Gekühlte Schwerionen – Faszinierende Werkzeuge der Atomphysik

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Collaboration

Experiment

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

Theory

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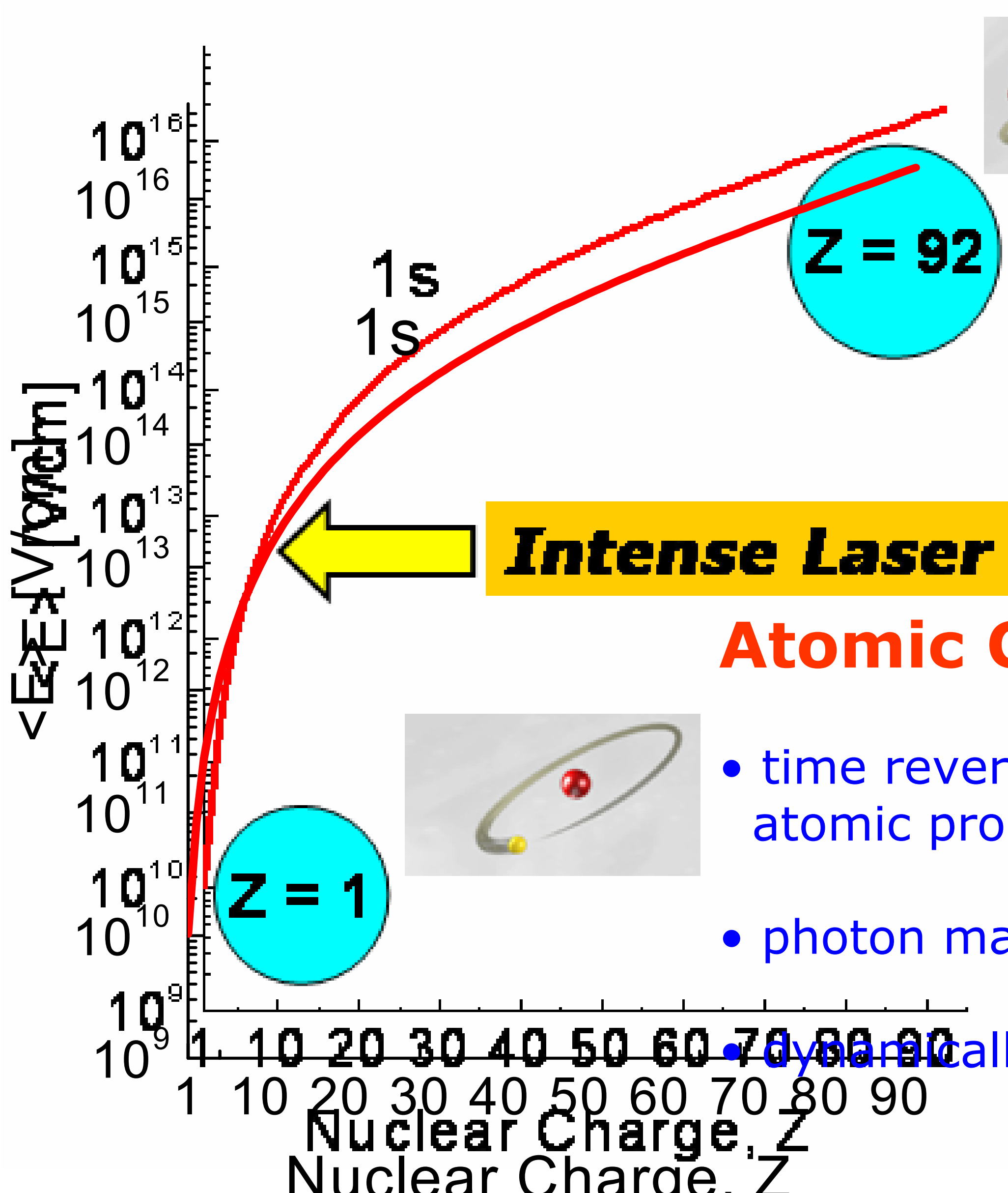
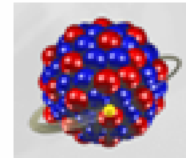
T. Shirai, V. Shabaev, A. Surzhykov**

FZ-Jülich, Germany
Theoretische Physik, HMI-Berlin, Germany
JAERI, Japan
University of Kassel, Germany
University of St. Peteresburg, Germany
MPI-K, Heidelberg, Germany

Atomic Physics in Extremly Strong Coulomb Fields





ure at High-Z

H-like Uranium
E_K = -132 • 10^3 eV
<E>= 1.8 • 10^{16} V/cm

um electrodynamics (QED)

on the atomic structure

n in the
strong fields

Atomic Collision at High-Z

- time reversal of elementary atomic processes
- photon matter interaction
- dynamically induced strong field effects

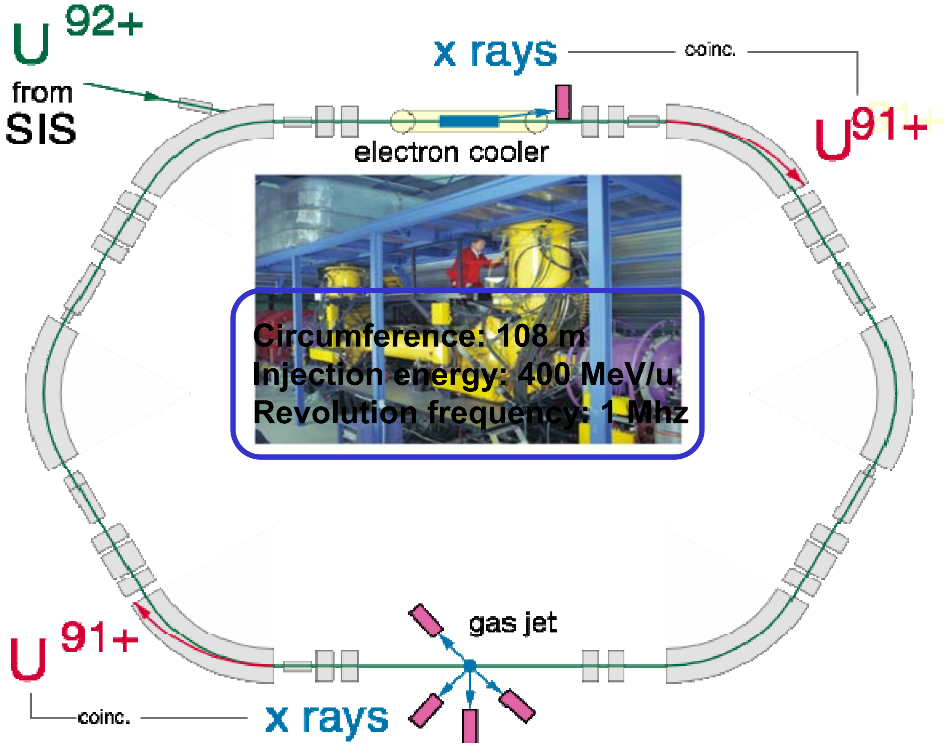
Hydrogen
E_K = -13.6 eV
<E>= 1 • 10^{10} V/cm

- **Atomic Structure Studies at High-Z**
    - **Current Status of the 1s Lamb Shift Experiments**
    - **He-like Ions: Two-Electron Contribution to Ionization Potential for He-Like Uranium**

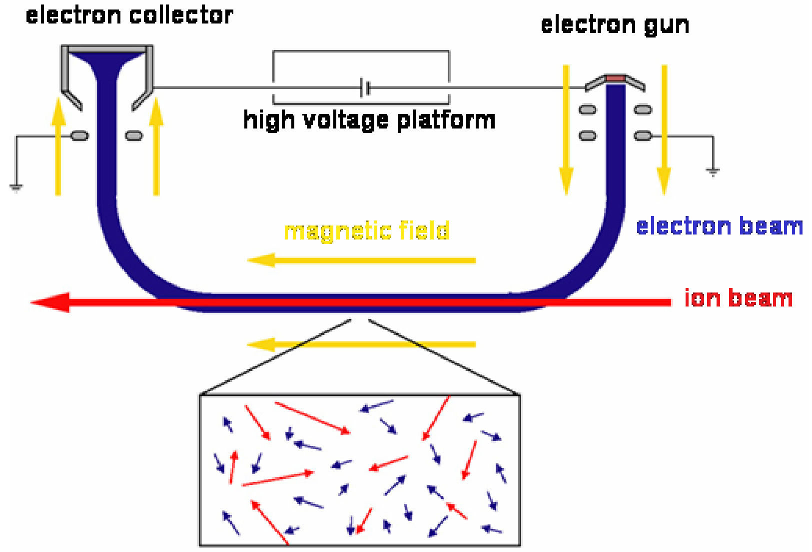
      Two-Photon Decay
    - **Few-Electron Ions**
- **Dynamics: Atomic Collisions at High-Z**
    - **Radiative Recombination/Electron Capture Studies**

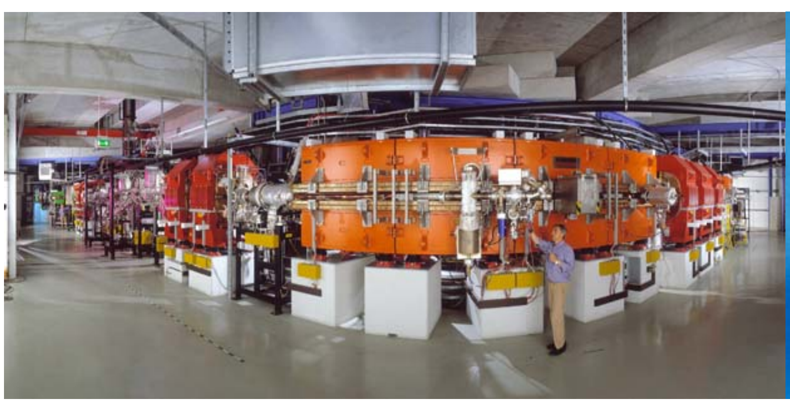
      Angular Correlation and Polarization Studies
- **Development of Position Sensitive X-Ray Detectors**
- **Summary**
- **Outlook**
    - **Challenges and Opportunites: Atomic Physics at FAIR**

