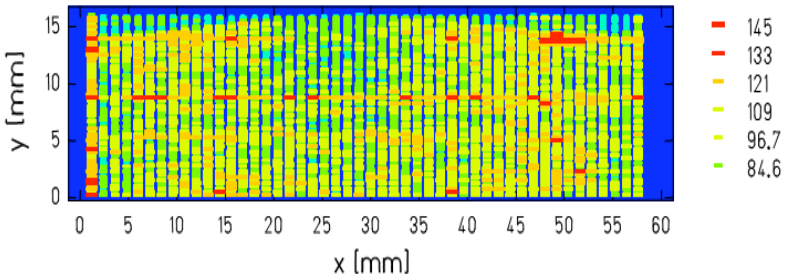


- Data acquisition period: 2 weeks
- 4 events per hour
- One calibration acquisition per day

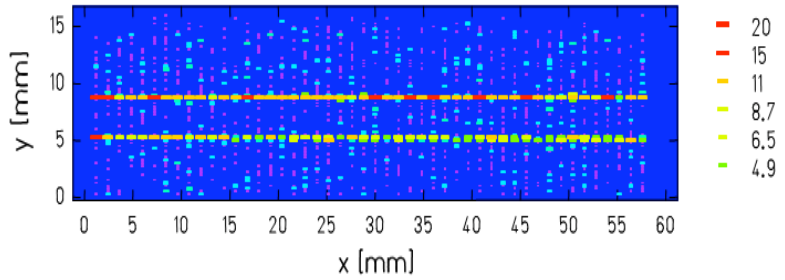
x-ray image (10 keV to 130 keV)



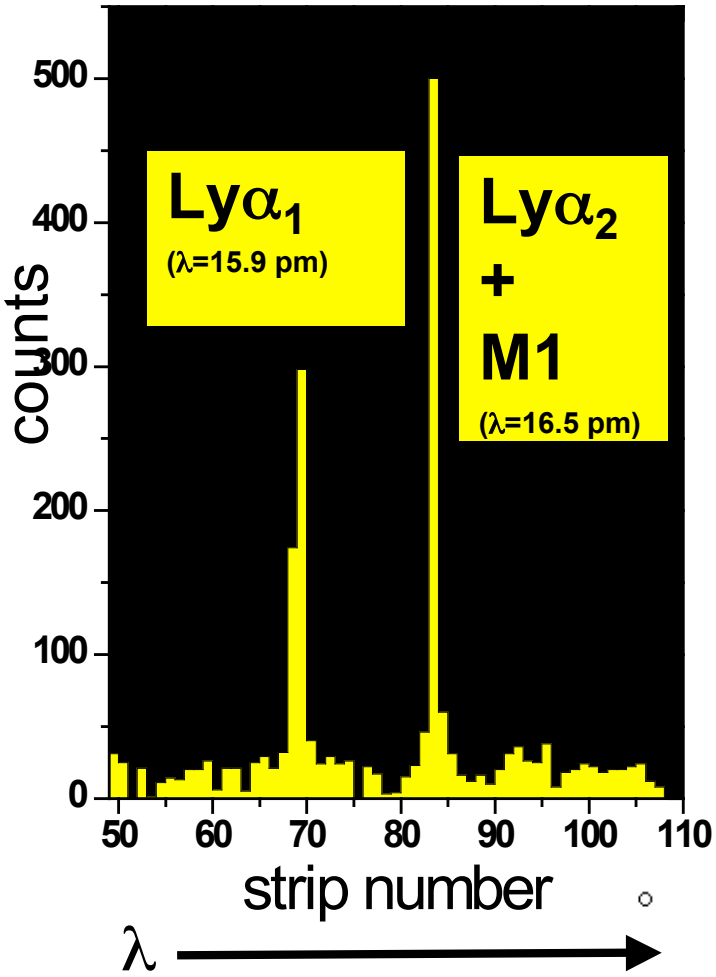
x-ray image (10 keV to 130 keV)
+ time condition



x-ray image (58 keV to 65 keV)
+ time condition

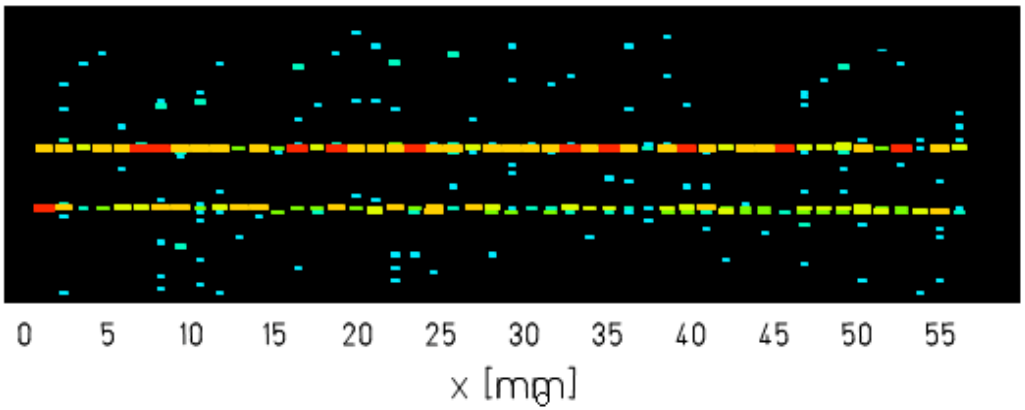


Preliminary data: March 2006



- Total counts: ~600 in each line
- Preliminary analisis
  - Statistical error: ~ 4.5 eV
  - Systematic error: in evaluation

