Arbeitstreffen Kernphysik Schleching
22 February - 1 March 2007

Atomic Physics with Highly Charged Ions at Storage Rings

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Collaboration

Mainz

Paris

Frankfurt

Jülich

Grenoble

Darmstadt

Caen

Cracow

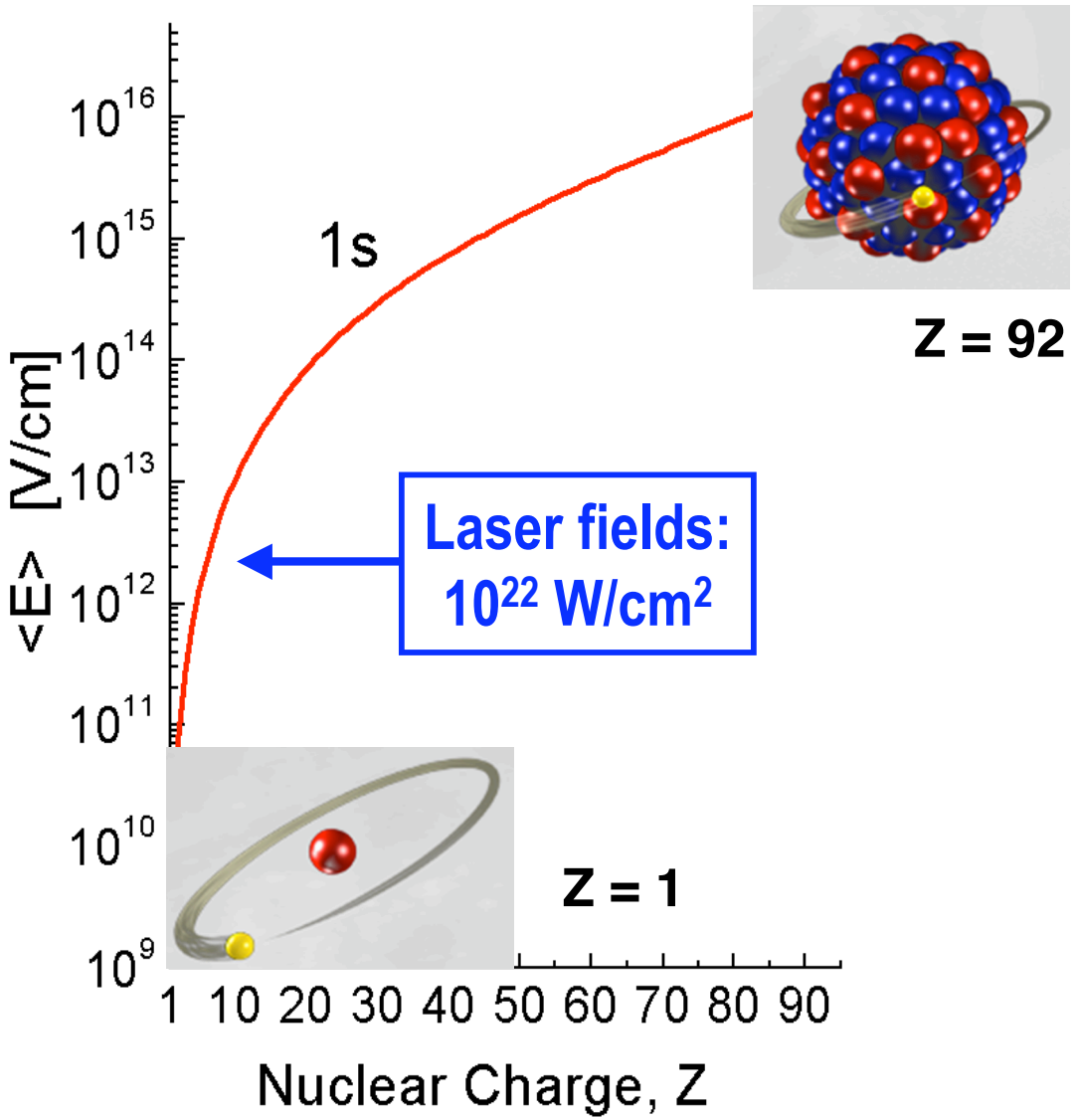
Madison

Jena

Greenbelt

Kielce

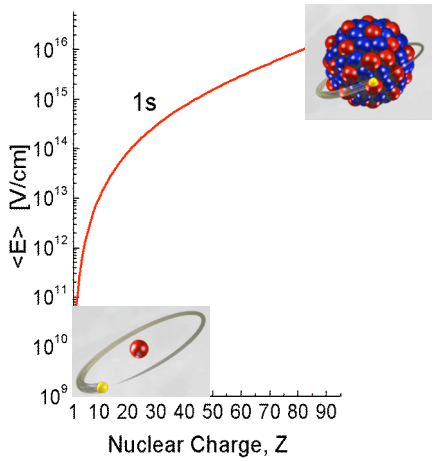
Atomic Physics in Extremely Strong Coulomb Fields



H-like Uranium
ΔE ≈ 500 eV
Z · α ≈ 1
<E>= 1.8 • 10^16 V/cm

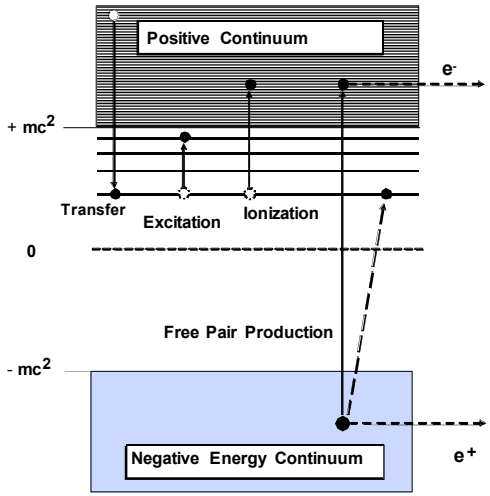
Hydrogen
ΔE ≈ 10^-6 eV
Z · α ≈ 10^-2
<E>= 1 • 10^10 V/cm

Atomic Physics in Extremely Strong Coulomb Fields



Atomic Structure

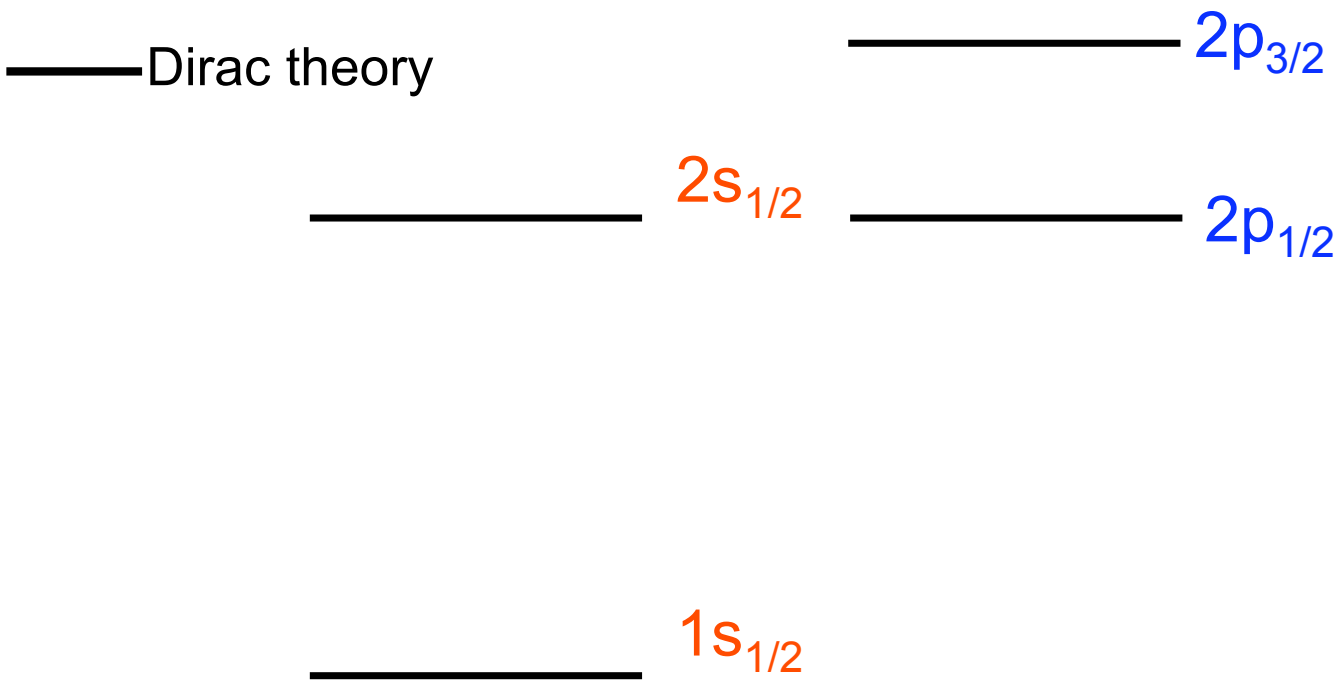
- Bound state quantum electrodynamics (QED)
- Effects of relativity on the atomic structure
- Electron correlation in the presence of strong fields
- Parity violation



Atomic Collisions

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

Atomic structure



Atomic structure

Dirac theory

$2p_{3/2}$

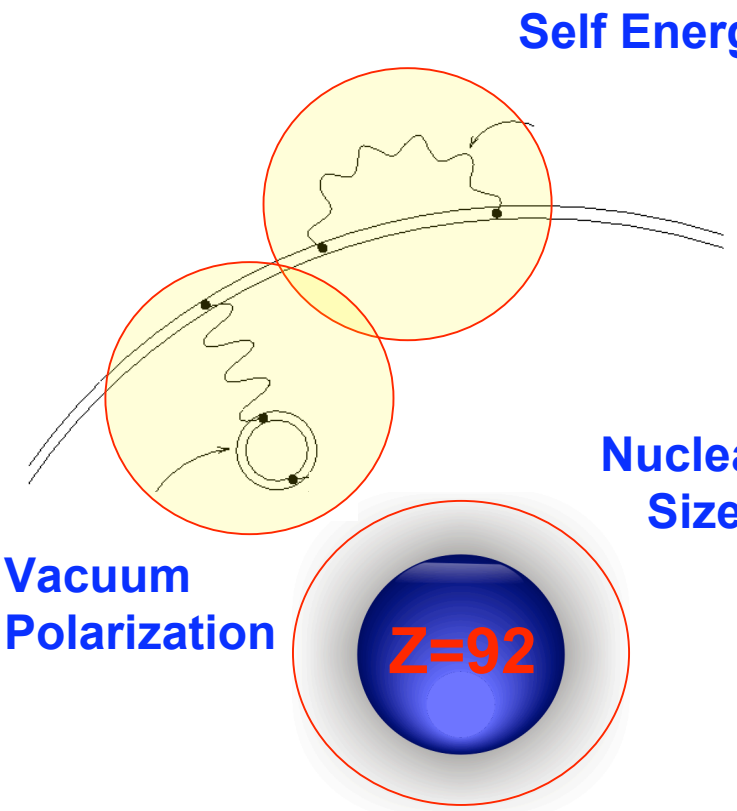
2s Lamb shift

$2s_{1/2}$

$2p_{1/2}$

1s Lamb shift

$1s_{1/2}$



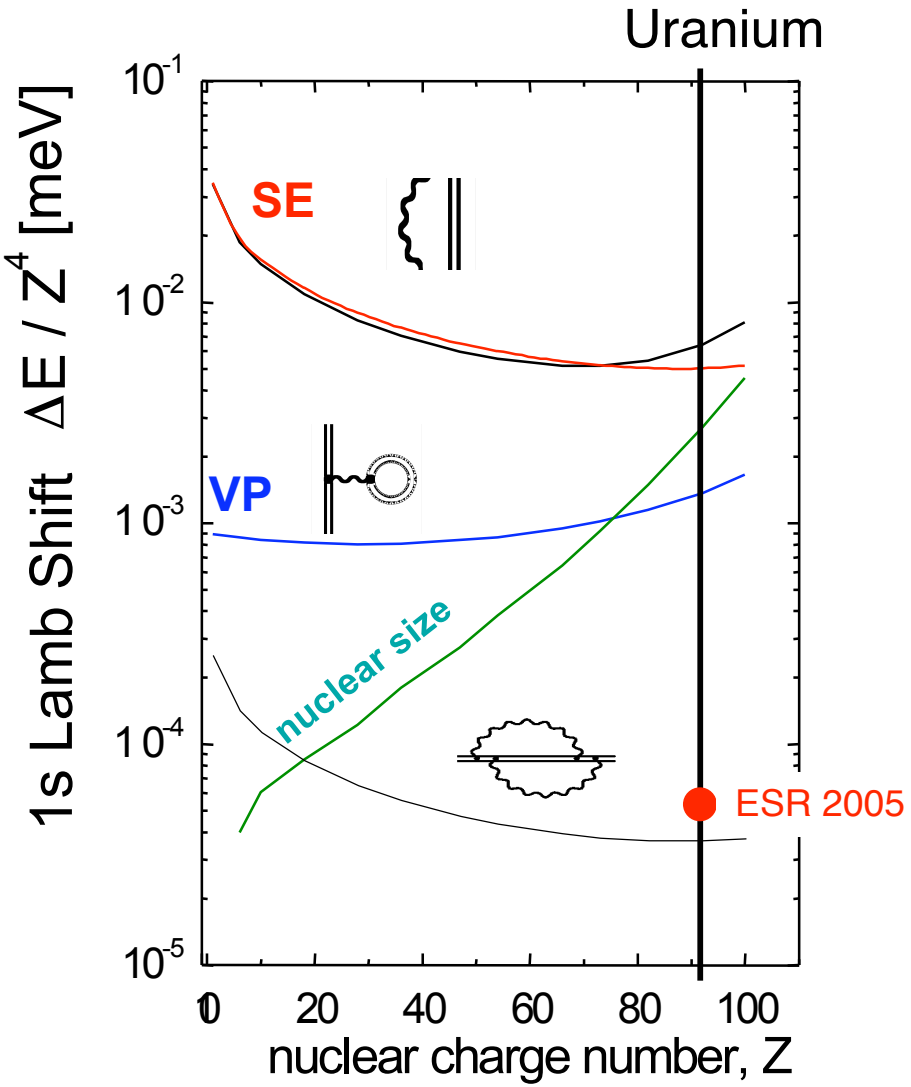
QED corrections

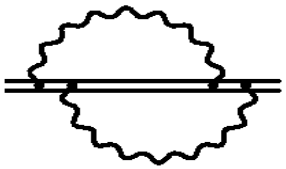
$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

Important for s-states

QED corrections



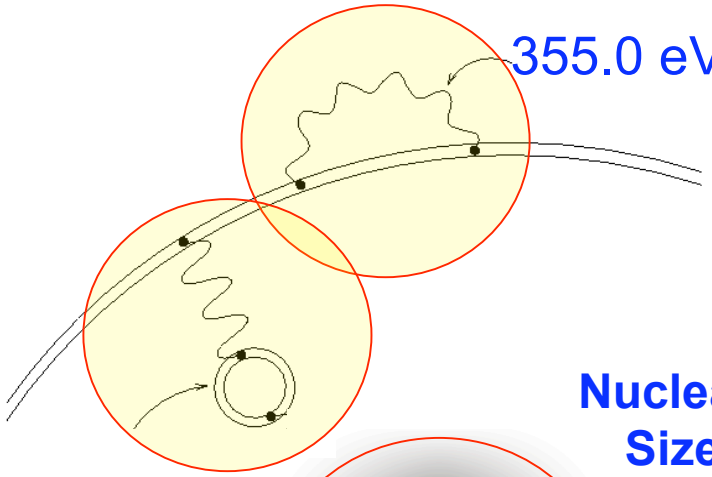


Two-loop corrections

~ -4 eV

Self Energy

355.0 eV

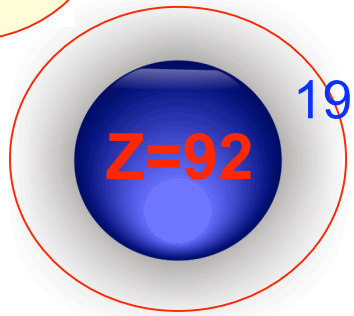


Nuclear Size

198.7 eV

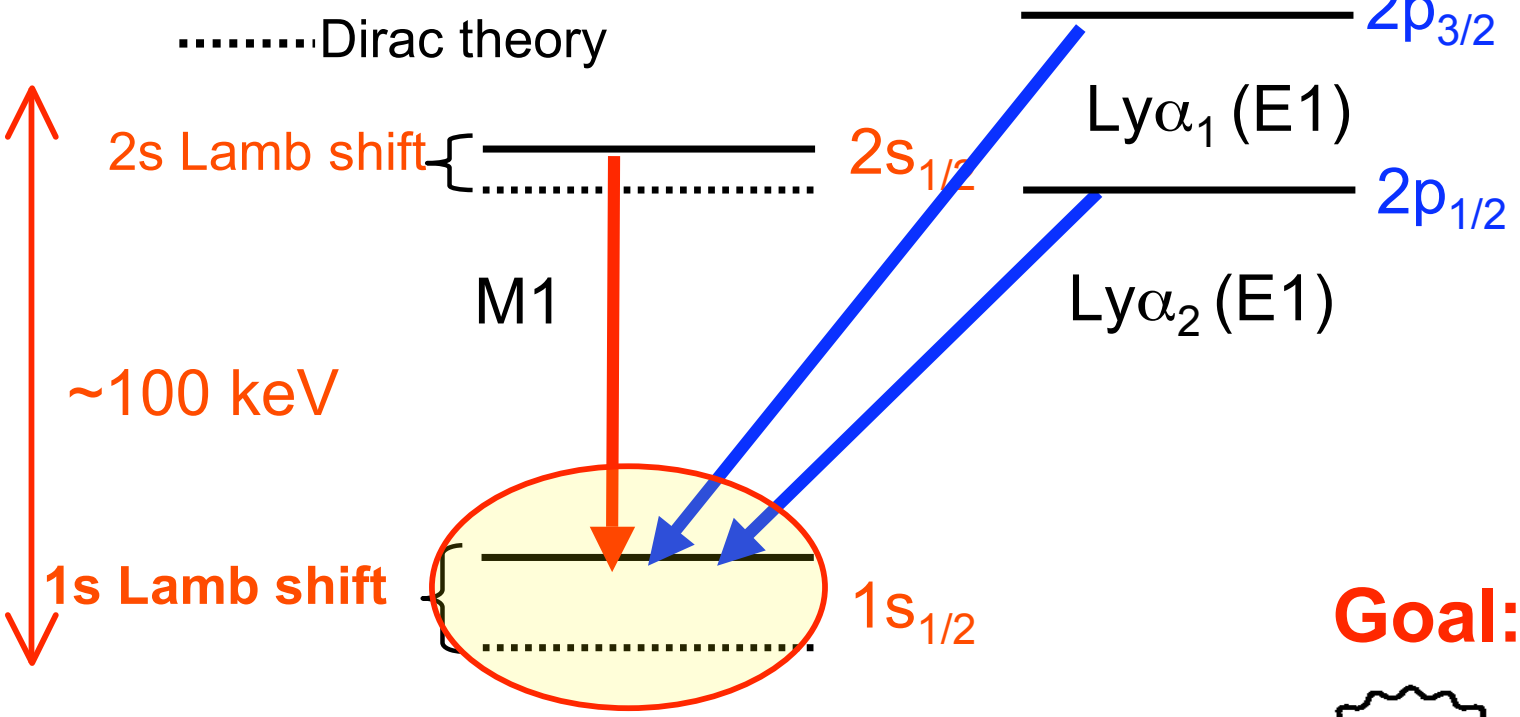
Vacuum Polarization

-88.6 eV

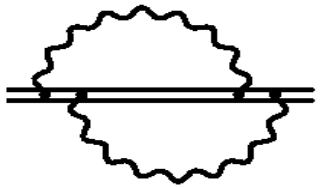


V.A. Yerokhin *et al.*, Phys. Rev. A 71, 040101-4 (2005).

Atomic structure: 1s Lamb shift

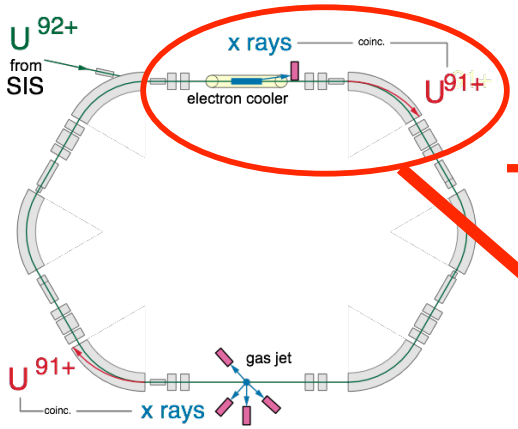


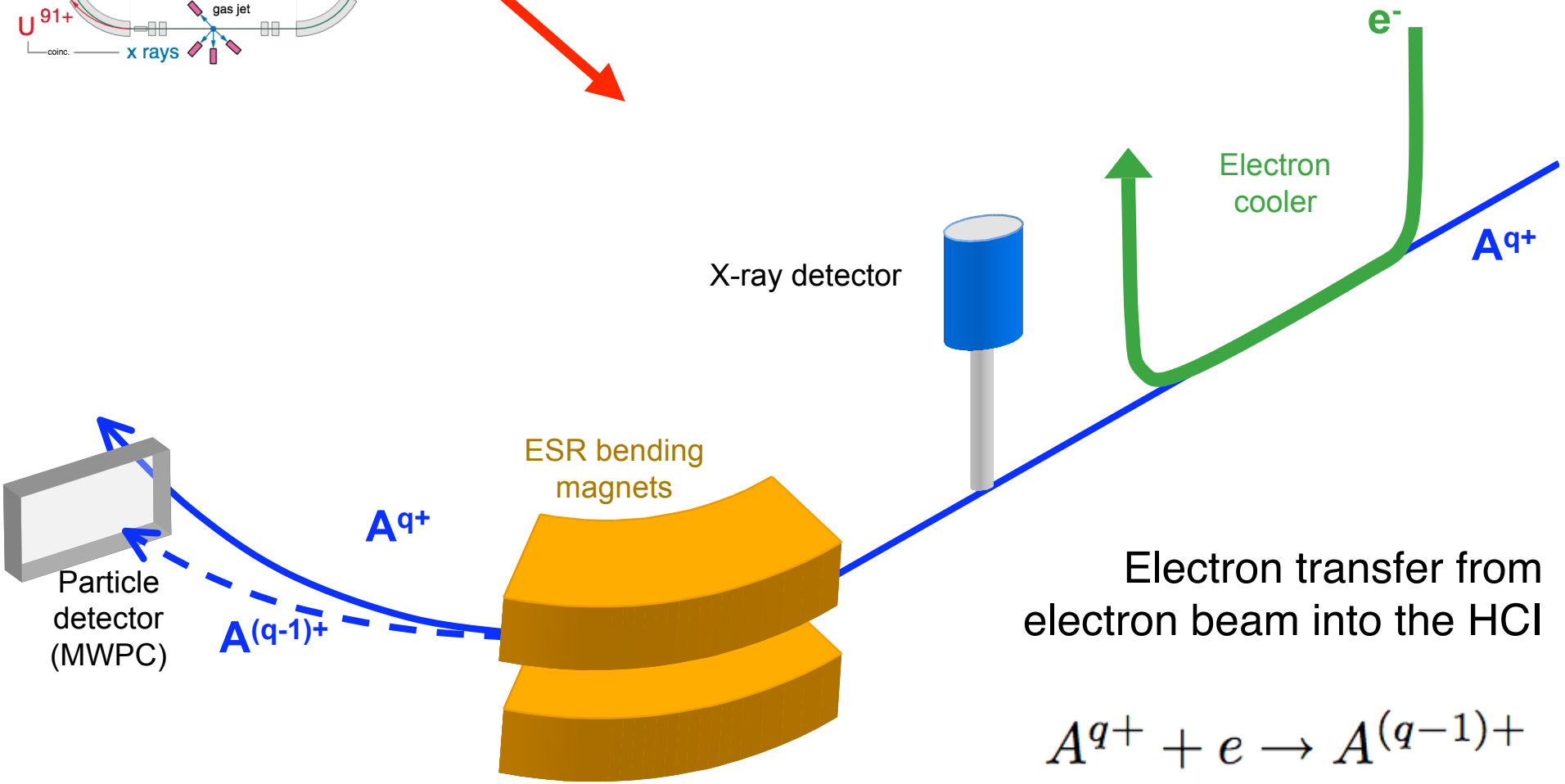
Goal:



±1 eV

Experiments at the cooler

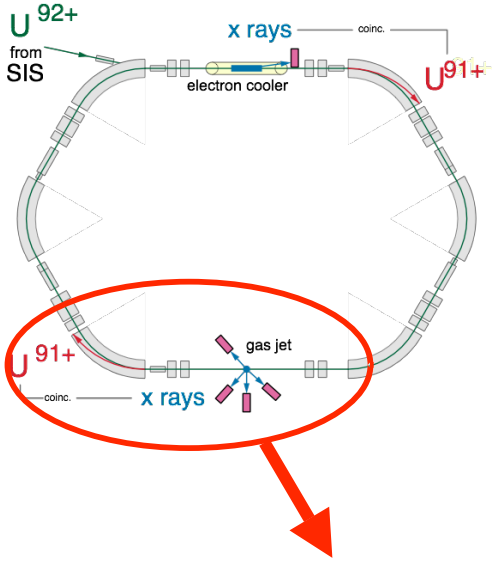


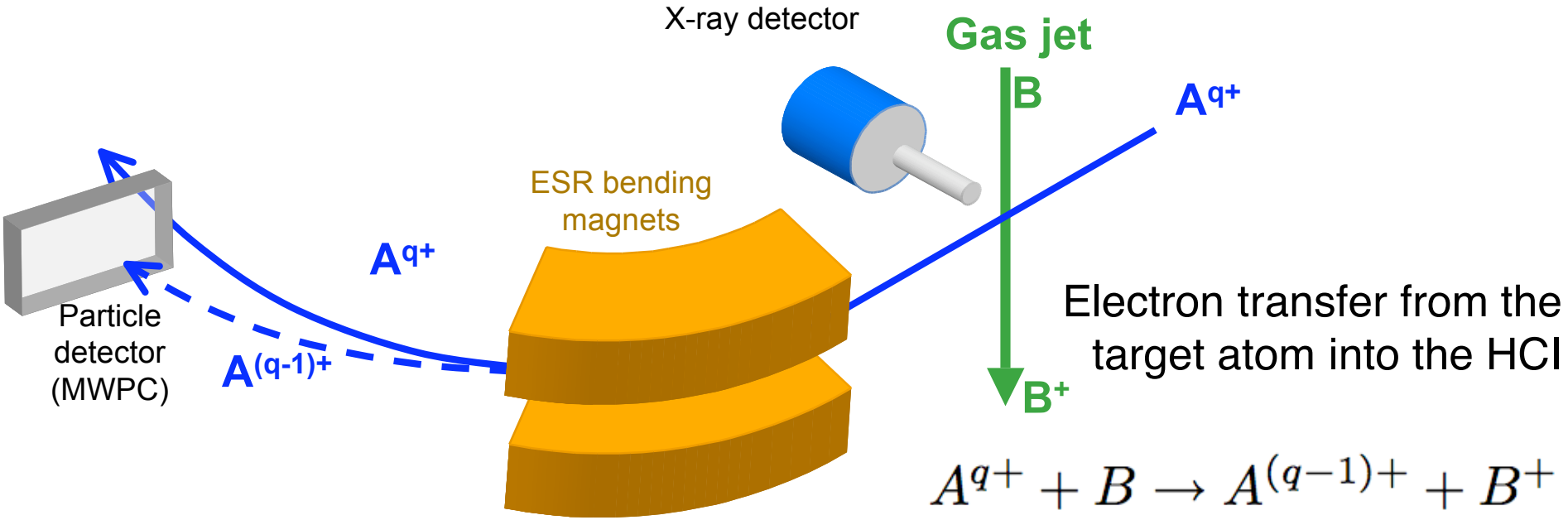


Electron transfer from electron beam into the HCI

$$A^{q+} + e \rightarrow A^{(q-1)+}$$

Experiments at the Jet-target

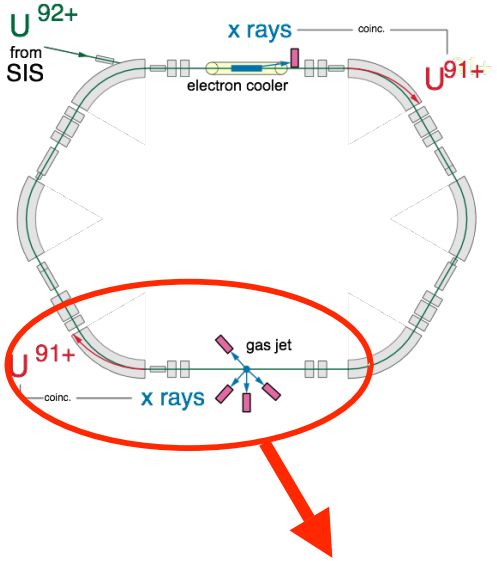


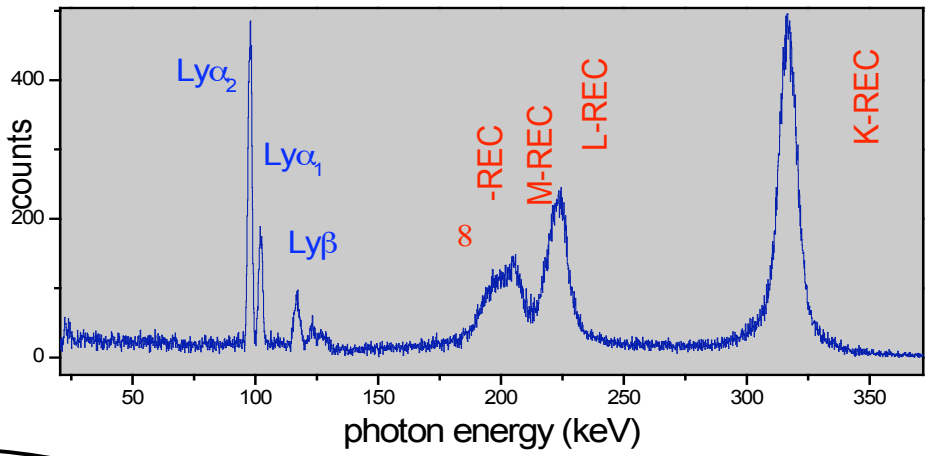


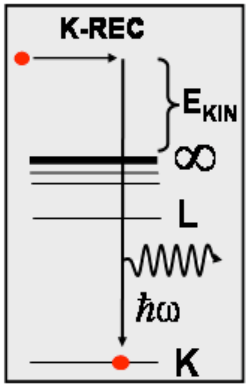
Electron transfer from the target atom into the HCI

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+}$$

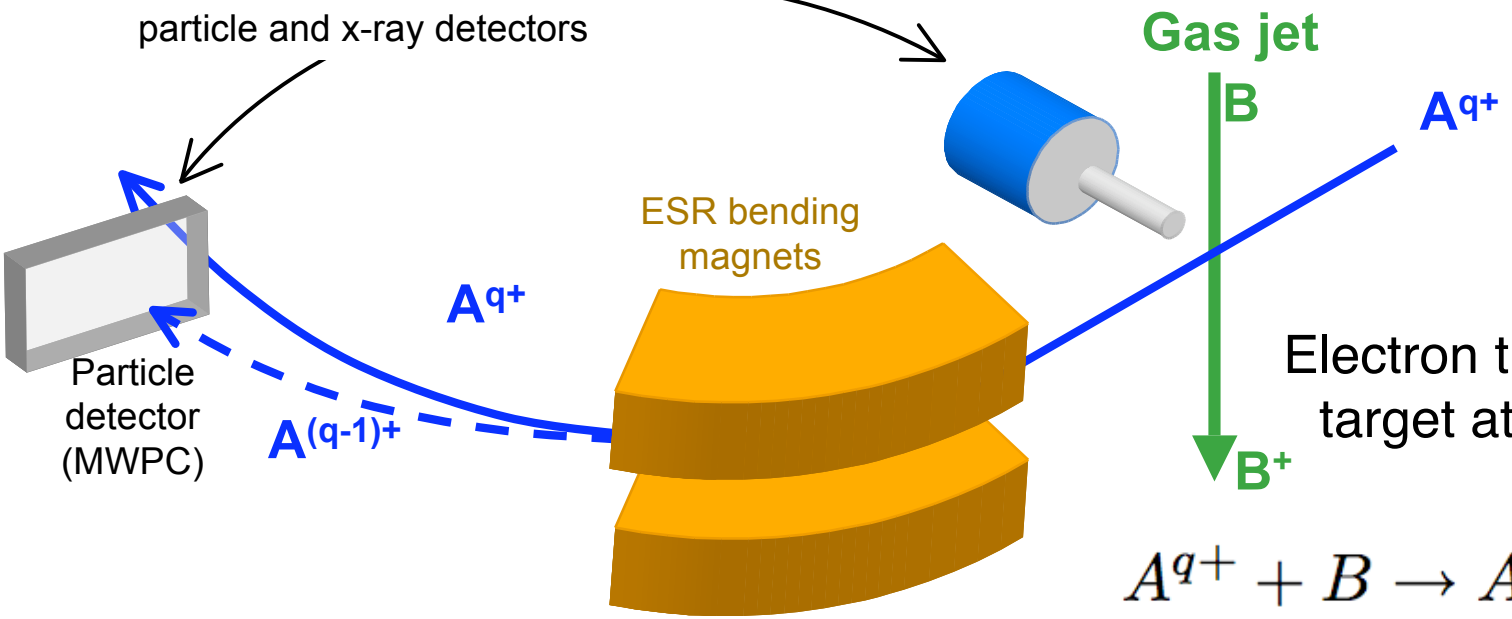
Experiments at the Jet-target







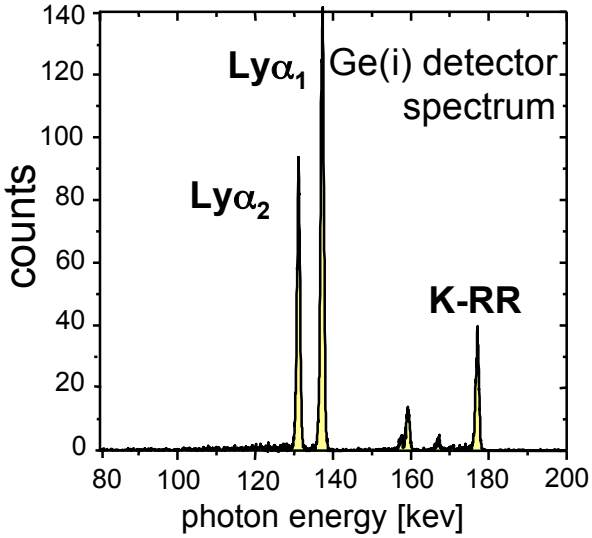
Coincidences between particle and x-ray detectors