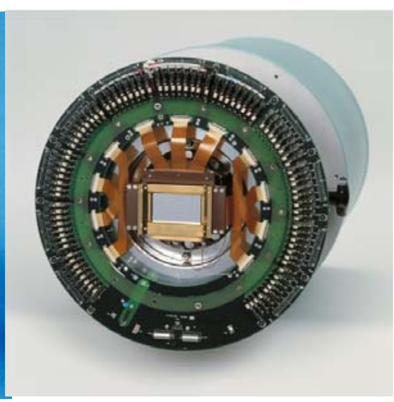
Atomic Physics @ GSI

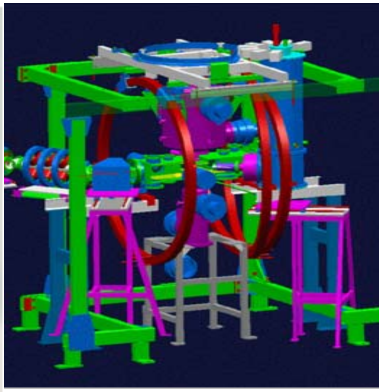


Electron Cooling









Storing and Cooling

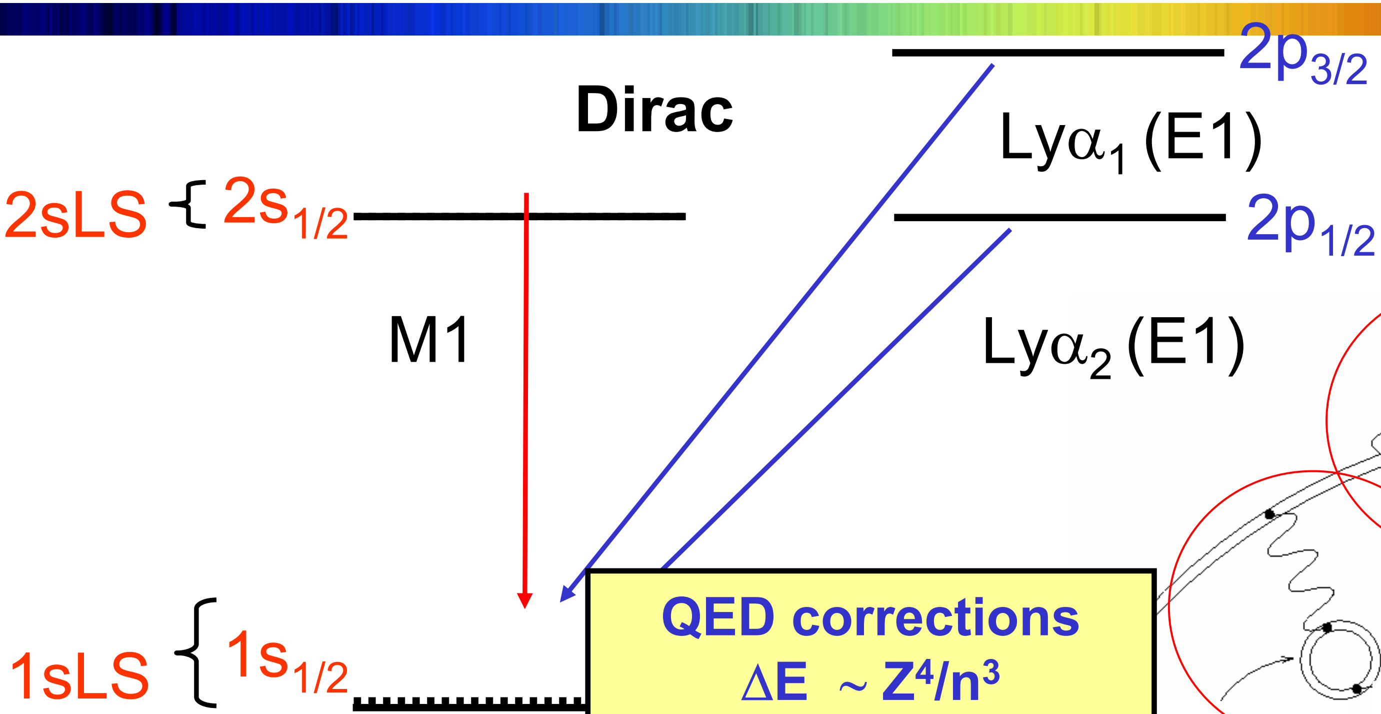
Detector and Spectrometers

I Atomic Structure Studies at High-Z

- Current Status of the 1s Lamb Shift Experiments
- He-like Ions: Two-Electron Contribution to Ionization Potential for He-Like Uranium
- Few-Electron Ions:

  Dielectronic Recombination – Spectroscopy Without Photons

The Structure of One-Electron Systems

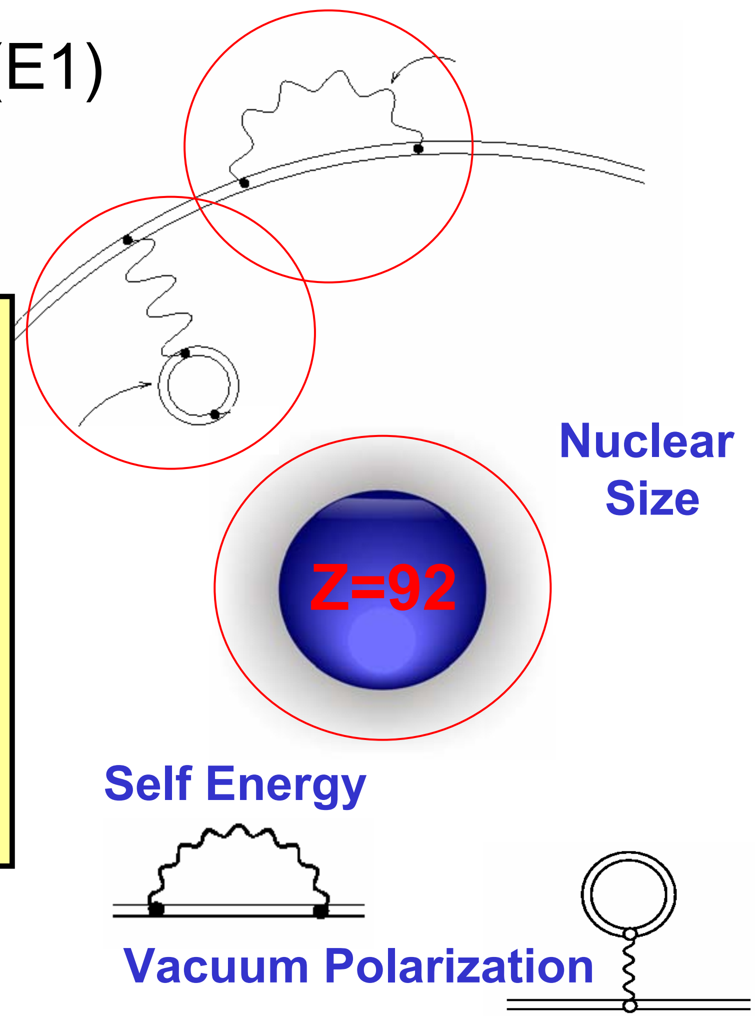


QED corrections
$\Delta E \sim Z^4/n^3$

Z: nuclear charge

n: prinzipal quantum number

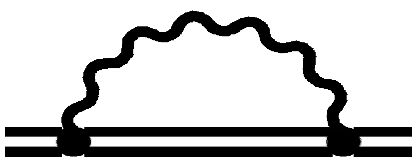
Important for s-states



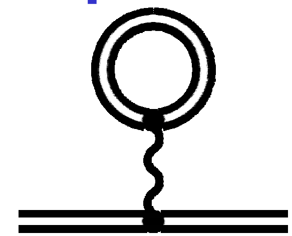
Bound-State QED: 1s Lamb Shift

Sum of all corrections, leading to deviations from the Dirac theory for a point like nucleus

Self energy



Vacuum polarization



U^{91+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

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

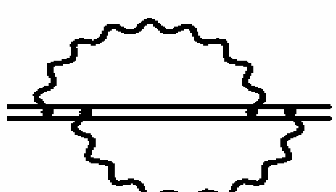
Low Z-Regime: $\alpha Z \ll 1$

$F(\alpha Z)$: series expansion in αZ

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

$F(\alpha Z)$: series expansion in αZ not appropriate

Goal:



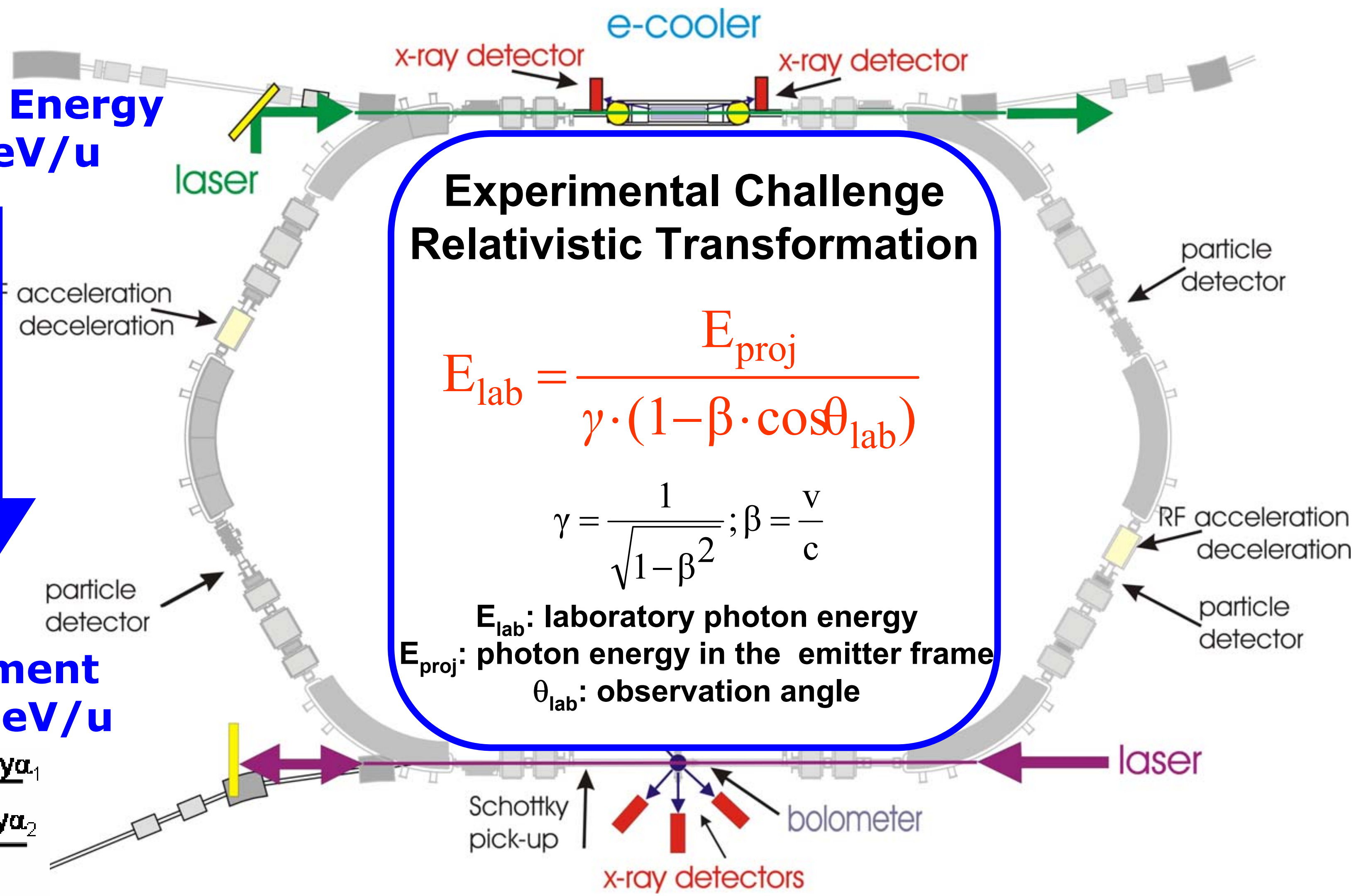
±1 eV

X-Ray Spectroscopy at the ESR Storage Ring

Injection Energy 400 MeV/u

deceleration

Experiment @ 10 MeV/u

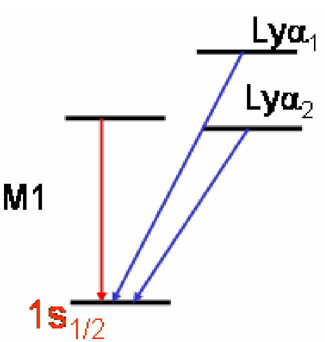


Experimental Challenge
Relativistic Transformation

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

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}; \beta = \frac{v}{c}$$

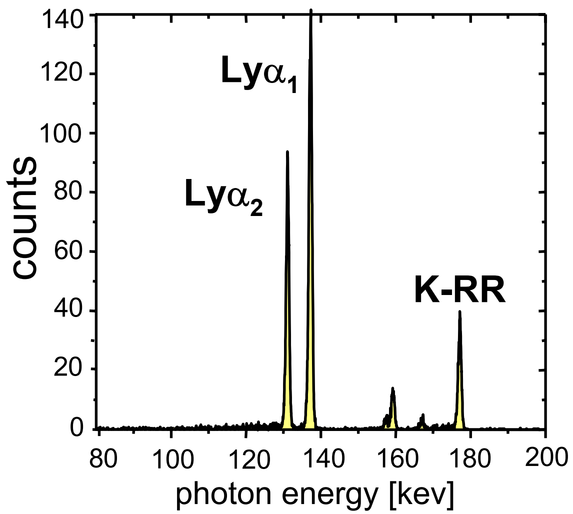
E_{lab}: laboratory photon energy
E_{proj}: photon energy in the emitter frame
θ_{lab}: observation angle



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

Test of Quantum Electrodynamics (1s-LS)