Lyman-α: $^{208}Pb^{81+}$ @210 MeV/u

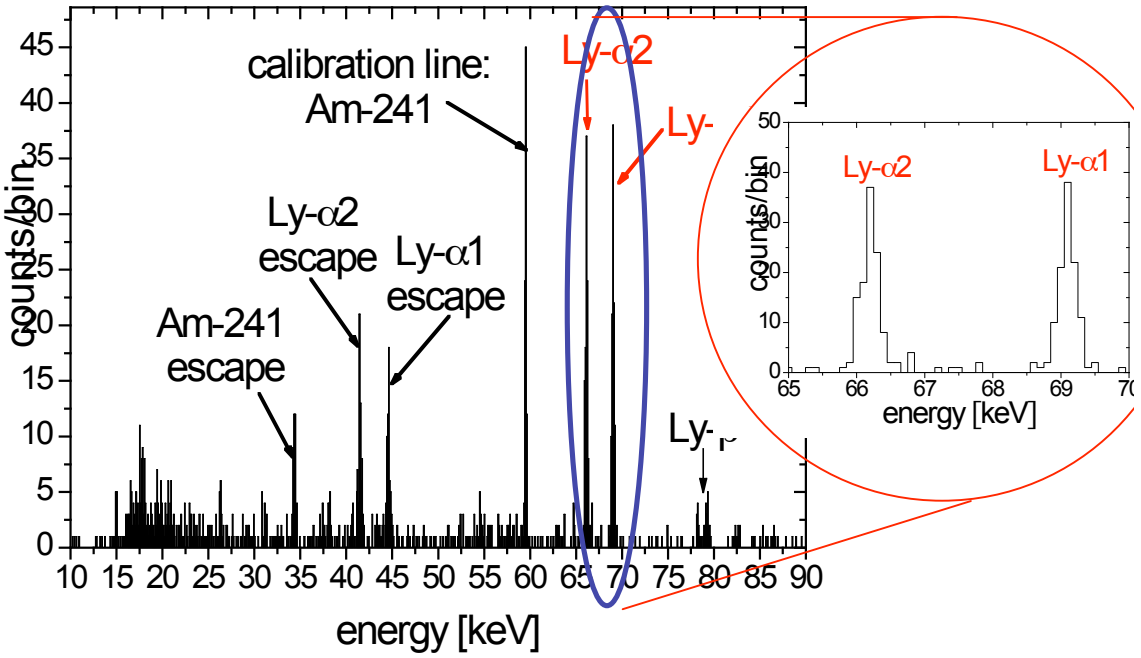


-> see R. Reuschl poster

1s Lamb shift measurement with a microcalorimeter

A. Bleile et al., NIM A 444, 488 (2000)

2 days of $^{238}U^{91+}$ beam time at the ESR

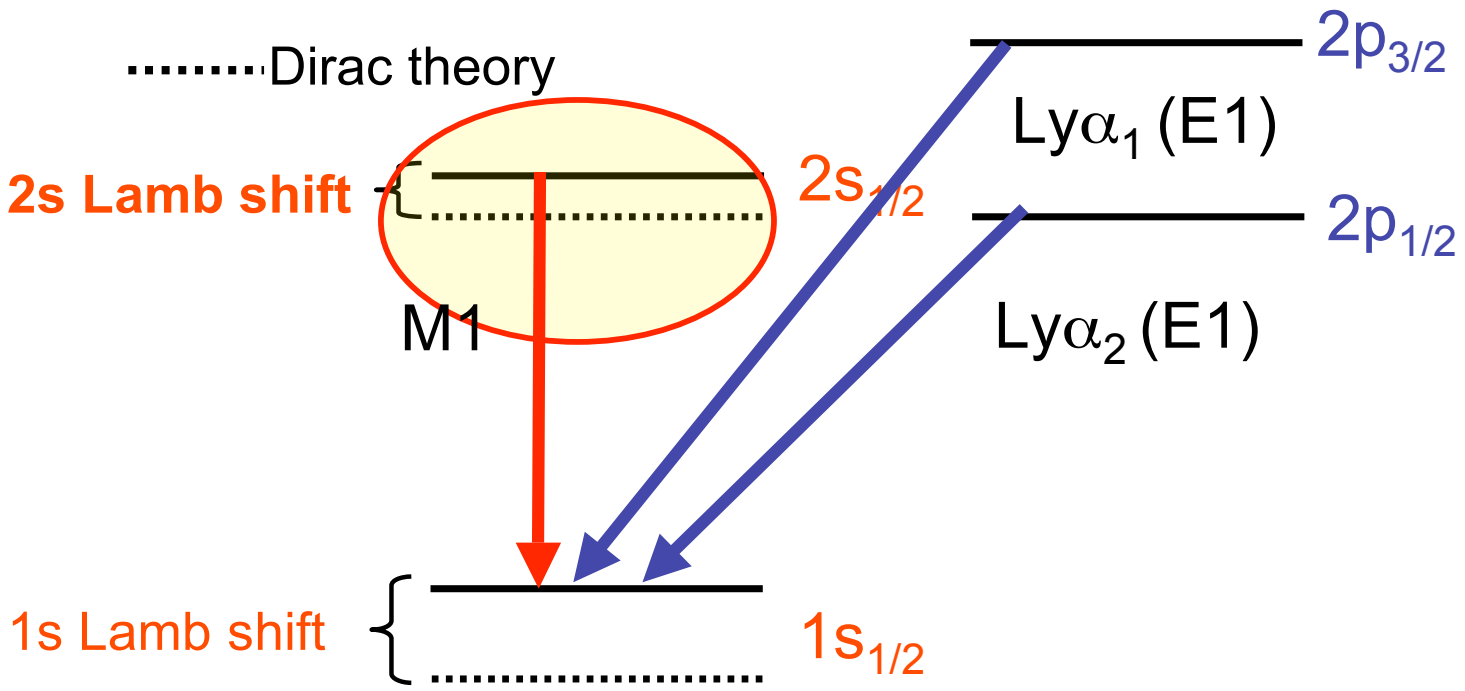


Detection efficiency (4 pixels): 1 x 10^{-7}

P. Egelhof et al., Oct. 2005

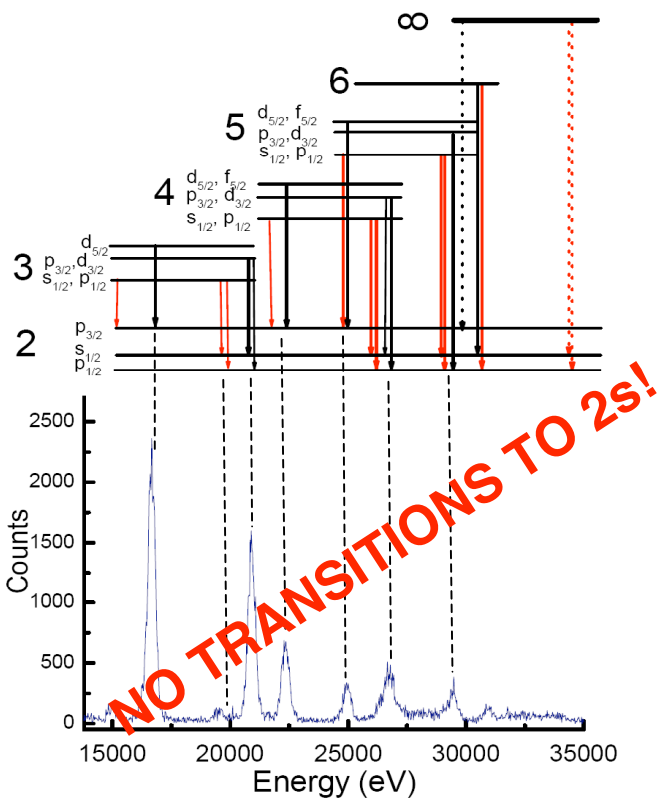
-> see P.Egelhof contribution

Atomic structure: 2s Lamb shift



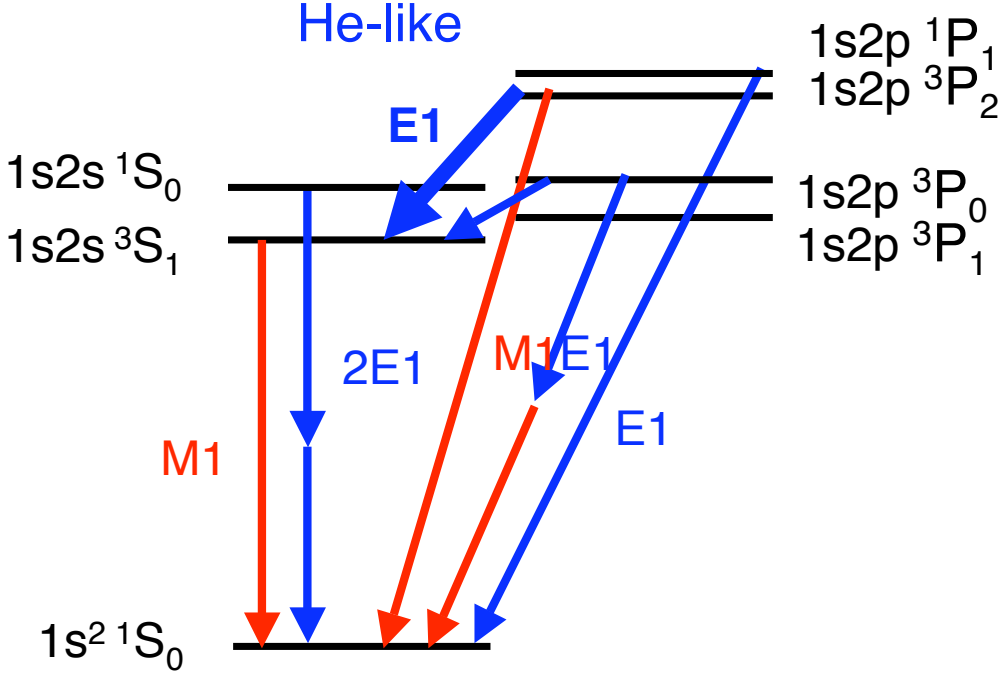
Atomic structure: 2s Lamb shift

H-like ions



Balmer transitions
(16-35 keV for Uranium)