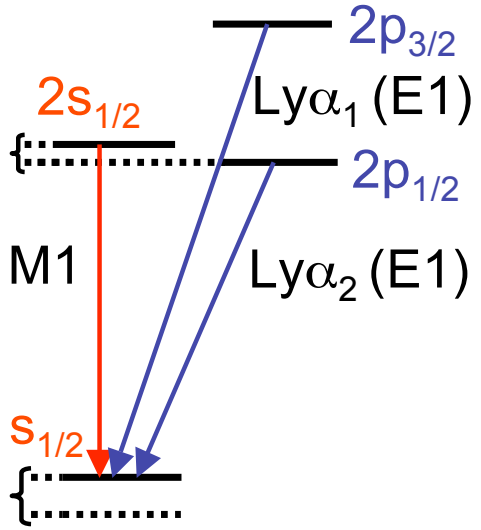


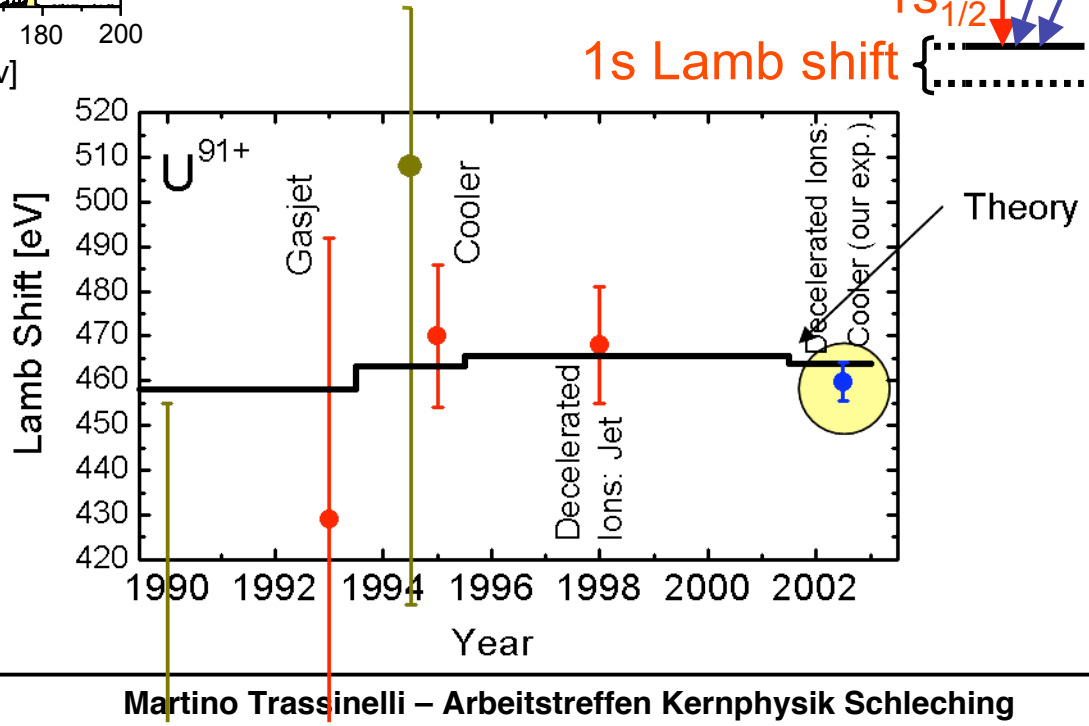
Electron transfer from the target atom into the HCI

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+}$$

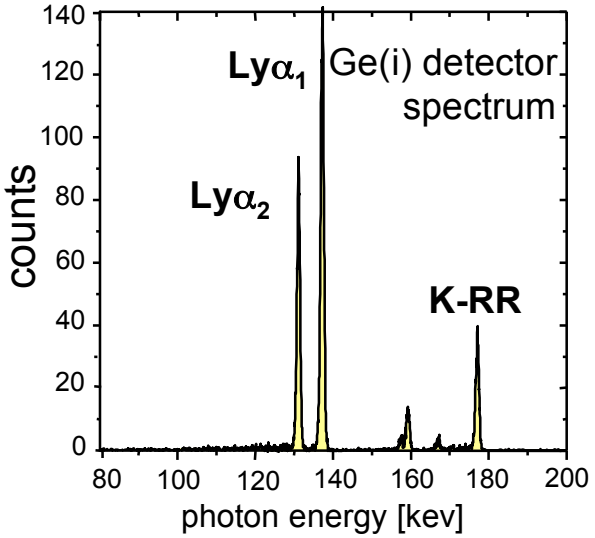
Test of QED in hydrogenlike Uranium







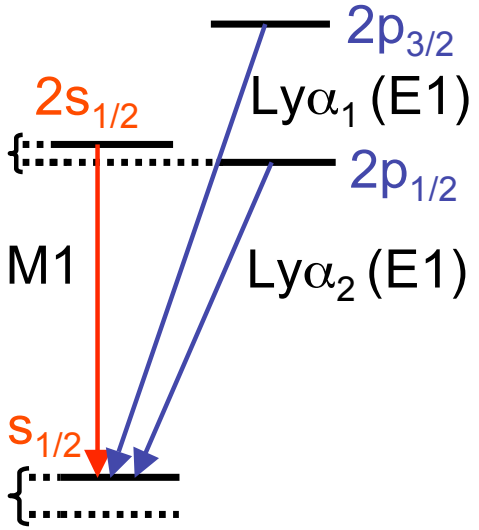
Test of QED in hydrogenlike Uranium

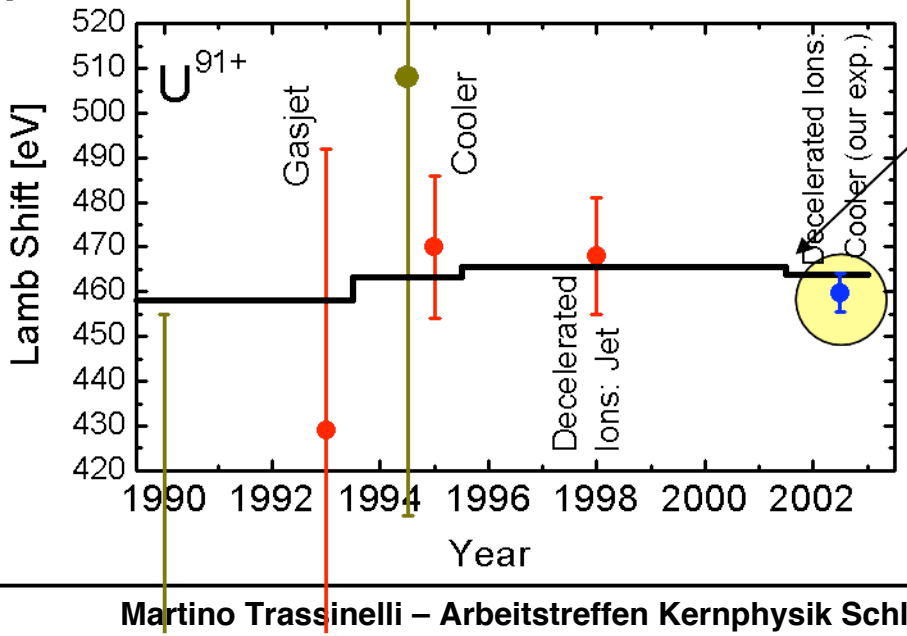


1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



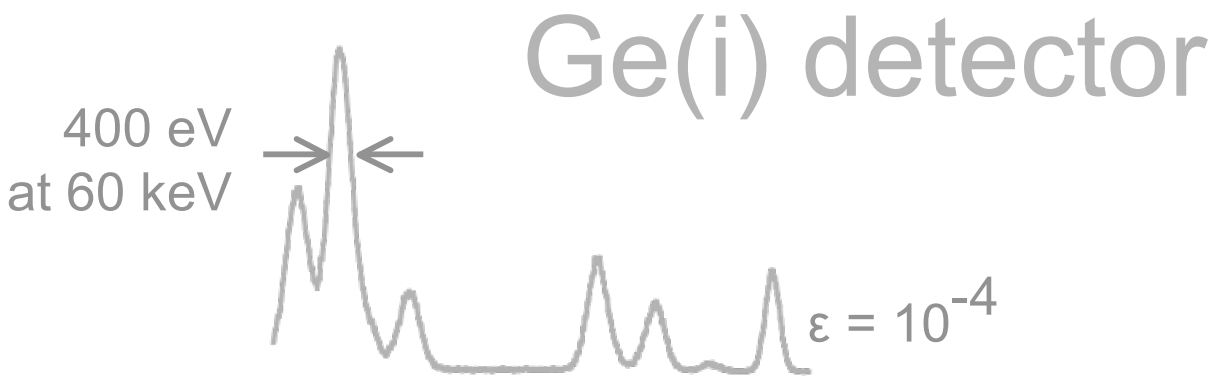


nature

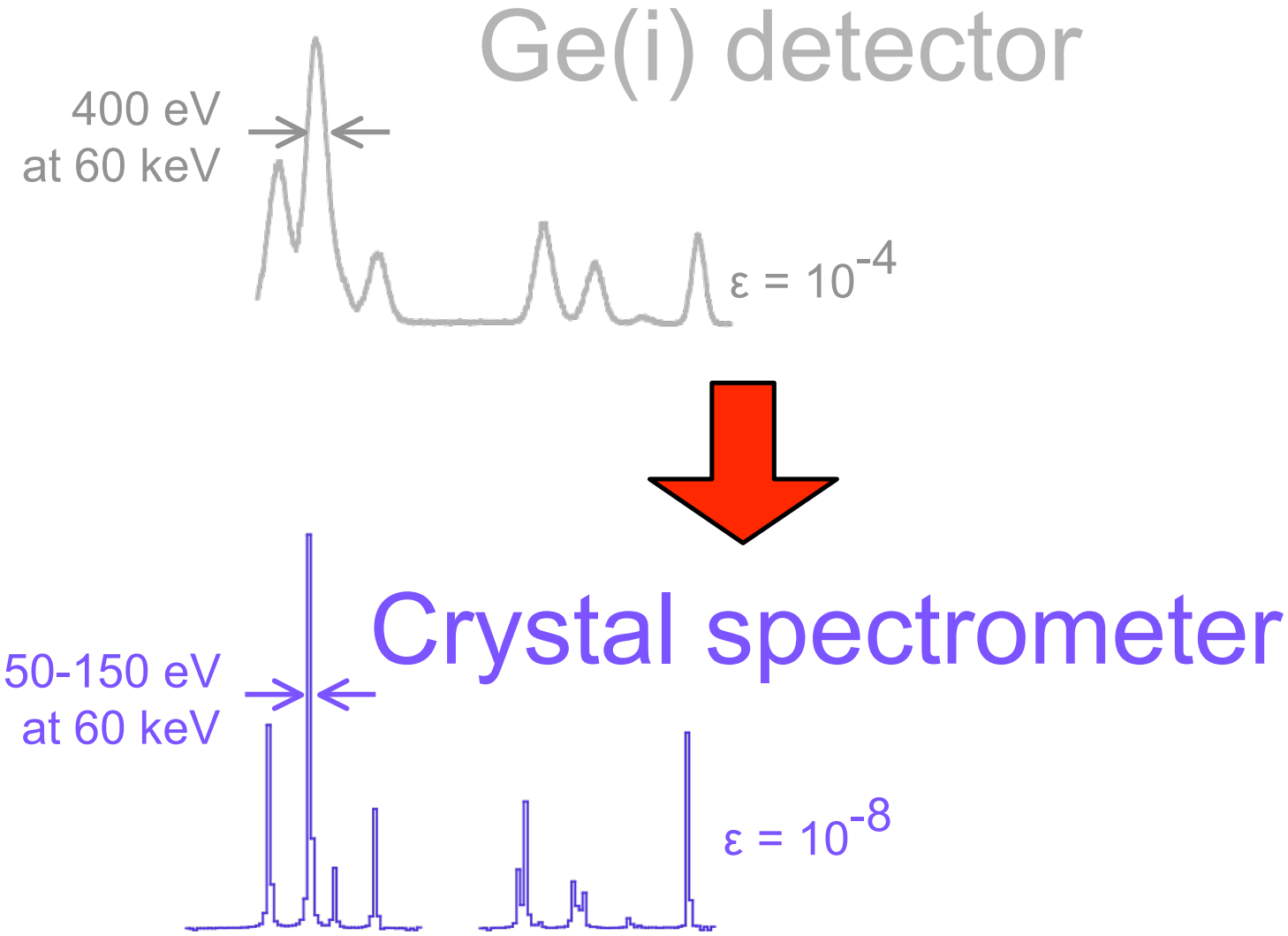
Research Highlights
Nature **435**, 858-859
(16 June 2005)

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

Towards an accuracy of 1 eV



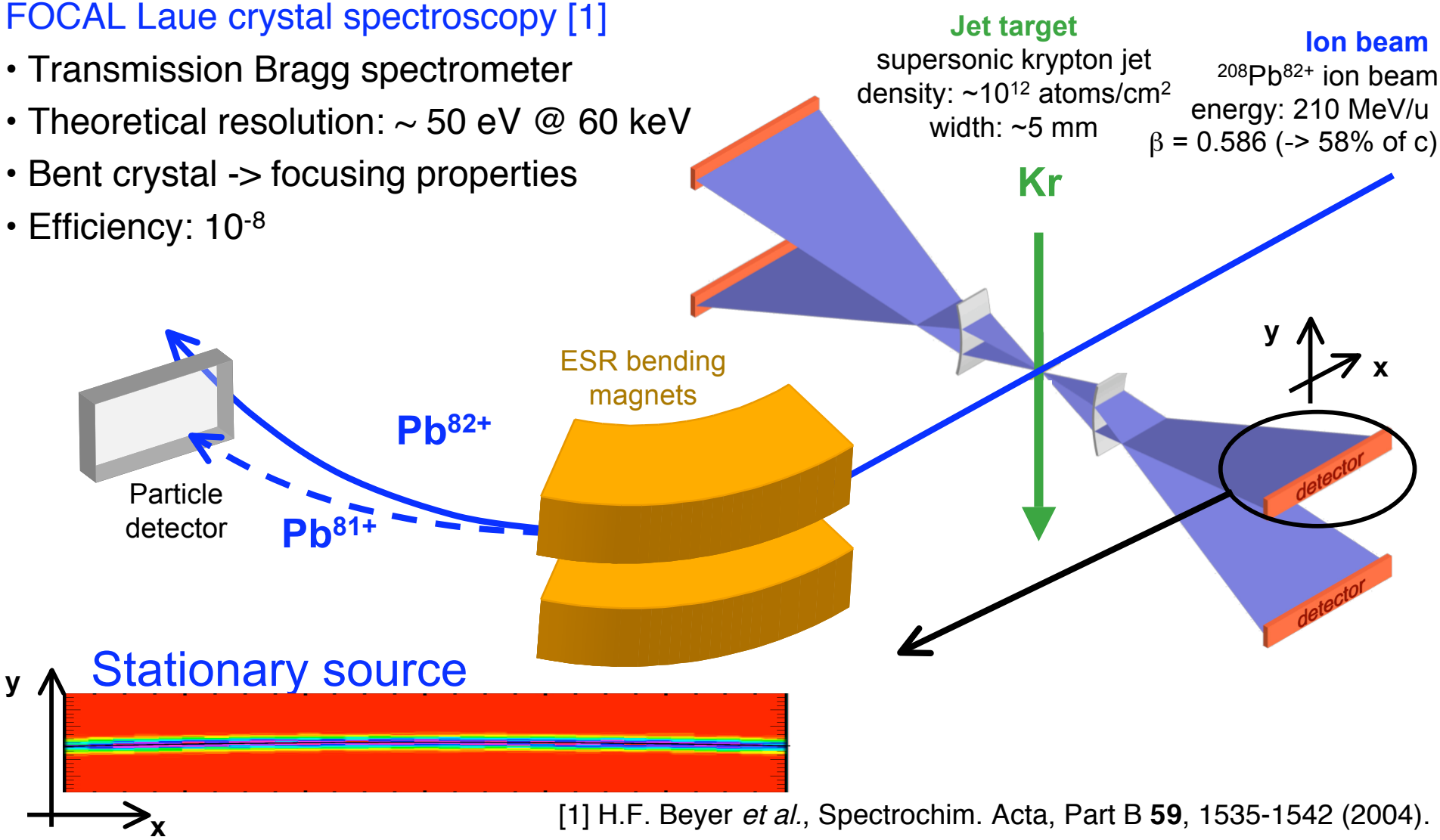
Towards an accuracy of 1 eV



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).

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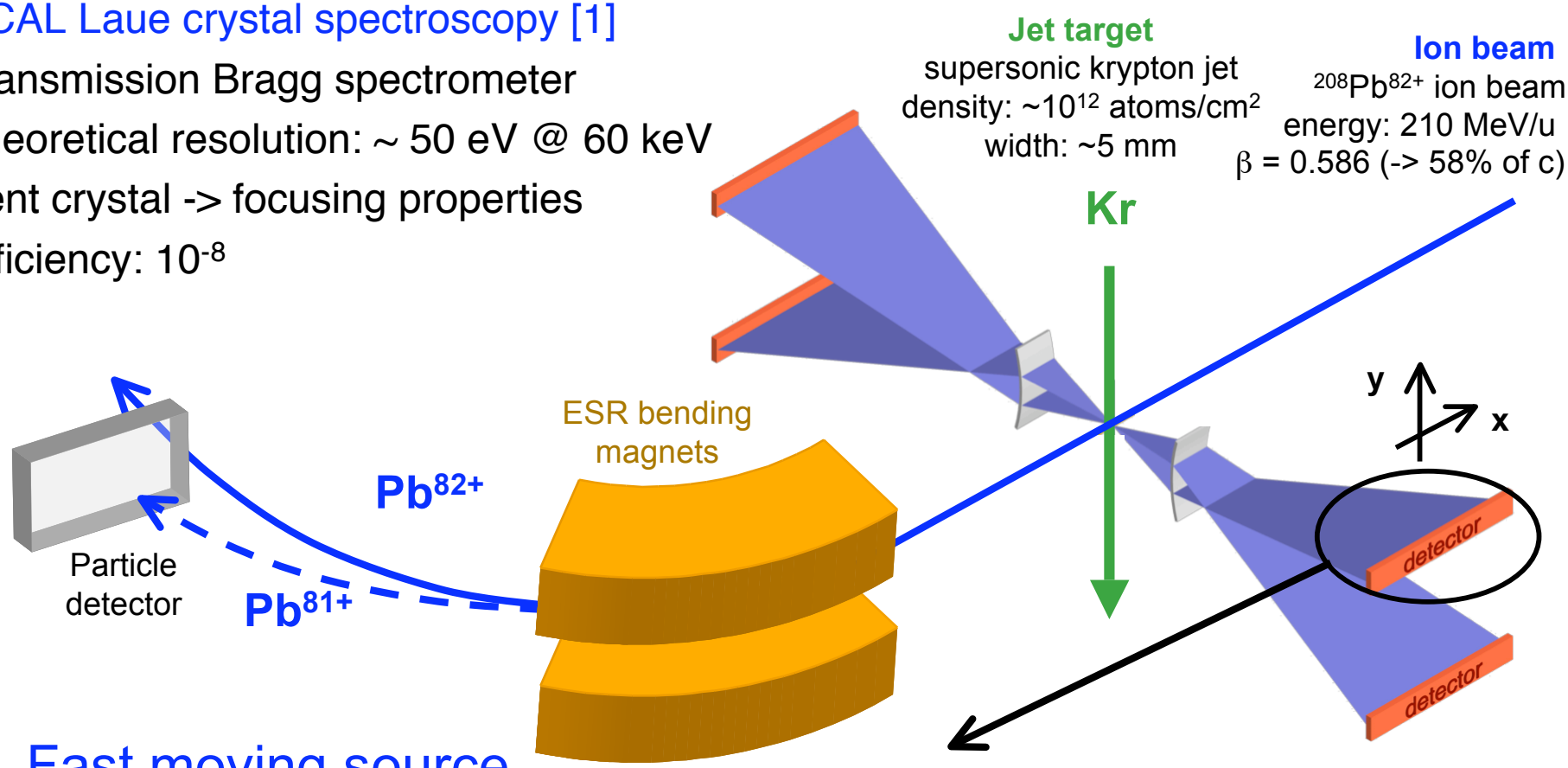
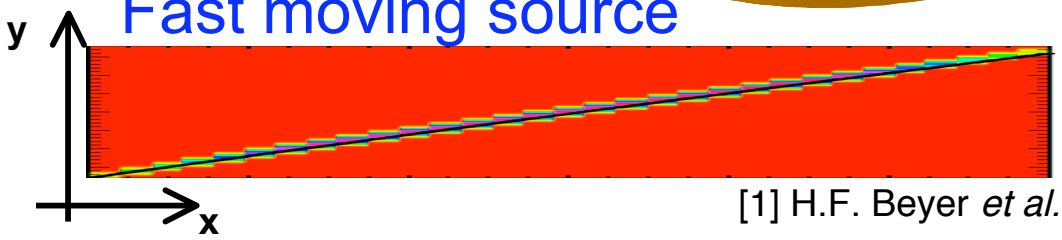
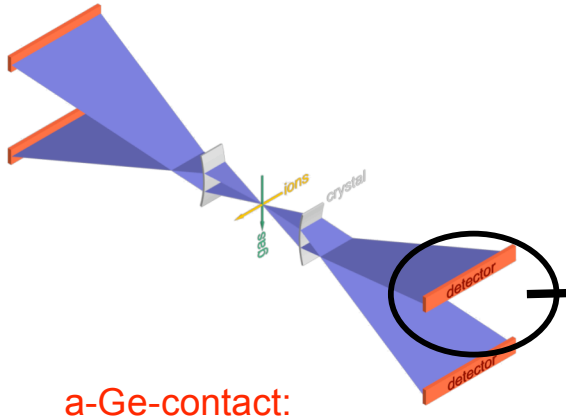




$$E_{\mathrm{Lab}} = \frac{E_{\mathrm{Proj}}}{\gamma(1 - \beta \cos\theta_{\mathrm{Lab}})}$$

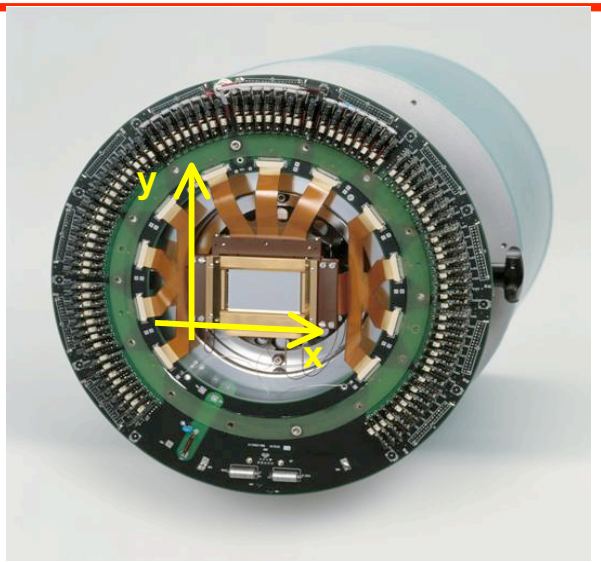
[1] H.F. Beyer *et al.*, Spectrochim. Acta, Part B **59**, 1535-1542 (2004).

Position-sensitive detector

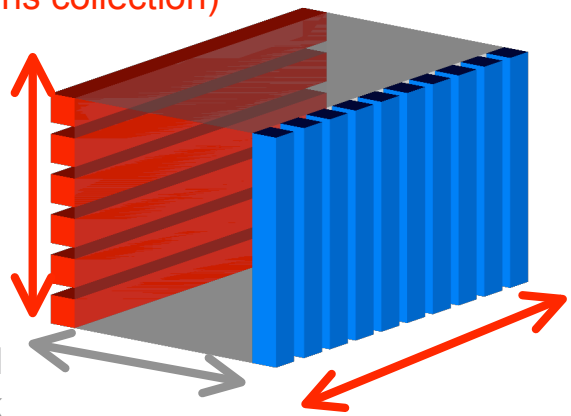


2D μSTRIP germanium detector

J-GSI



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



Ge(i) crystal
11 mm thick

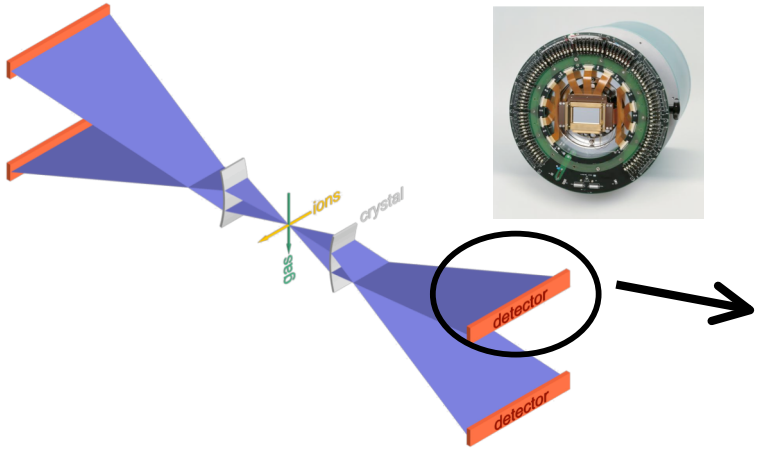
p⁺-contact:
128 strips in the front side
("holes" collection)

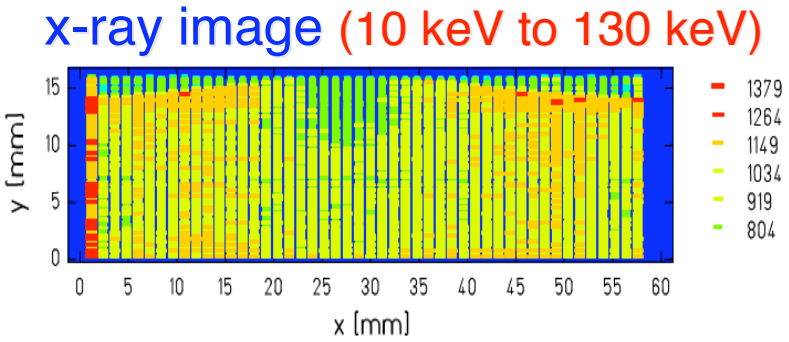
2D detector [1,2]
Ge(i) crystal
128 X 48 Strips
Δx ~ 1167 μm
Δy ~ 250 μm (< 150 eV)
ΔE ~ 2.1 keV
Δt ~ 50 ns

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)

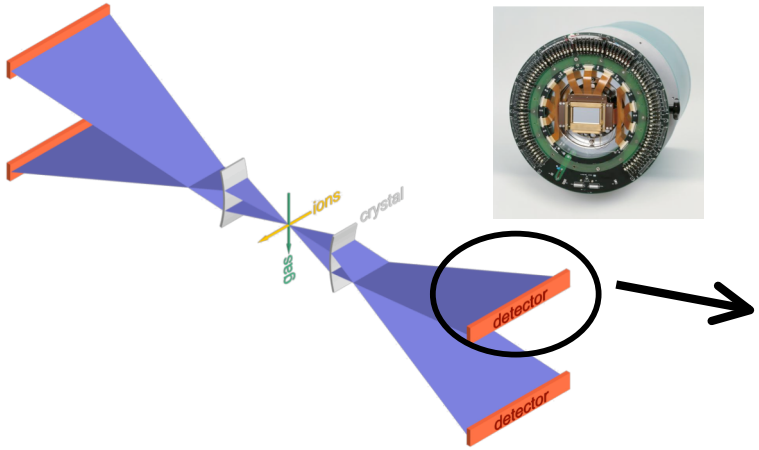
Preliminary data: March 2006



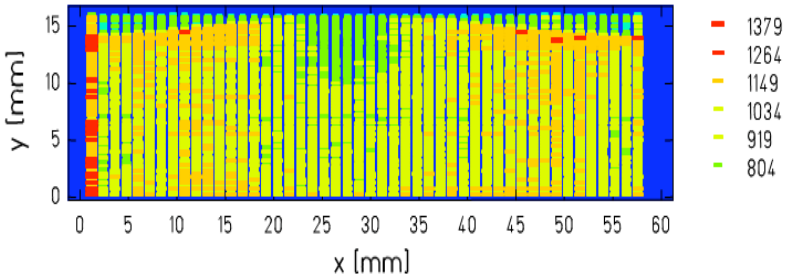


- Data acquisition period: 2 weeks
- 4 events per hour
- One calibration acquisition per day

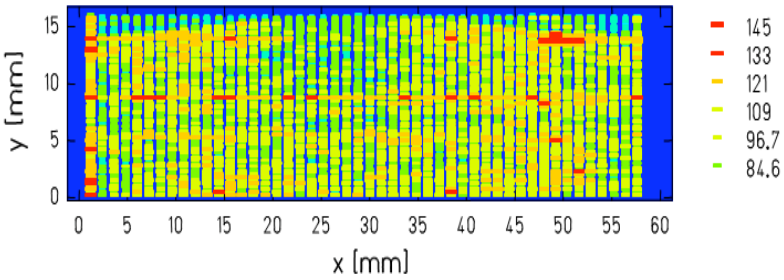
Preliminary data: March 2006



x-ray image (10 keV to 130 keV)



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



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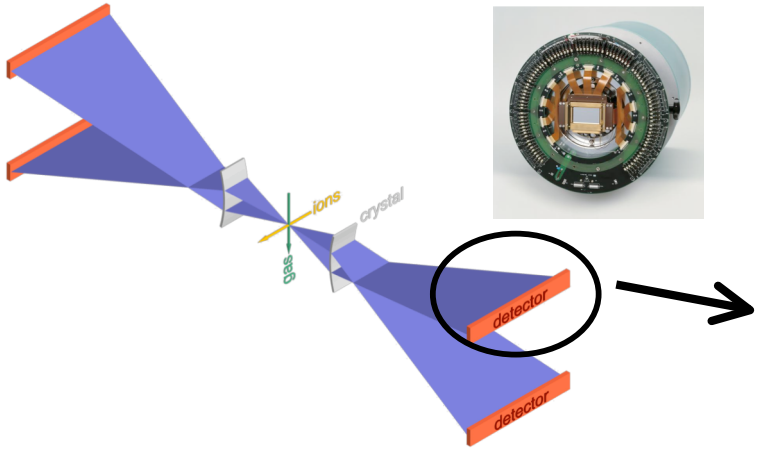