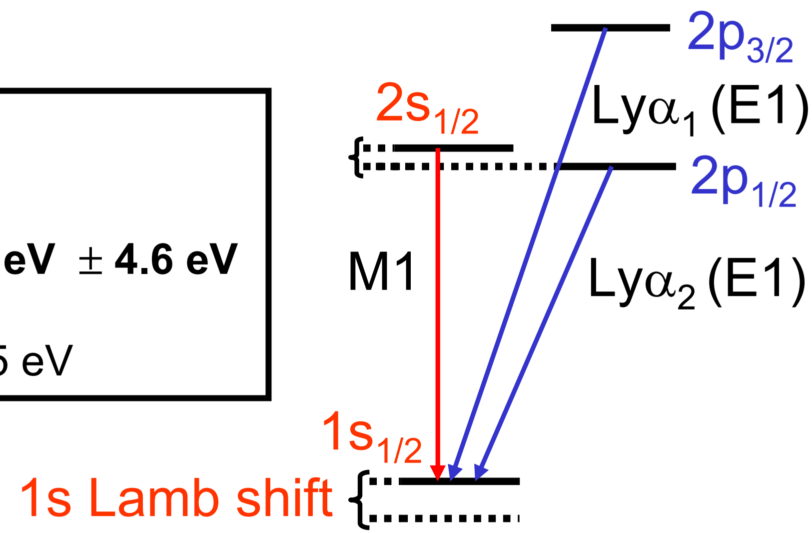
The 1s-LS in H-like Uranium

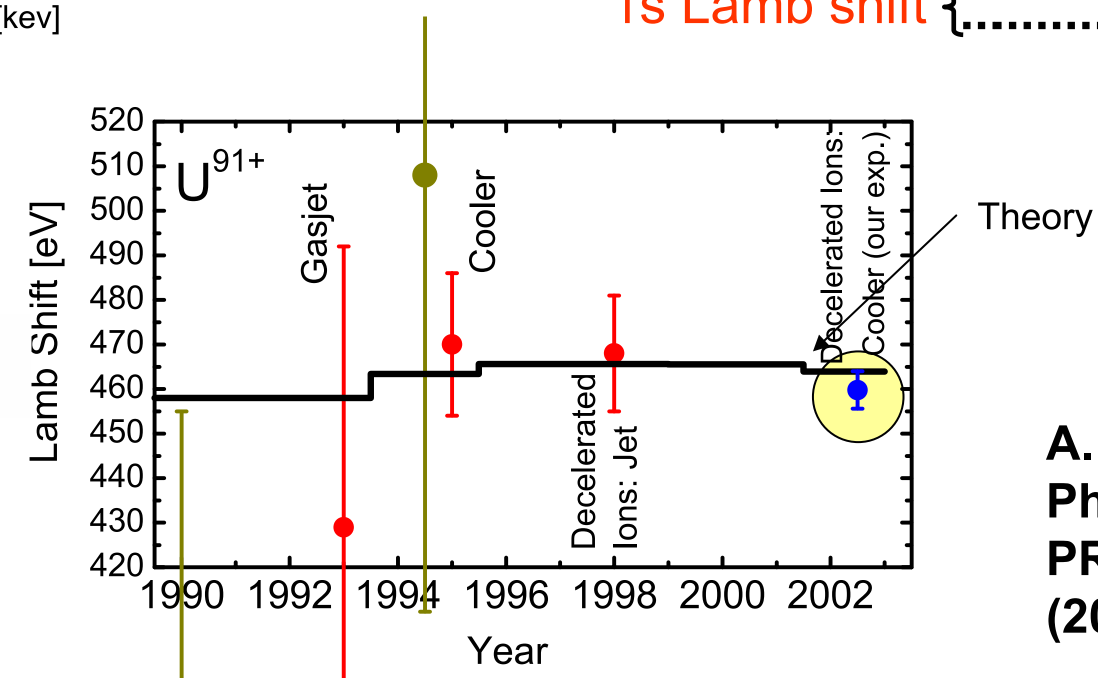


1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



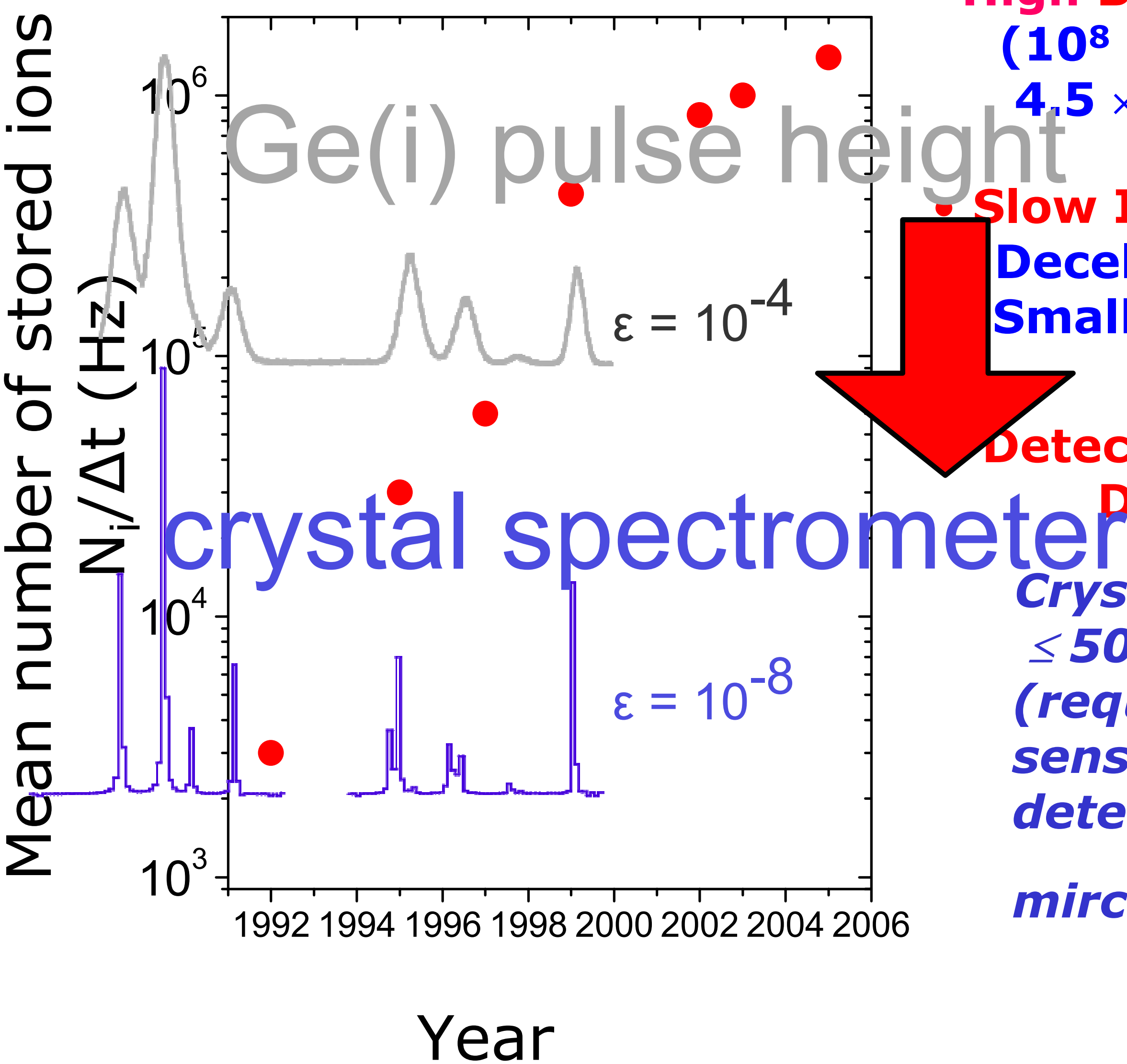


nature

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

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

Towards an Accuracy of 1 eV



- **High Beam intensities**
  (10^8 Ions per Minute ⇒ 4.5×10^5 Photons in 4π)
- **Slow Ions or Ions in Rest**
  Deceleration of the Ions
  Small Doppler correction

Detector and Spectrometer Development

Crystal spectrometer $\leq$ 50 eV (requires position sensitive solid state detectors)

mircocalorimeter

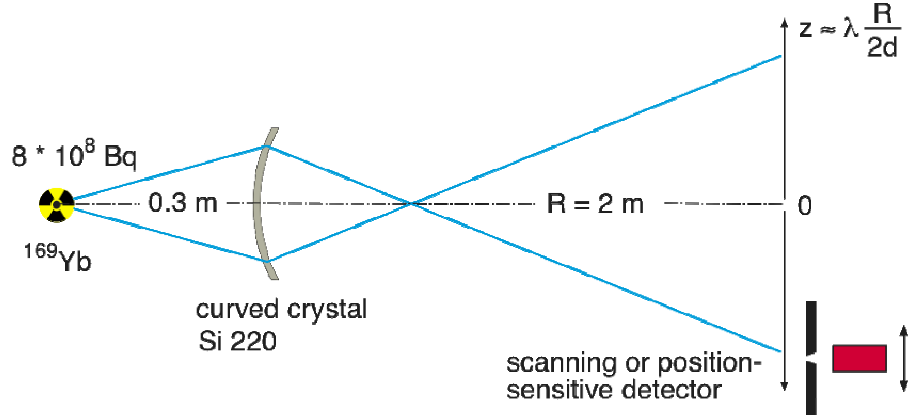
The 1s-Lamb-Shift at High-Z

H.F. Beyer
K. Beckert
P. Beller
A. Bleile
D. Banas
J. Bojowald
F. Bosch
P. Egelhof
E. Förster
B. Franzke
A. Gumberidze
S. Hagmann
J. Hoszowska
P. Indelicato
O. Klepper
H.-J. Kluge
St. König
Chr. Kozhuharov
D. Liesen
X. Ma
B. Manil
D. McCammon
I. Mohos
A. Orsic-Muthig
F. Nolden
U. Popp
D. Protic
A. Simionovici
D. Sierpowski
U. Spielmann
C.K. Stahle
Z. Stachura
M. Steck
Th. Stöhlker
S. Tashenov
M. Trassinelli
A. Warczak
M. Weber
O. Wehrhan

Mainz
Paris
Frankfurt
Grenoble
Jülich
Darmstadt
Caen
Cracow
Madison
Greenbelt
Jena

FOCAL

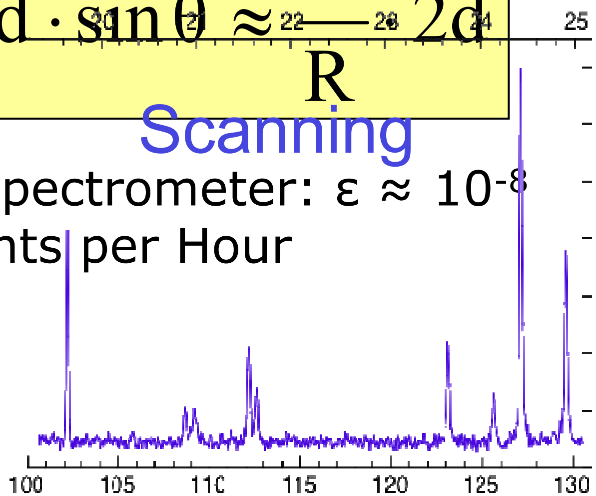
Scanning technique versus micro-strip detectors



Bragg-Laue Relation

$$\lambda = 2 \cdot d \cdot \sin\theta \approx \frac{z}{R} 2d$$

λ (pm) ⟶



Scanning

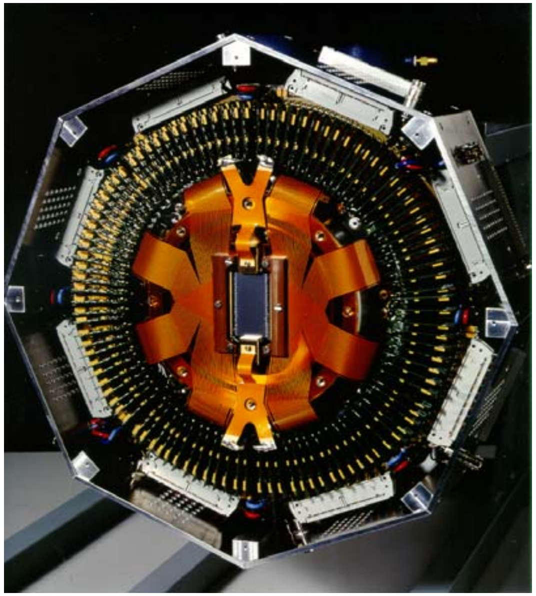
FOCAL Spectrometer: ε ≈ 10^{-8}

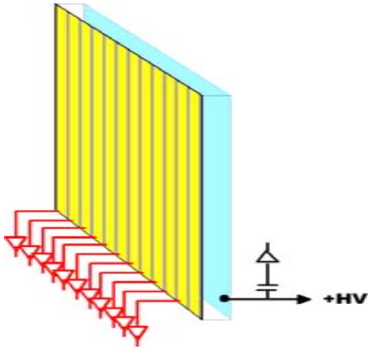
⇒ 3 Events per Hour

z (mm) ⟶

Micro-Strip Germanium Detector

Timing, Energy and Position Resolution



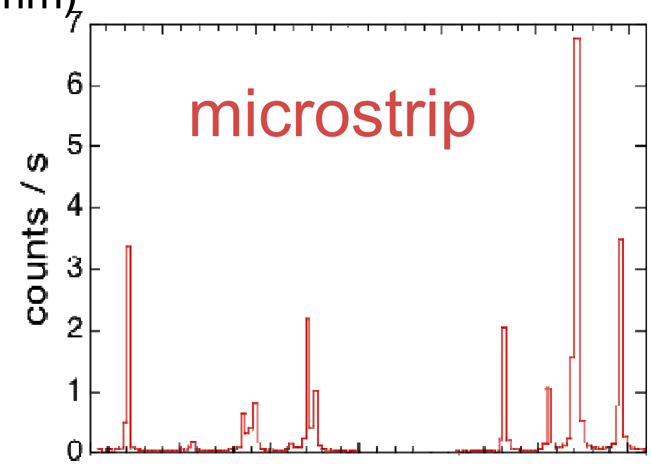


200 Strips

Δx ≈ 200 µm

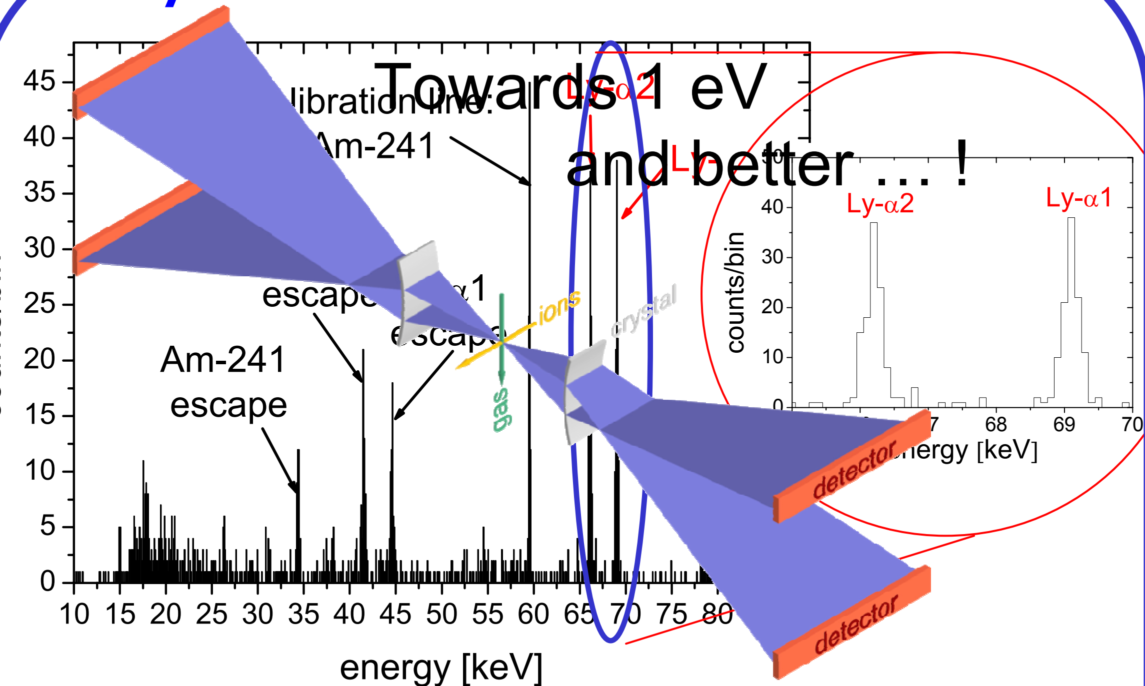
ΔE ≈ 1.6 keV

Δτ ≈ 50 ns



First Test Experiment for Lamb Shift Measurements on Hydrogen-like Heavy Ions with Cryogenic Detectors