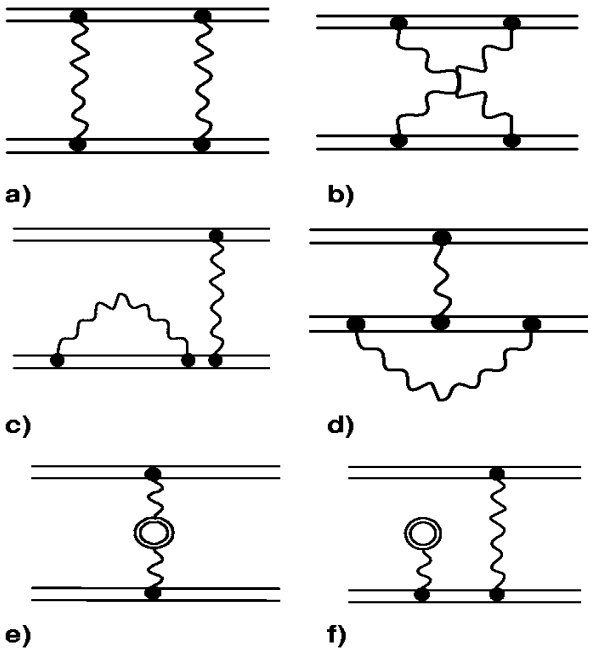
He-like

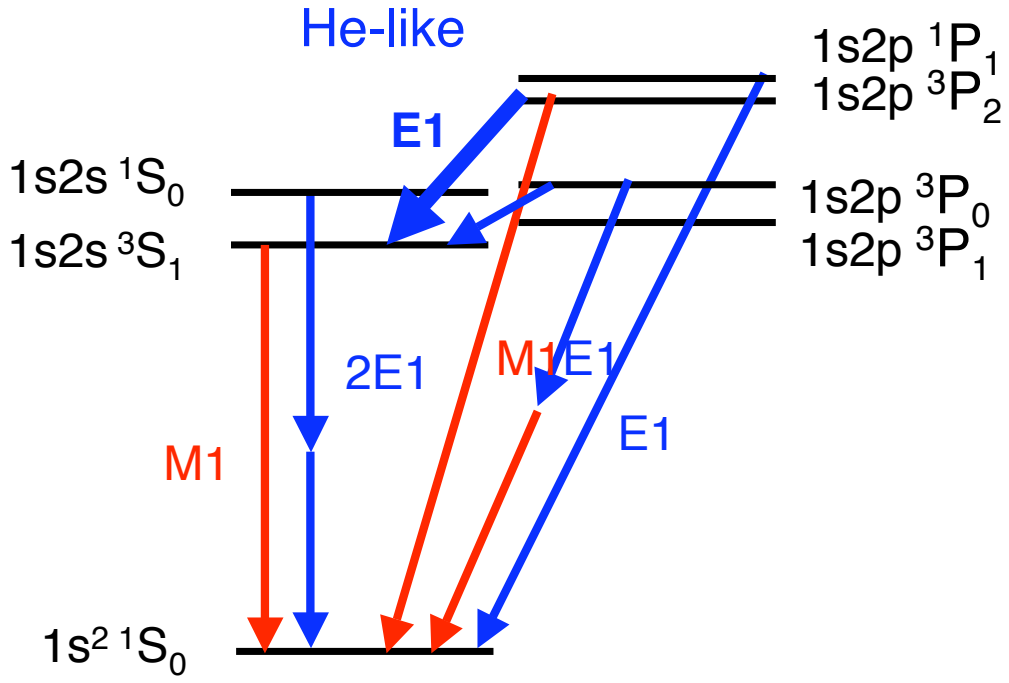


Intra-shell transition
(4.5 keV in Uranium)

Atomic structure: 2s Lamb shift

- Non-Radiative QED
- Two-Electron Self Energy
- Two-Electro Vacuum Polarization





- SIMPLEST "MANY"-BODY SYSTEM

A.N. Artemyev *et al.*, Phys. Rev. A **71**, 062104-26 (2005).

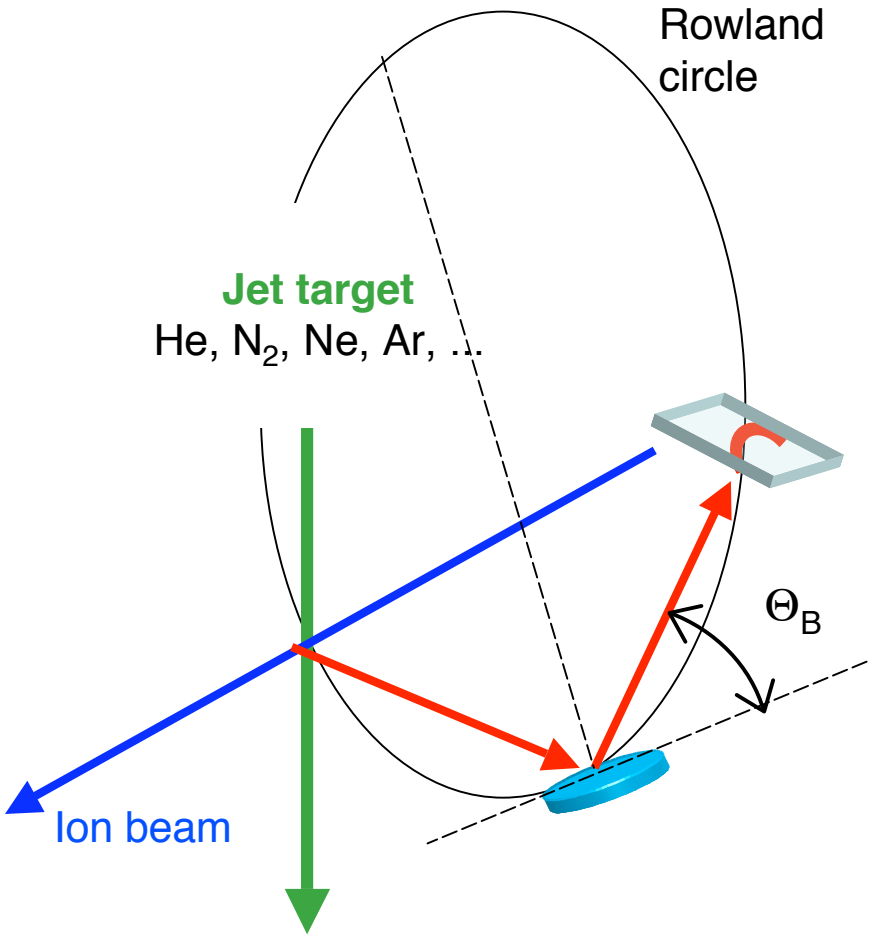
Bragg spectrometer for fast ions

- Bragg spectrometer for 2-10 keV

Fast ion:

-> vertical geometry

-> Doppler tuning, flexibility to chose the calibration source



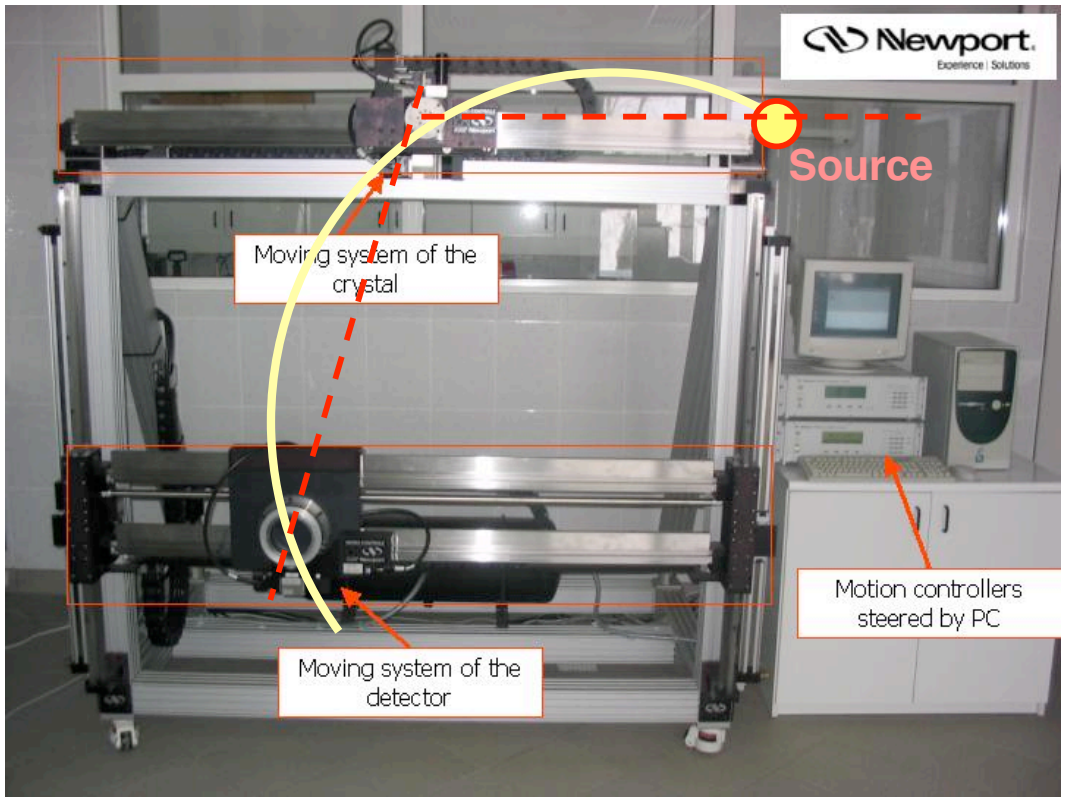
Two type of spectrometer in construction:

- with fixed Bragg angle
- **with moveable crystal and detector supports**

Bragg spectrometer for fast ions

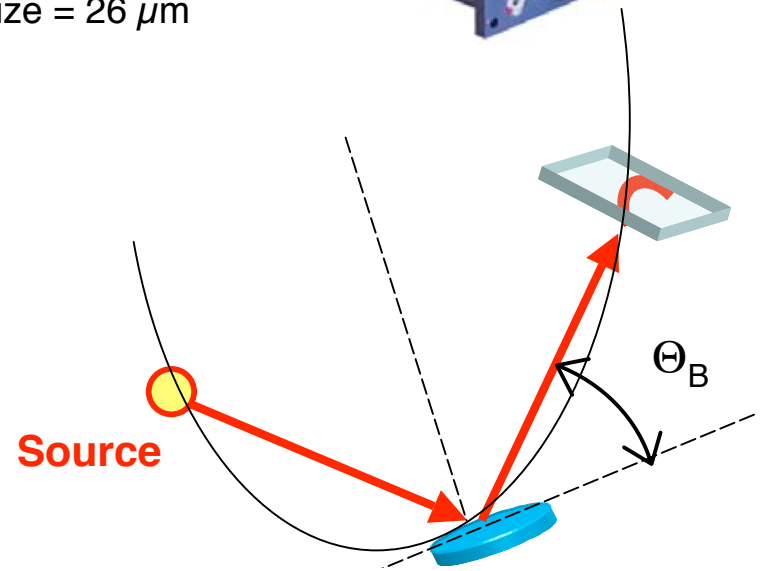
Newport Mounting system

2 linear motorized stages (acc.= 1μm)
1 pneumatic linear stage (acc.= 1μm)
2 rotation motorized stages (acc.=0.001°)
1 high precision angular encoder (acc.=0.5")