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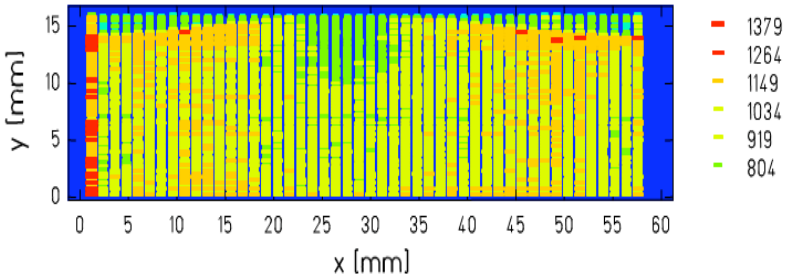
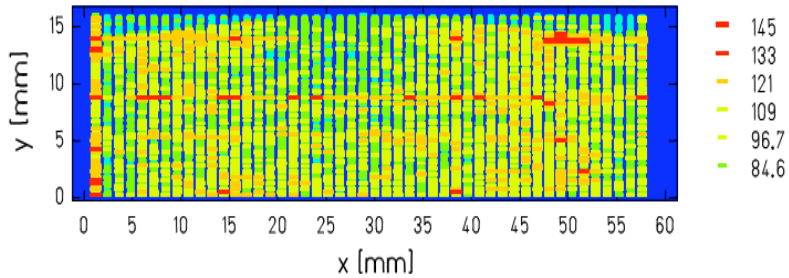
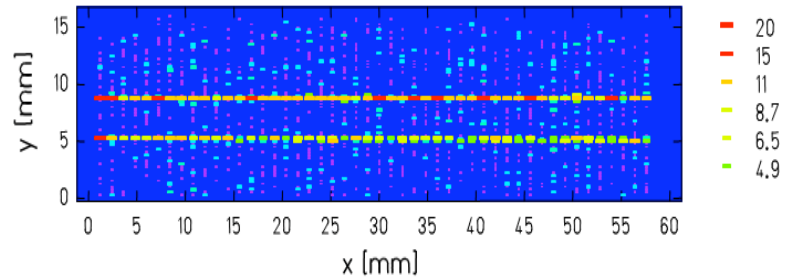


x-ray image (10 keV to 130 keV)
+ time condition

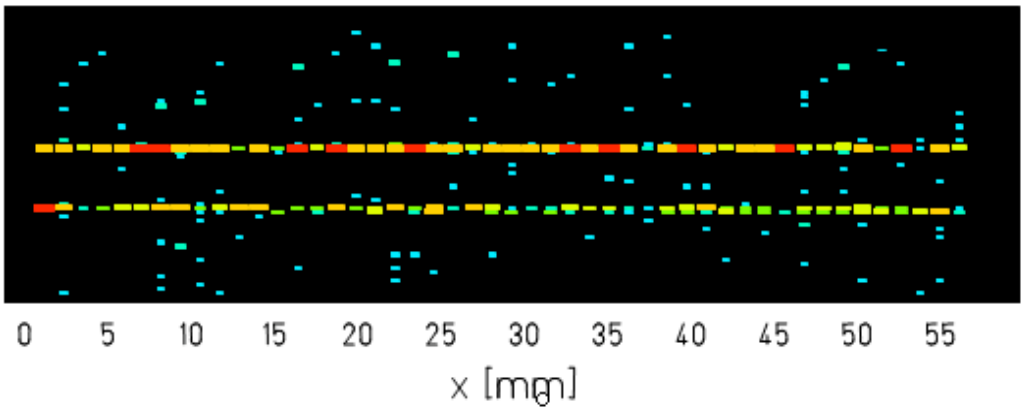


x-ray image (58 keV to 65 keV)
+ time condition

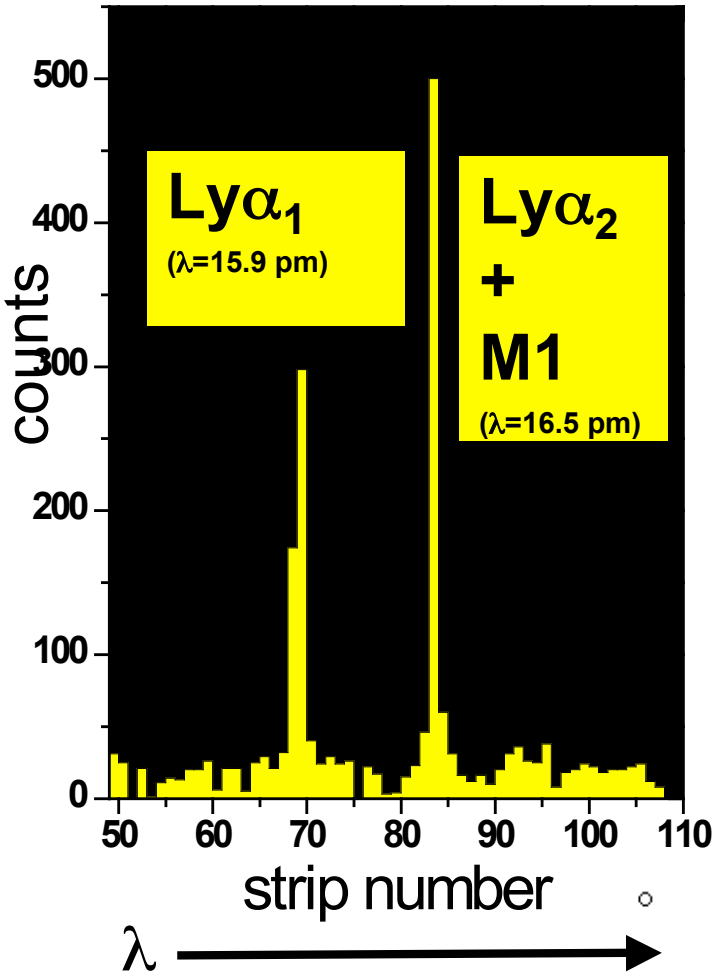


Preliminary data: March 2006

Lyman-α: $^{208}Pb^{81+}$ @210 MeV/u

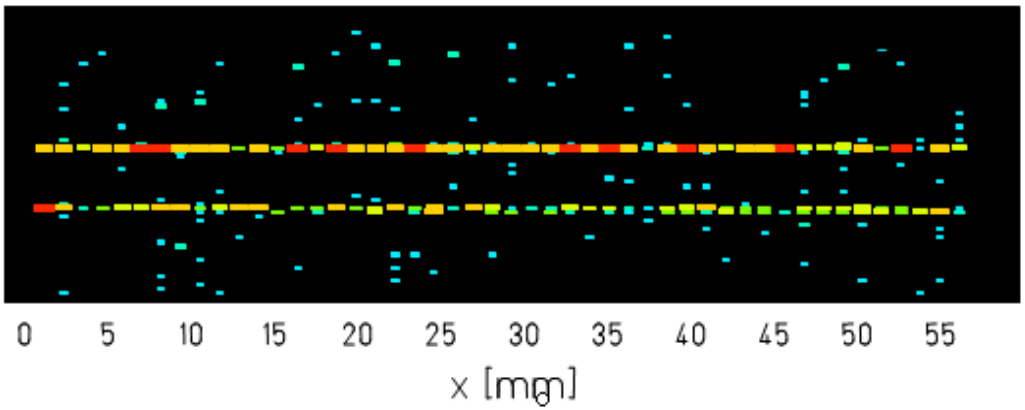


Preliminary data: March 2006



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

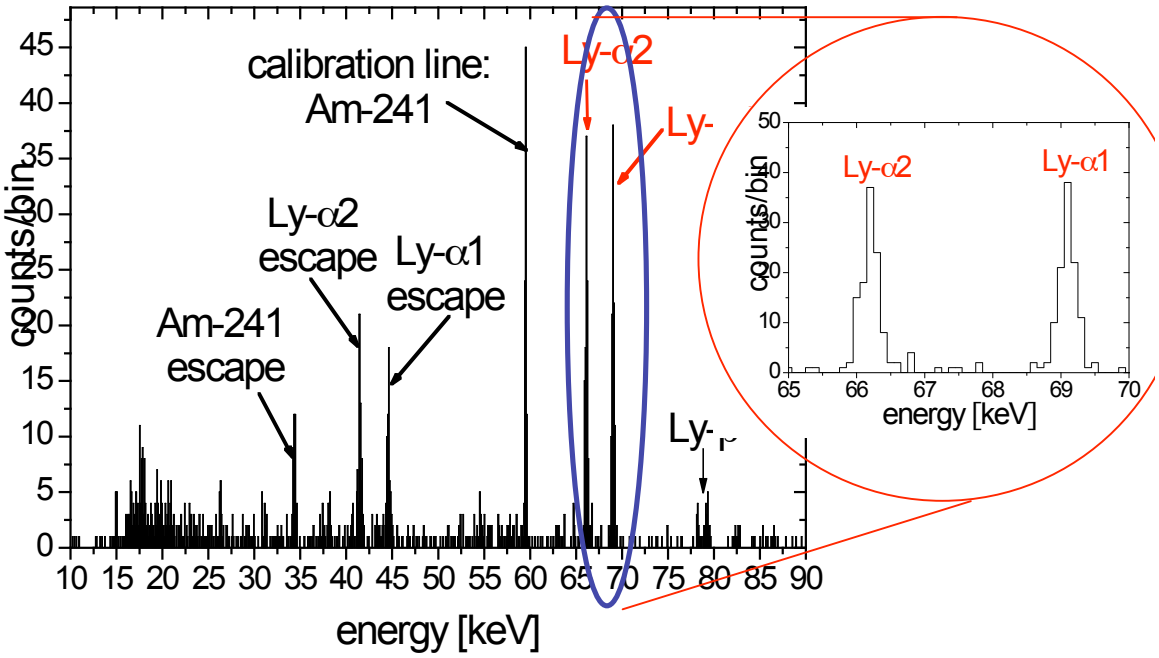
Lyman-α: $^{208}Pb^{81+}$ @210 MeV/u



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

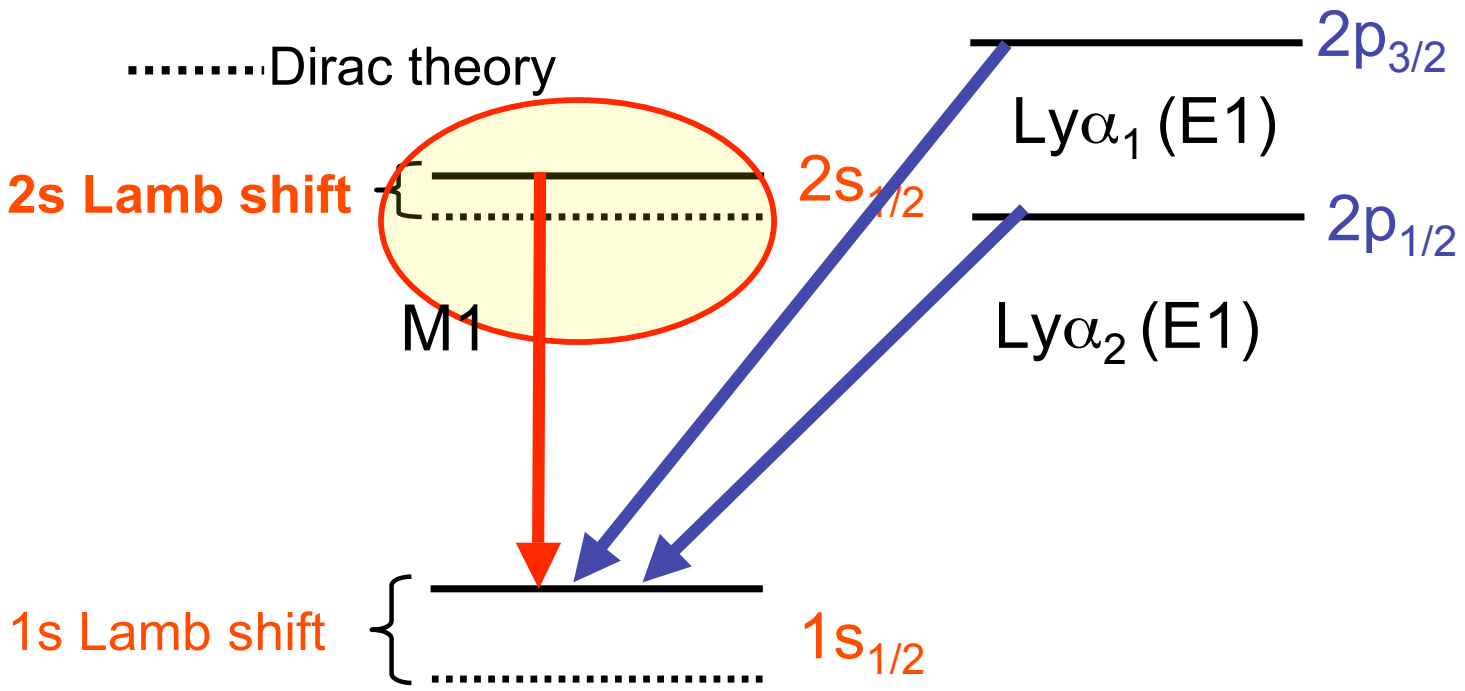


Energy resolution: ~115 eV

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

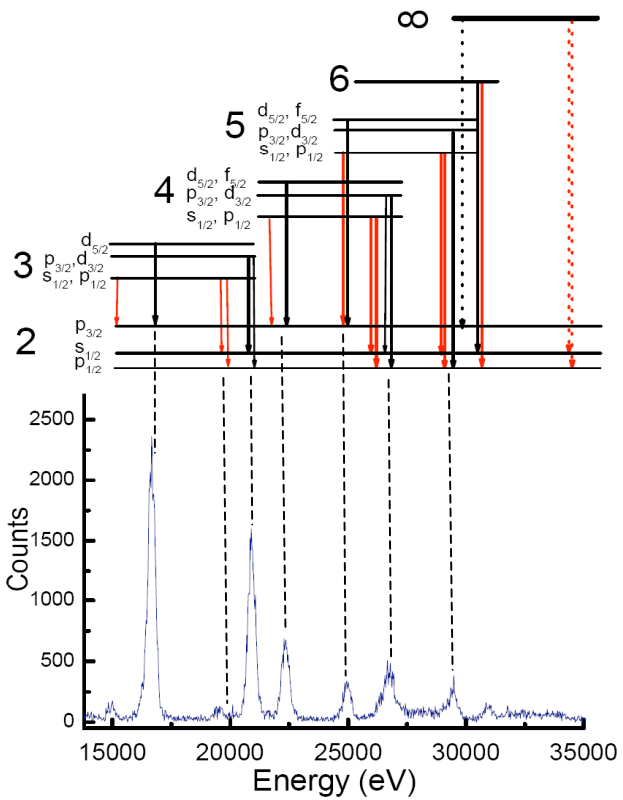
P. Egelhof et al., Oct. 2005

Atomic structure: 2s Lamb shift



Atomic structure: 2s Lamb shift

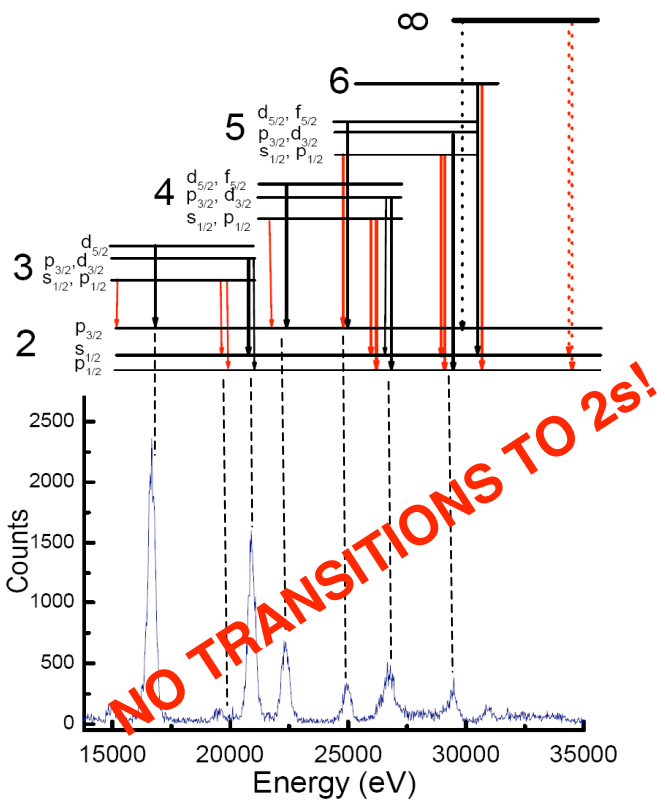
H-like ions



Balmer transitions
(16-35 keV for Uranium)

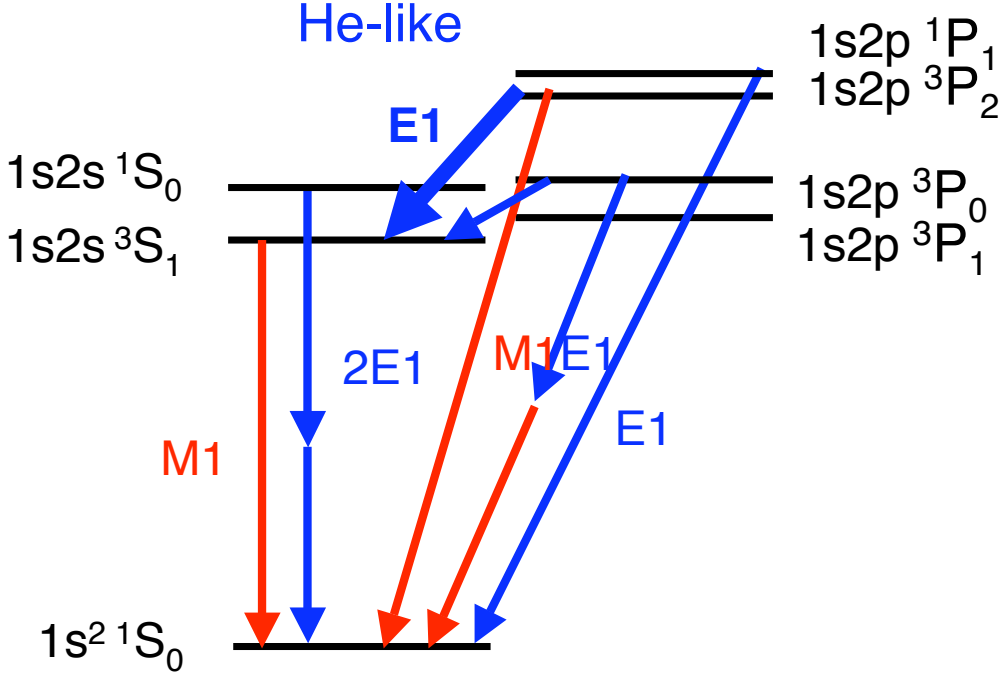
Atomic structure: 2s Lamb shift

H-like ions



Balmer transitions
(16-35 keV for Uranium)

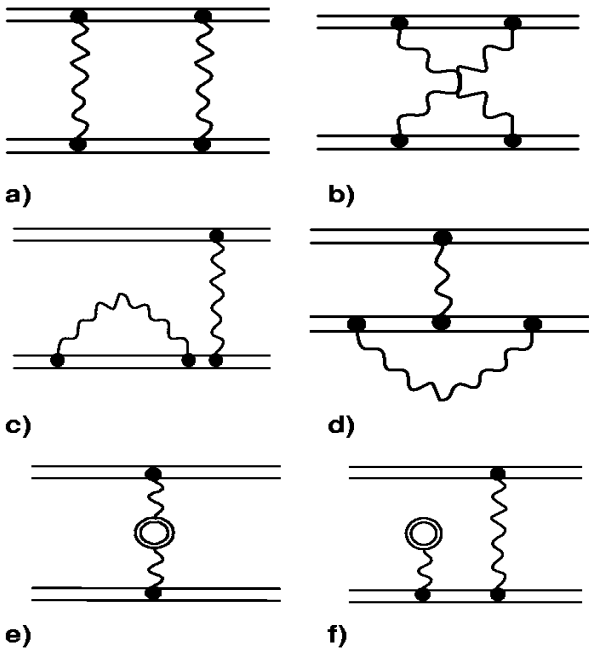
He-like

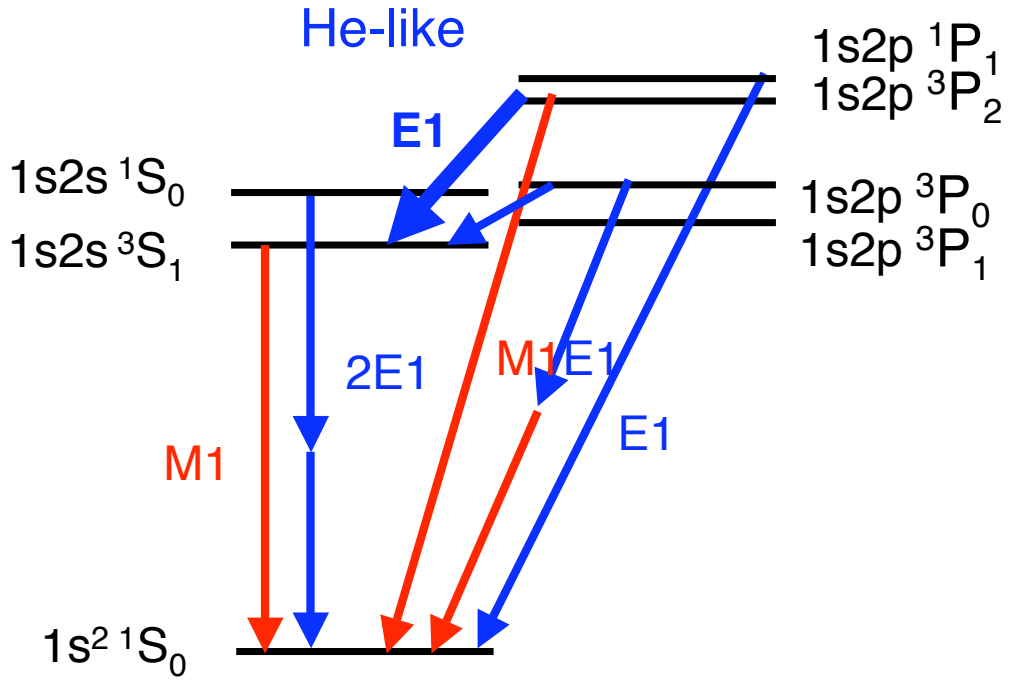


Intra-shell transition
(4.5 keV in Uranium)

Atomic structure: 2s Lamb shift

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

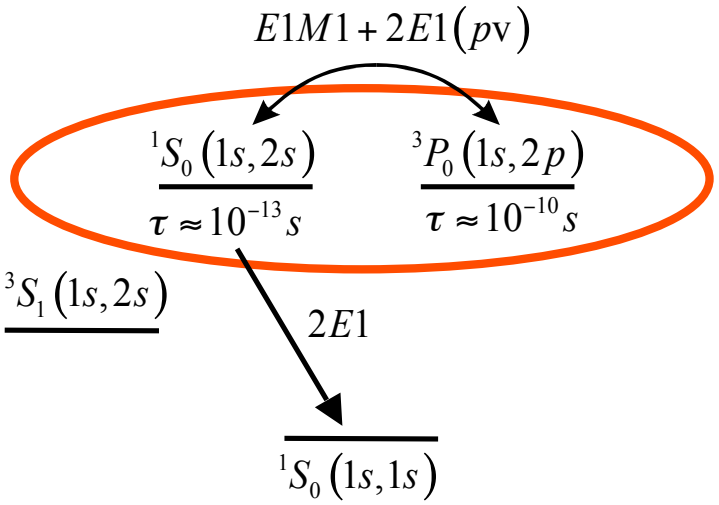


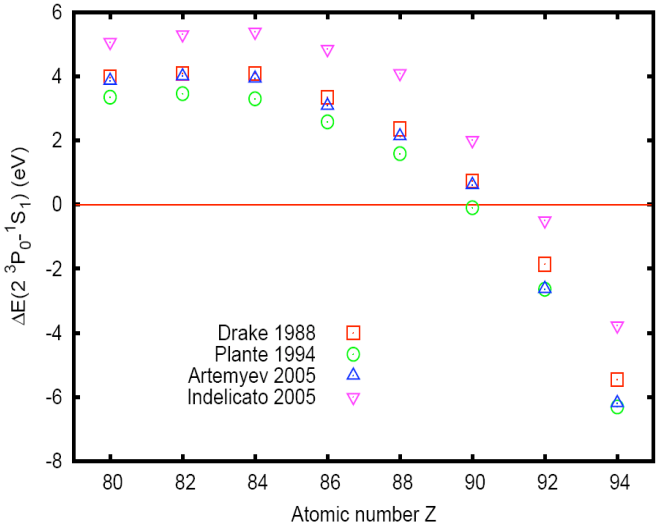


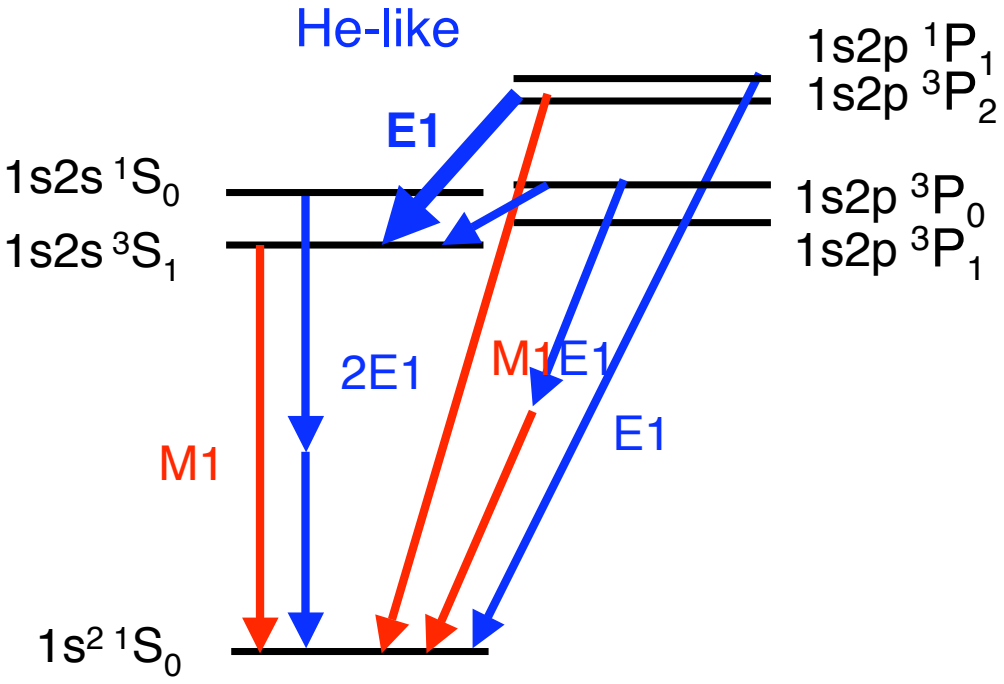
- SIMPLEST "MANY"-BODY SYSTEM

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

Atomic structure: 2s Lamb shift





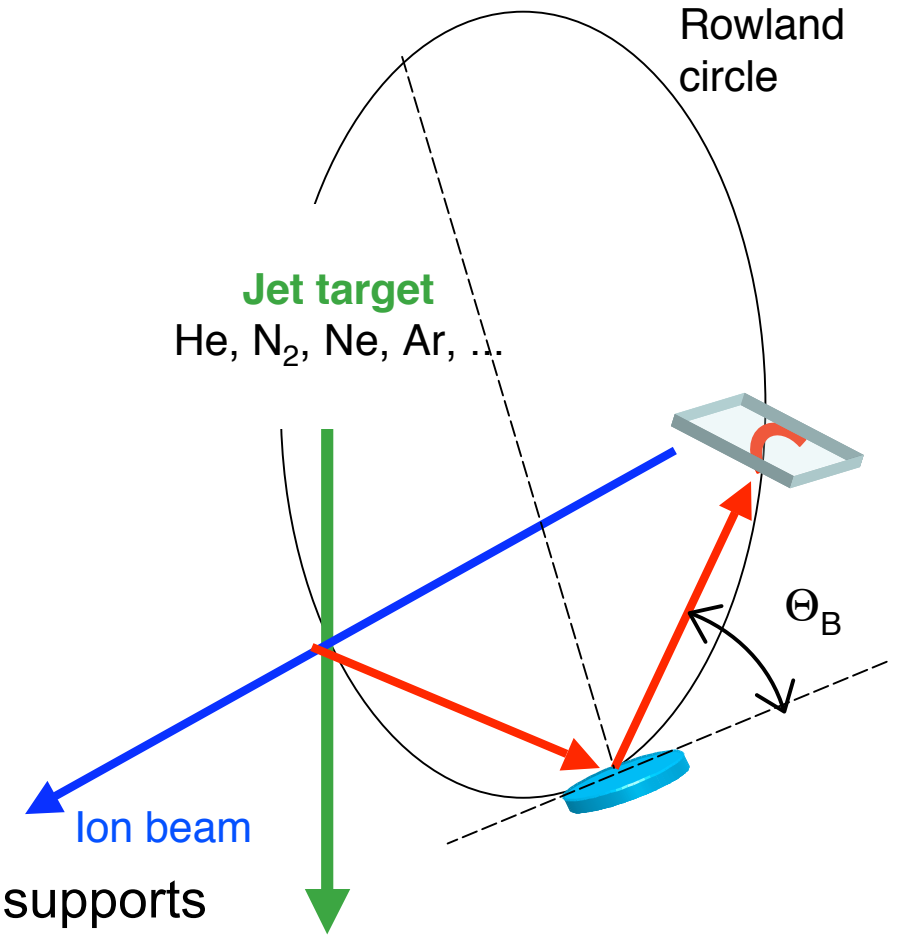


- SIMPLEST "MANY"-BODY SYSTEM
- Possible parity violation measurement

A. Schäfer *et al.*, Phys. Rev. A **40**, 7362 (1989).

Bragg spectrometer for fast ions

- Bragg spectrometer for 2-10 keV
- Johann geometry:
  -> X-ray focusing
- Fast ion:
  -> vertical spectrometer plane
- Resolution ≥ 0.5 eV



Two type of spectrometer in construction:

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

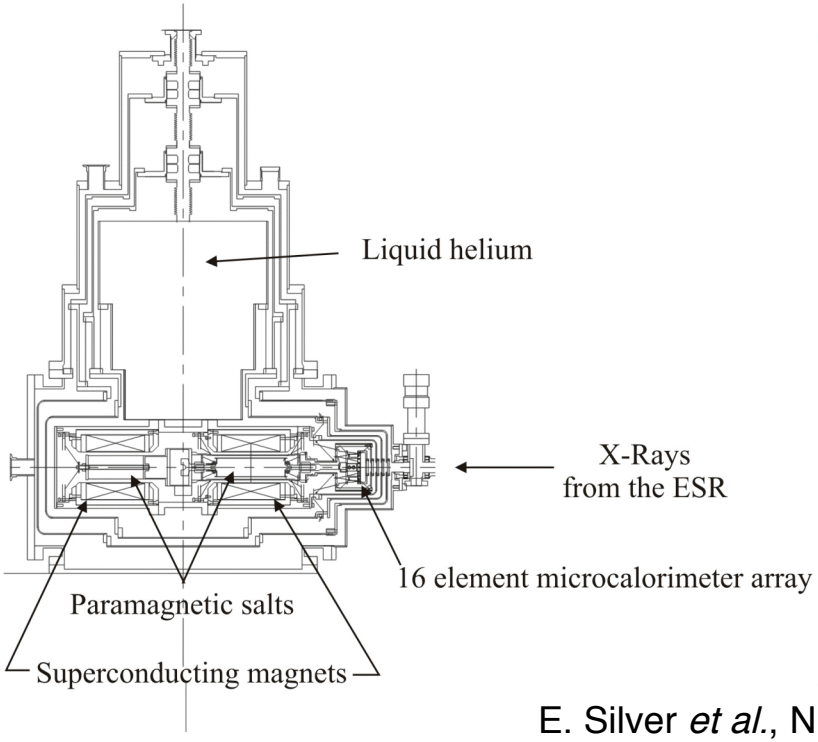
Efficiency in the order of 10^{-6} !!

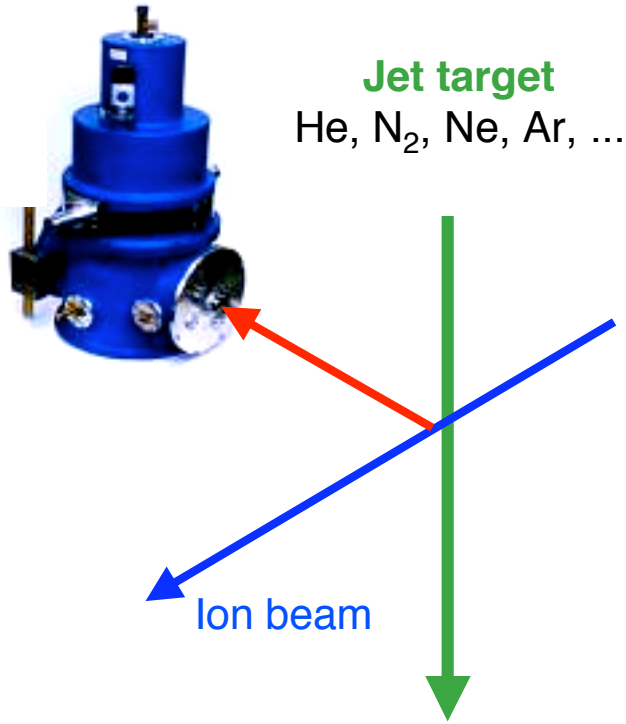
M. Trassinelli *et al.*, Canadian Journal of Physics accepted (2006).