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



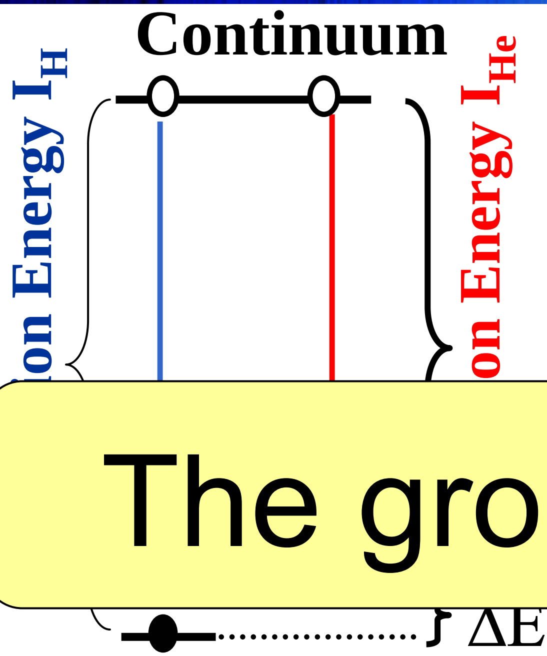
- achieved energy resolution: ΔE = 149 eV
- detection efficiency (4 pixels): 1 x 10^{-7}

Experiment: March 2006

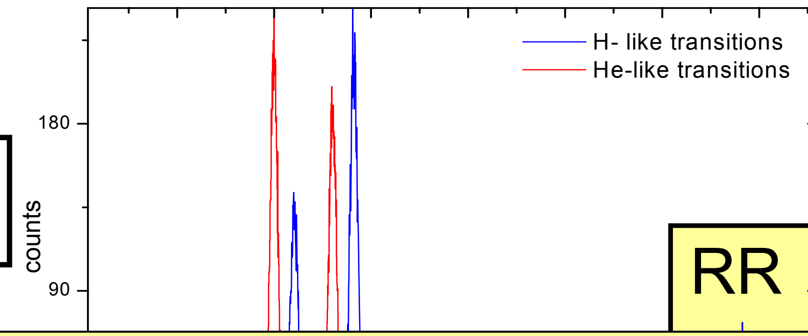
A. Bleile et al., NIM A 444, 488 (2000)

P. Egelhof et al., Oct. 2005

Correlation and 2eQED Studies for He-like Uranium



$$I_H - I_{He} = \Delta E$$

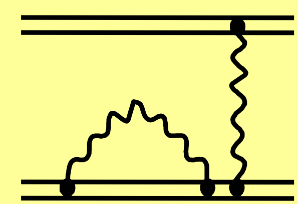


The groundstate of He-like ions

- extension of former experiments at SuperEBIT to He-like uranium
- for the ground-state of high-Z He-like ions a sensitivity to 2eQED has been achieved

Two-Electron QED, e.g. 2nd order Self Energy

-9.7 eV [U^{90+}]

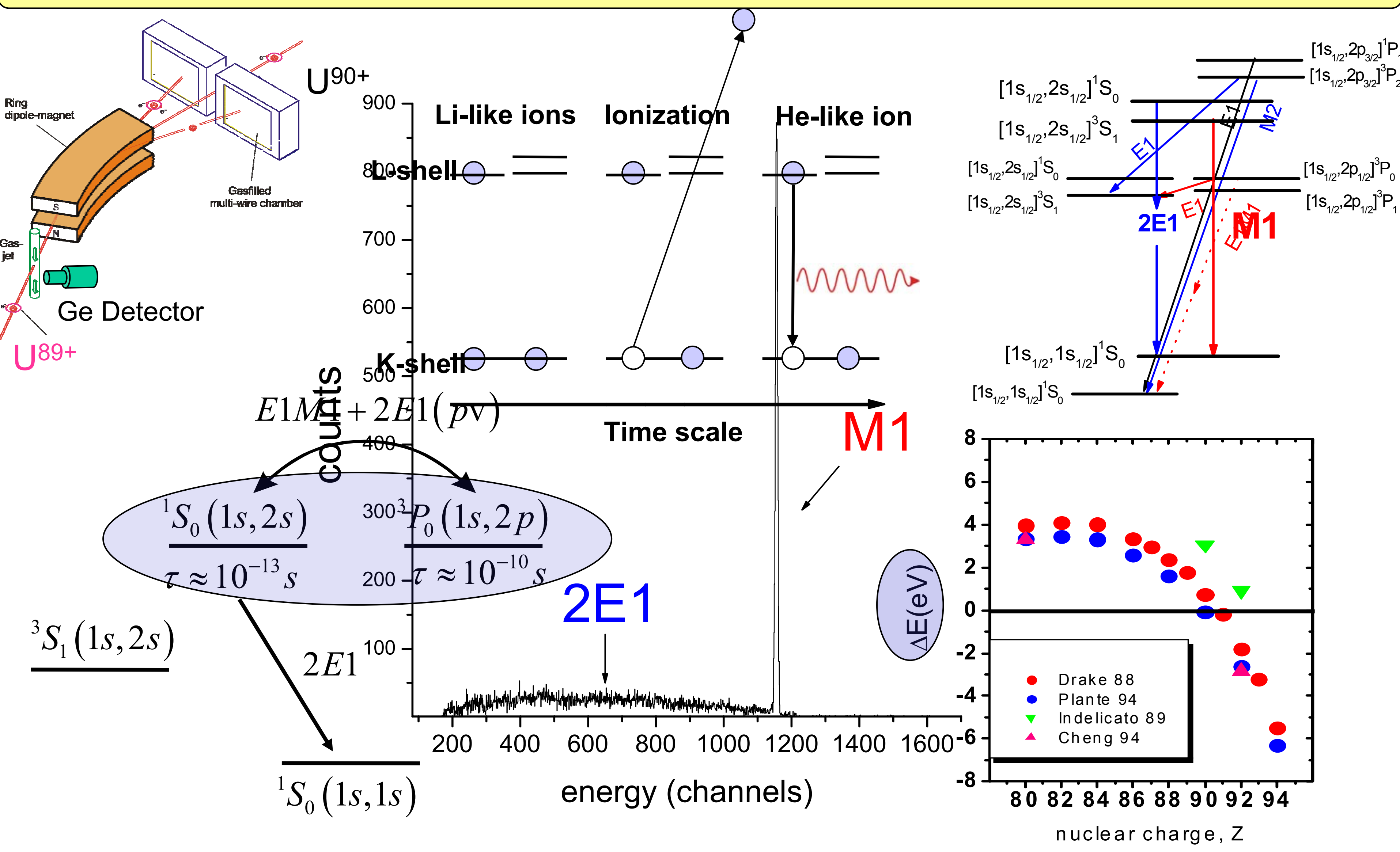


all one electron effects such as the nuclear size contribution cancel out almost completely