X-ray CCD camera

Back side illuminated
Range = 1-10 keV
Q.E. ~ 90%
1021 X 256 pixels
pixel size = 26 μm



Silicon (111) crystal

Spherically bent
R. of curvature = 1 m
d-spacing = 0.31 nm
Diameter = 75 mm

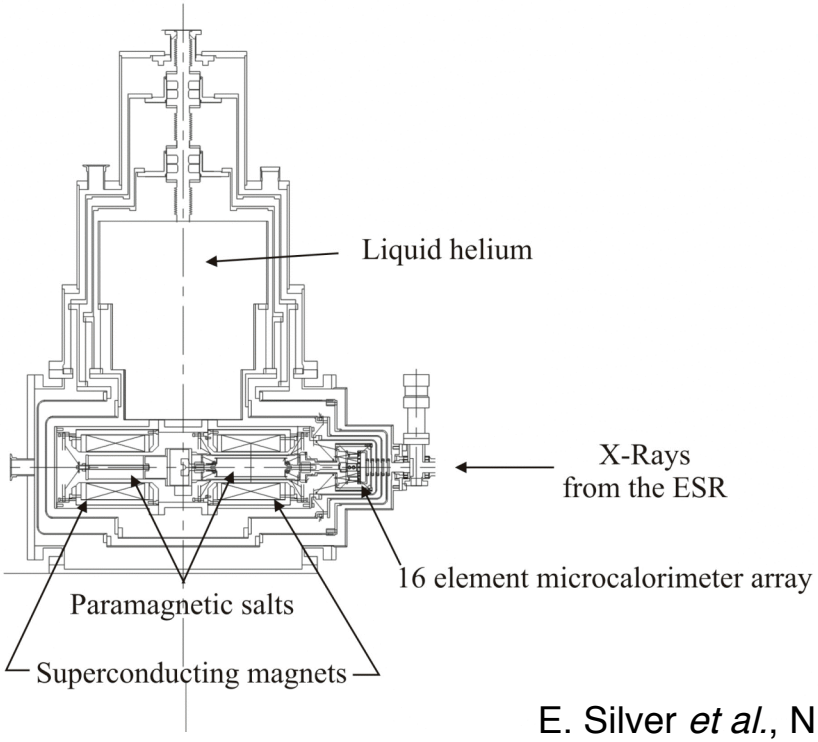
M. Trassinelli *et al.*, Canadian Journal of Physics accepted (2006).

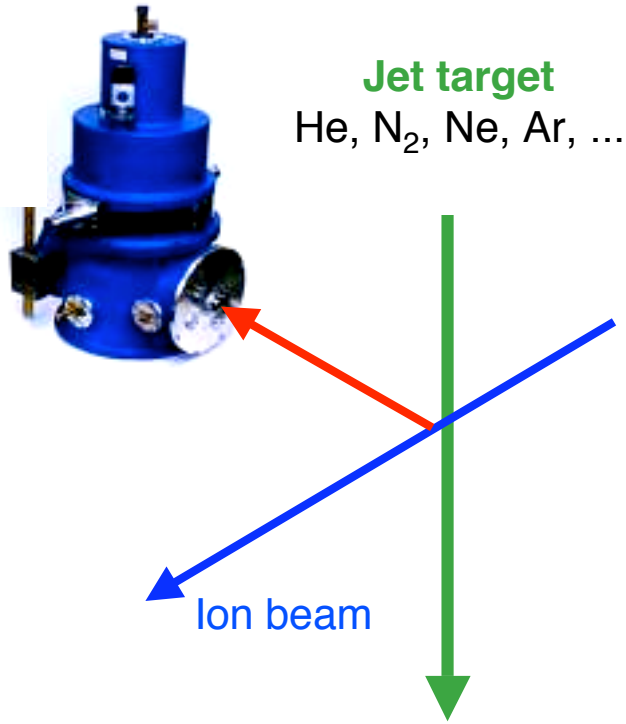
-> see D.Banas poster

2s Lamb shift measurement with a microcalorimeter

E. Silver et al., Harvard Smithsonian

- 4 X 4 bolometers (0.1 X 0.1 mm^2)
- Energy range: 3-50 keV
- High resolution: around 3 eV @ 6 keV
- Magnetic cooler recycling: 60 hours

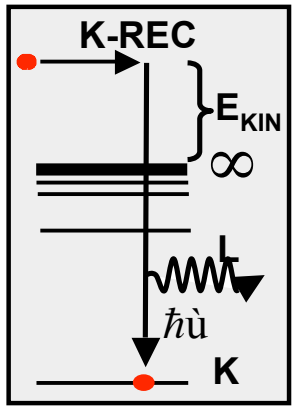


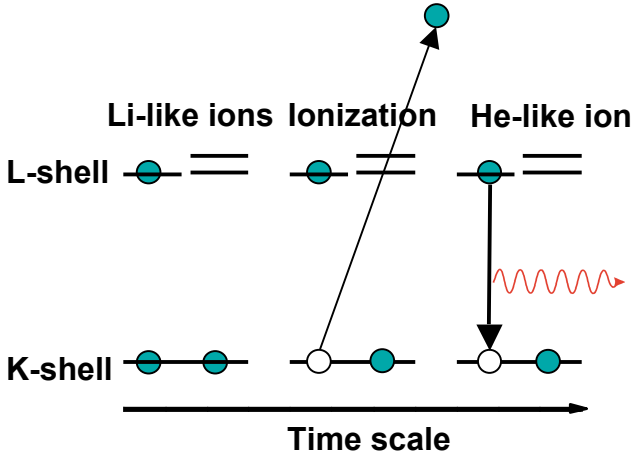


E. Silver *et al.*, Nucl. Instrum. Meth. A **520**, 60-62 (2004).

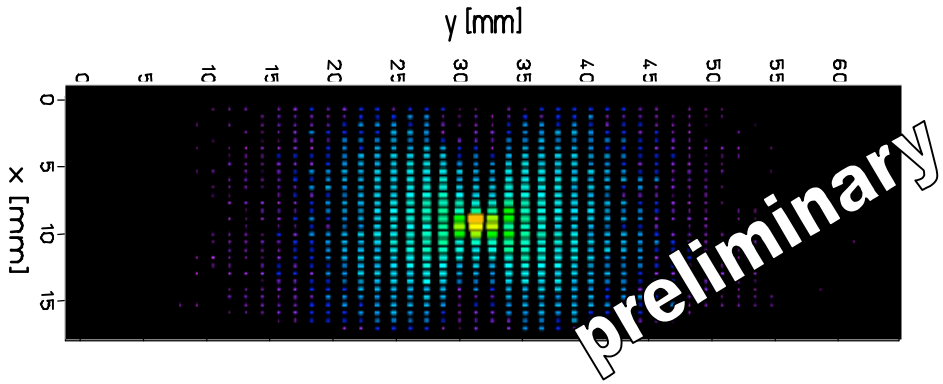
Dynamics

- Radiative and non radiative electron capture
- Selective ionization
- Alignment
  - Angular distribution
  - Polarization