2s Lamb shift measurement with a microcalorimeter

E. Silver et al., Harvard Smithsonian

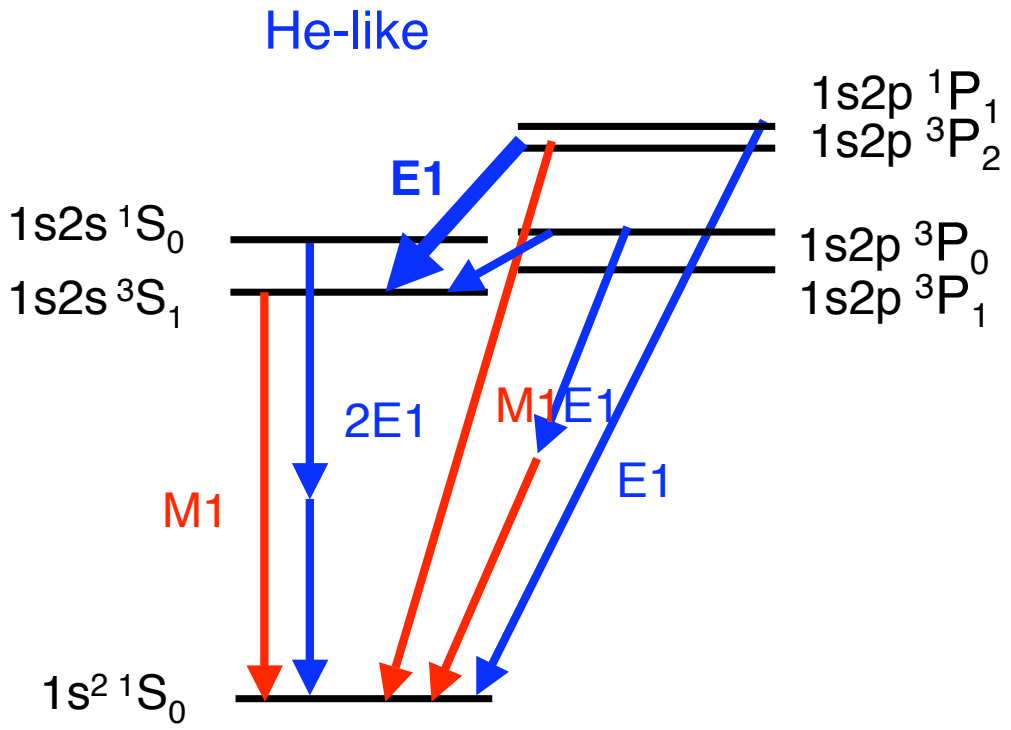
- 4 X 4 bolometers (0.1 X 0.1 mm^2)
- Energy range: 3-50 keV
- High resolution: around 3 eV @ 6 keV
- Magnetic cooler recycling: 60 hours

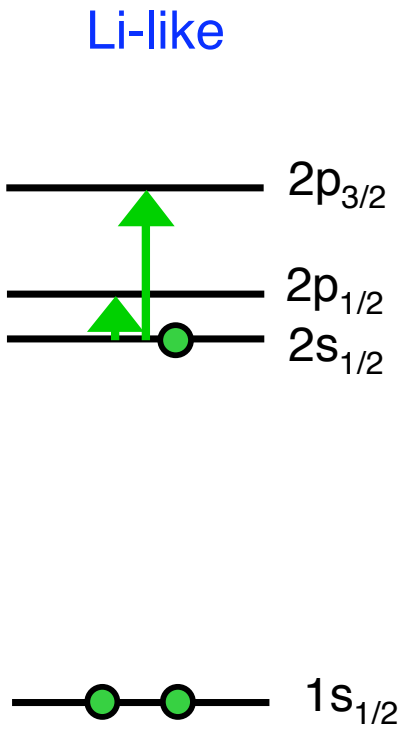




E. Silver *et al.*, Nucl. Instrum. Meth. A **520**, 60-62 (2004).

Atomic structure: 2s Lamb shift

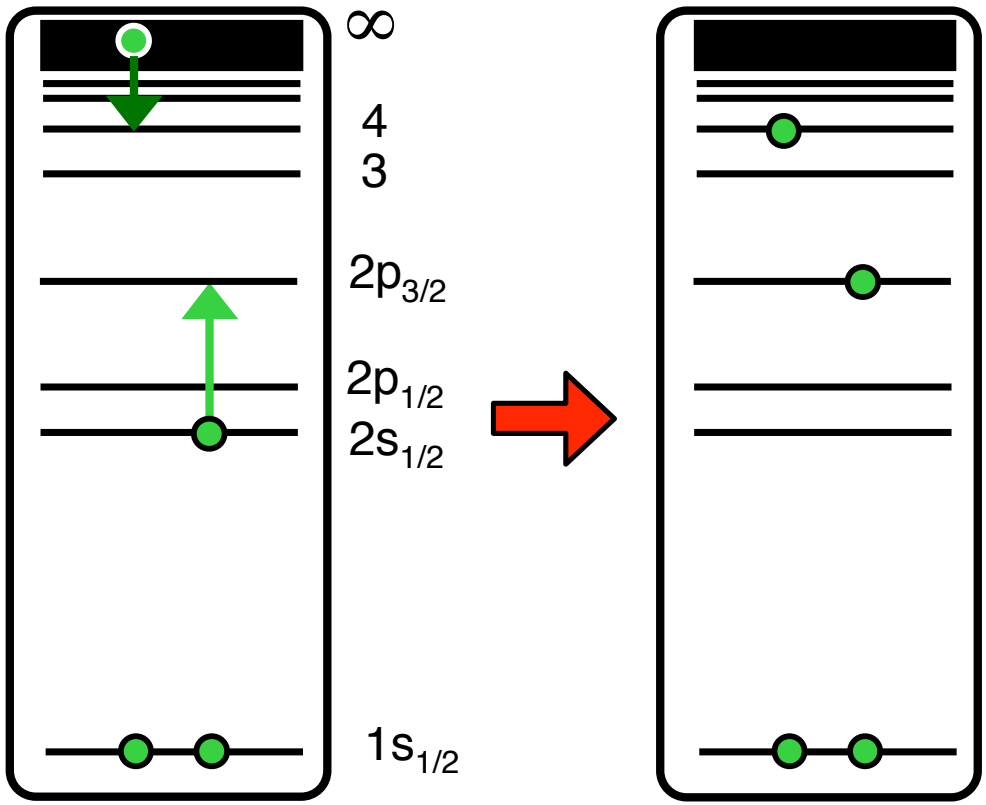




Intra-shell transition branching ratio: 30%

Dielectric recombination

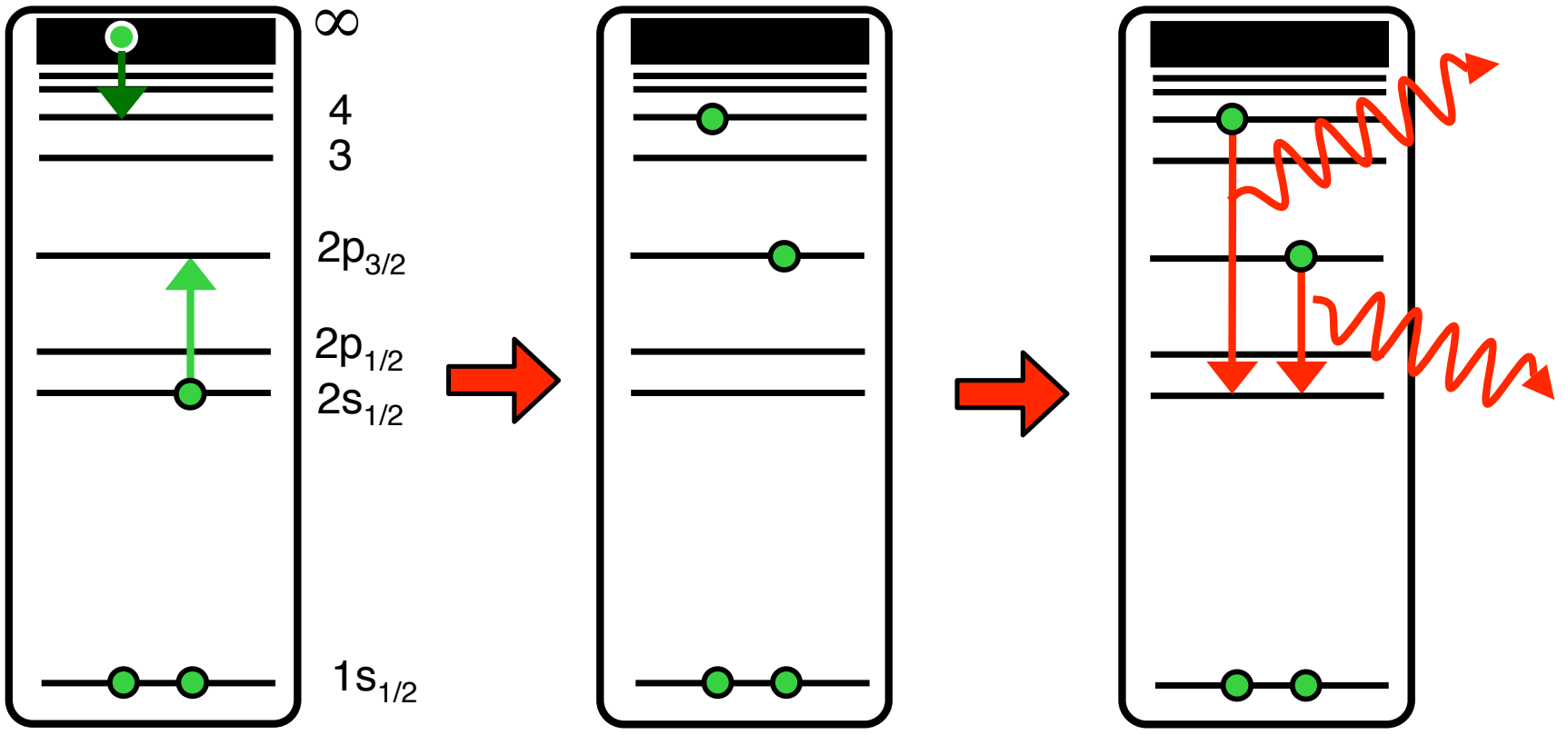
Dielectric recombination



$A^{q+} + e^{-} \rightarrow [A^{(q-1)+}]^{**}$

Dielectric Recombination (DC)
(time-reverse to autoionization)

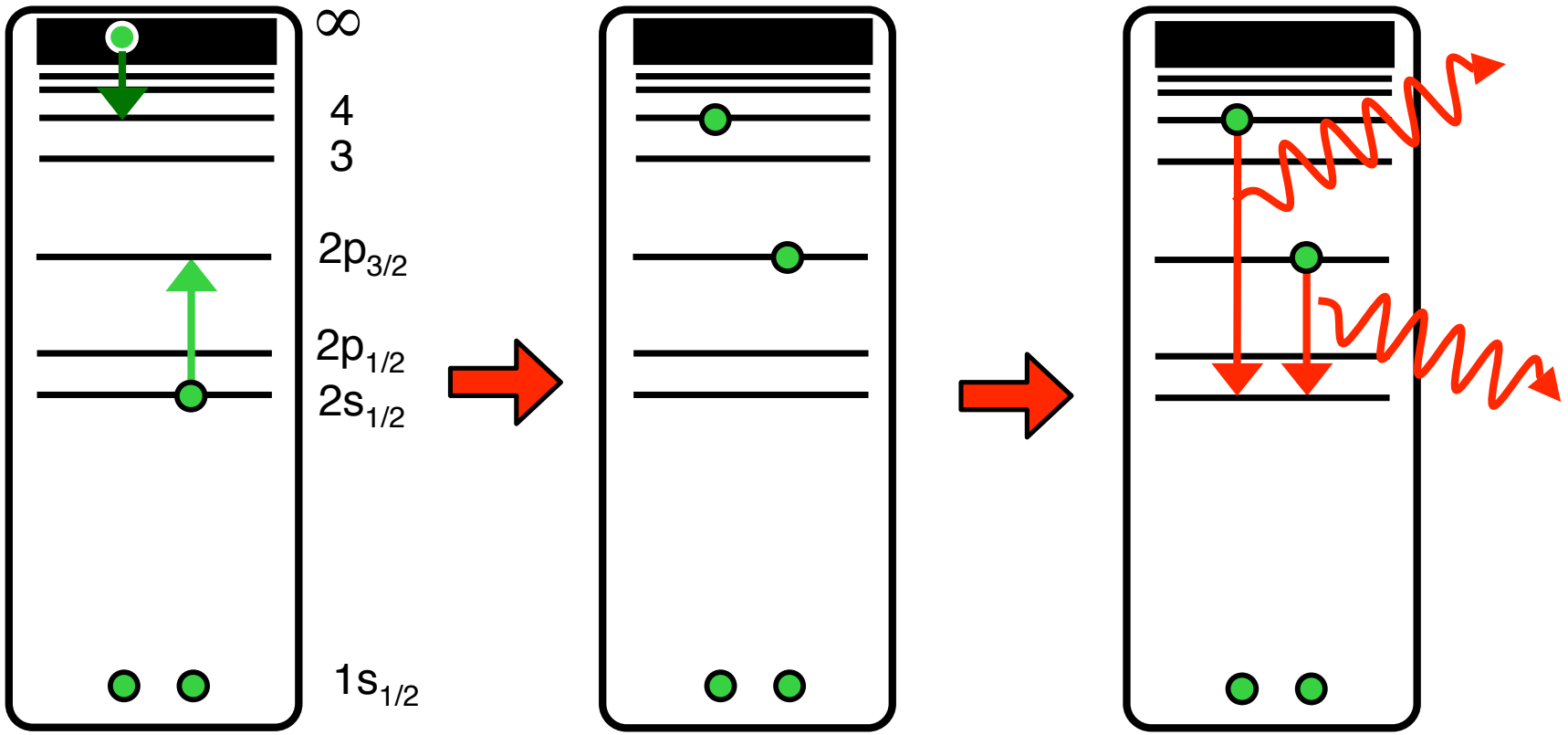
Dielectric recombination



Dielectric Recombination (DC)
(time-reverse to autoionization)

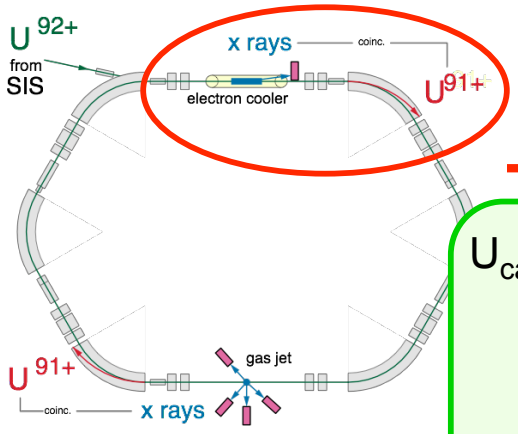
Radiative stabilization
in competition with autoionization

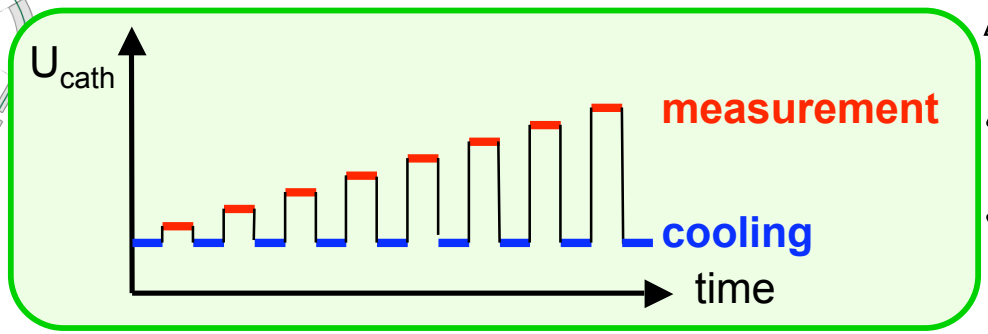
Dielectric recombination



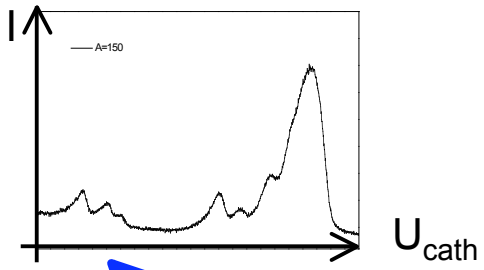
$E_{kin}(e^-) = (E_{2p} - E_{2s}) - E_n$ ⇒ Large capture cross section

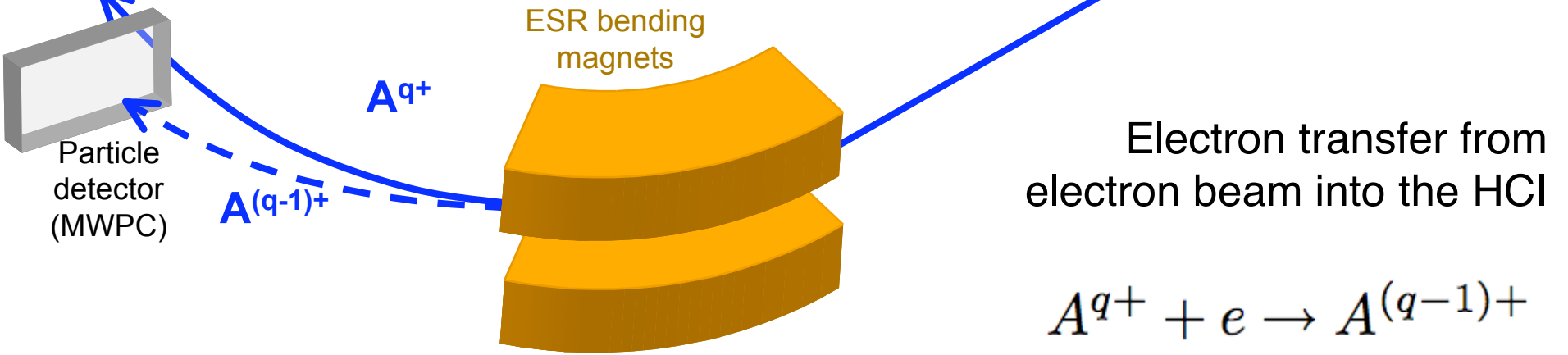
Experiments at the cooler





$\Delta E \rightarrow E_{kin}(e^-)$

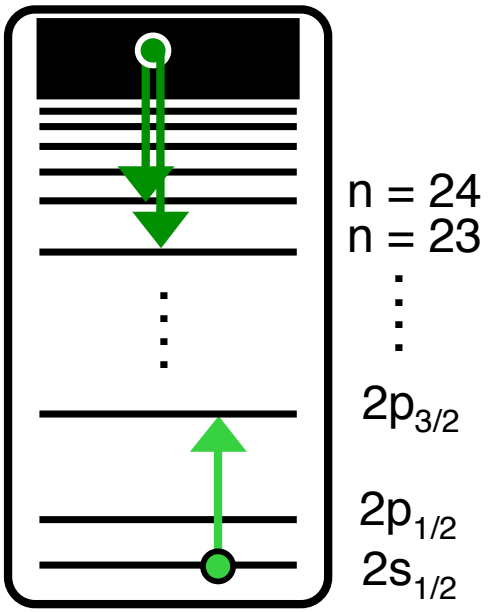


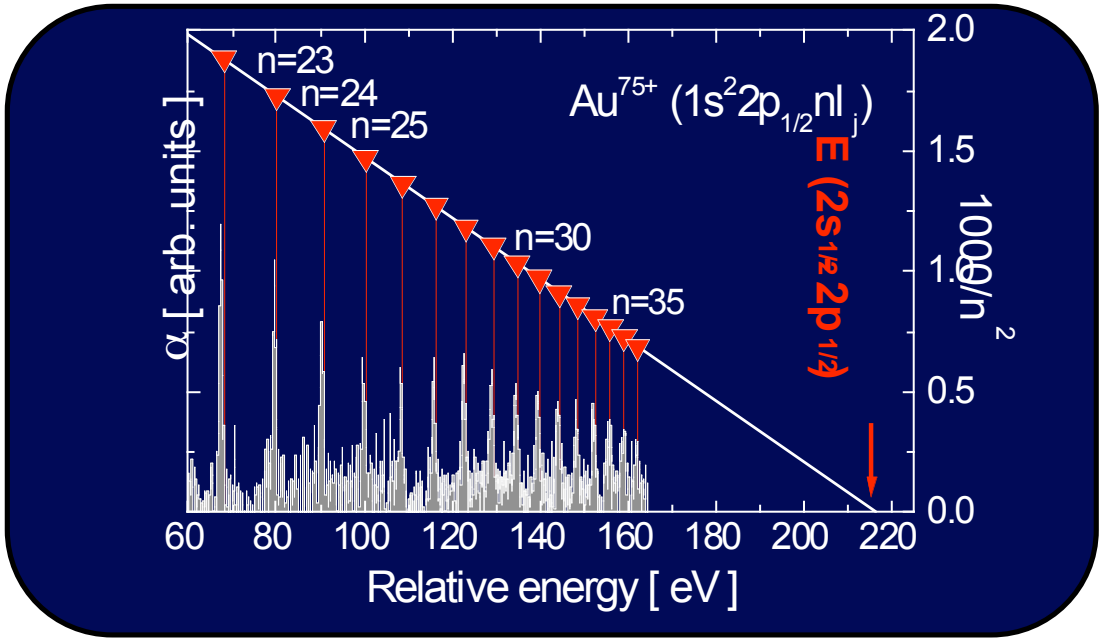


Electron transfer from electron beam into the HCI

$$A^{q+} + e \rightarrow A^{(q-1)+}$$

Determination of $2s_{1/2}$ - $2p_{1/2}$ Splitting





$$E_{kin}(e^-) = (E_{2p} - E_{2s}) - E_n$$

- fine structure of peaks (Rydberg – core e-e interact.)
- relativisitc description of Rydberg electron (Dirac)
- apparaus function (velocity spread of electrons)

Au^{76+}
216.167(29)(67) eV

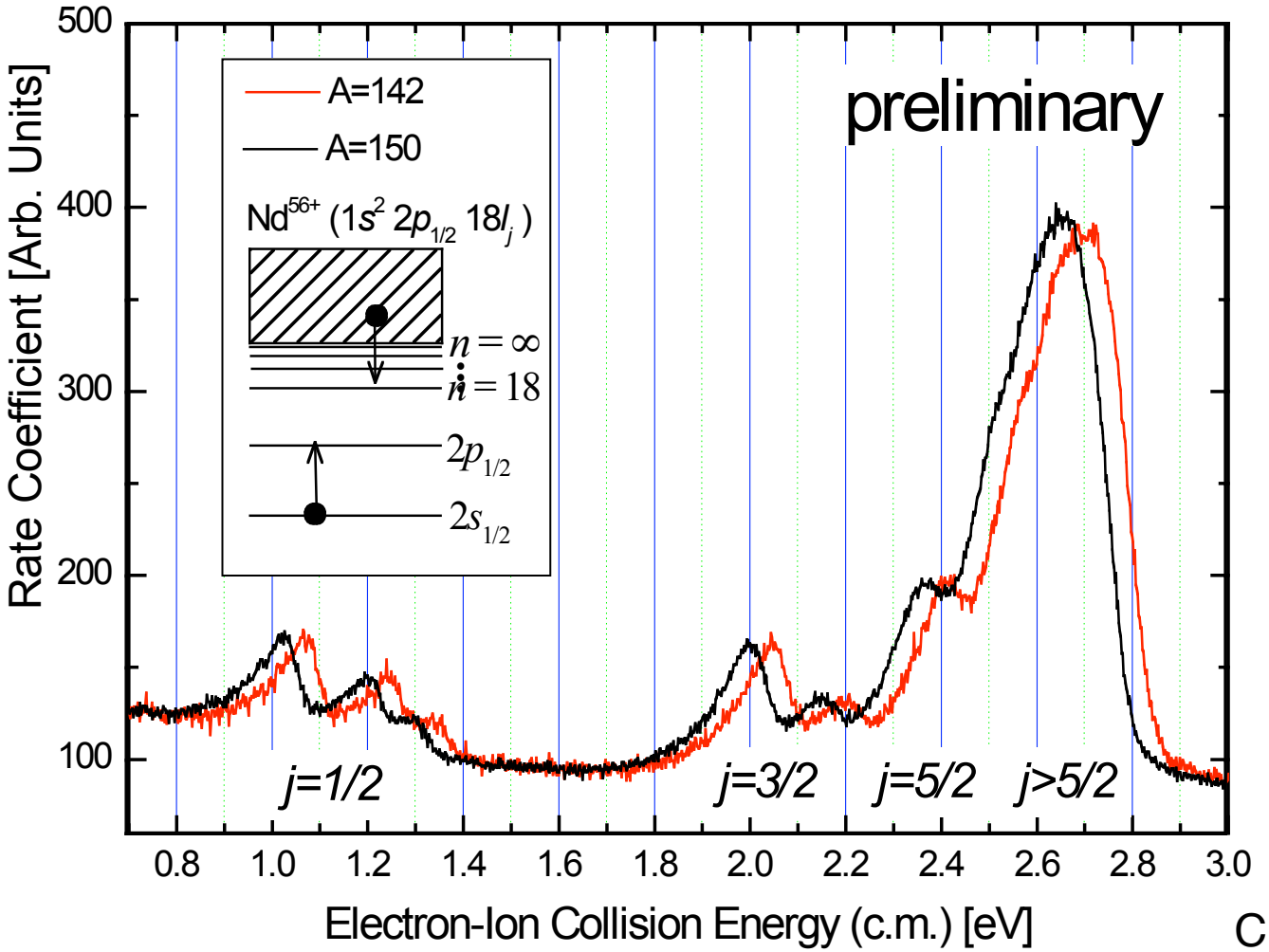
Pb^{79+}
230.650(30)(51) eV

U^{89+}
280.516(34)(65) eV

C. Brandau et al., Phys. Rev. Lett 91, (2003) 073202

Isotopic Shift of Li-like $^{142}Nd^{57+}$ vs. $^{150}Nd^{57+}$

First preliminary results of the Aug 2005 beamtime



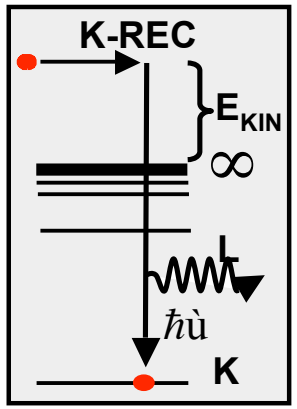
$^{142}Nd^{57+}$

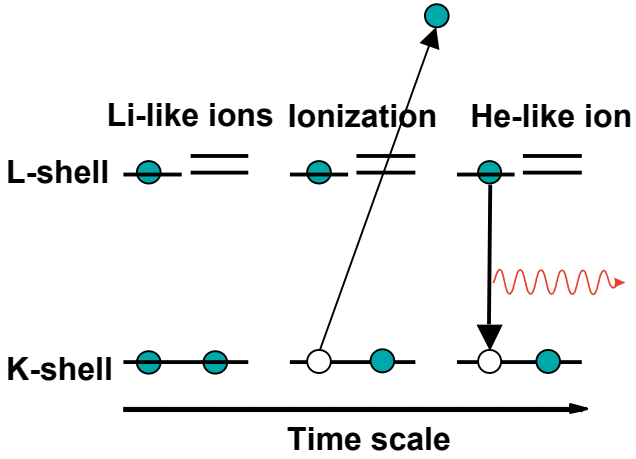
$^{150}Nd^{57+}$

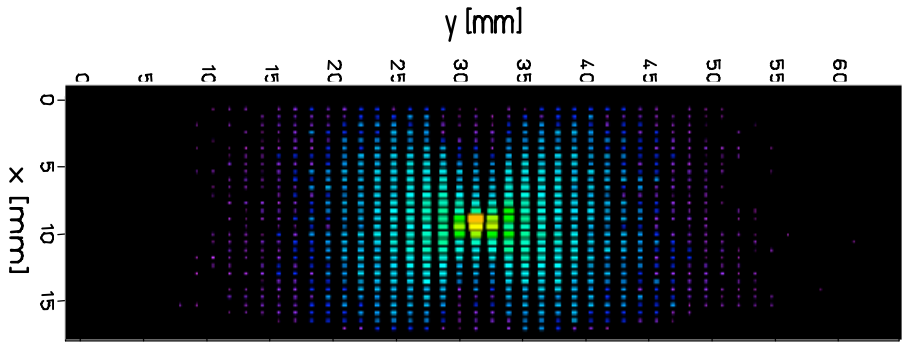
C. Brandau et al.

Dynamics

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



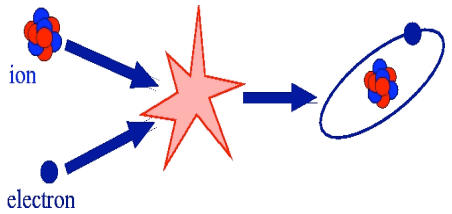




Dynamics

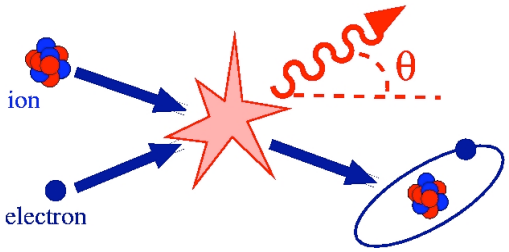
Established

- **Total Electron Capture Cross Sections**



$$\sigma \sim \sum_{polariz.} \mathrm{d}\Omega |M|^2$$

- **Photon Angular Distributions**



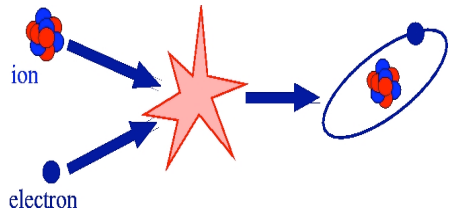
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta) \sim \sum_{polariz.} \mathrm{d}\Omega |M|^2$$

Dynamics

Established

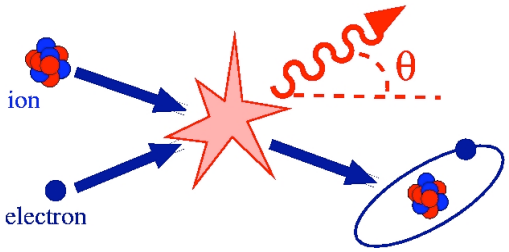
New Directions

- **Total Electron Capture Cross Sections**



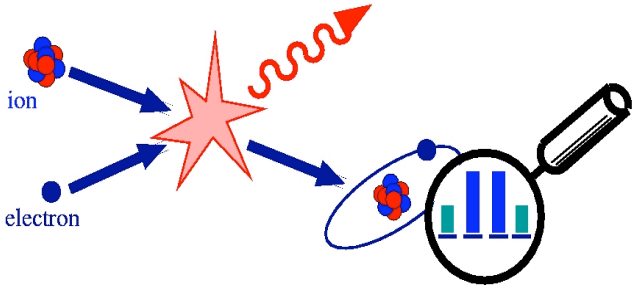
$$\sigma \sim \sum_{polariz.} \mathrm{d}\Omega |M|^2$$

- **Photon Angular Distributions**

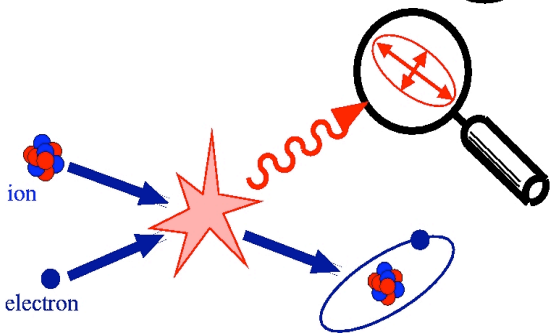


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta) \sim \sum_{polariz.} \mathrm{d}\Omega |M|^2$$

- **Alignment**



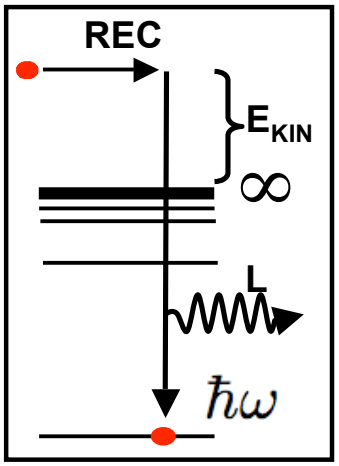
- **Polarization**

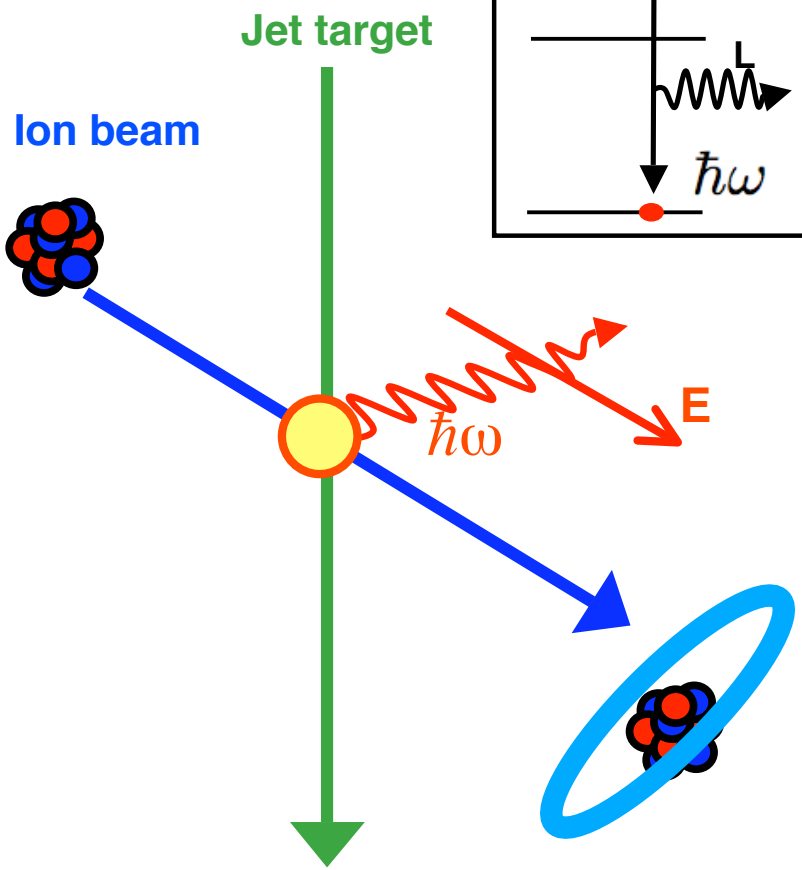


$$\sim |M|^2$$

No summation over polarization states !