A. Gumberidze, PhD Thesis 2003, PRL (2004)

Selective Production of the Two-Photon Decay

Isolation of s-states in He-like heavy ions: Two-photon decay



The HITRAP Project @ GSI

UNILAC

11.4 MeV/u

U^{73+}

experiments for slow particles

post-decelerator

experiments with particles

cooling trap

SIS

400 MeV/u

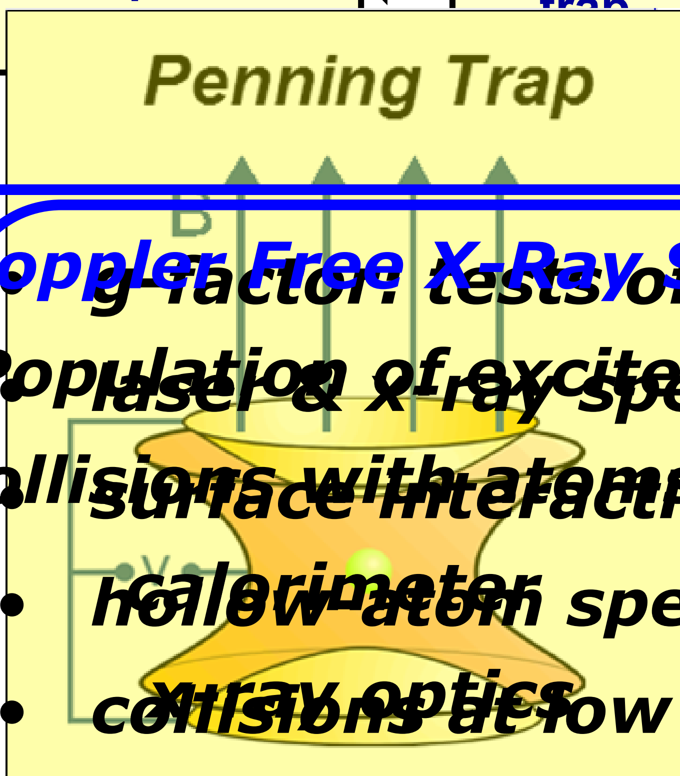
U^{92+}

U^{73+}

stripper target

U^{92+}

ESR



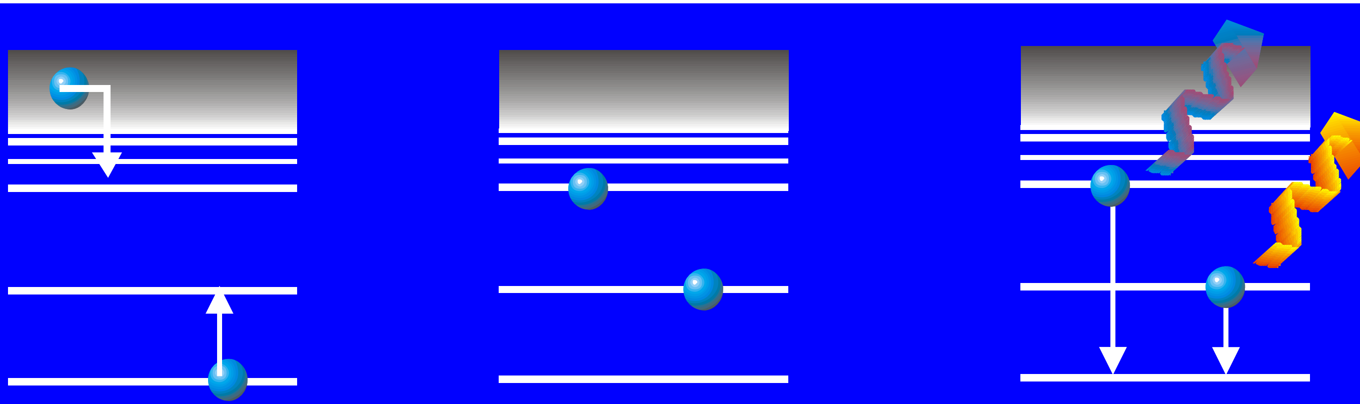
Doppler Free X-Ray Spectroscopy

Population of excited states by collisions with atoms and electrons

- calorimeter
- x-ray optics

- g-factor: tests of QED
- laser & x-ray spectroscopy
- surface interactions
- hollow atom spectroscopy
- collisions at low velocities

Few-Electron Systems: Dielectronic Recombination



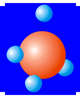
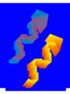
$$A^{q+} + e^{-} \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + n \cdot h\nu$$

Dielectronic Capture (DC)

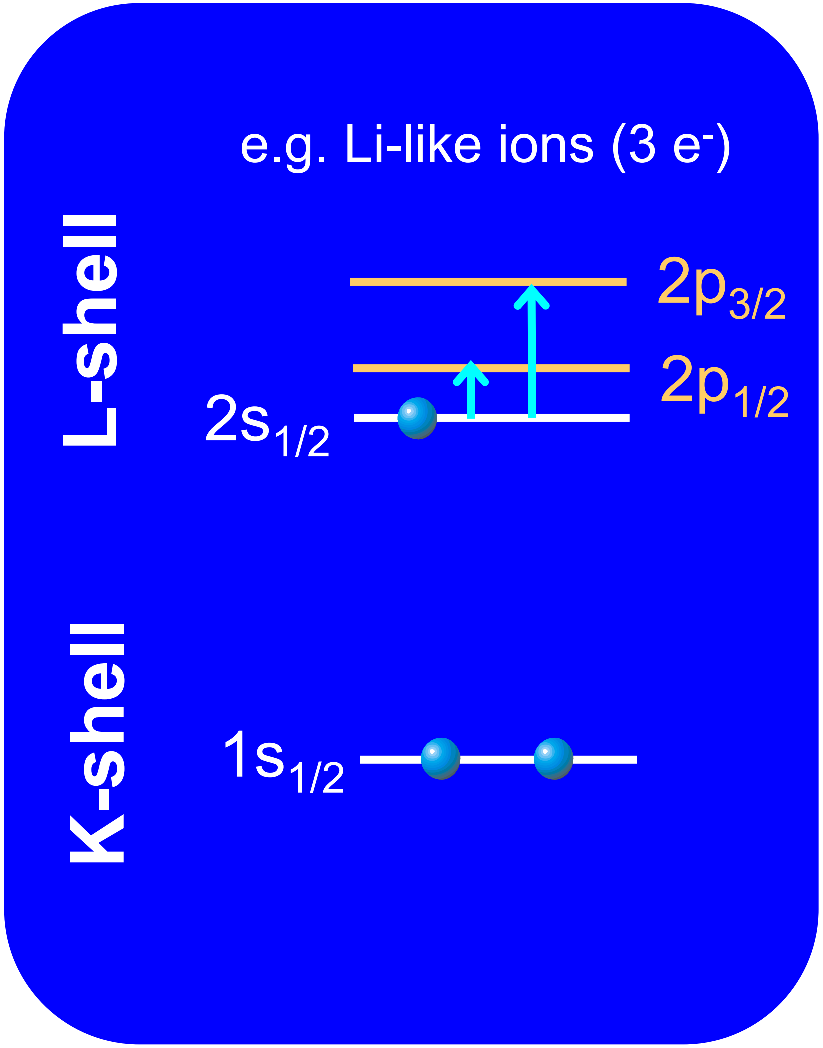
(time-reverse to autoionization

Radiative Stabilization

(in competition to autoionization)

two observables: recombined ion  or photons  (e.g. EBIT, RTE @ Gasjet)

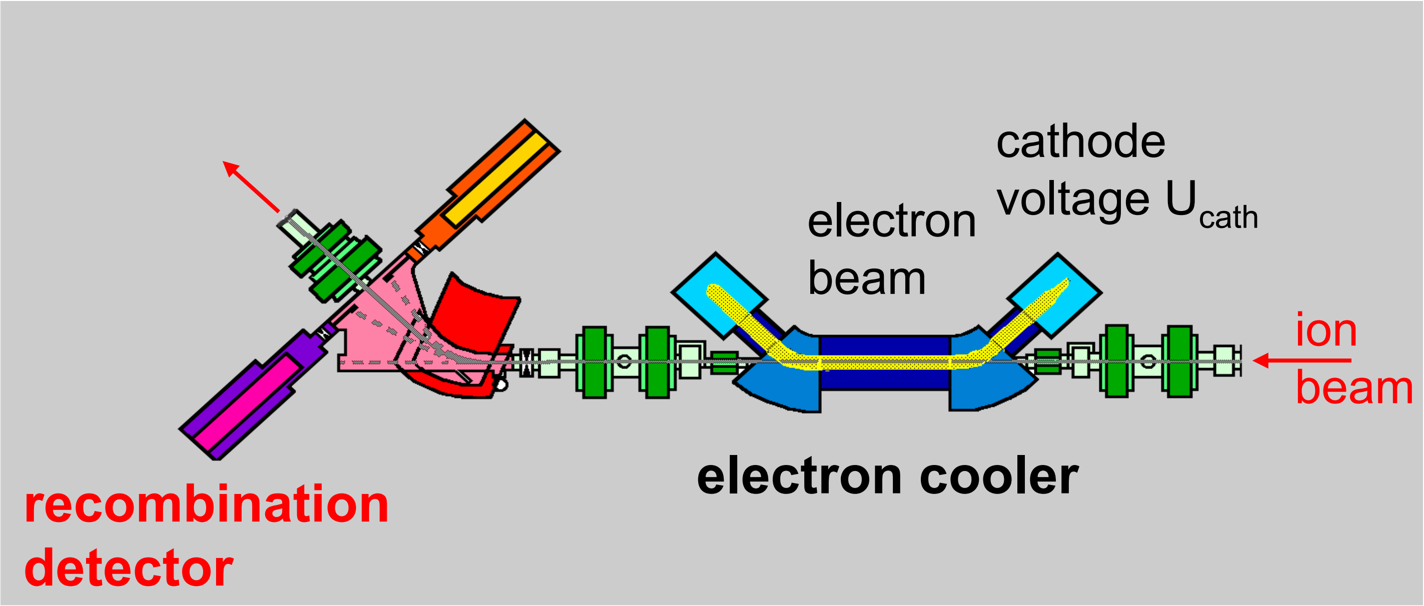
Why Investigate L-shell Ions (Li-like, Be-like,...)?



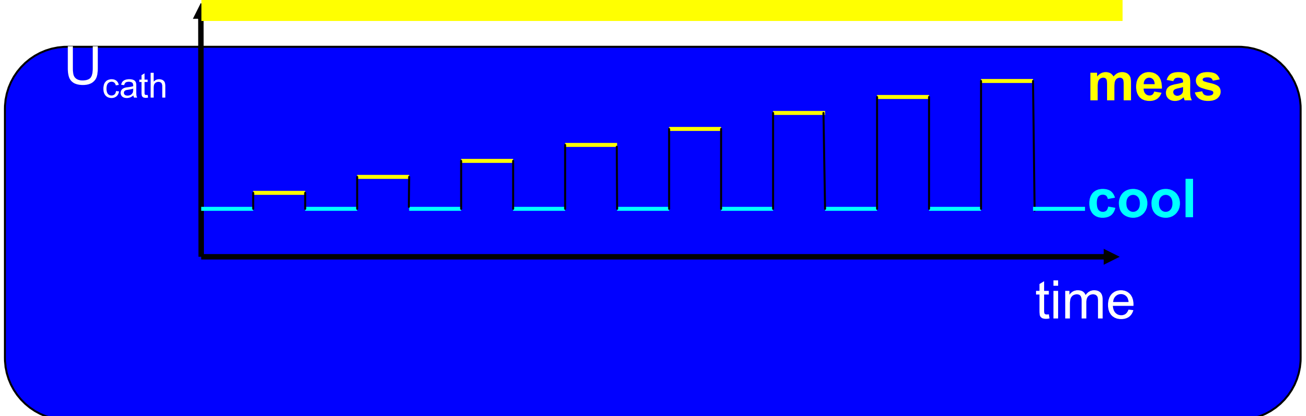
- simplest atomic systems with „low-energy“ intra-shell transitions ($\Delta n = 0$)
- large contributions from QED and nuclear size