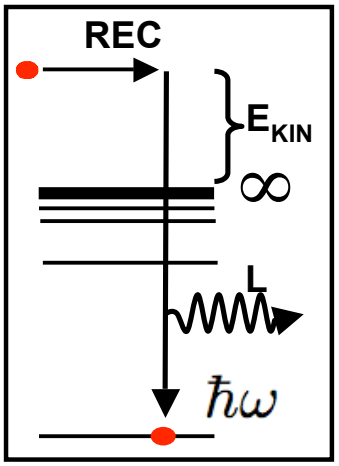


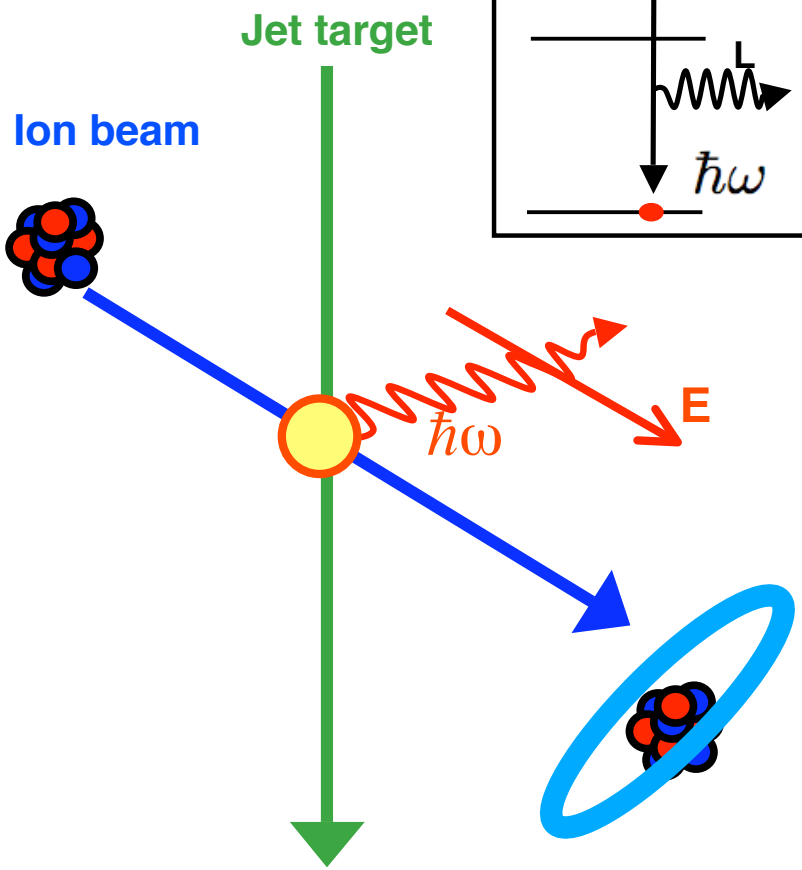


-> see A. Kumar poster



Polarized photon emission

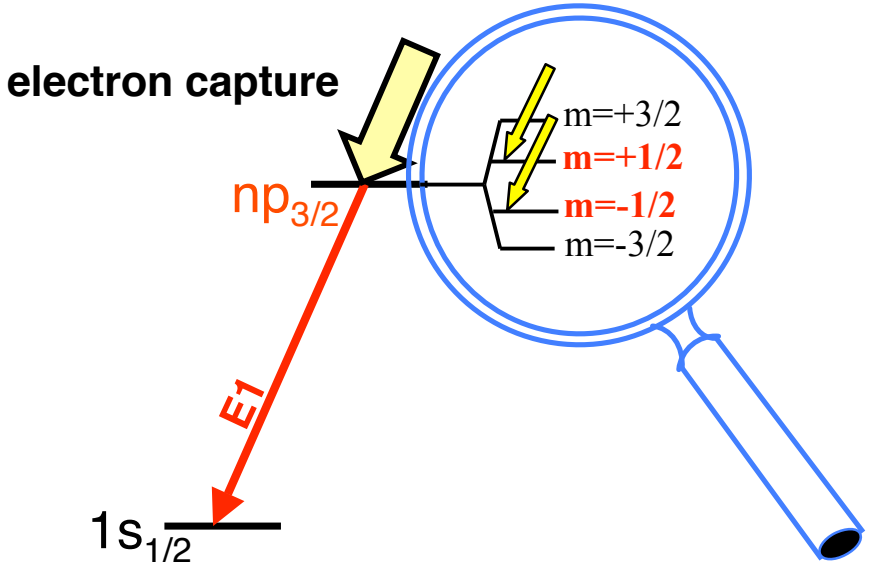




Polarization of the emitted photon due to:

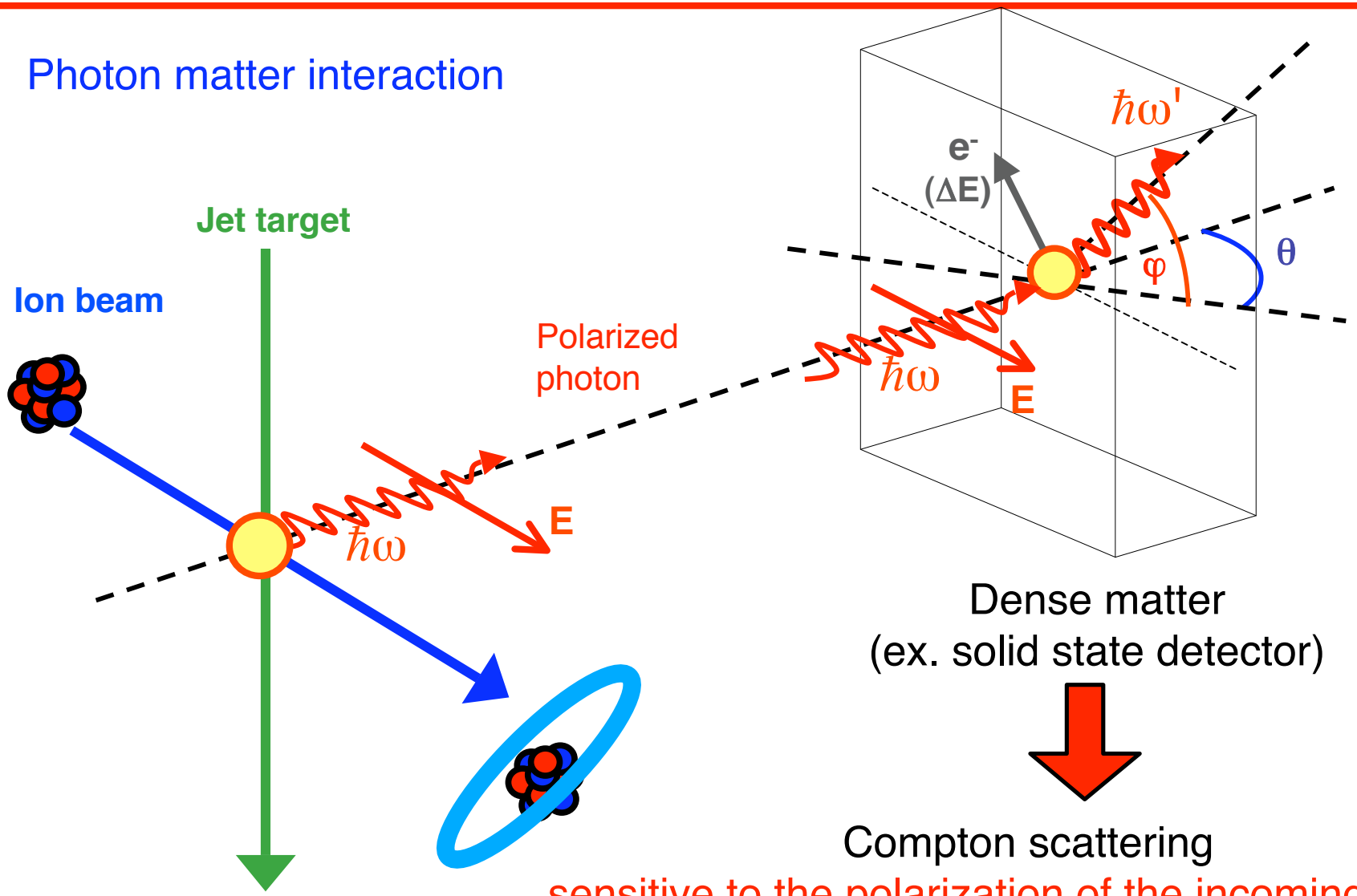
- **Recombination process (inverse than photoionization)**

(Non-relativistic dipole approximation:
100 % polarization for all emission angles)



Polarization detection

Photon matter interaction



Dense matter
(ex. solid state detector)

Compton scattering
sensitive to the polarization of the incoming photon

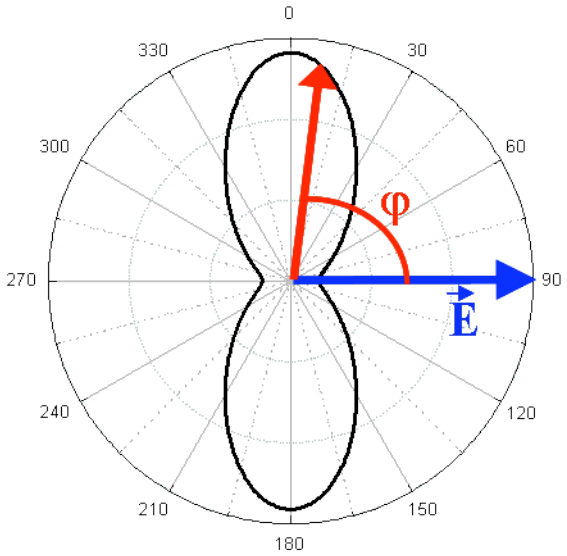
Polarization detection

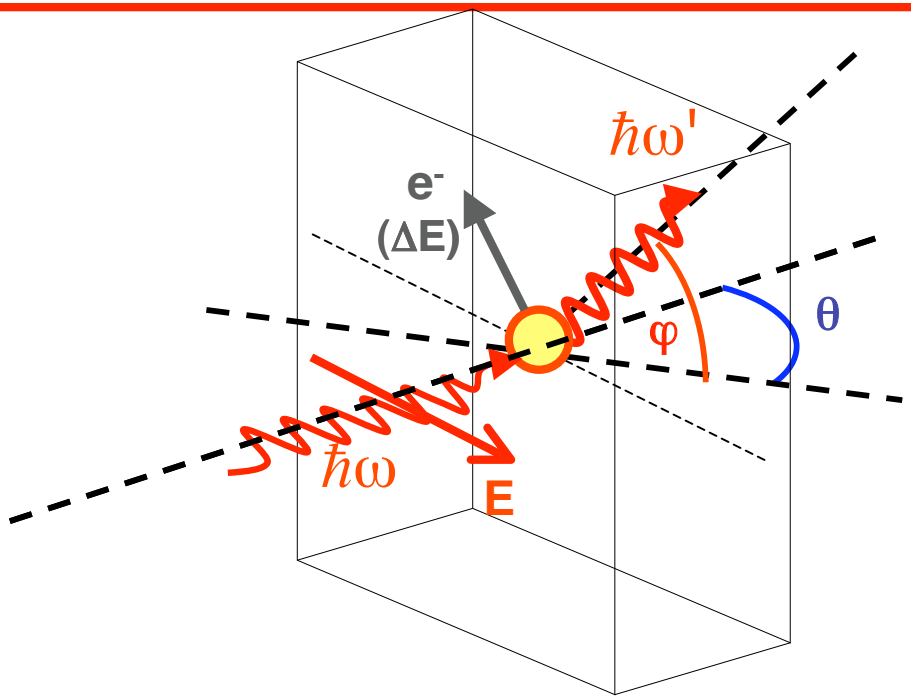
Electron-photon scattering:

$$\hbar\omega = \hbar\omega' + \Delta E$$

ΔE : electron recoil energy

$$\hbar\omega' = \frac{\hbar\omega}{1 + (1 - \frac{\hbar\omega}{m_e c^2}\cos\theta)}$$



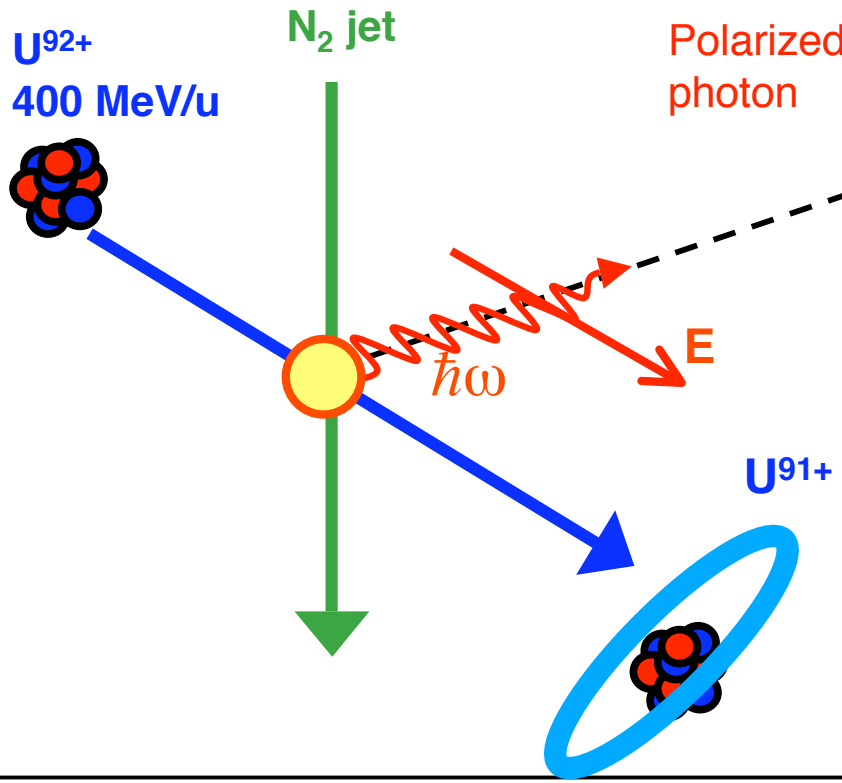


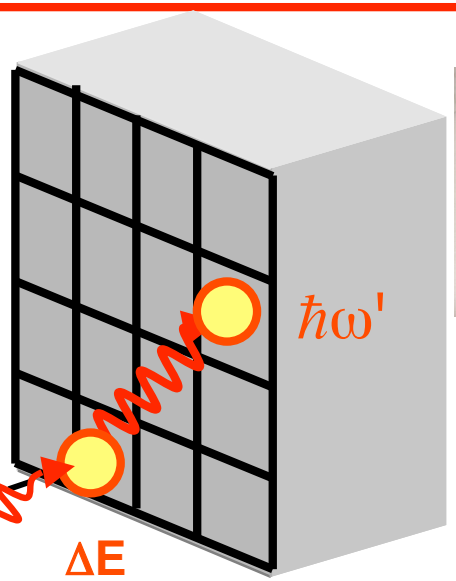
Klein-Nishina equation

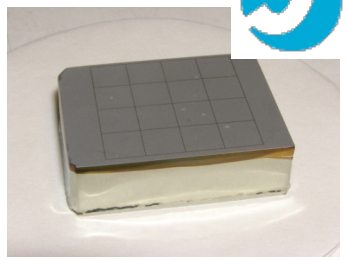
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)\left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega'}{\hbar\omega} - \sin^2\theta\,\cos^2\varphi\right)$$

Ge pixel detector

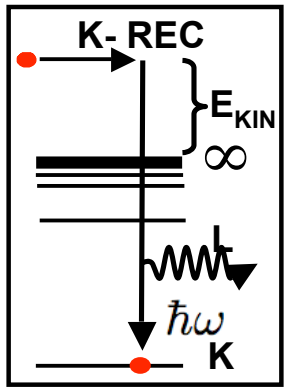
Polarization Measurement for Radiative Electron Capture Transitions ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)