Polarized photon emission

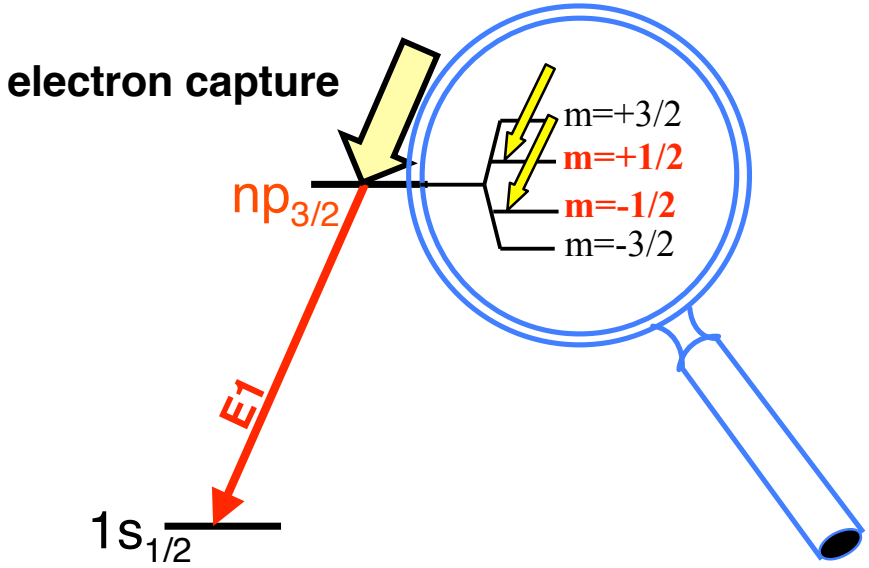




Polarization of the emitted photon due to:

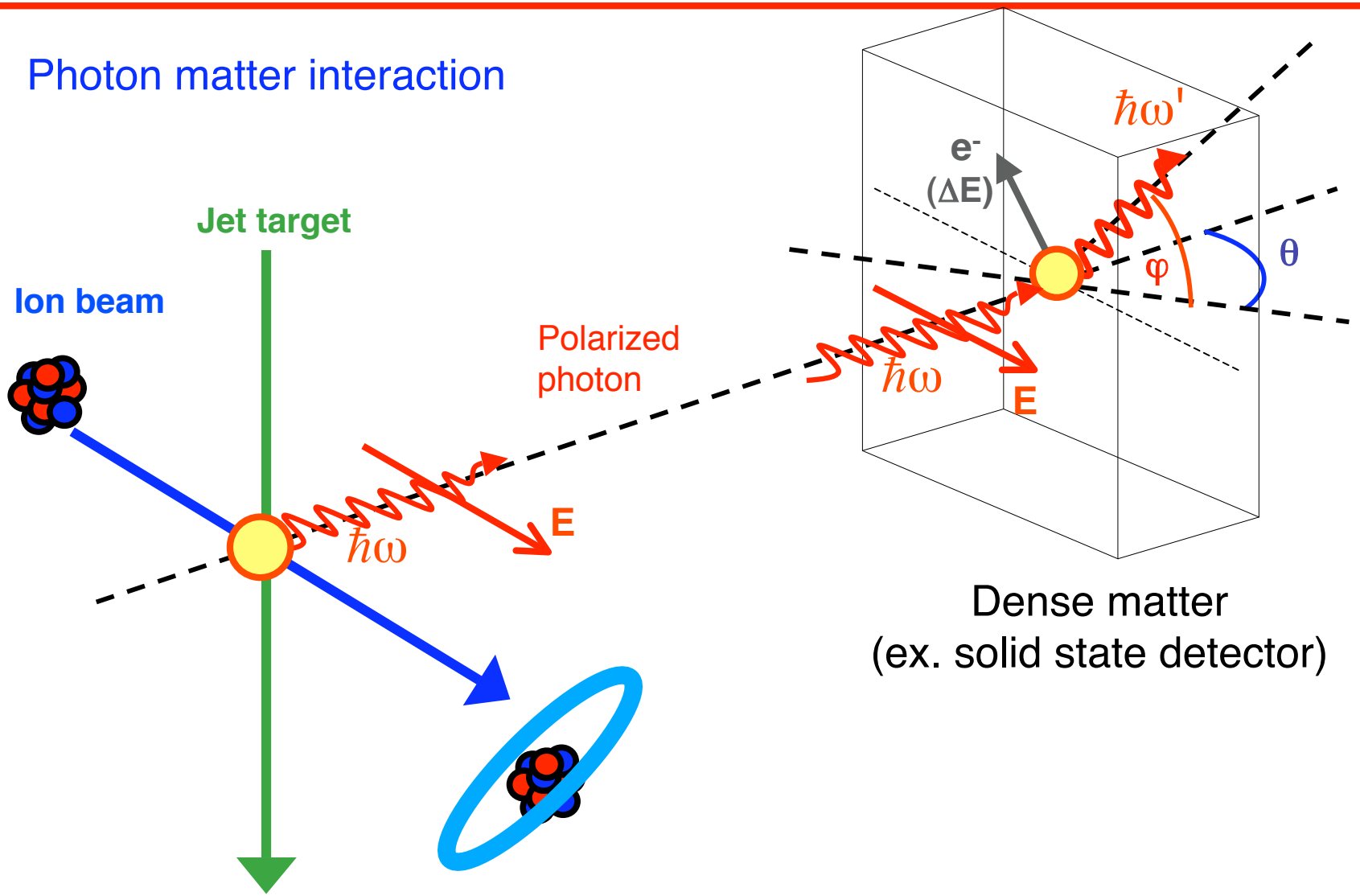
- **Recombination process (inverse than photoionization)**

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



Polarization detection

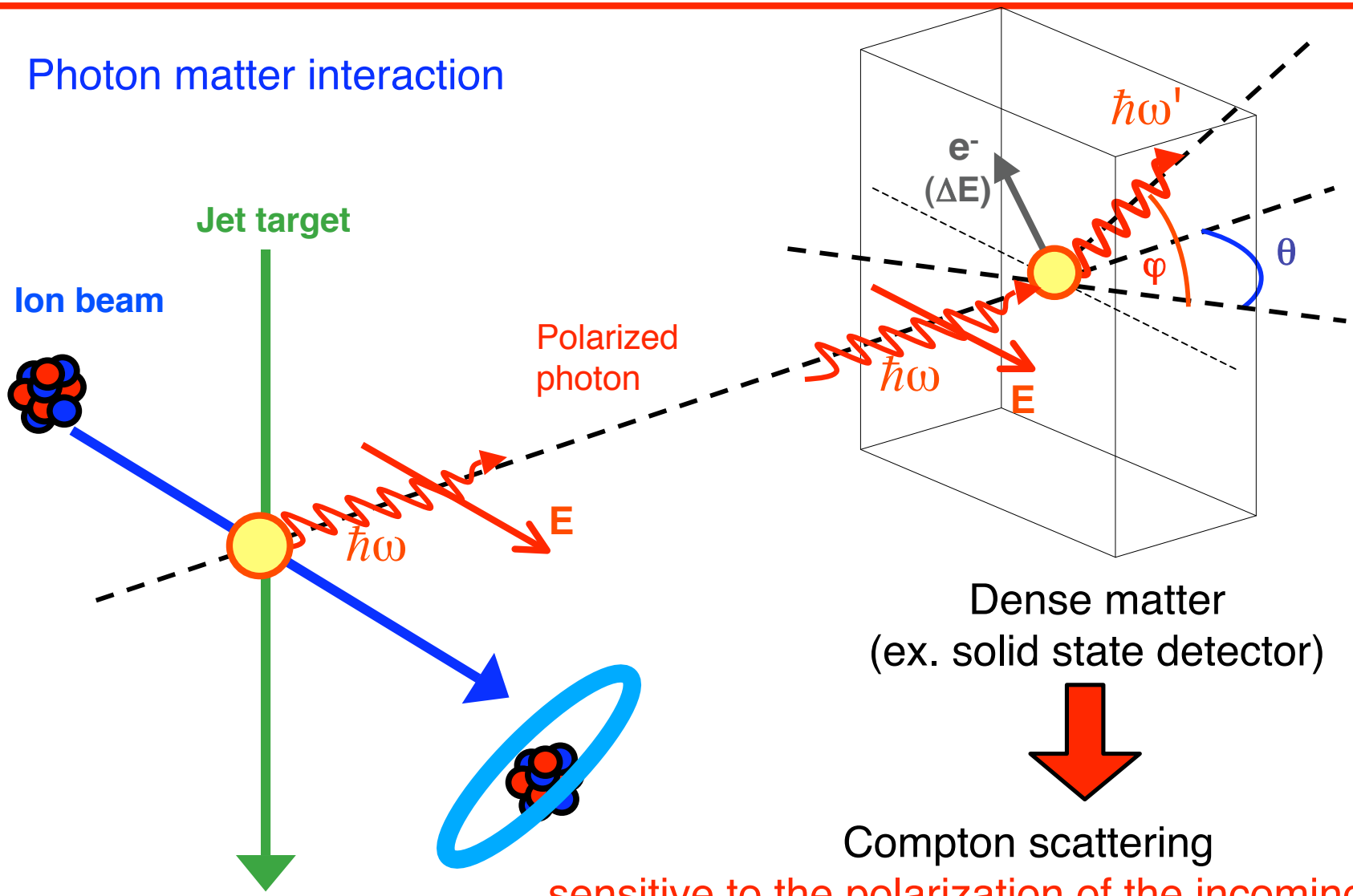
Photon matter interaction



Dense matter
(ex. solid state detector)

Polarization detection

Photon matter interaction



Dense matter
(ex. solid state detector)

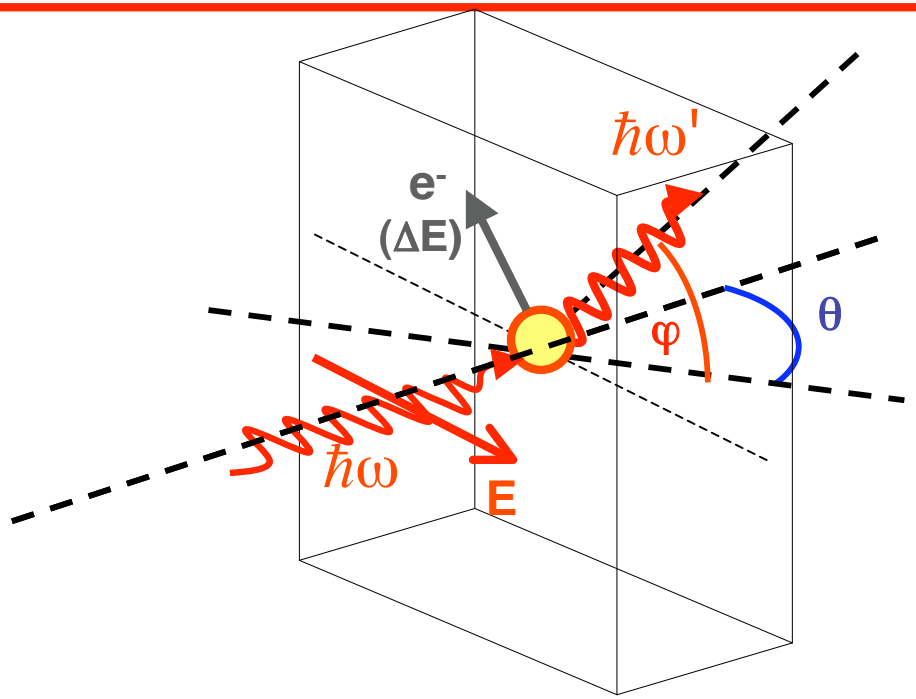
Compton scattering
sensitive to the polarization of the incoming photon

Polarization detection

Electron-photon scattering:

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

ΔE : electron recoil energy



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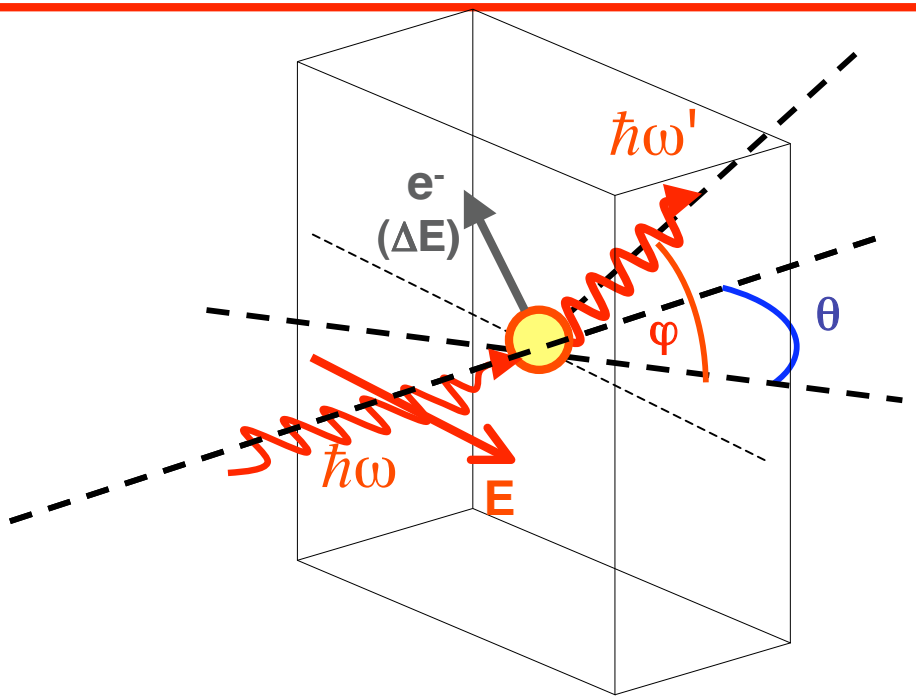
$$\hbar\omega' = \frac{\hbar\omega}{1 + (1 - \frac{\hbar\omega}{m_e c^2}\cos\theta)}$$



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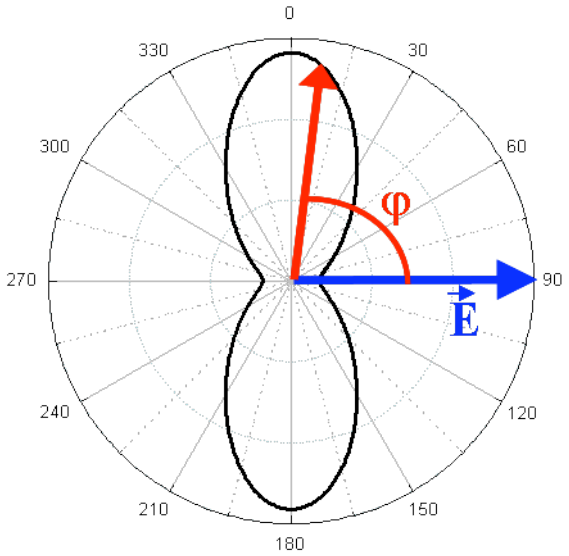
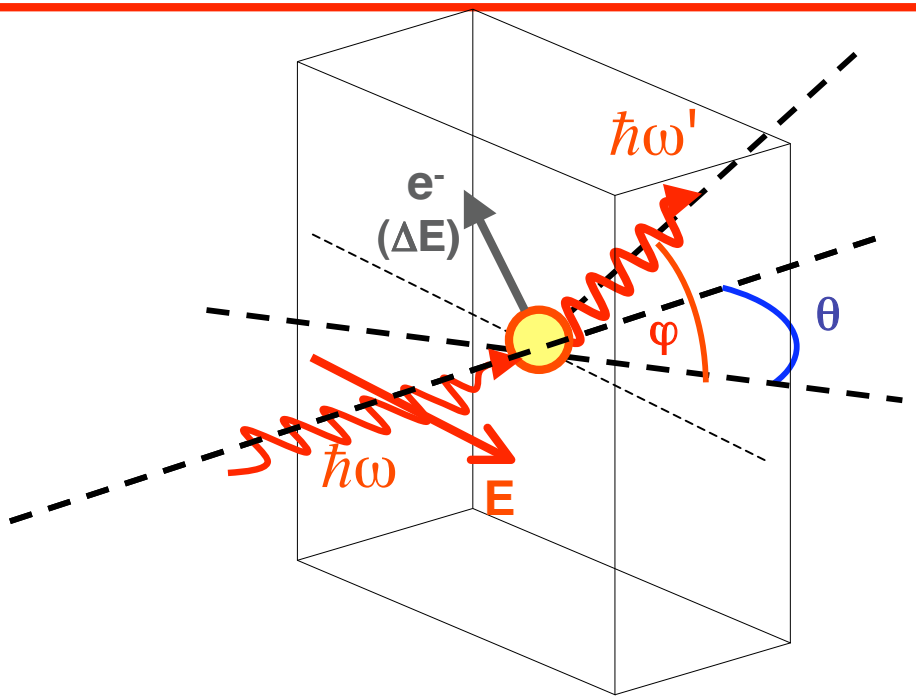


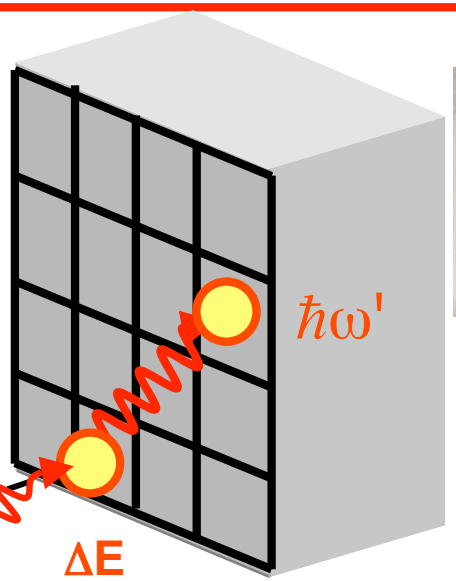


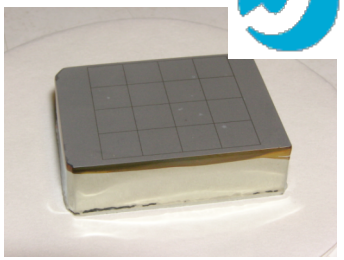
Klein-Nishina equation

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

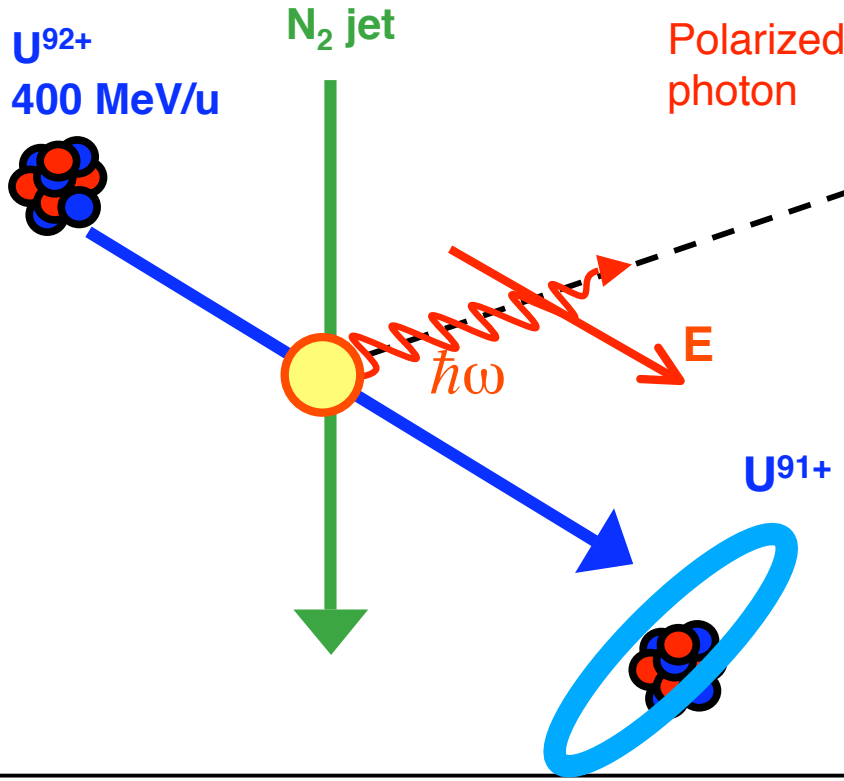
Ge pixel detector

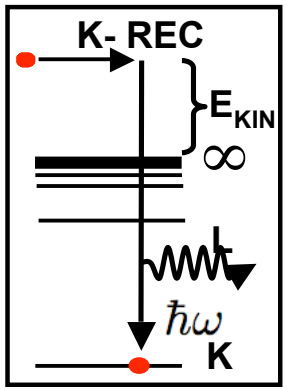
Polarization Measurement for Radiative Electron Capture Transitions ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)





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

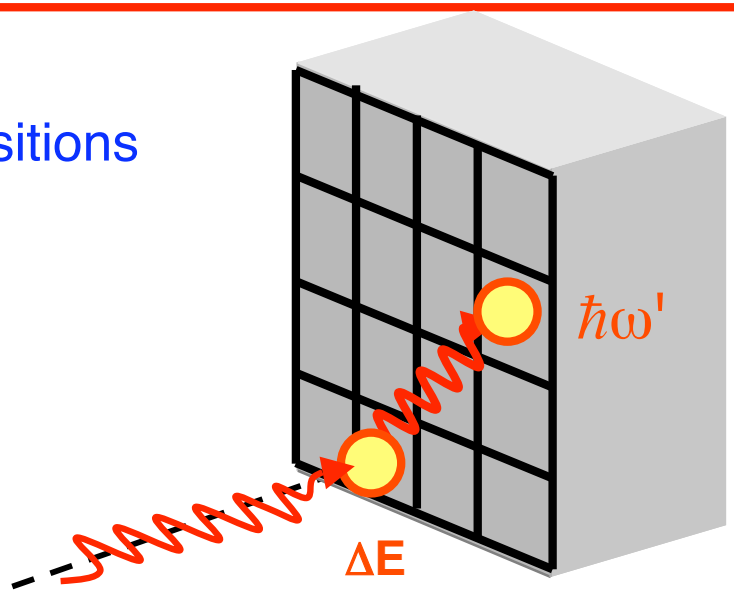


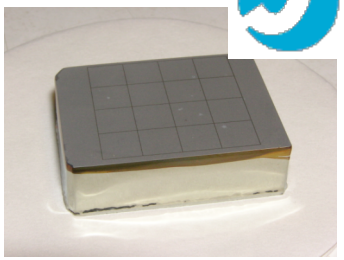


S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

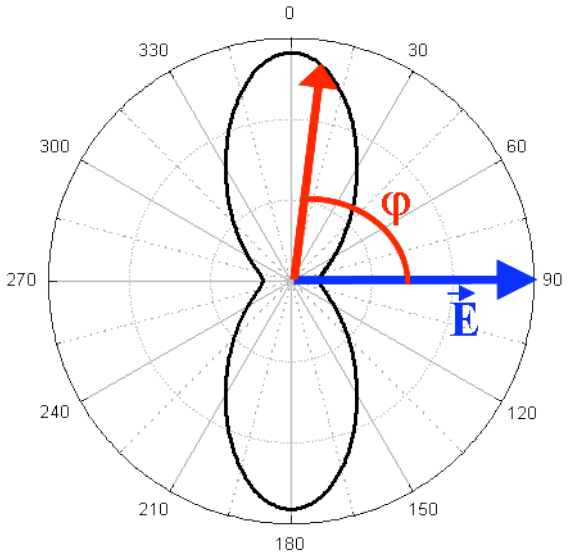
Ge pixel detector

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





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



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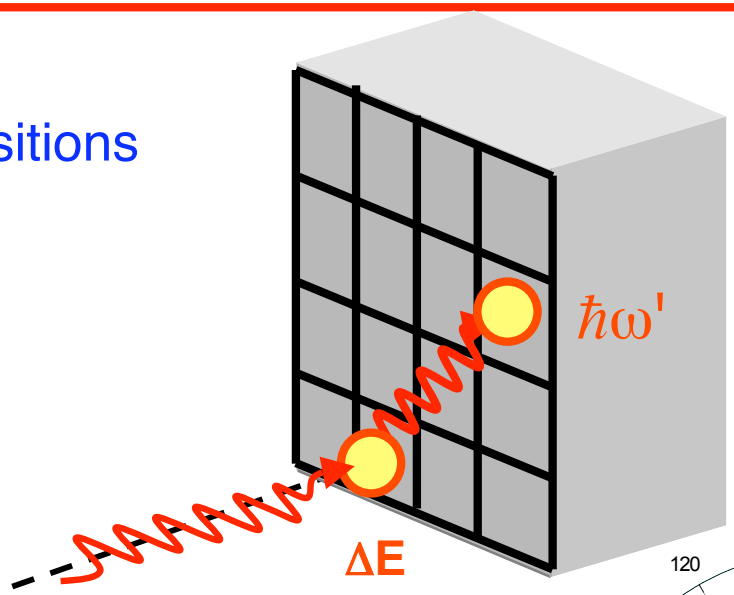
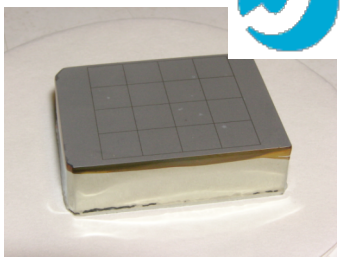
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

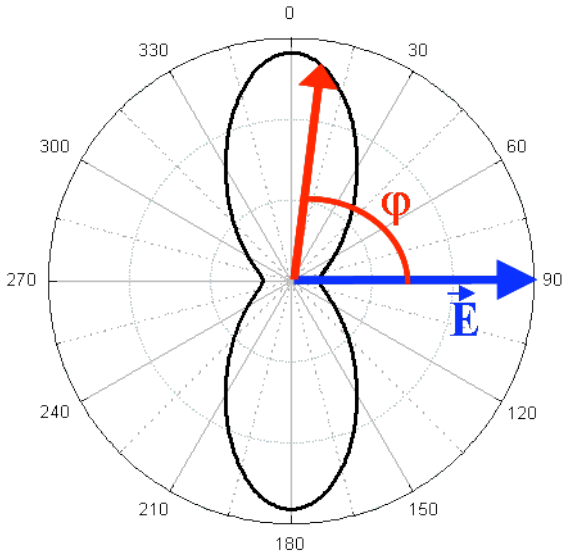
Ge pixel detector

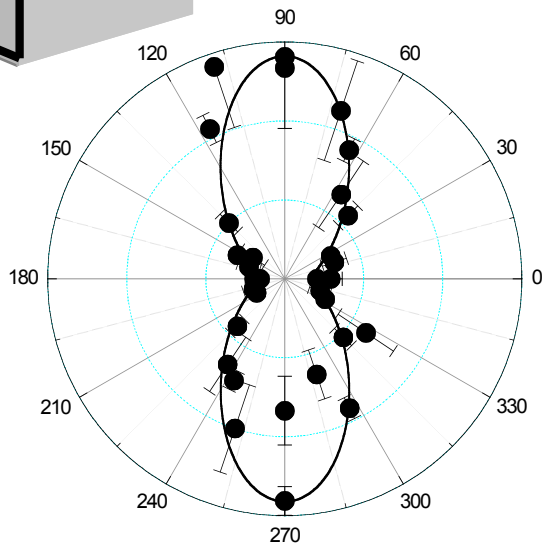
Polarization Measurement for Radiative Electron Capture Transitions ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)





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

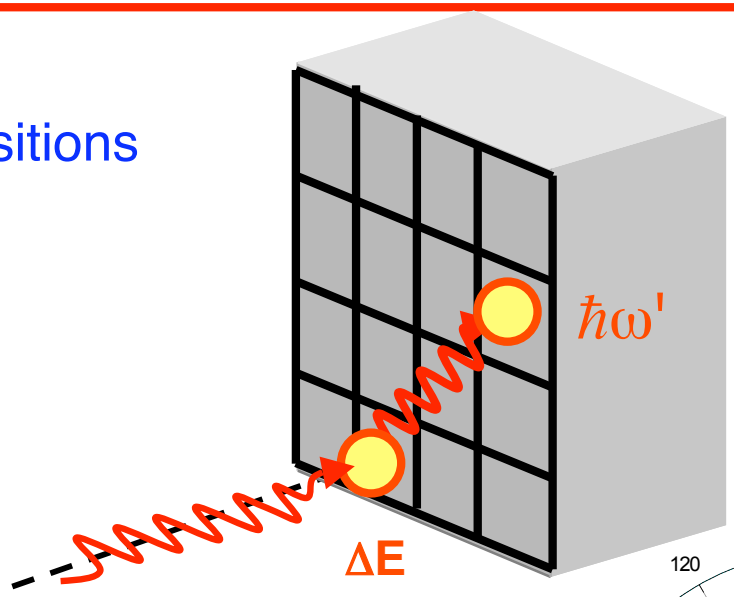


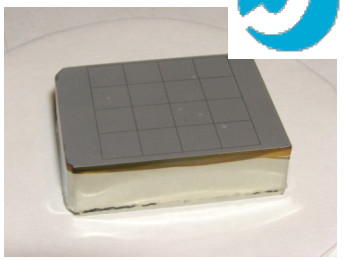


S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

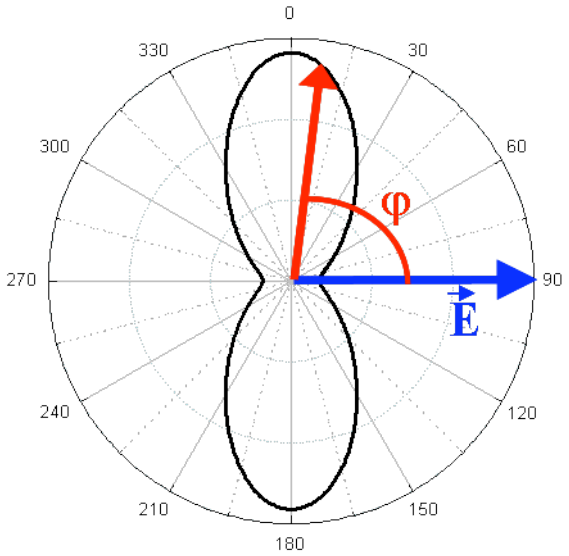
Ge pixel detector

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

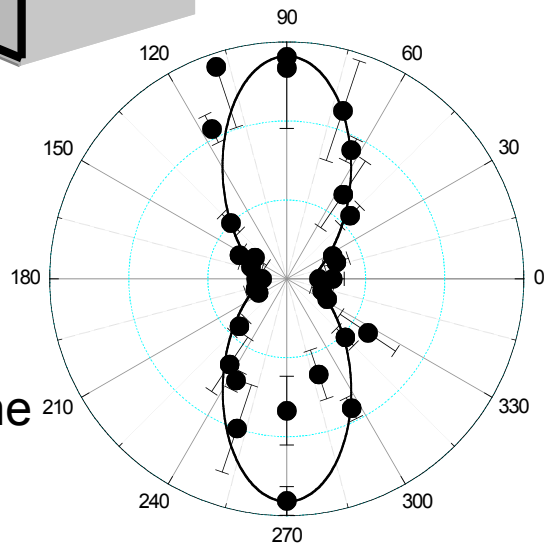




4X4 Ge detector
(24 X 24 $mm^{2)}$



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



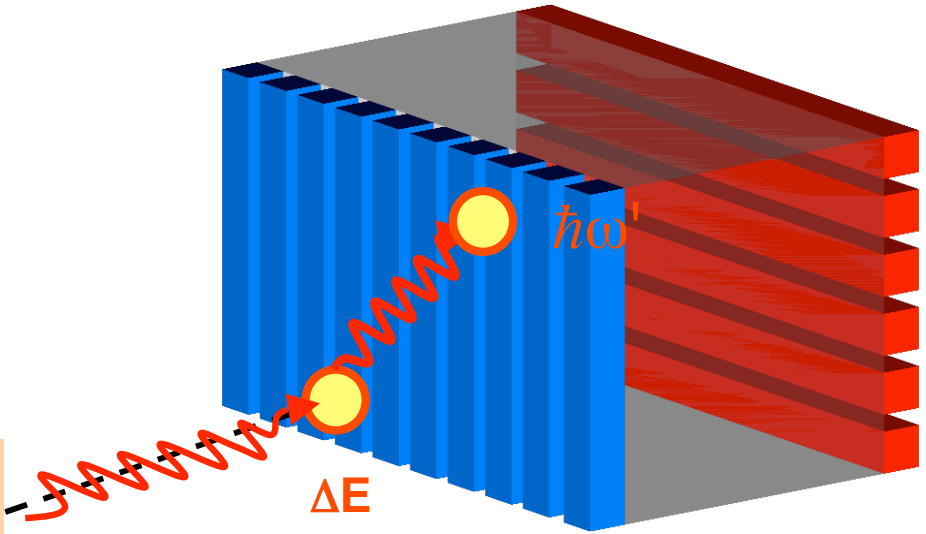
S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