  $\Rightarrow$ high sensitivity
- simple to describe theoretically, e.g. Li-like
  $\Rightarrow$ 1 „valance“ electron with small contributions from e-e-interaction

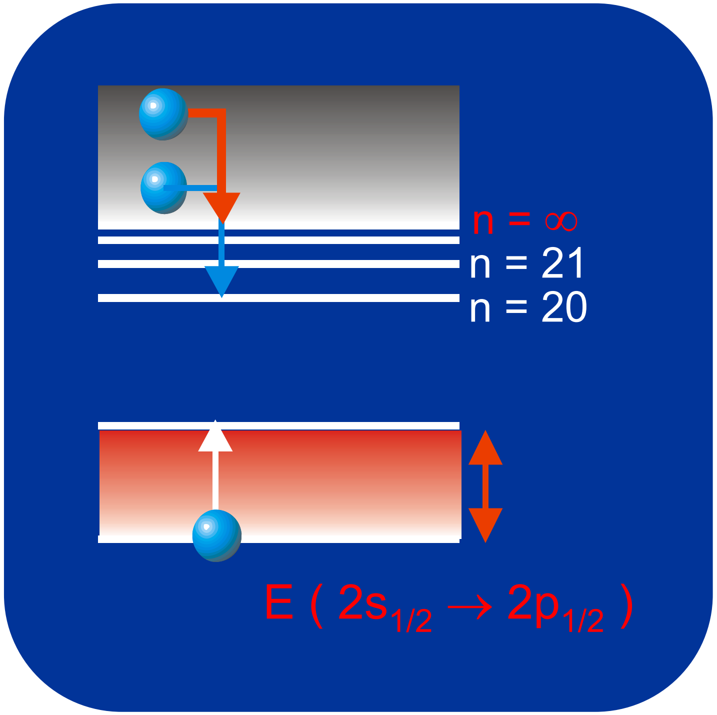
Dielectronic Recombination: The Technique

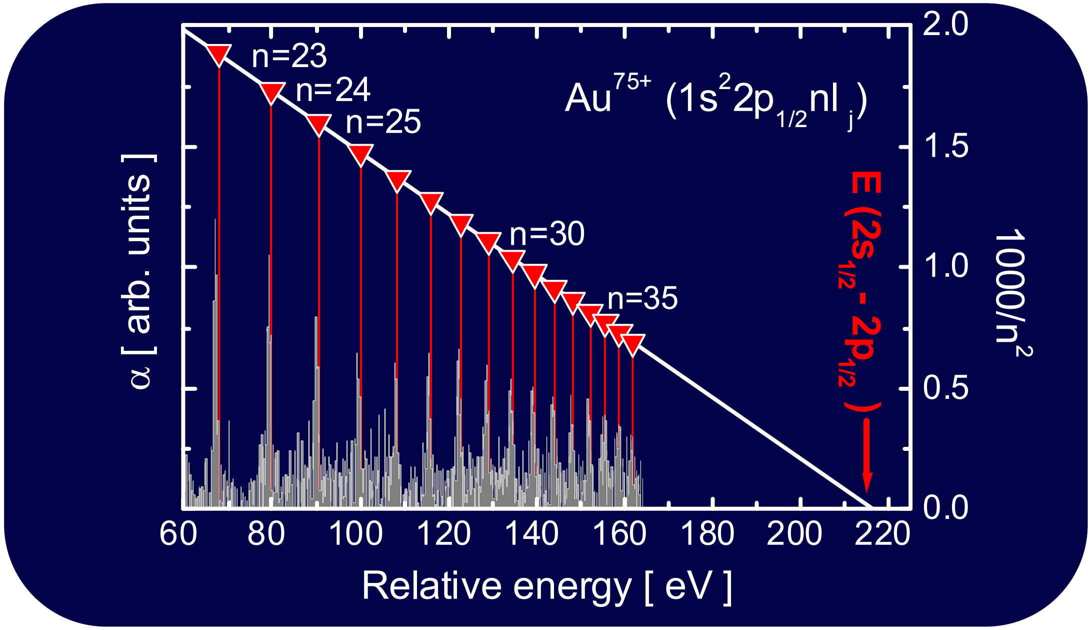


merged-beams rate coefficient: $\alpha = \langle \sigma \mathbf{v} \rangle$



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





idea:
extrapolation to the series limit

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

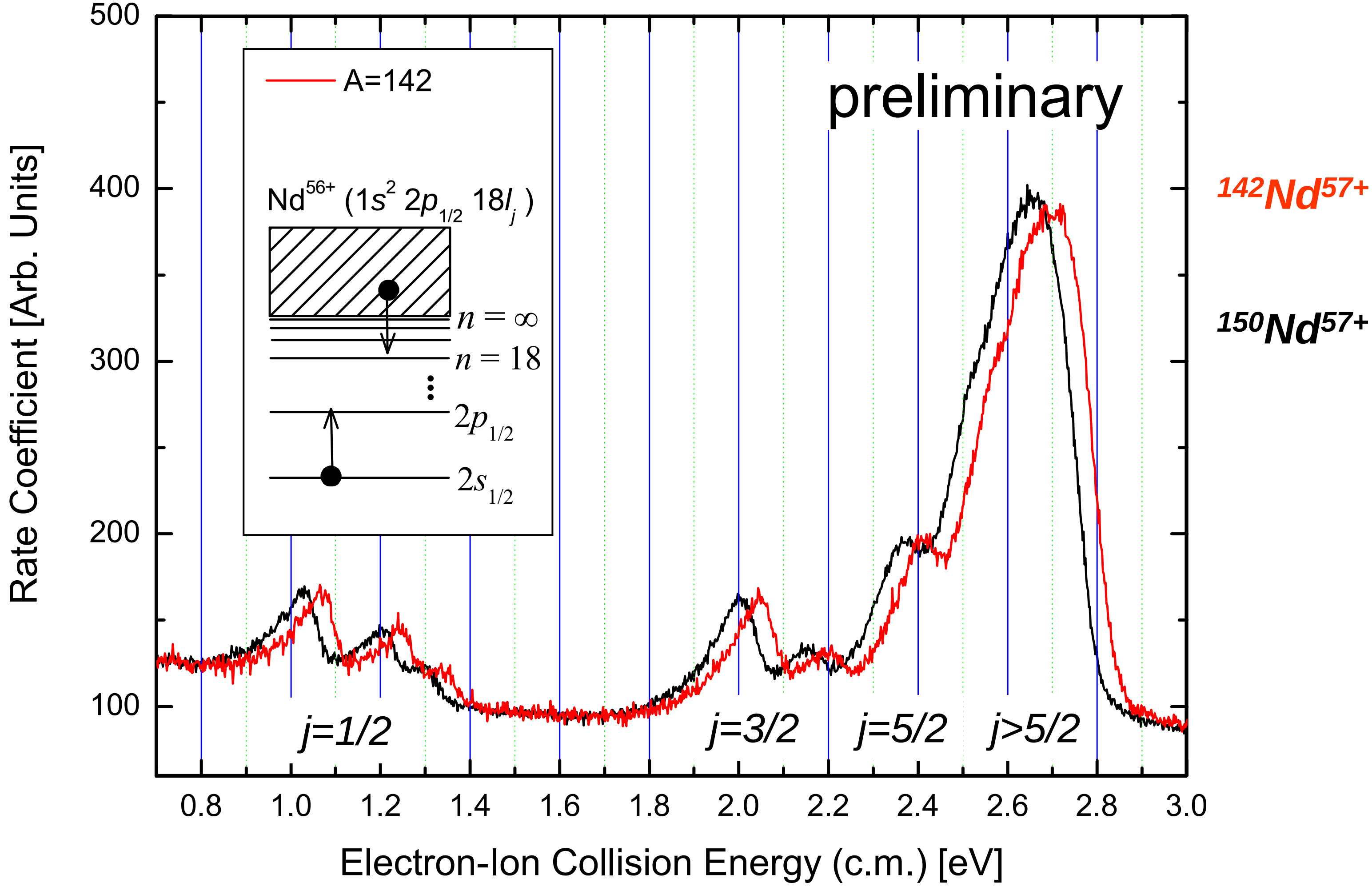
Au^{76+}	Pb^{79+}	U^{89+}
216.167(29)(67) eV	230.650(30)(51) eV	280.516(34)(65) eV

C. Brandau et al., PRL 91, (2003) 073202

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

by Means Dielectronic Recombination

(First Preliminary Results of the Aug 2005 Beamtime)