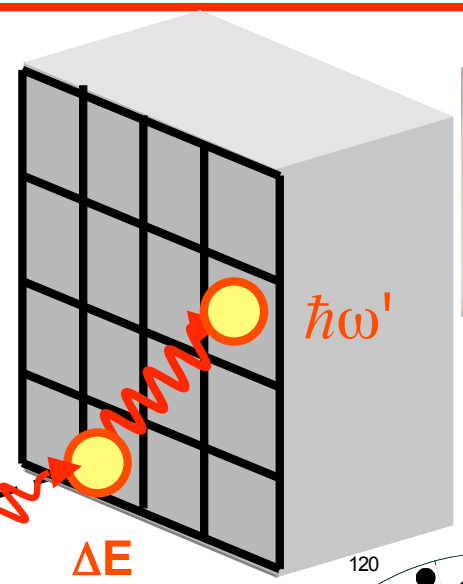
4X4 Ge detector
(24 X 24 mm$^{2)}$

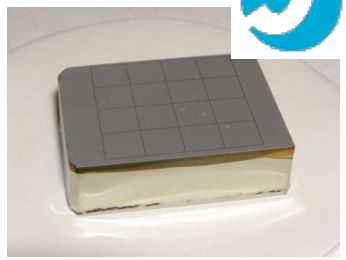


S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

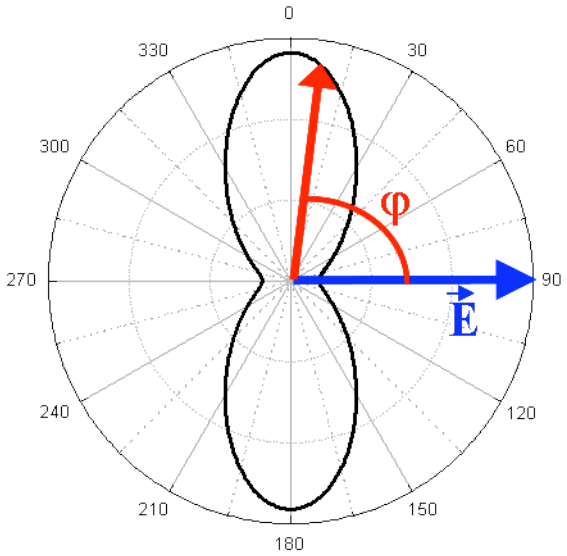
Ge pixel detector

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

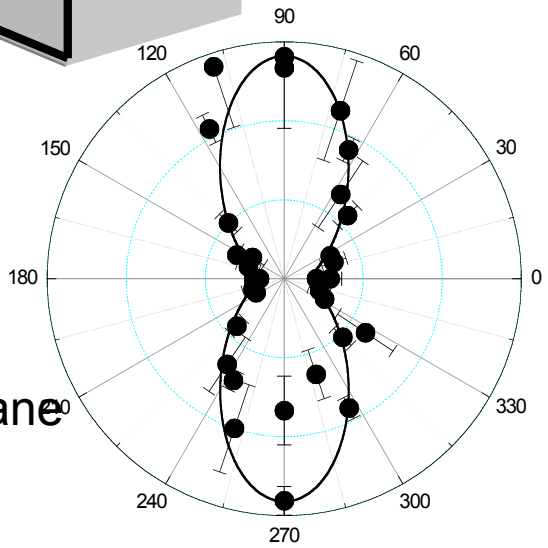




4X4 Ge detector
(24 X 24 $mm^{2)}$



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



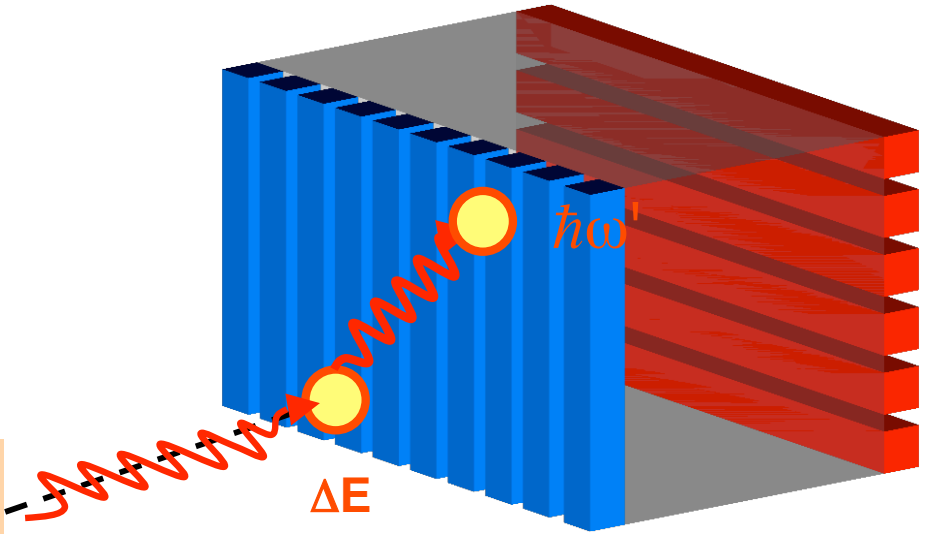
S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