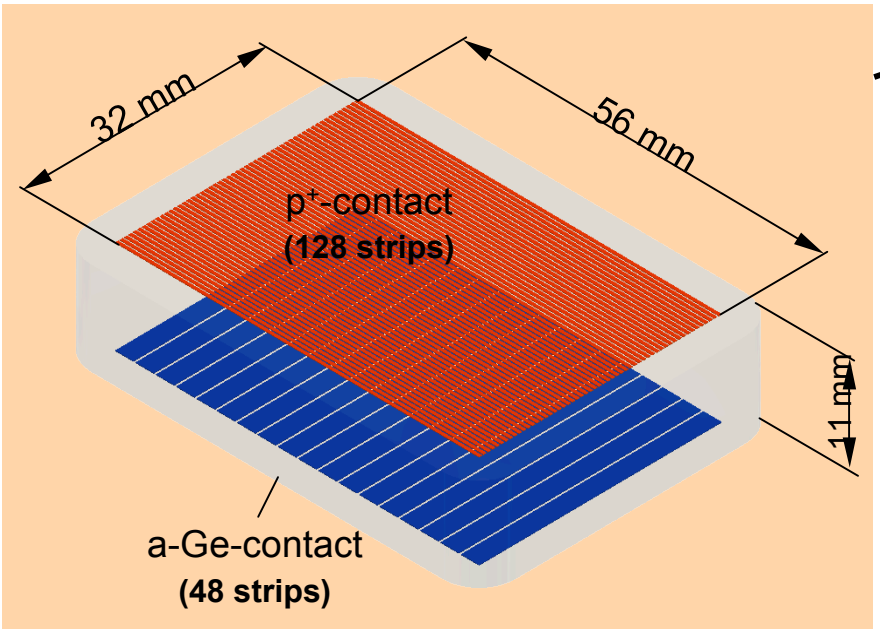
Ge 2D segmented detector

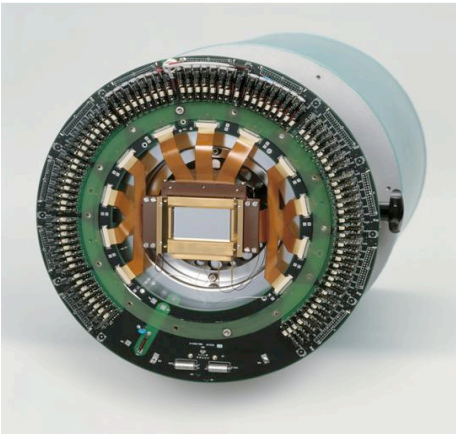
Front: 128 strips pitch ~250μm

Back: 48 strips pitch ~1167μm

Equivalent to 6144 pixel

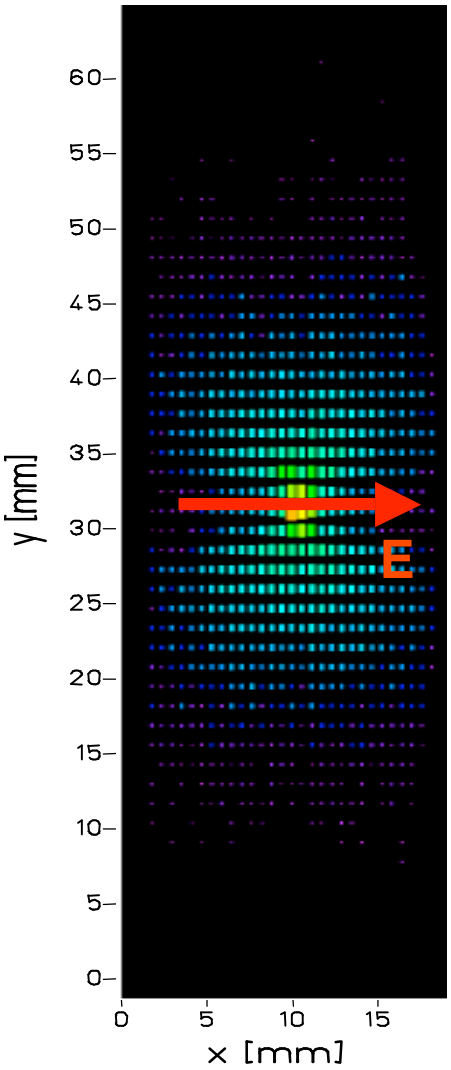




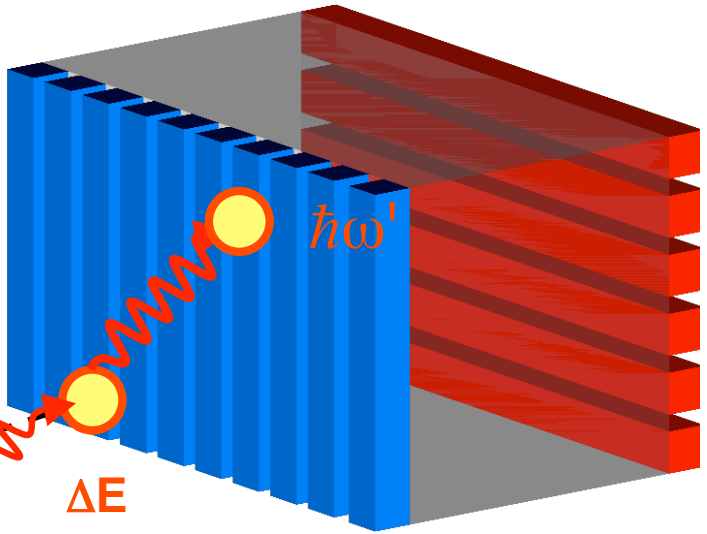


Ge 2D segmented detector

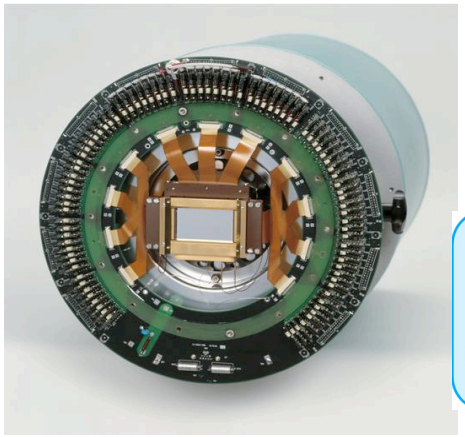
Experiment



98% Polarized
photon
E=210 keV



ESRF

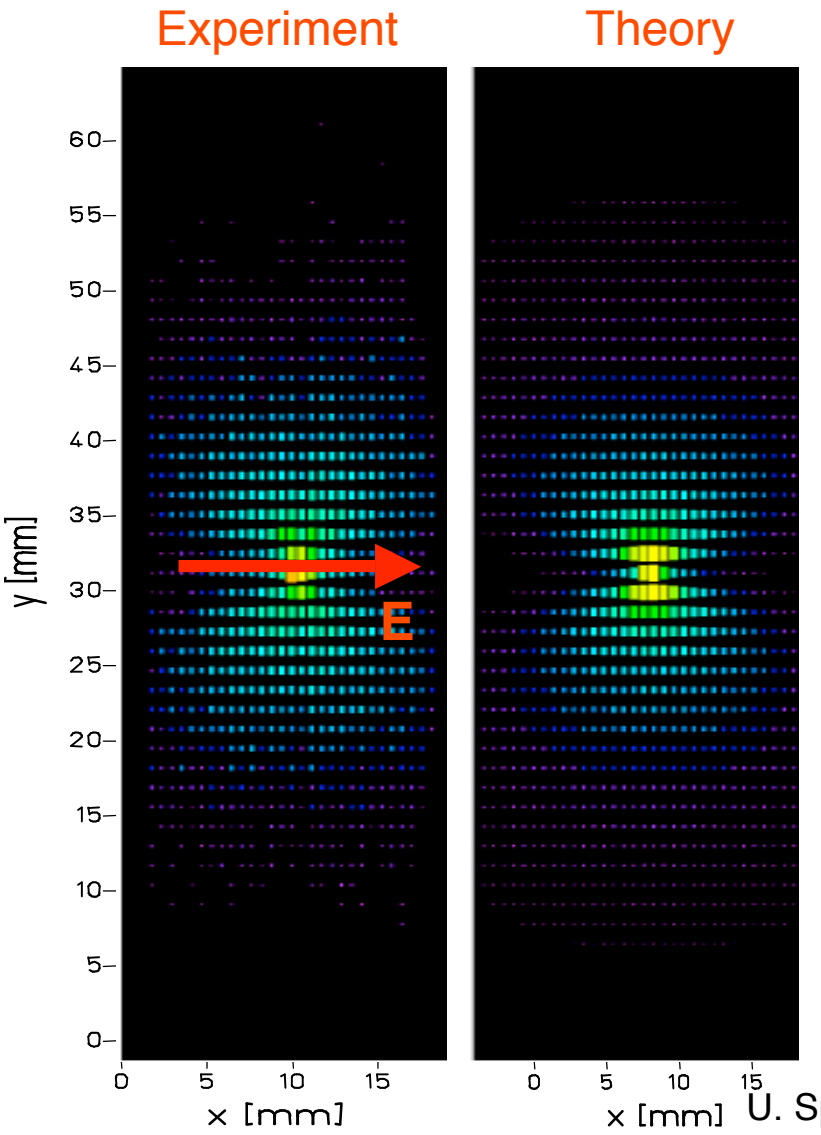


2D μSTRIP germanium detector

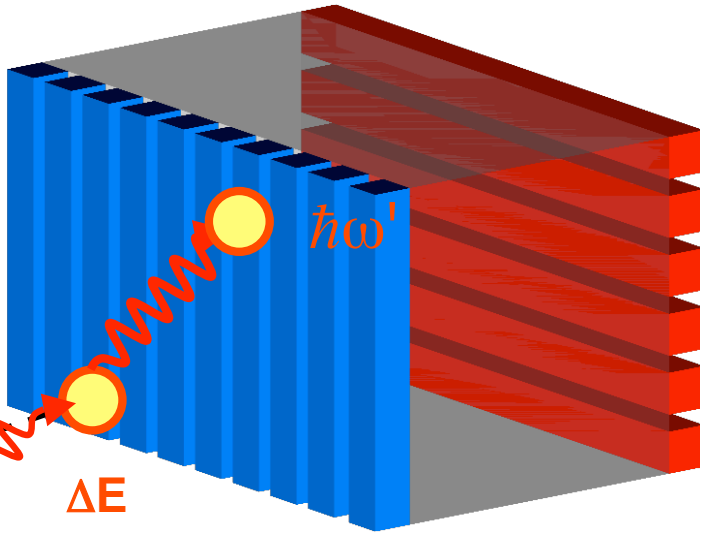
-GSI

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

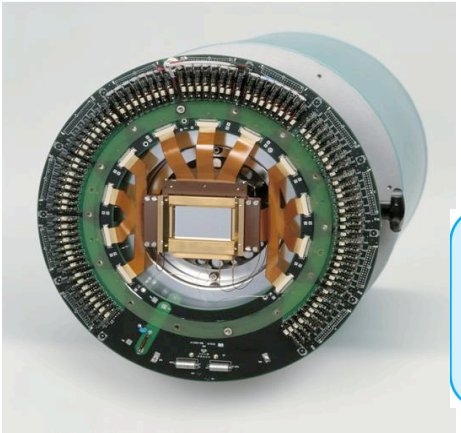
Ge 2D segmented detector



98% Polarized photon
E=210 keV



ESRF

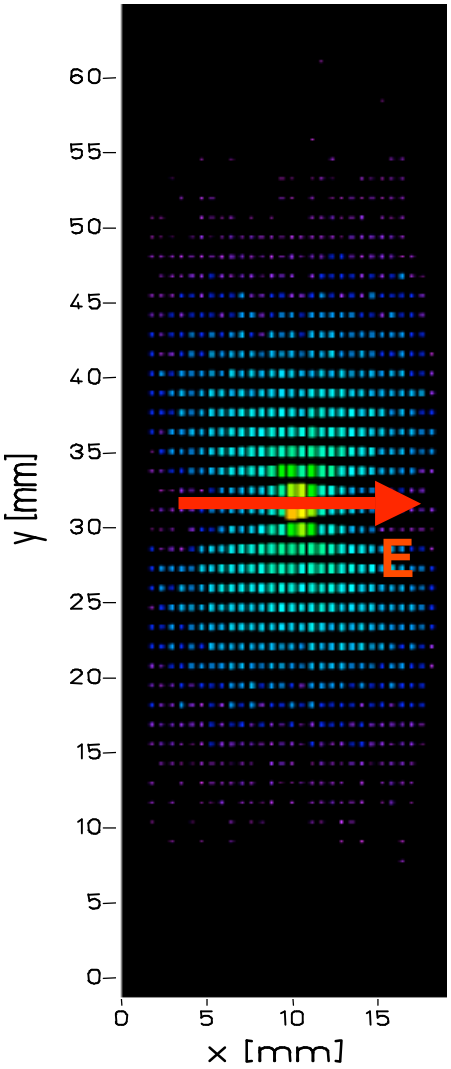


2D μSTRIP germanium detector

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

Detection of the ion beam polarization

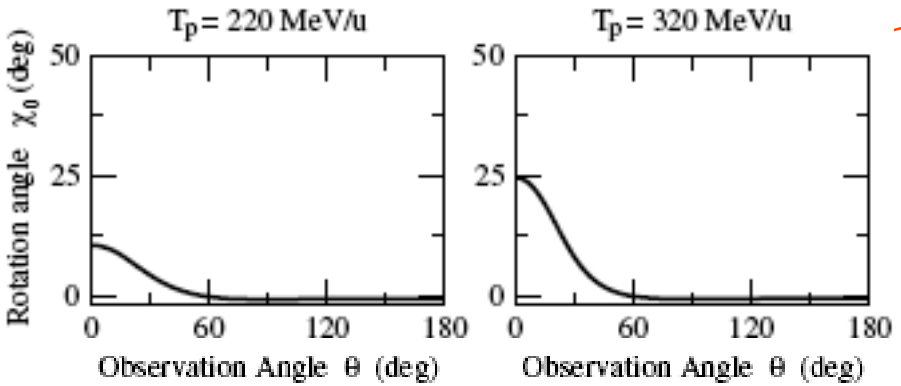
Non-polarized



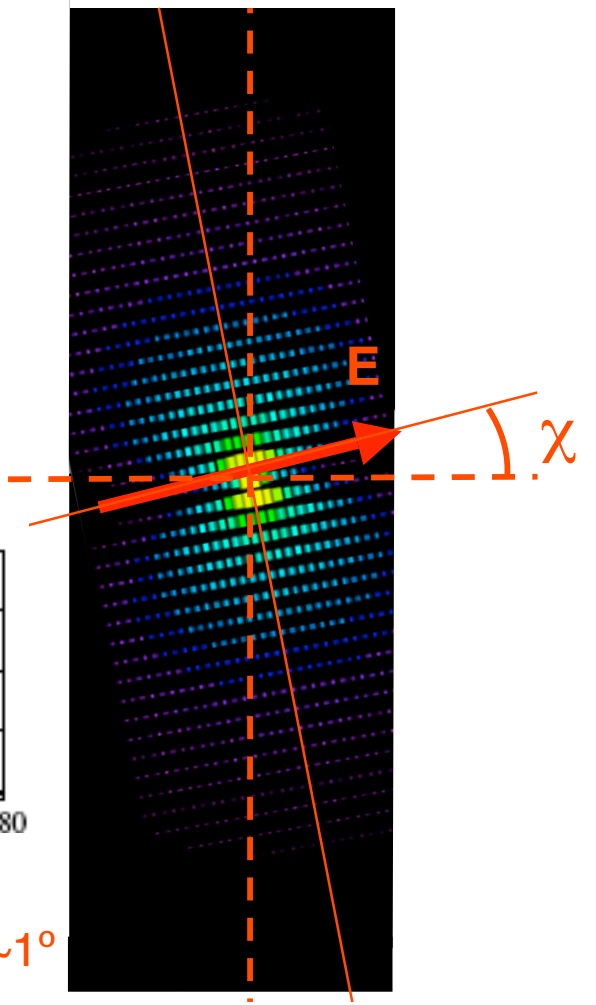
Polarized ion beam

Rotation of the photon polarization

$$\chi \propto \arctan\left(\sum_{m_F} n_{m_F} m_F\right)$$



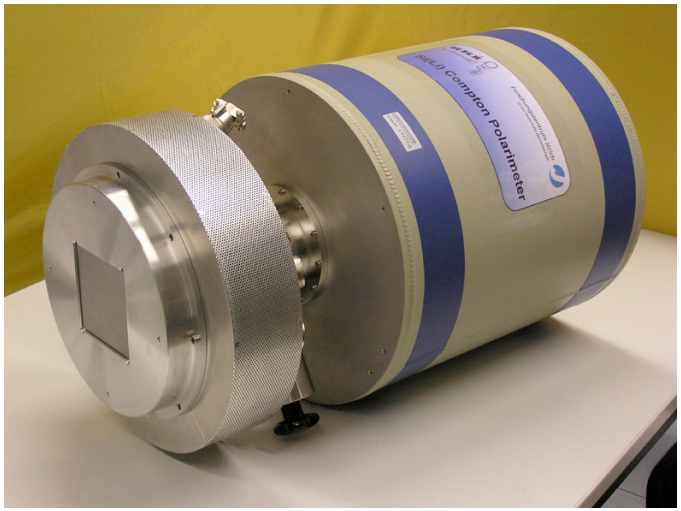
Polarized

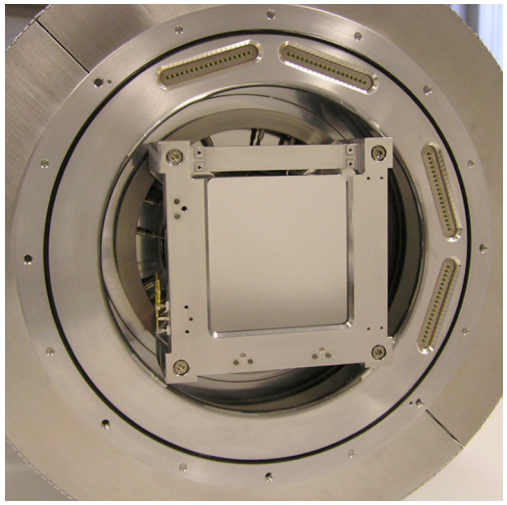


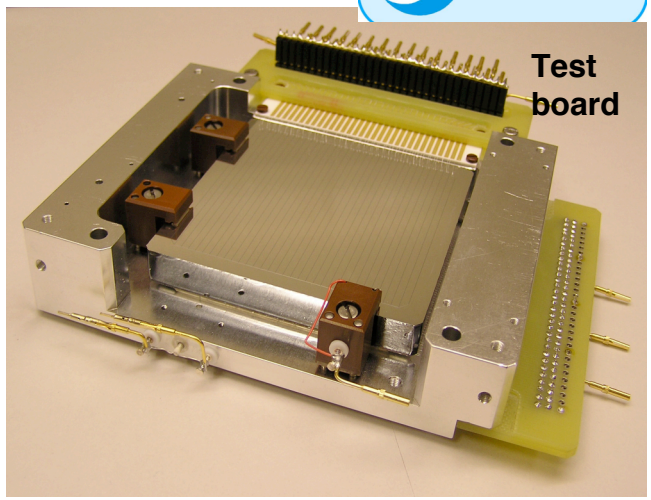
Expected accuracy: $\Delta\chi \sim 1^{o}$

Surzhykov *et al.*, Phys. Rev. Lett. **94**, 203202-4 (2005).

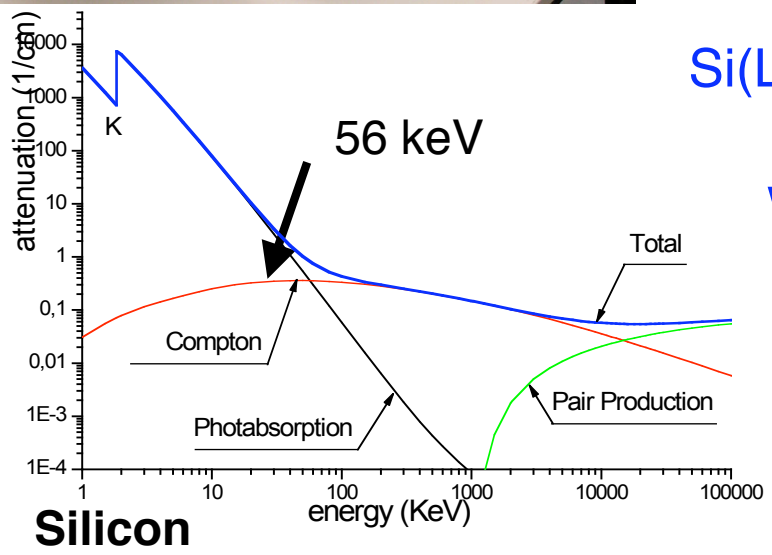
2D/3D Si(Li)-Detector for Compton Polarimetry







crystall size: 4" x 4"



Si(Li) based Compton polarimeter will be available this year !

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

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

Conclusions

New QED tests with HCI

- 1s Lamb shift (FOCAL spectrometer, microcalorimeter)
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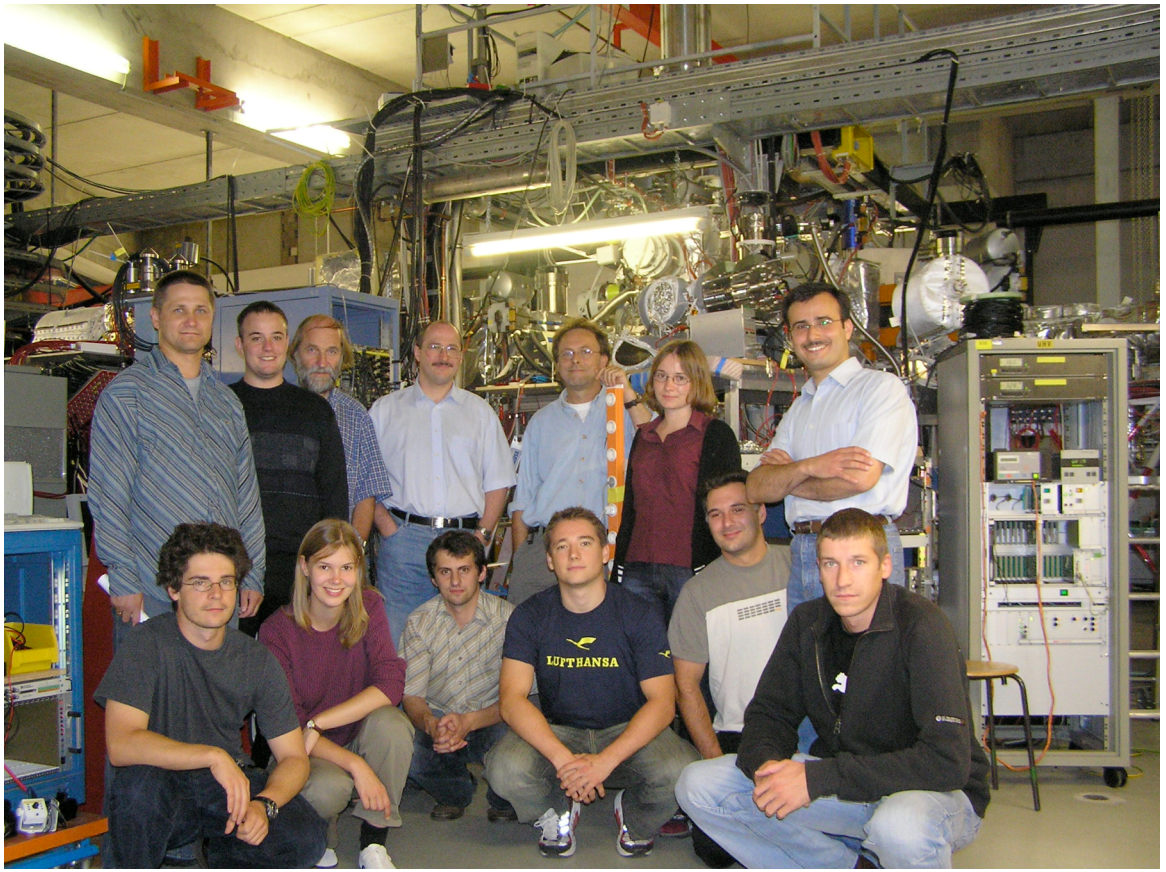
Ion-atom collision

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

New instruments ready for FAIR!!

Our group

Thomas Stöhlker Group

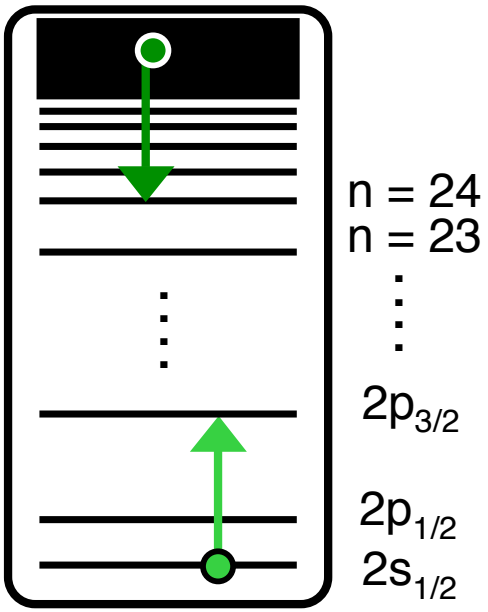


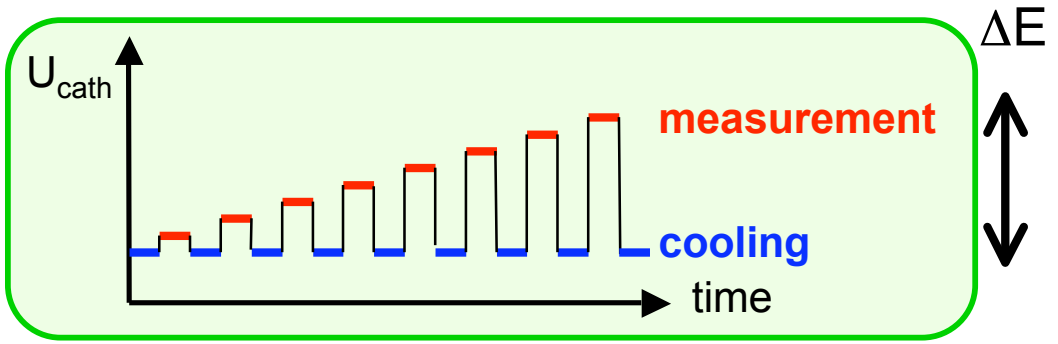
The speaker's attendance at this conference was sponsored by the Alexander von Humboldt Foundation.

► http://www.humboldt-foundation.de

Other material

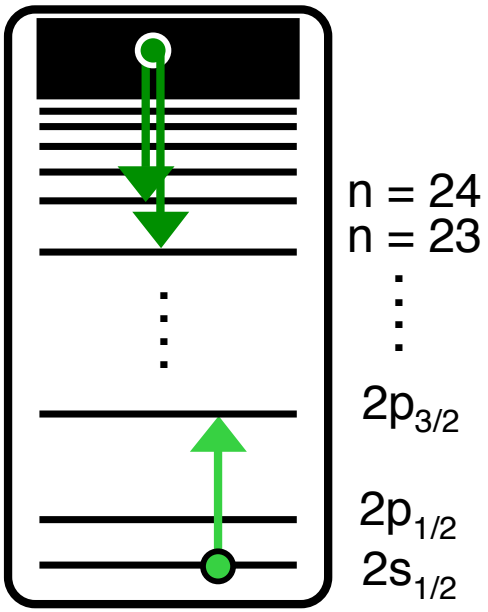
Determination of $2s_{1/2}$ - $2p_{1/2}$ Splitting

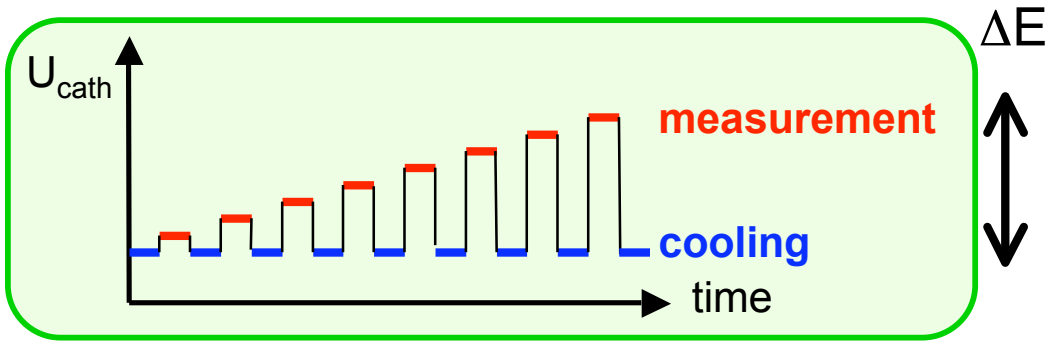




$$\Delta E = eU_{cath} = (E_{2p} - E_{2s}) - E_n$$

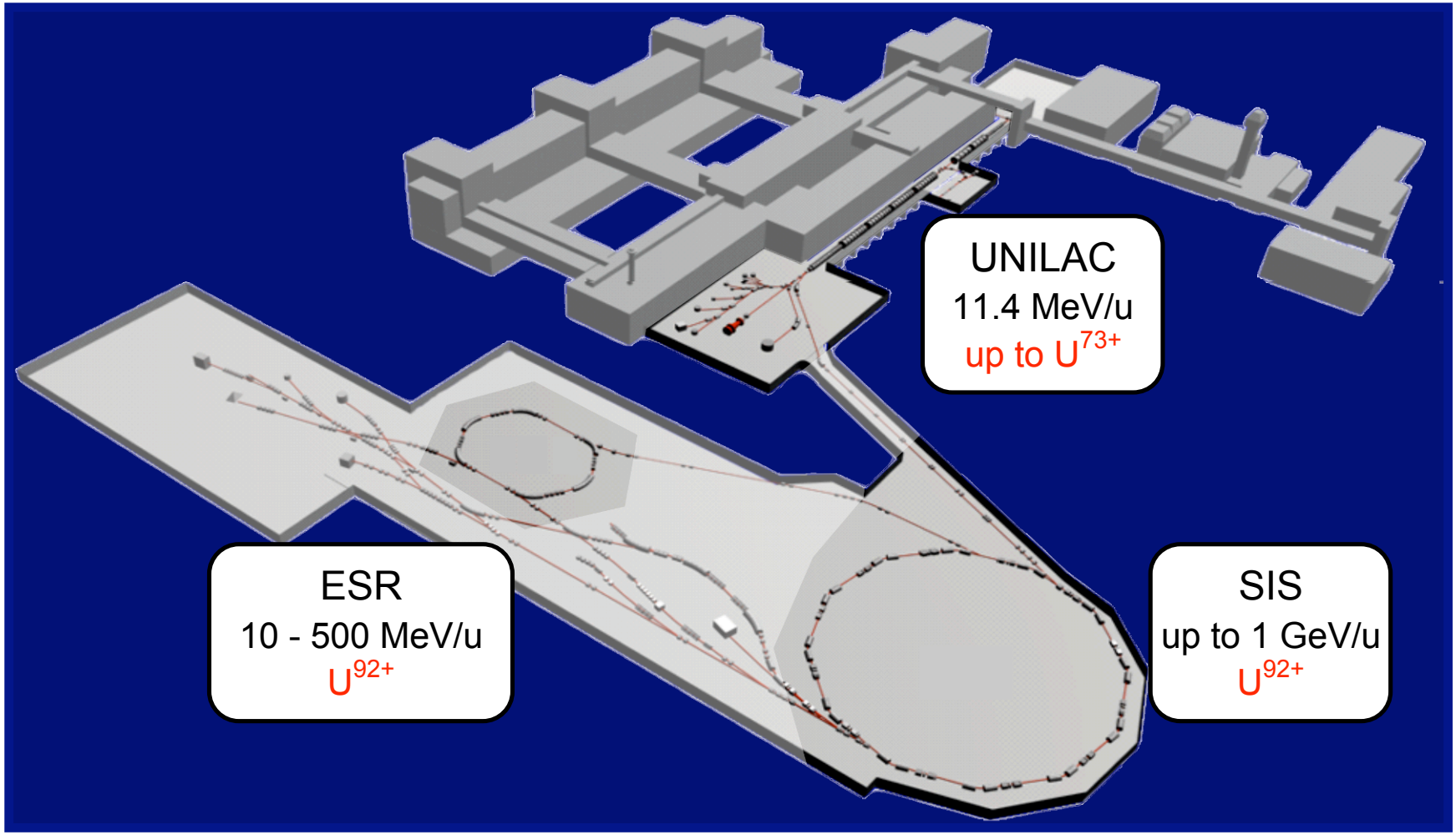
Determination of $2s_{1/2}$ - $2p_{1/2}$ Splitting



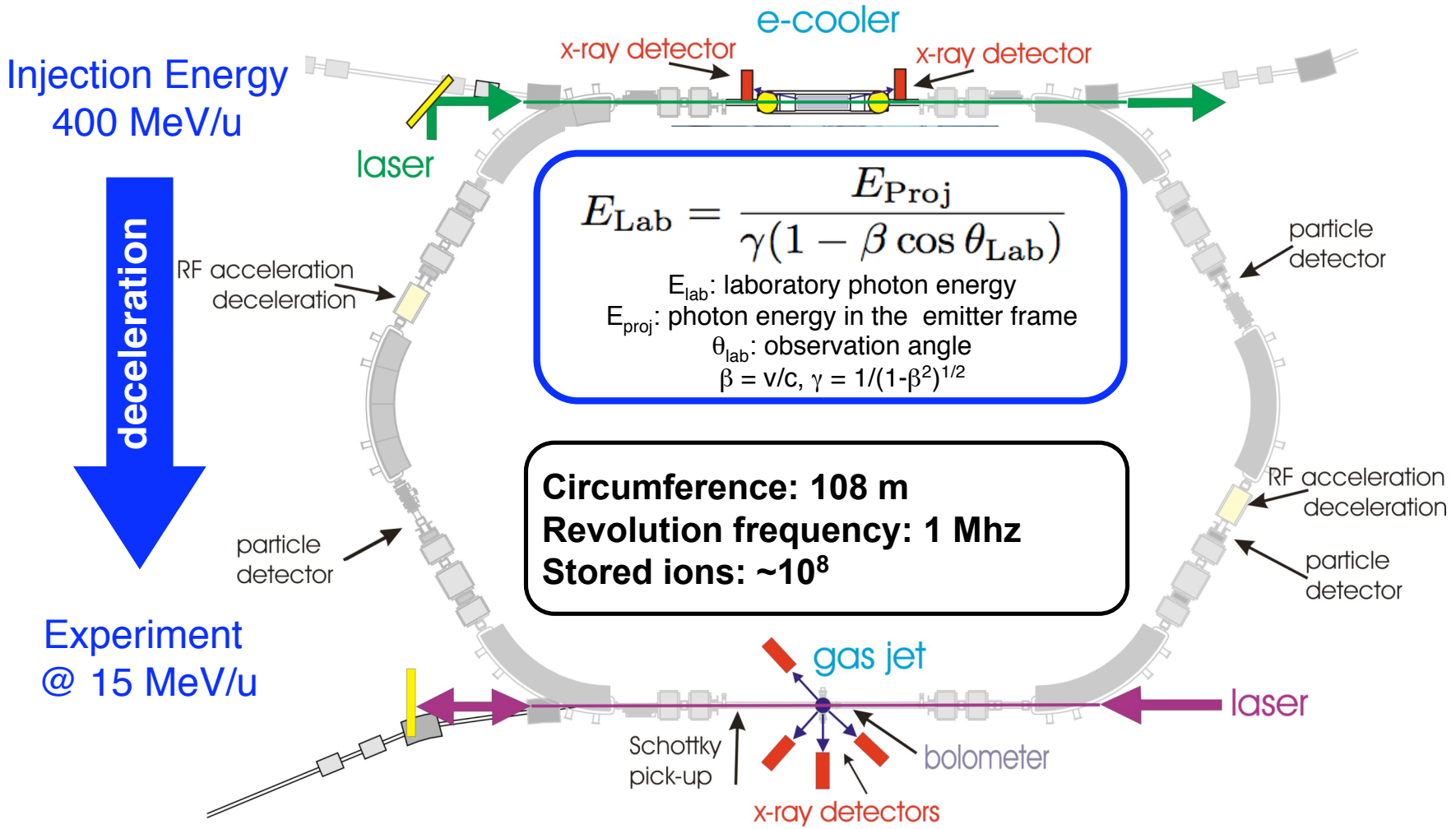


$$\Delta E = eU_{cath} = (E_{2p} - E_{2s}) - E_n$$

GSI Facilities

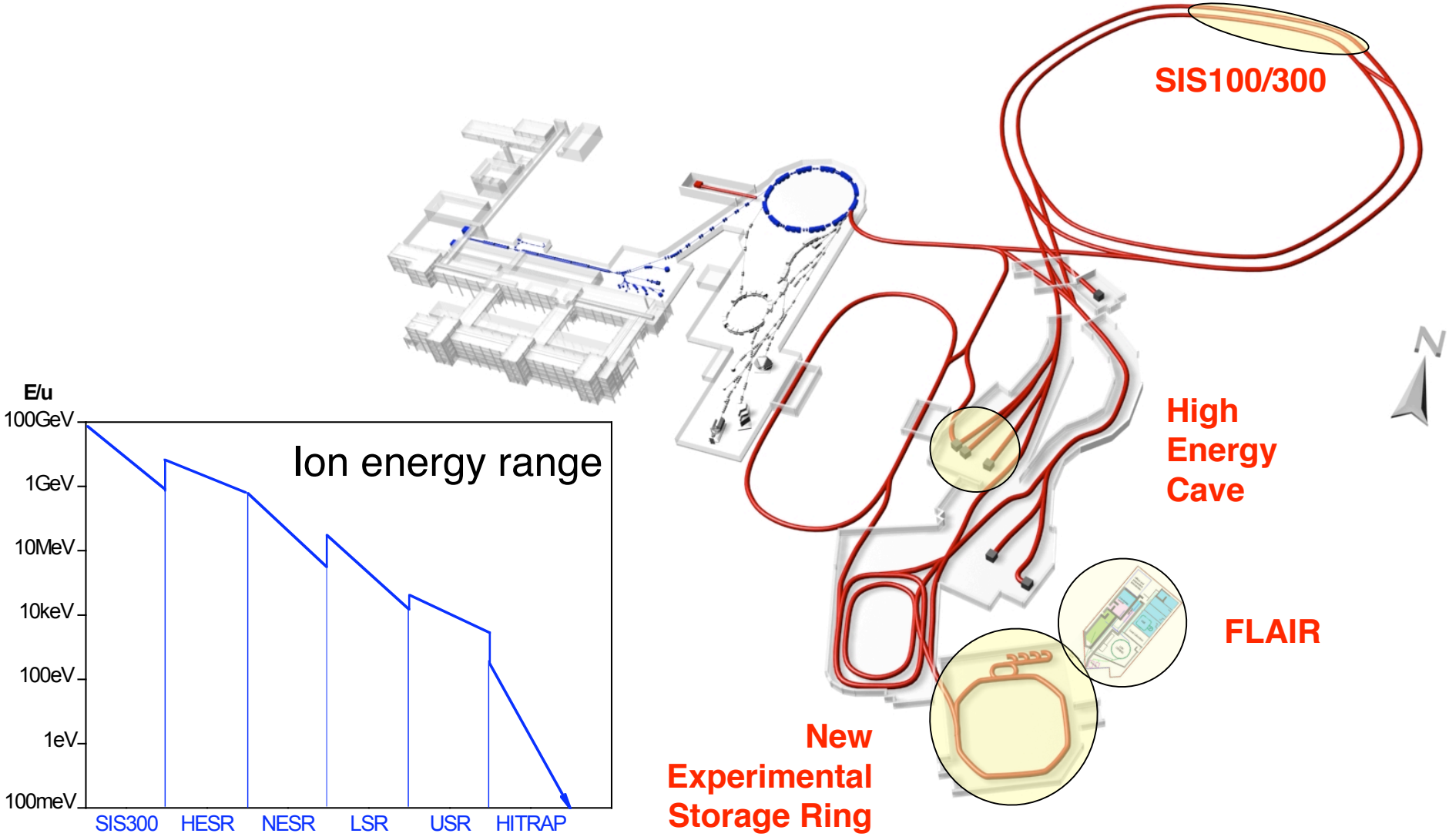


X-ray spectroscopy at the ESR storage ring



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

FAIR Facilities



New Experimental Storage Ring

Instrumentation

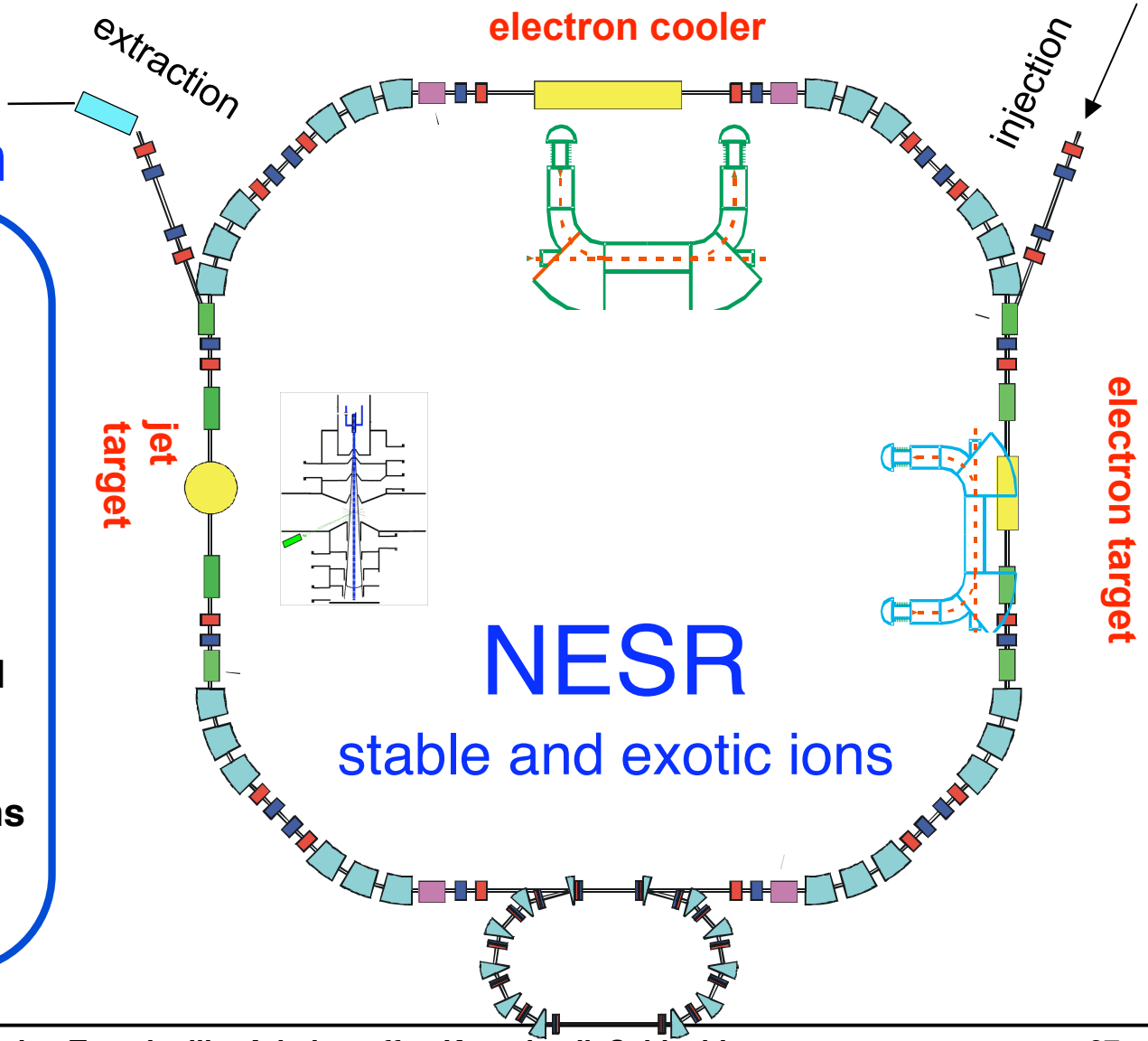
Ultracold electron target

Internal Target (atomic, cluster, micro-cluster)

In-Ring Recoil Momentum Microscope

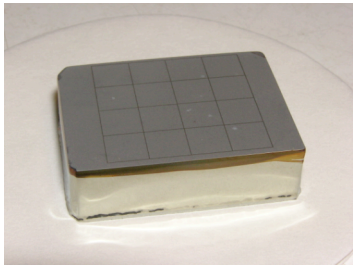
High Resolution X-Ray and Electron Spectrometers

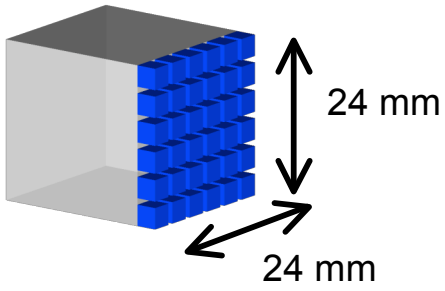
Highly Intense Laser Beams



New instruments: large position sensitive Ge detector

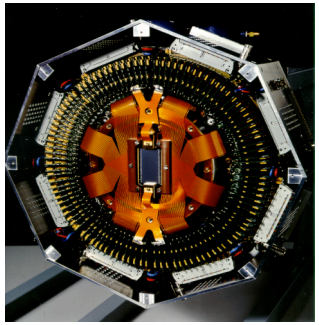
pixel detectors

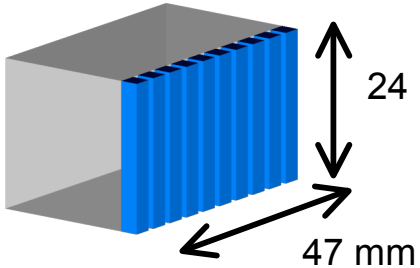




16 pixels

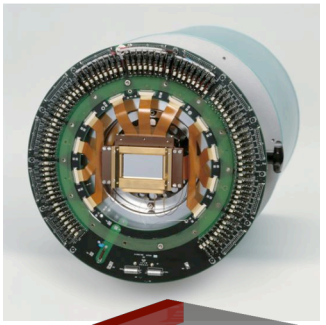
1D μ-strip detectors

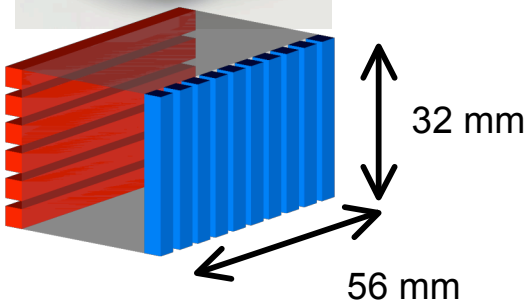




200 strips

2D μ-strip detectors



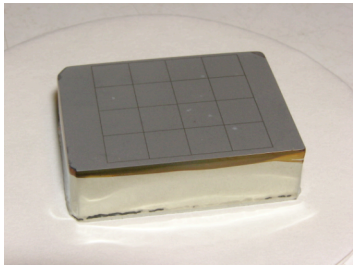


48 X 128 strips
equivalent to 6144 pixels

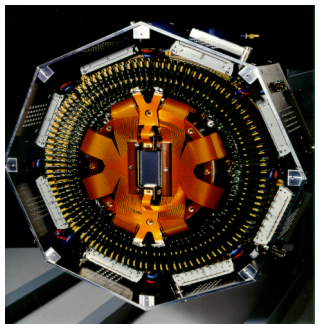
2D μ-strip Si(Li) detector arriving soon...

New instruments: large position sensitive Ge detector

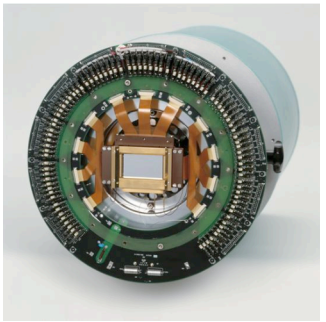
pixel detectors

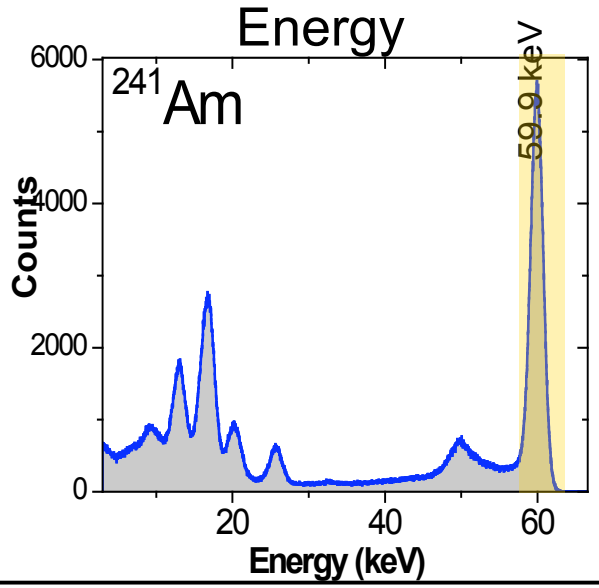


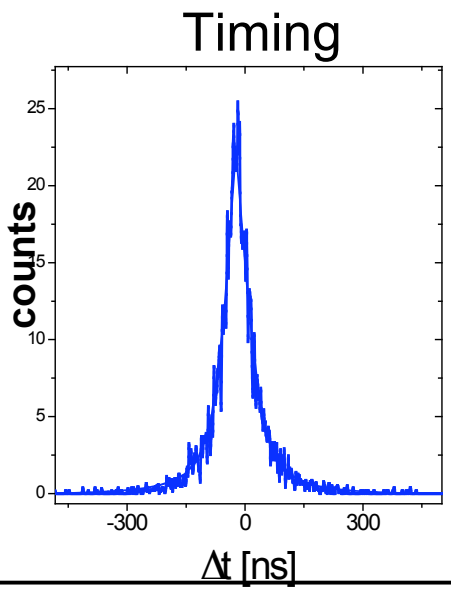
1D μ-strip detectors



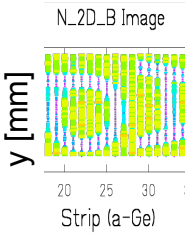
2D μ-strip detectors





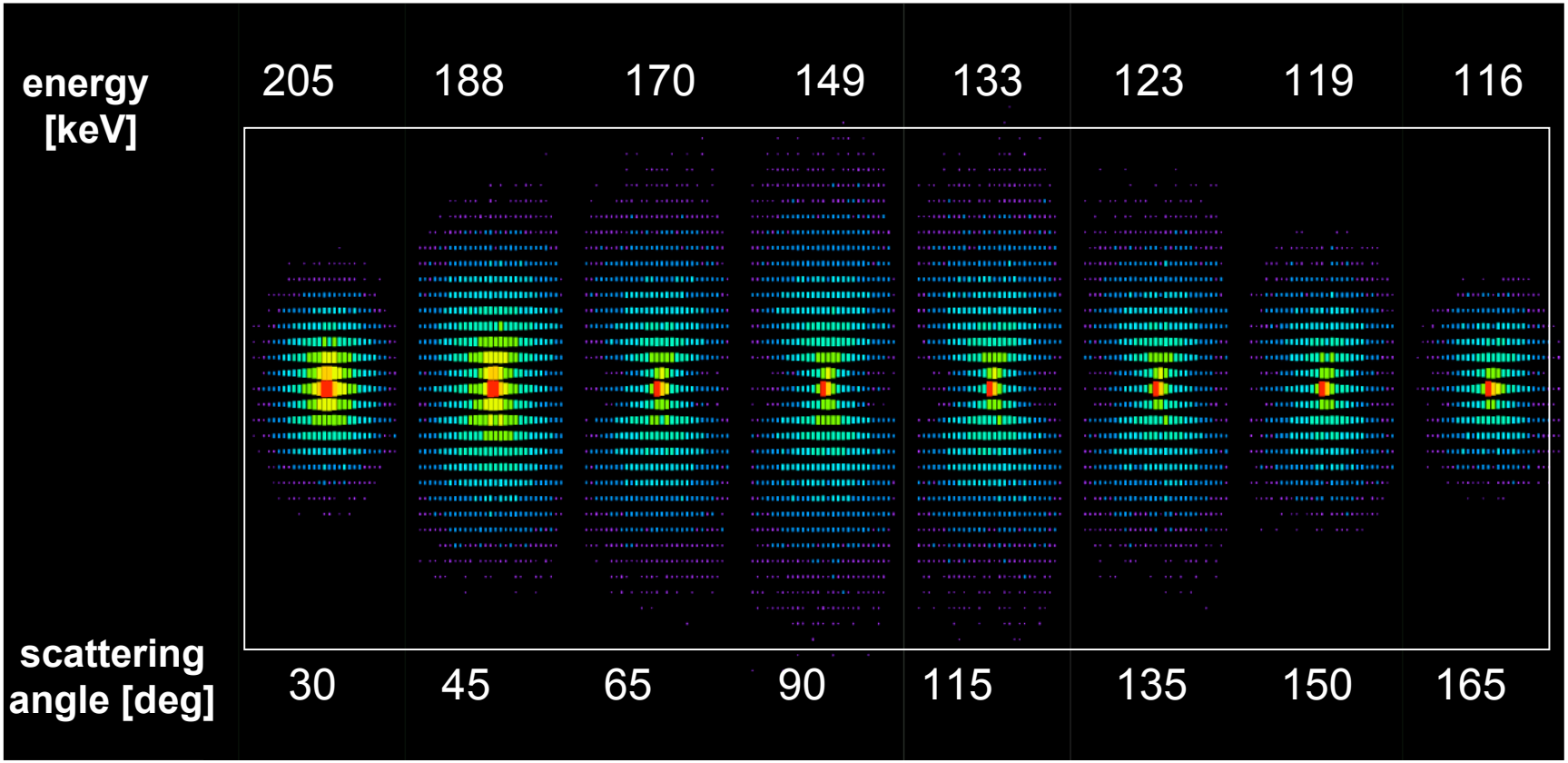


Position



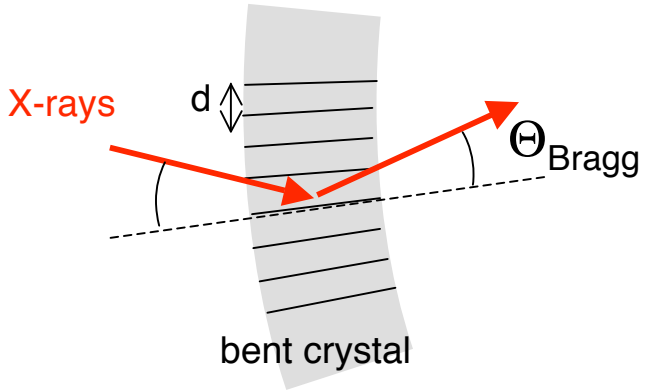
x [mm]

Ge 2D segmented detector



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

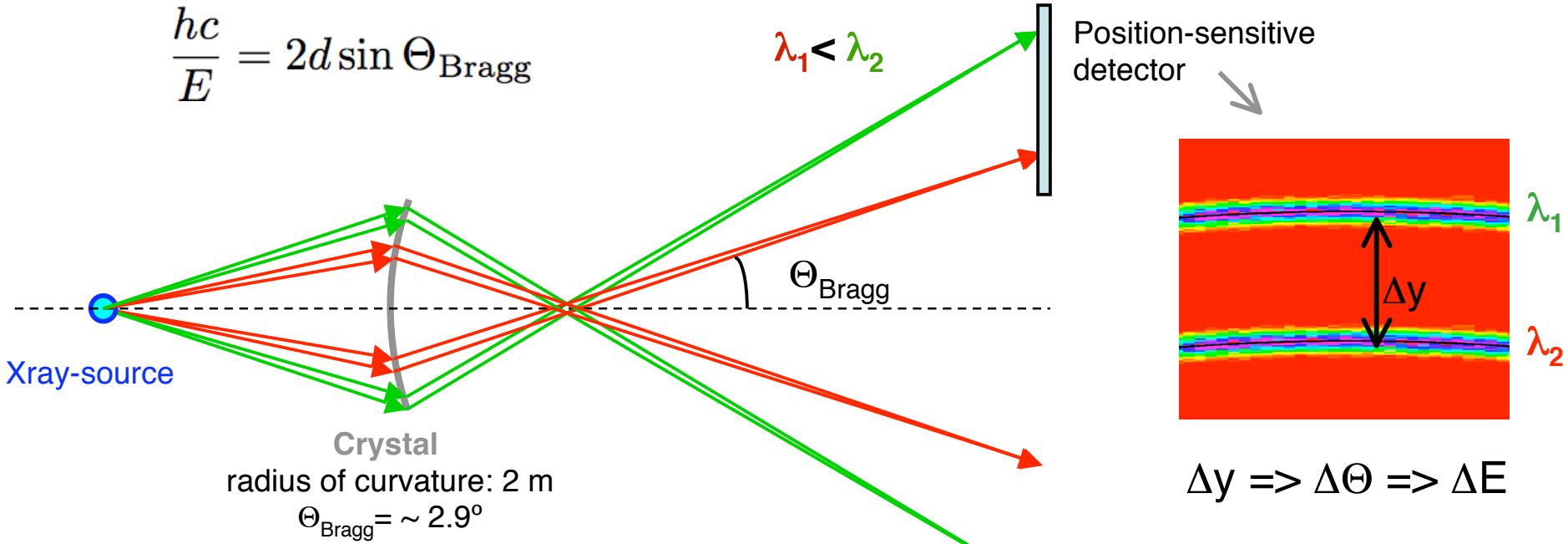
The FOCAL spectrometer



Crystal spectroscopy

- X-ray Bragg reflection
- Measurement of angles
  -> measurement of energy
- Theoretical resolution: ~ 50 eV @ 60 keV
- Bent crystal -> focusing properties

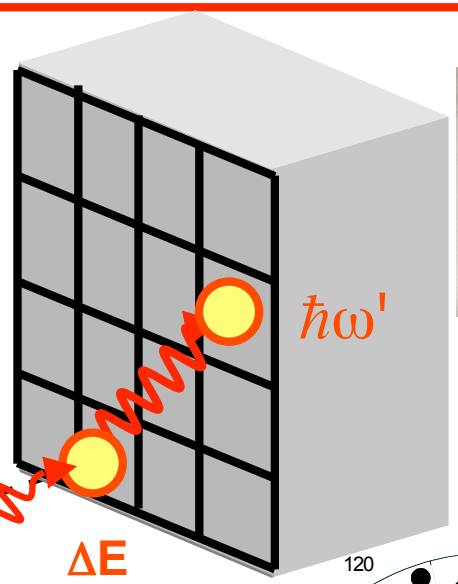
$$\frac{hc}{E} = 2d \sin \Theta_{Bragg}$$

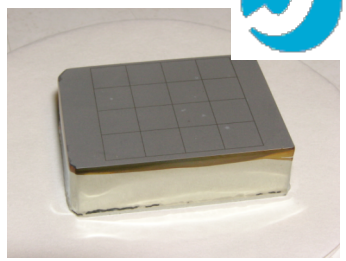


$\Delta y \Rightarrow \Delta\Theta \Rightarrow \Delta E$

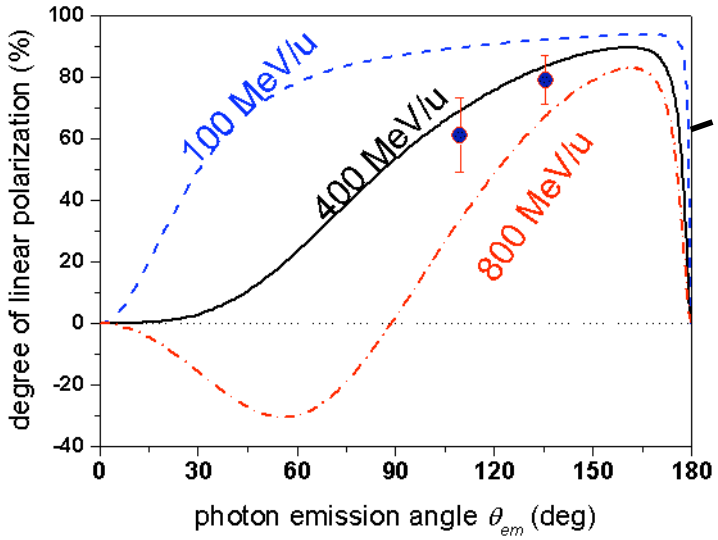
Ge pixel detector

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



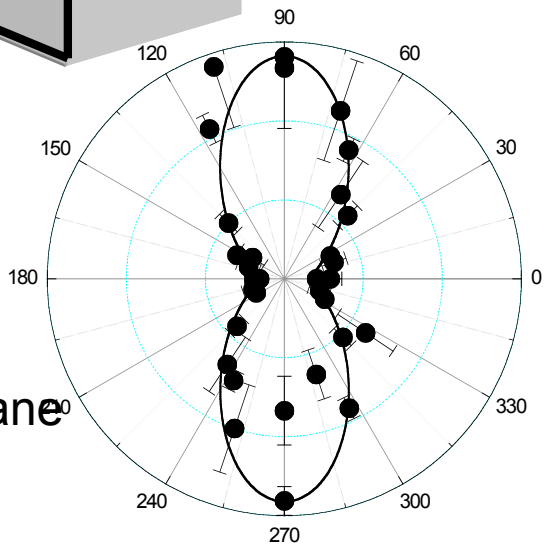


4X4 Ge detector (24 X 24 $mm^{2)}$



✔ K-REC radiation is strongly polarized

✔ Polarization is within the scattering plane

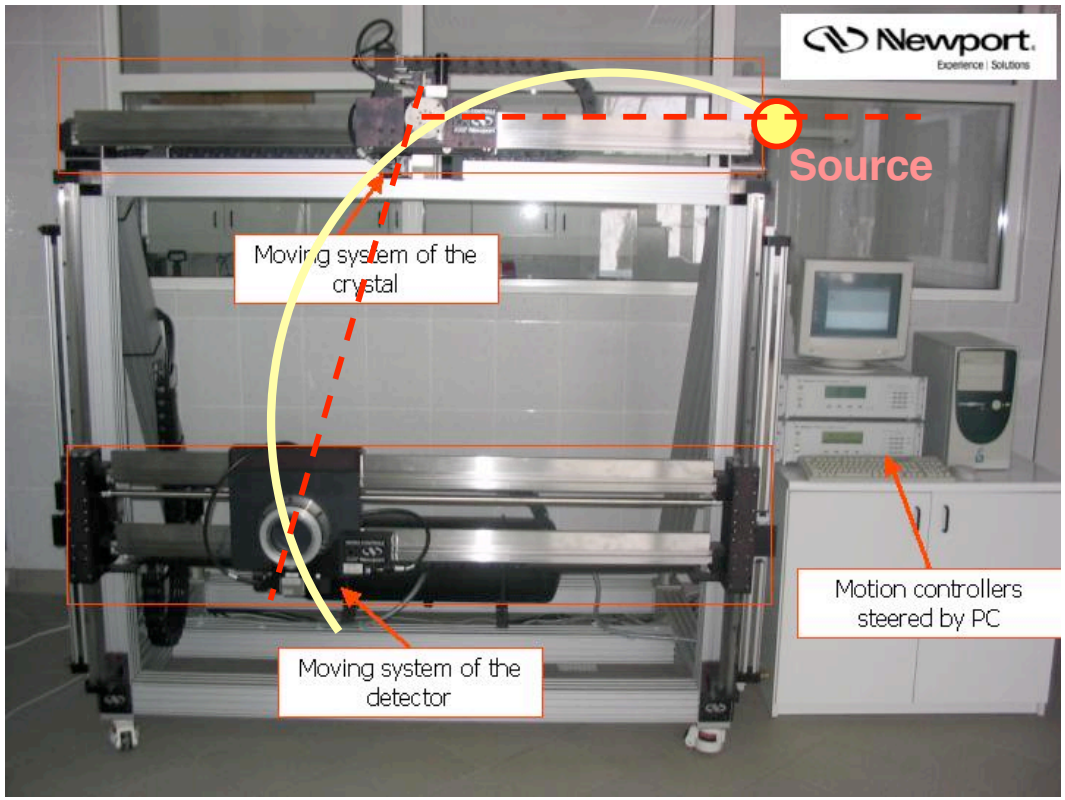


A. Surzhykov *et al.*, Phys. Rev. A **68**, 022710-7 (2003).
J. Eichler *et al.*, Phys. Rev. A **65**, 052716 (2002).
S. Tashenov Ph.D. Thesis, University of Frankfurt, 2005
S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202-4 (2006).

Bragg spectrometer for fast Bragg spectrometer for fast ions

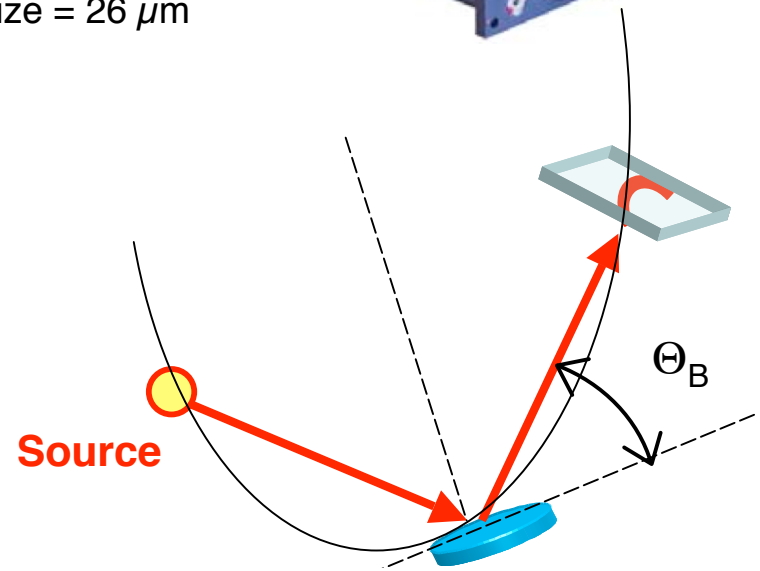
Newport Mounting system

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

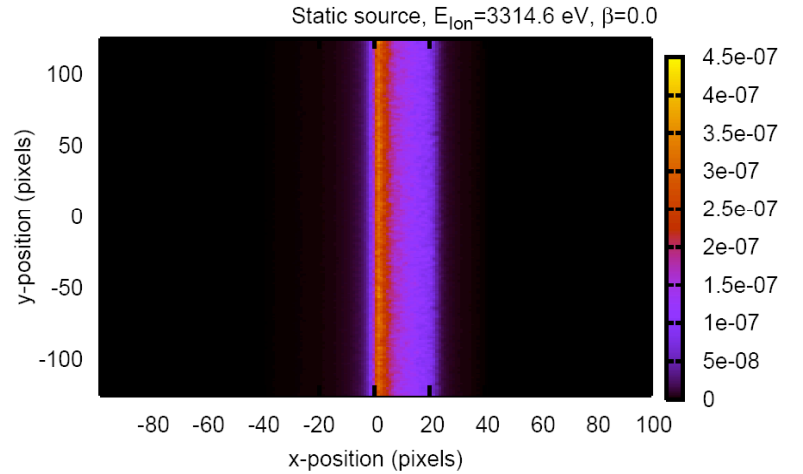


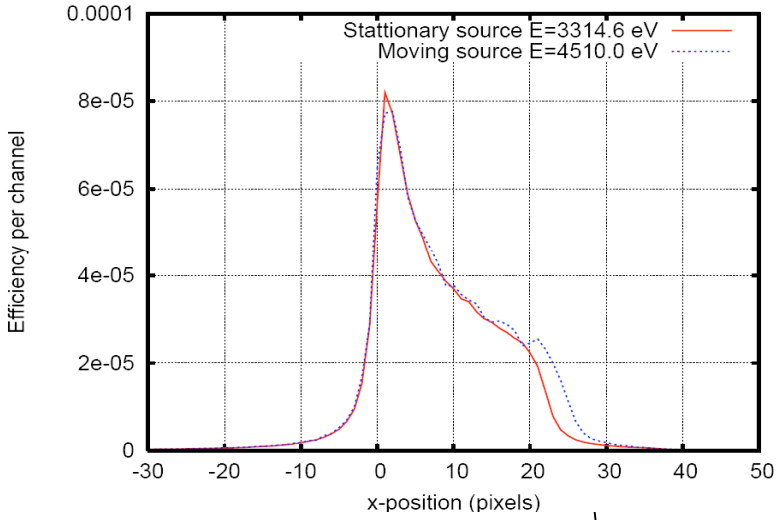
Silicon (111) crystal

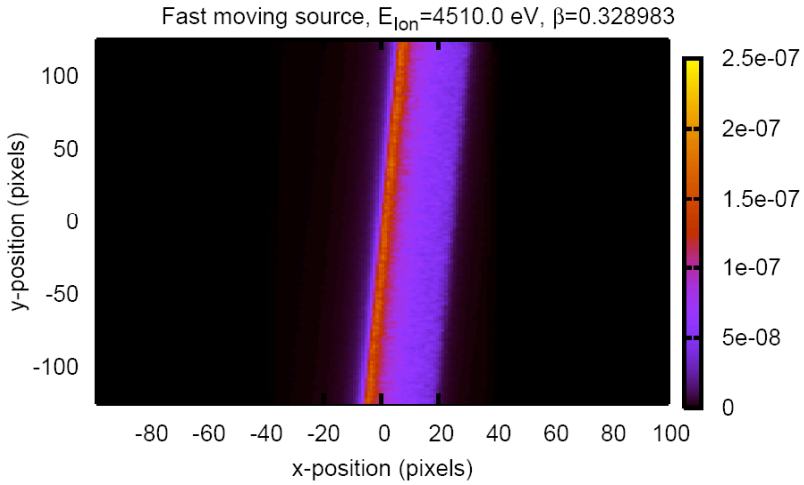
Spherically bent
R. of curvature = 1 m
d-spacing = 0.31 nm
Diameter = 75 mm

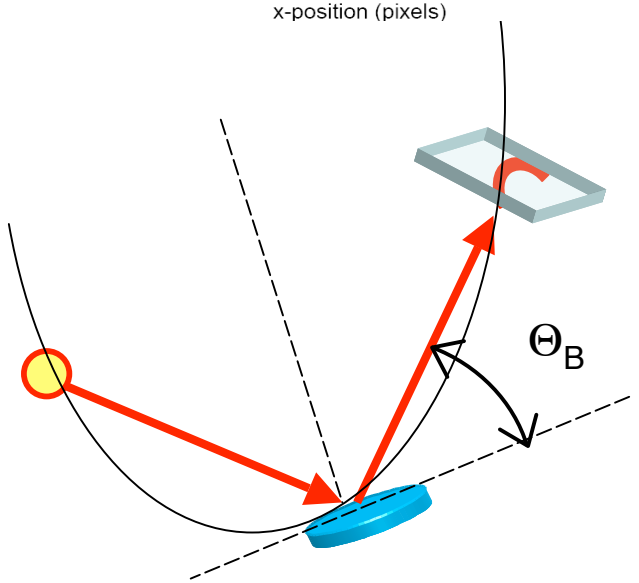
M. Trassinelli *et al.*, Canadian Journal of Physics accepted (2006).