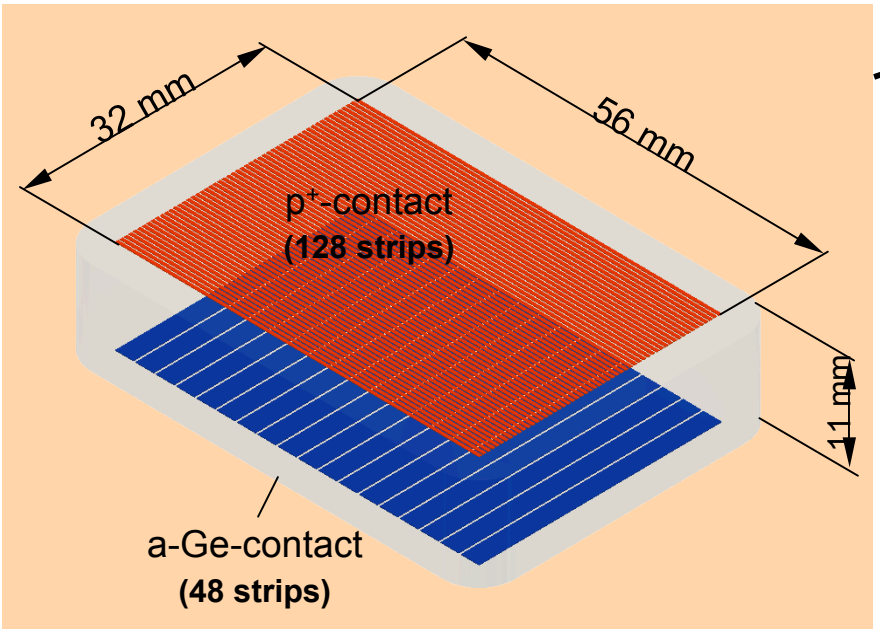
Ge 2D segmented detector

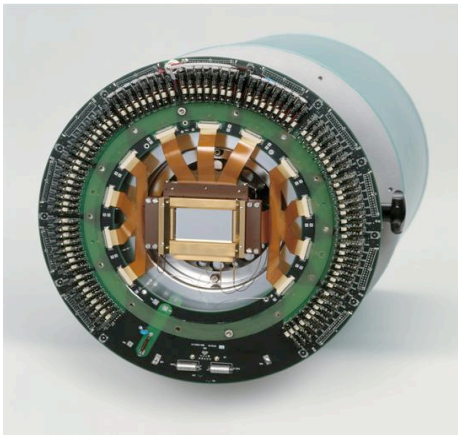
Front: 128 strips pitch ~250μm

Back: 48 strips pitch ~1167μm

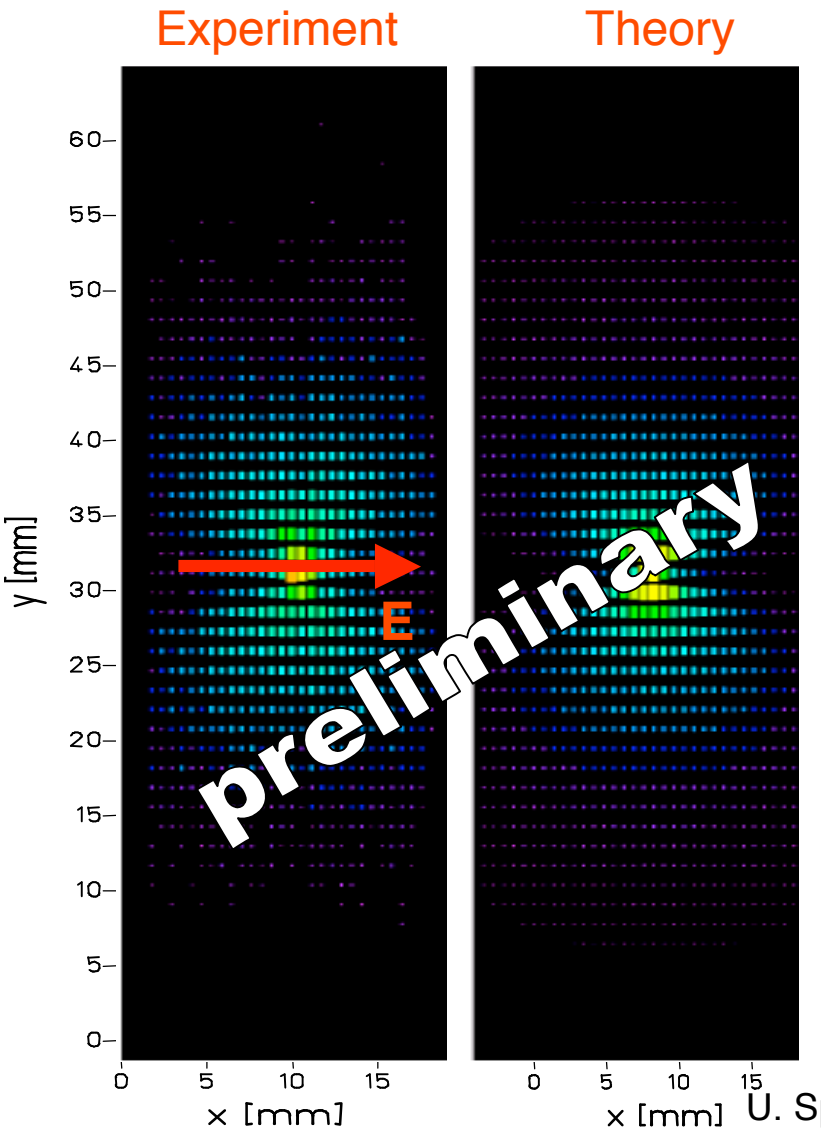
Equivalent to 6144 pixel



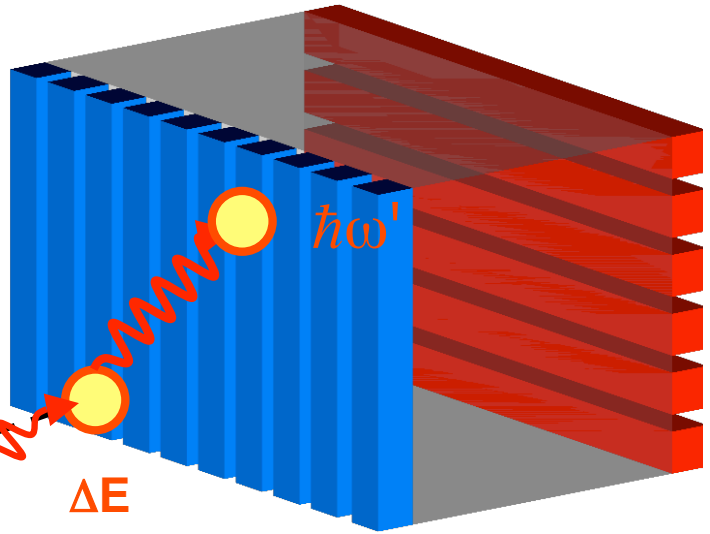




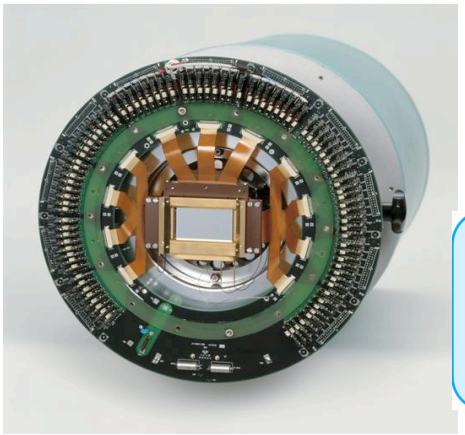
Ge 2D segmented detector



98% Polarized photon
E=210 keV



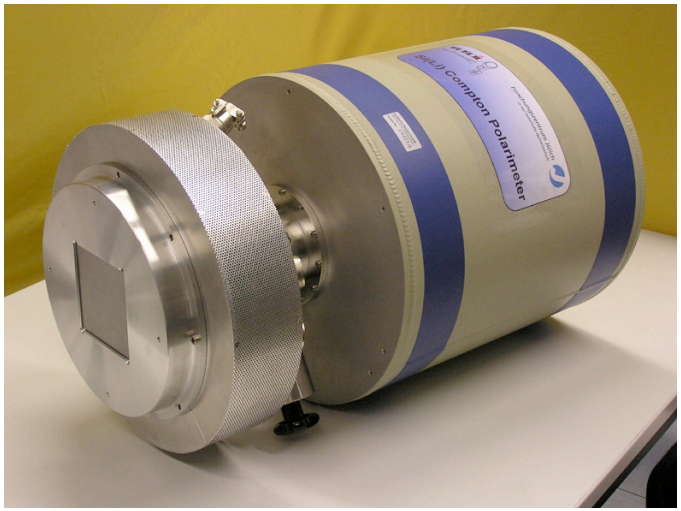
ESRF

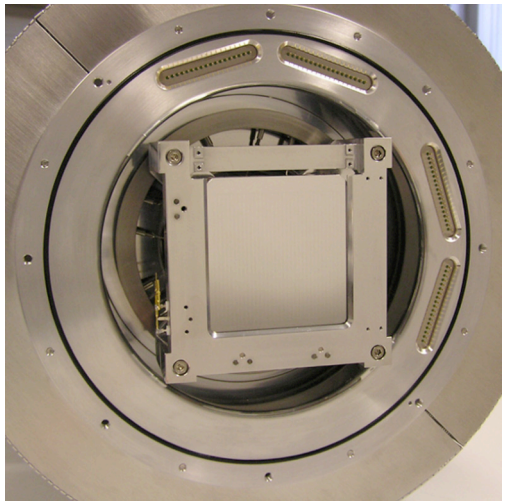


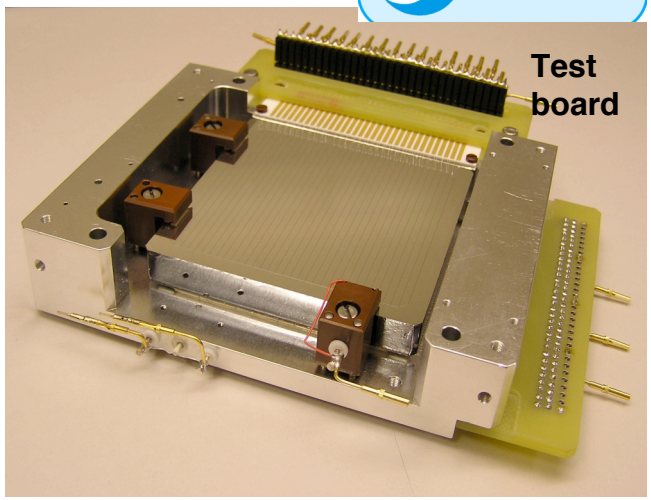
2D μSTRIP germanium detector

U. Spillmann Ph.D. Thesis, University of Frankfurt, 2006 (to be finished)

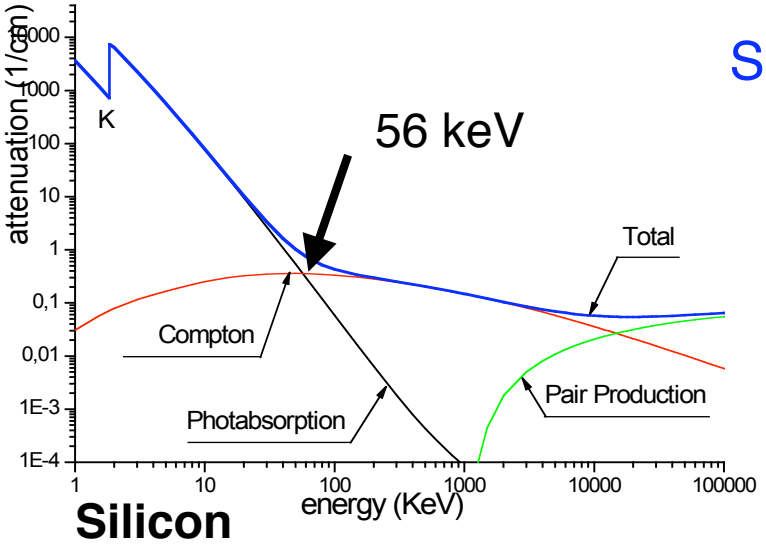
2D/3D Si(Li)-Detector for Compton Polarimetry







crystall size: 4" x 4"



Si(Li) based Compton polarimeter will be available in November 2006

- Imaging capability: starts at 5 keV
- Compton polarimetry: starts at 50 keV

-> see A. Surzhykov talk

Conclusions

New QED tests with HCI

- 1s Lamb shift (FOCAL spectrometer, microcalorimeter)
- 2s Lamb shift (new Bragg spectrometer, microcalorimeter)
- e-e interaction in strong field -> few electrons atoms

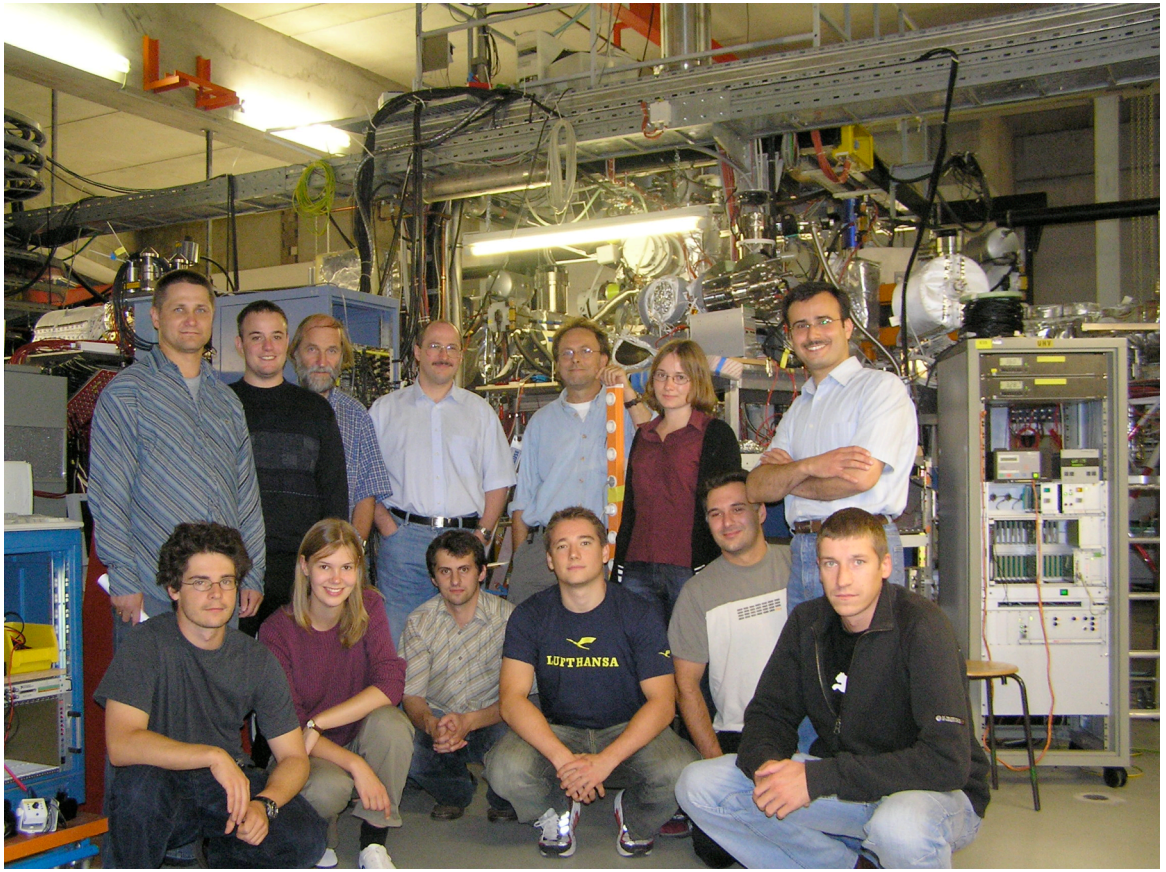
Ion-atom collision

- Detection of photon polarization
- State alignment studies
- Polarized ion beam characterization

New instruments ready for FAIR!!

Our group

Thomas Stöhlker Group



The speaker's attendance at this conference was sponsored by the Alexander von Humboldt Foundation.

► http://www.humboldt-foundation.d