Bragg spectrometer for fast ions







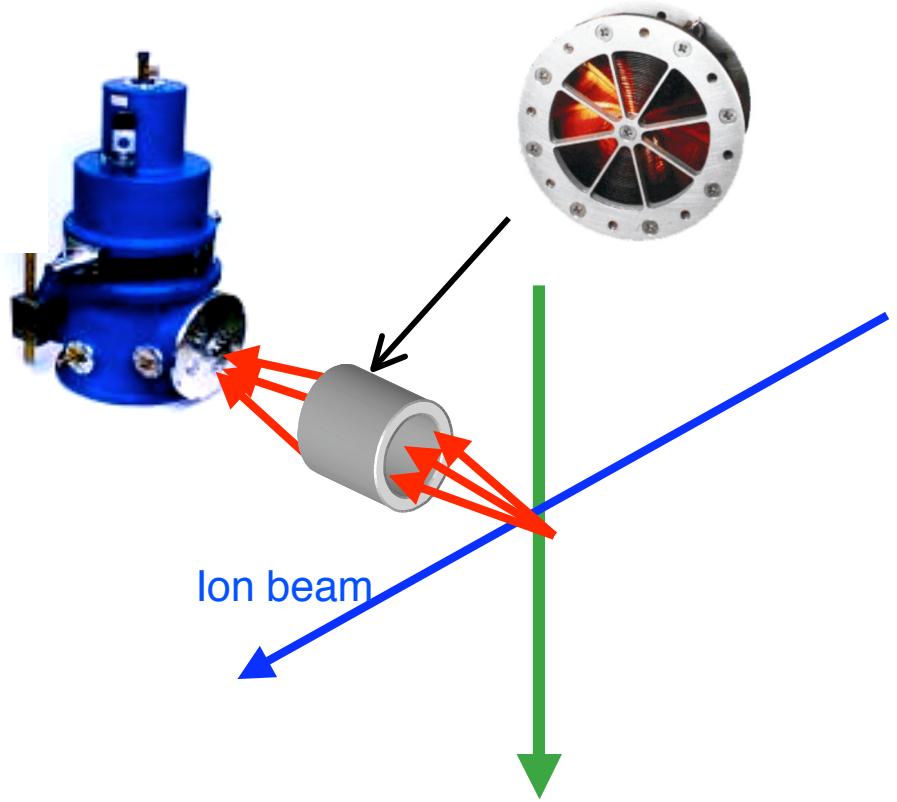


Expected efficiency: ~10^{-6}

2s Lamb shift measurement with a microcalorimeter

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

E. Silver et al., Harvard Smithsonian

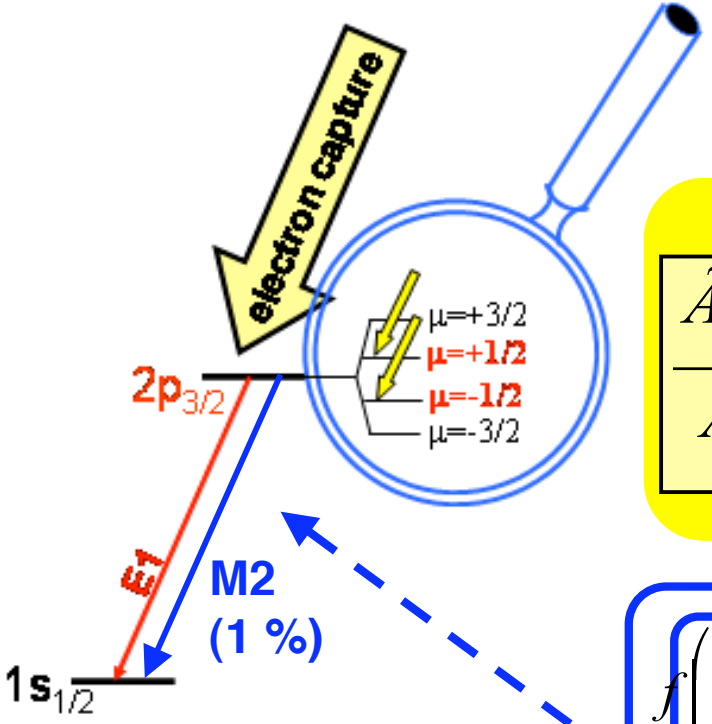


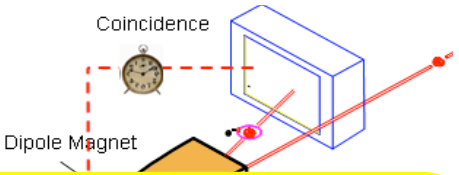
Grazing incidences X-ray lenses

Increase of efficiency up to a factor 6-8

Alignment Studies: Non-statistical population of magnetic sublevels

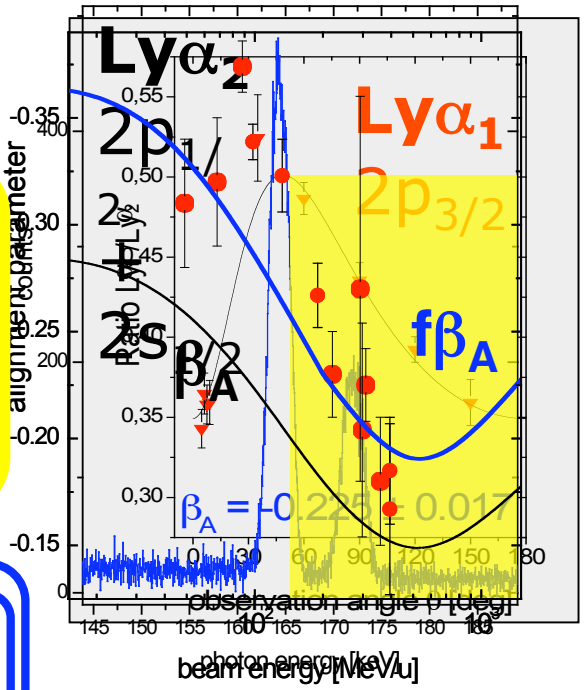
multipole mixing: M2 contribution to the 2p3/2 decay





M2 contribution

$$\frac{\tilde{A}_{M2}}{\tilde{A}_{E1}} = 0.0062 \pm 0.001$$



$$f\left(\frac{\|M2\|}{\|E1\|}\right) \propto 1 + \left[\hat{a}_A \bullet \left[1 - \frac{3}{2}\sqrt{3}\frac{\left\langle \|M2\| \right\rangle}{\left\langle \|E1\| \right\rangle}\sin^2\theta\right]\right]$$

Alignment Parameter

Surzhykov et al.,

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

$$W(\theta) \propto 1 + f\left(\frac{\|M2\|}{\|E1\|}\right) \cdot \hat{a}_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$

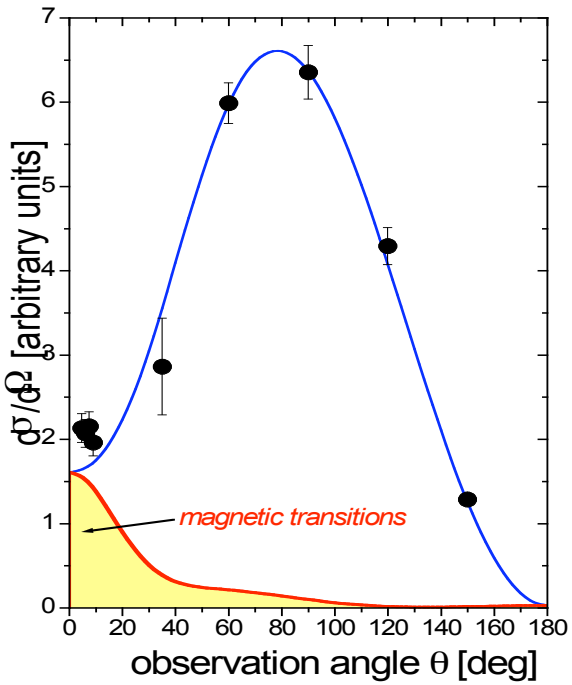
Photon Angular Distribution (U^{92+}, 310 MeV/u)

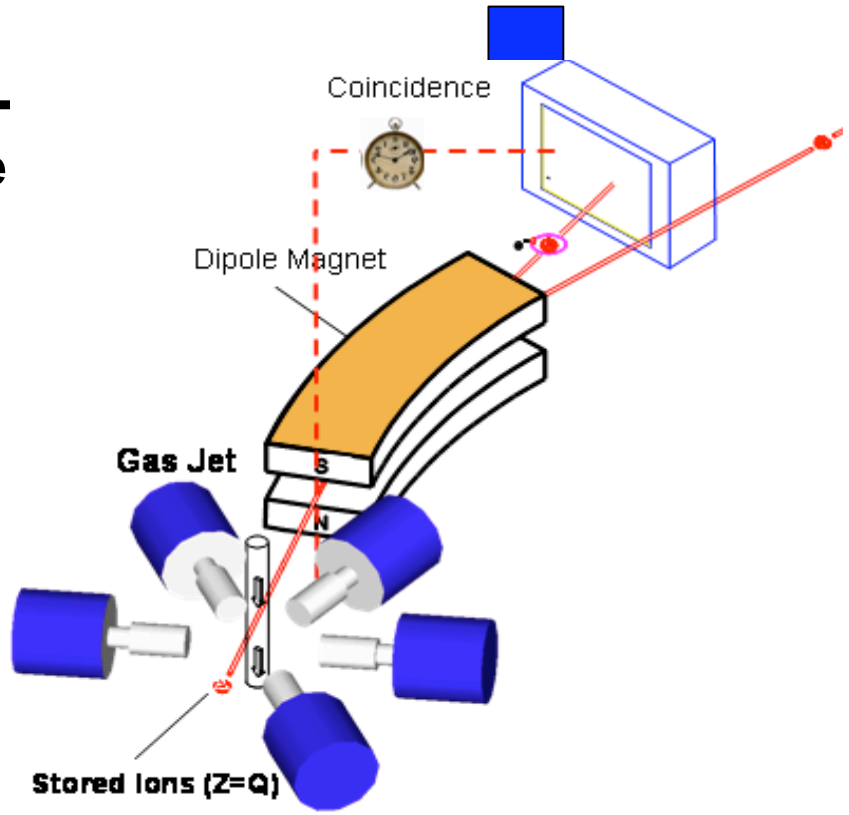
radiative capture into U^{92+}

laboratory frame

Time reve

photoionization of U^{91+}

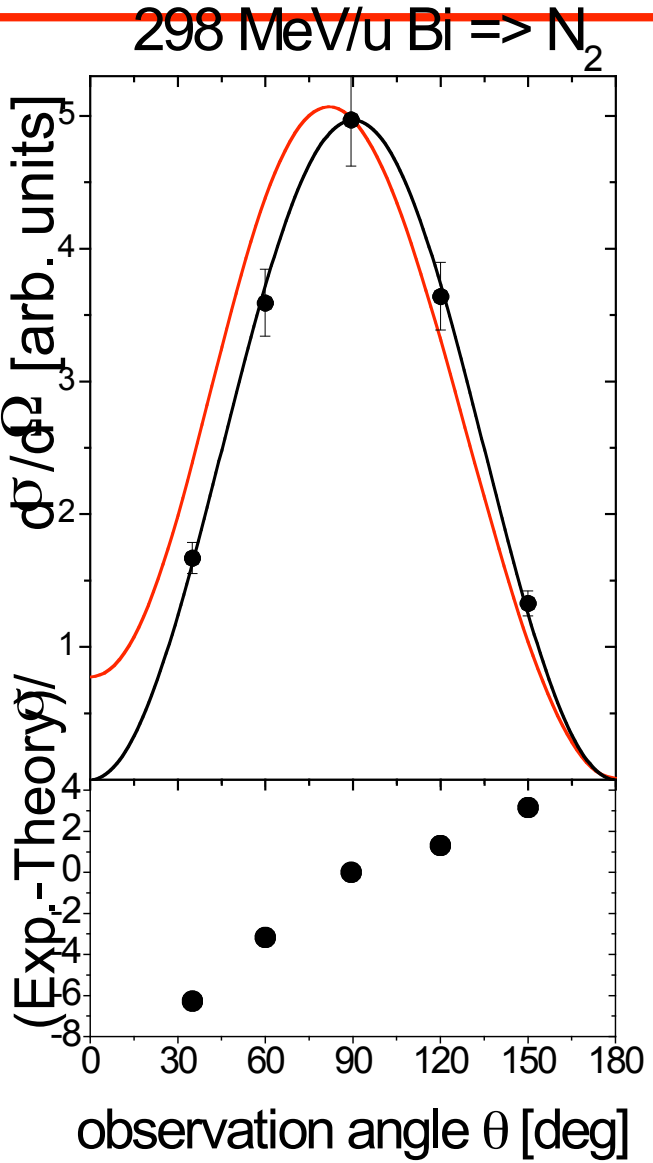




photon emission angle, θ' [deg]

REC has been established as research tool to study photoionization for high-Z few-electron ions close to the threshold

Nuclear Moment and the Photoionization Process

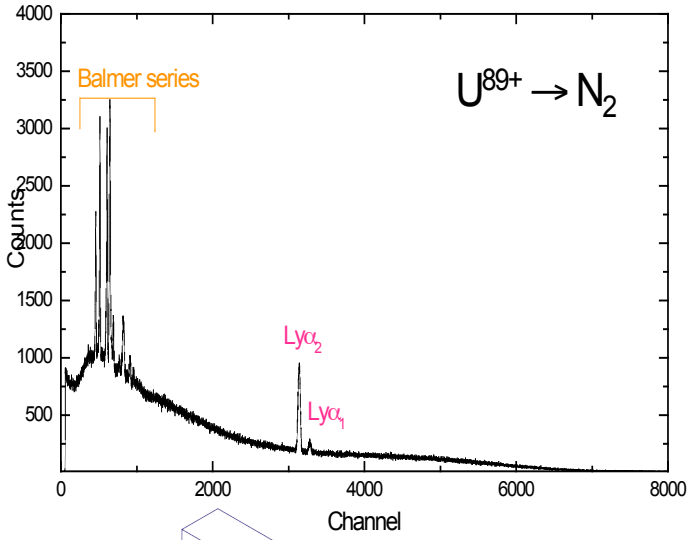


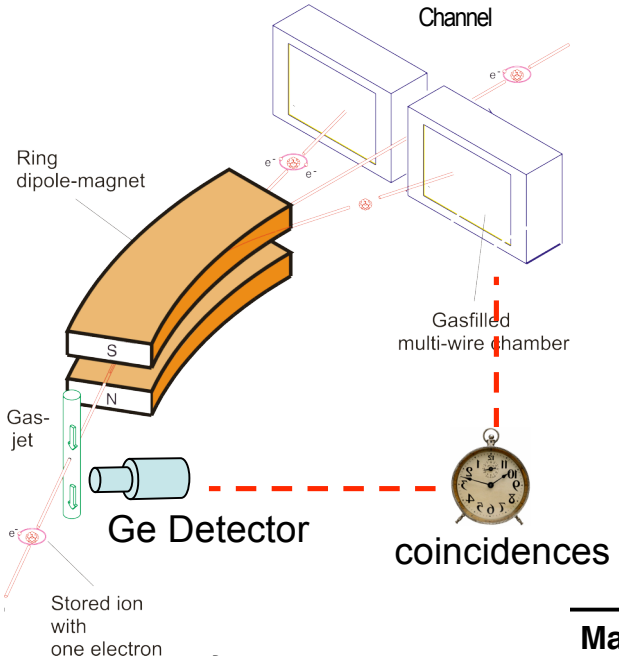
1s-REC for Bi^{83+} at 298 MeV/u

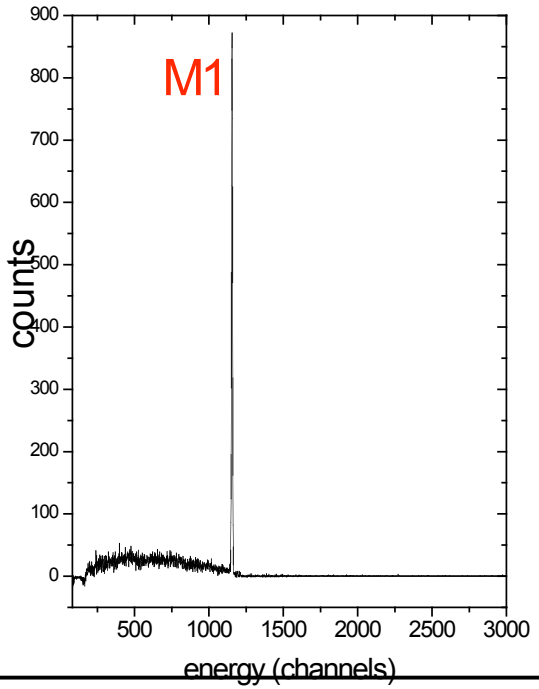
Nuclear spin of bismuth I=9/2

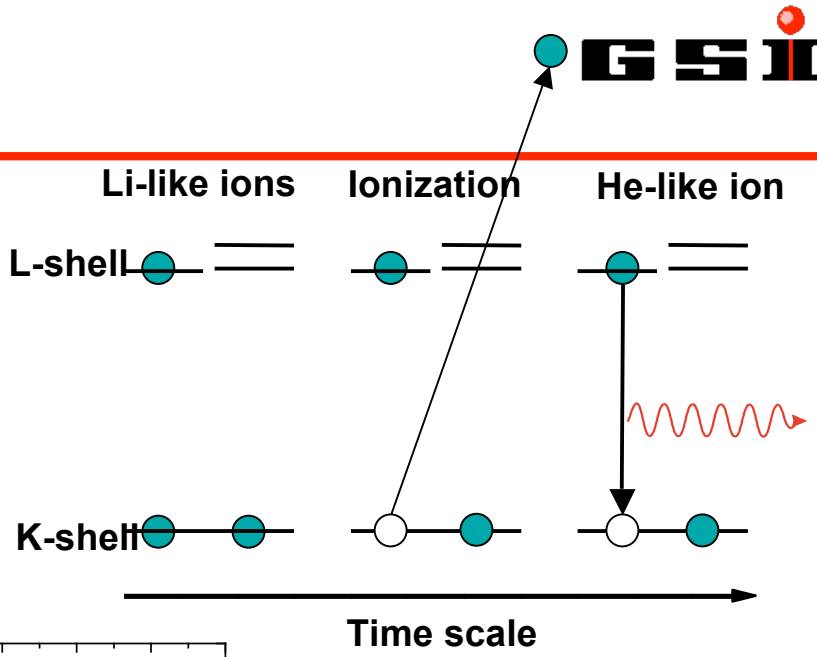
$$\vec{F} = \vec{I} + \vec{J}$$

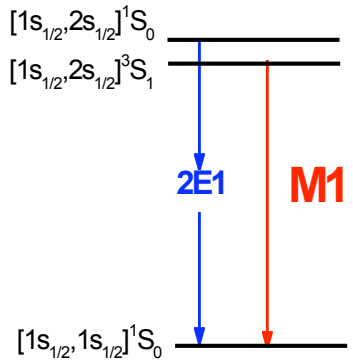
total x-ray yield

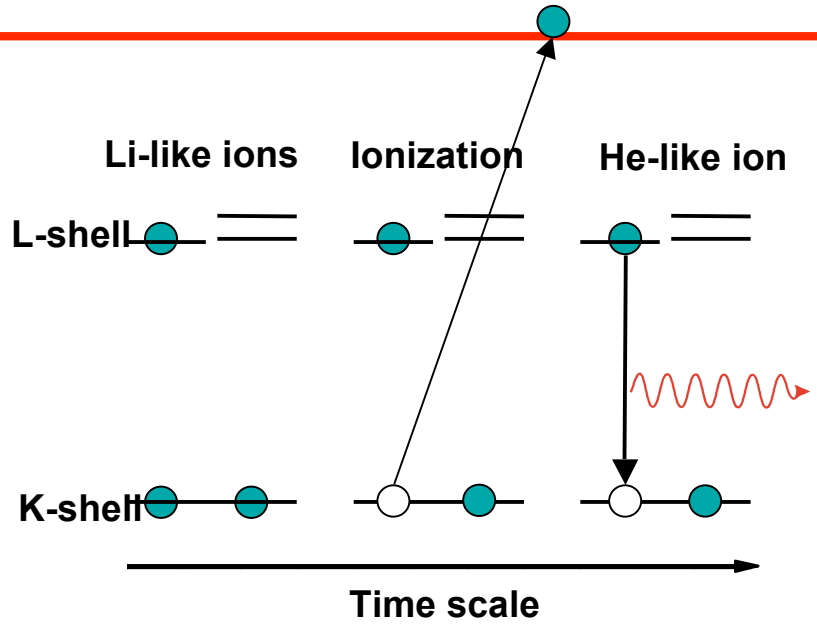


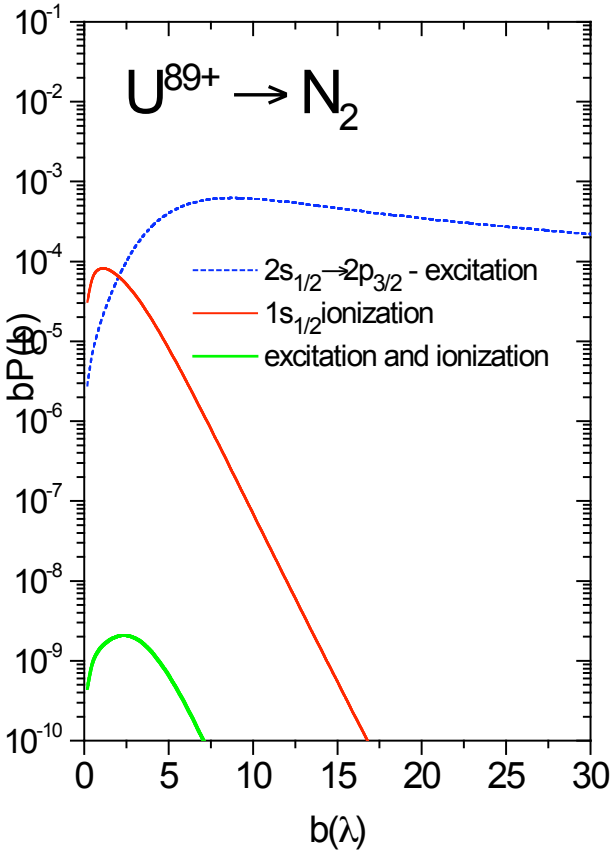


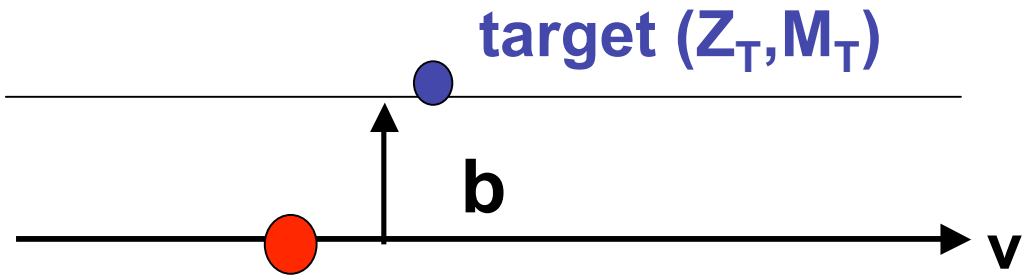






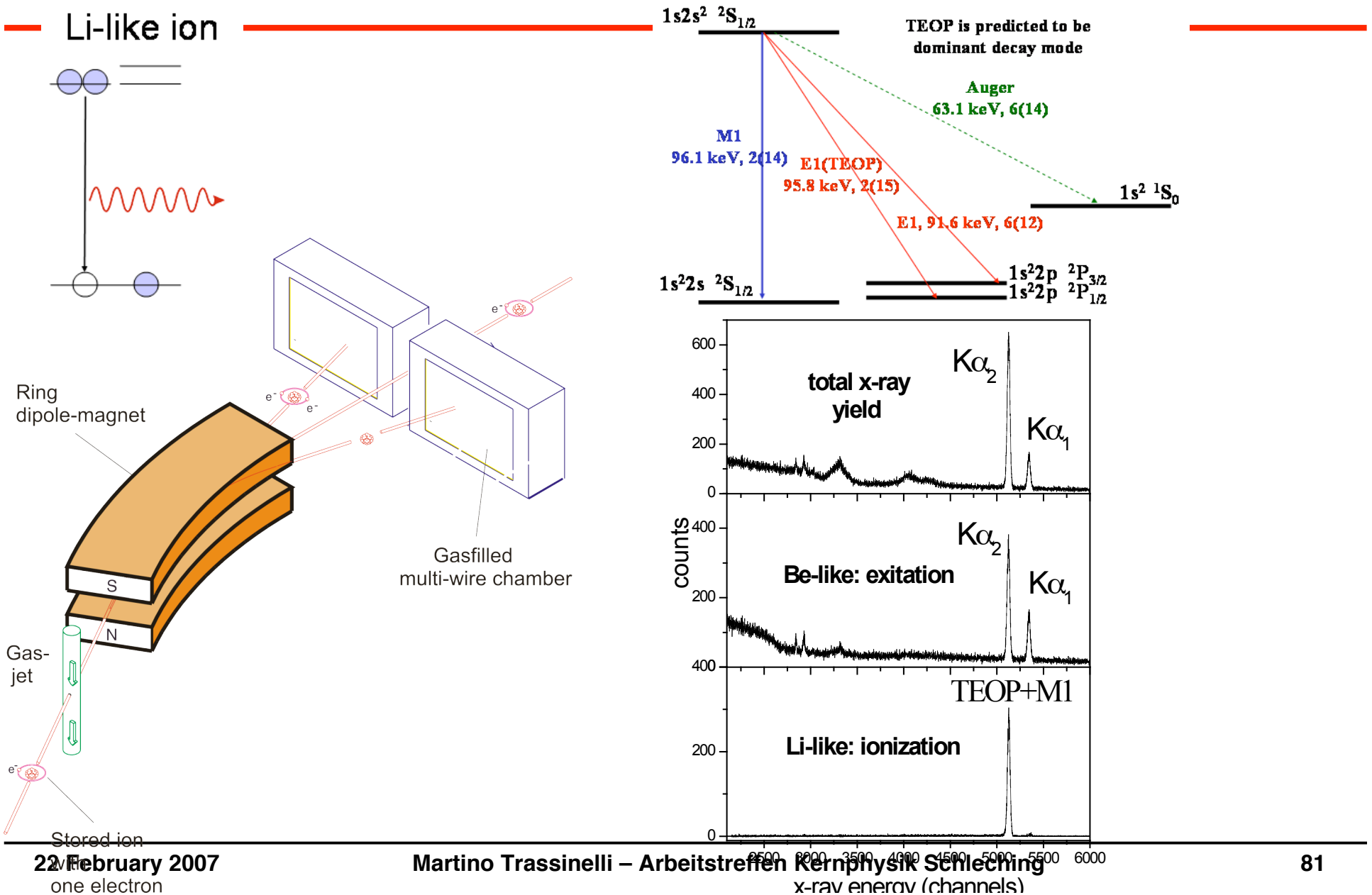




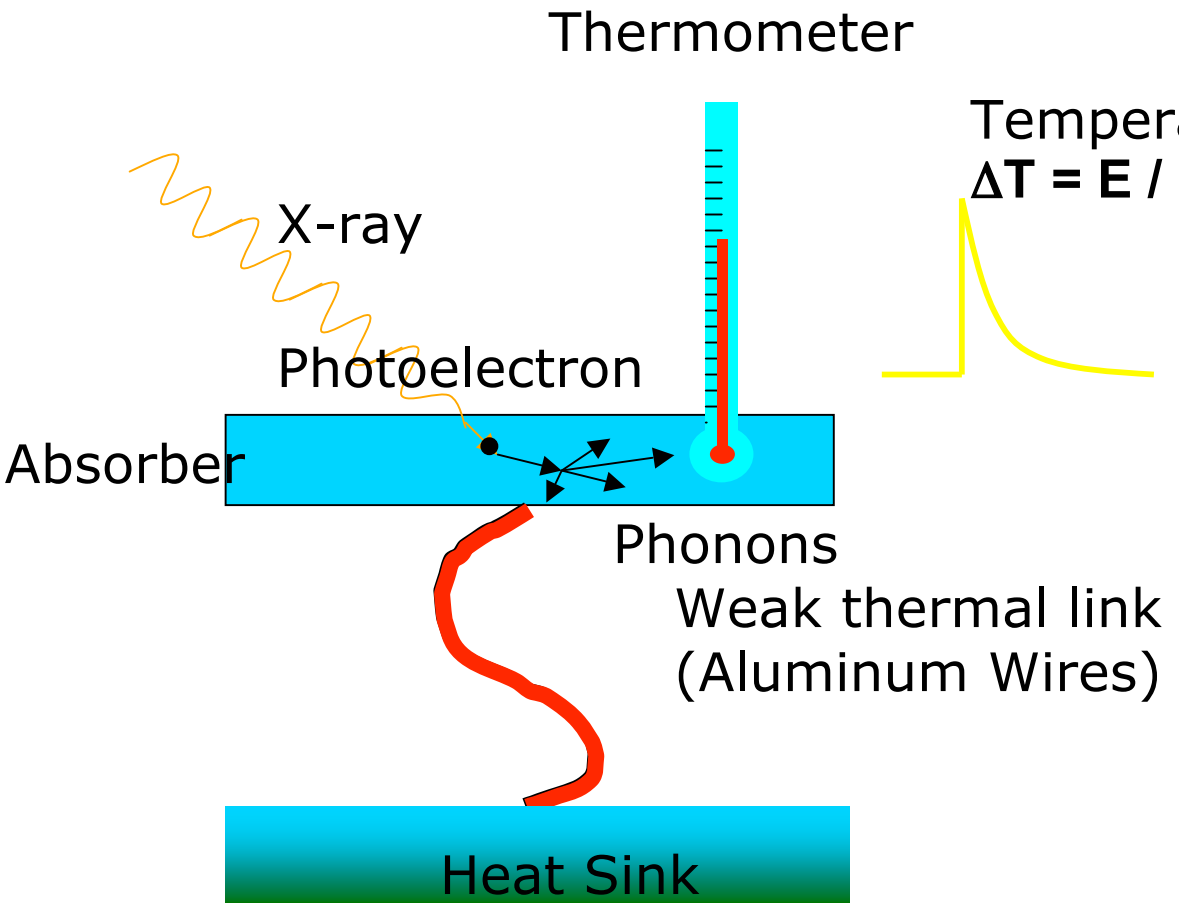


projectile
(Z_P,M_P)

$1s2s^2\ {}^2S_{1/2}$ U^{89+}: Two-Electron One-Photon Transition (TEOP)



Micro-Calorimeter



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Spezific heat capacity : c

Detector mass: m

Detector operates at about 50 mK

***Micro-calorimeter detector*: large wavelength acceptance, large quantum efficiency, and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).**