C. Brandau et al.

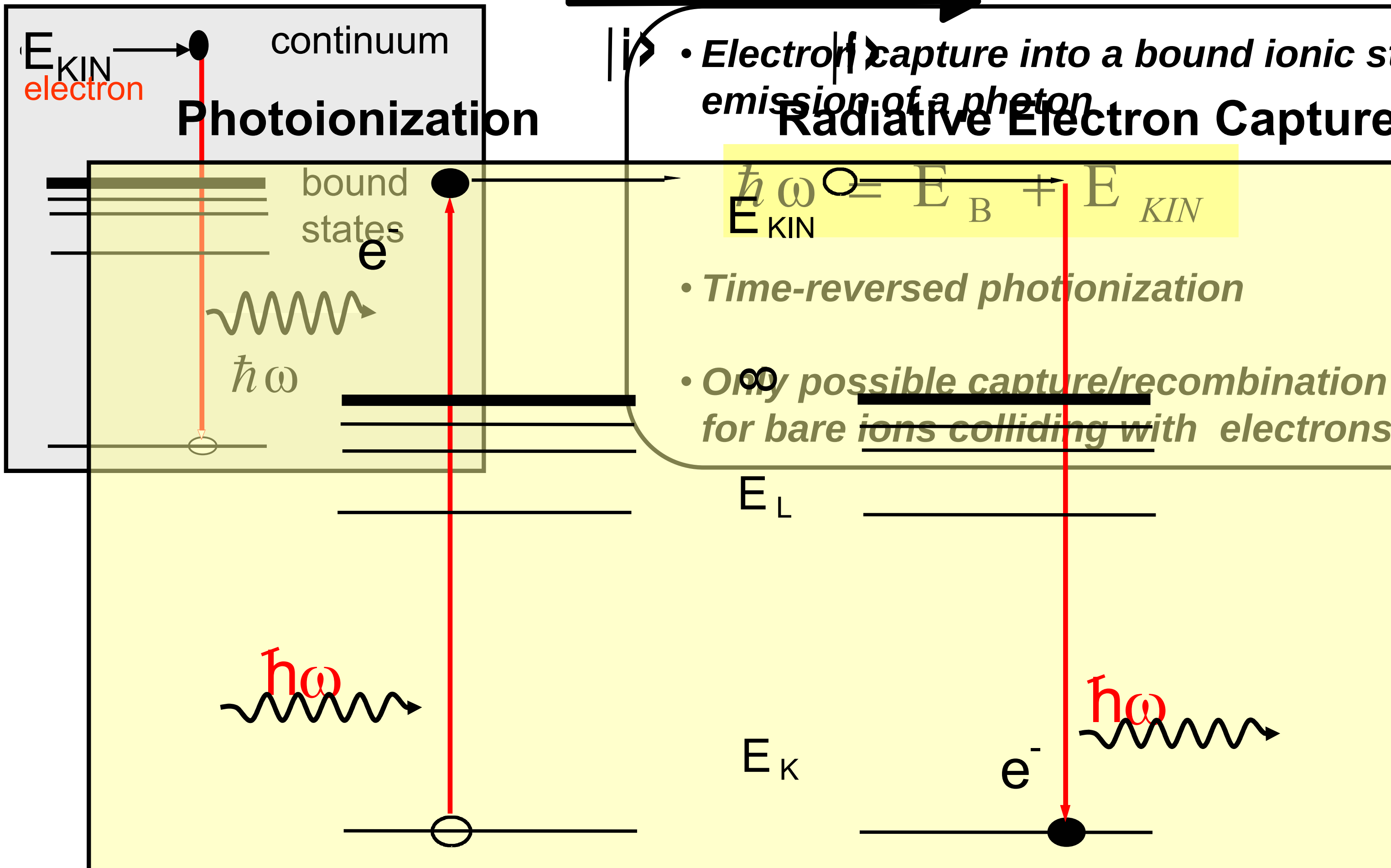
II Dynamics in Strong Fields

Radiative Recombination/Electron Capture

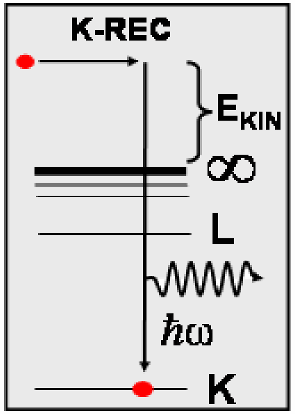
- *Electron capture into a bound ionic state by emission of a photon*

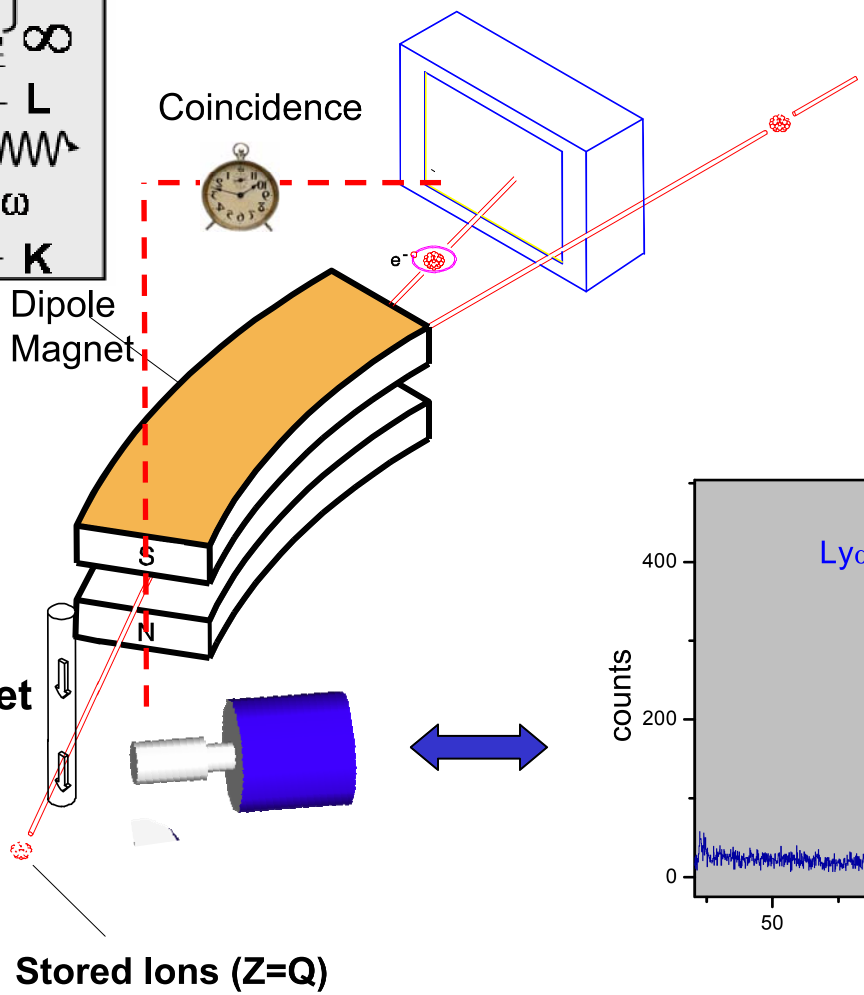
$$\hbar\omega = E_B + E_{KIN}$$

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



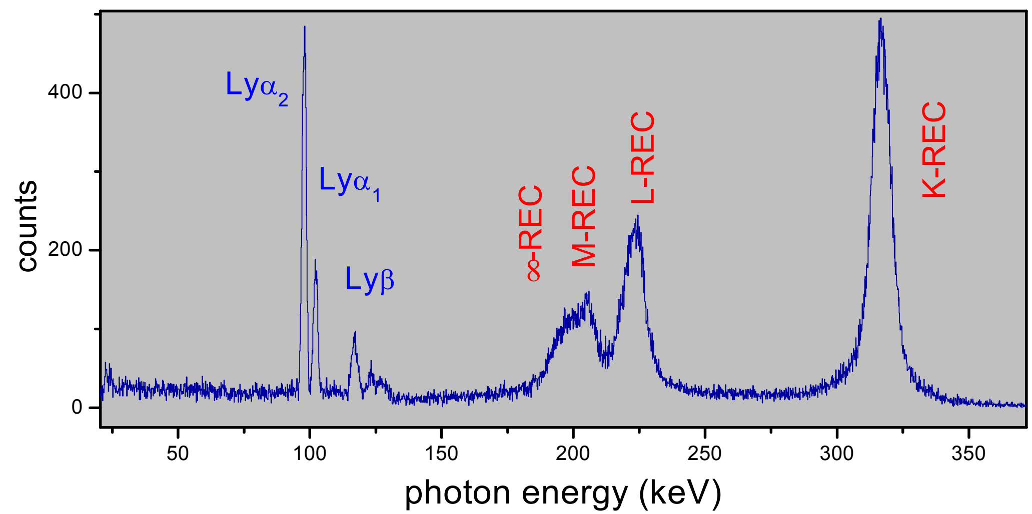
Experiments at the Jet-Target





Electron transfer from the target atom into the HCI

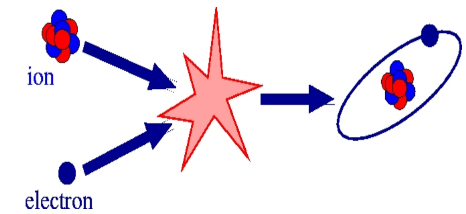
$$Z^{Q+} + e^{-} \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$$



II Dynamics: Radiative Recombination

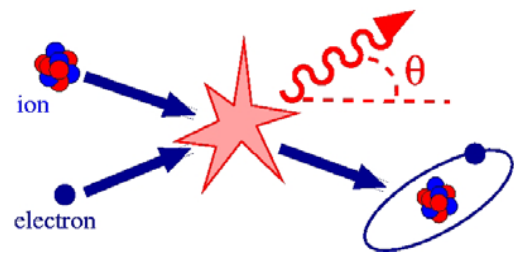
Established

- **Total Electron Capture Cross Sections**



$$\sigma \sim \sum_{polarization} d\Omega \left|M\right|^2$$

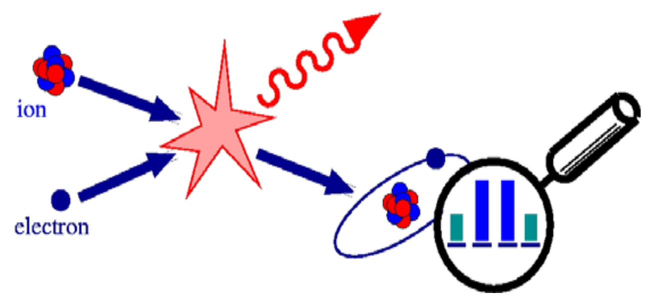
- **Photon Angular Distributions**



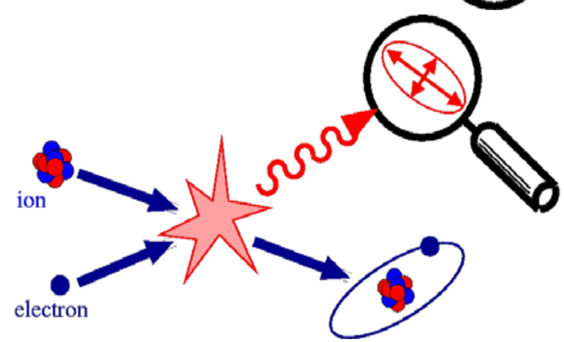
$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} \left|M\right|^2$$

New Directions

- **Alignment**



- **Polarization**

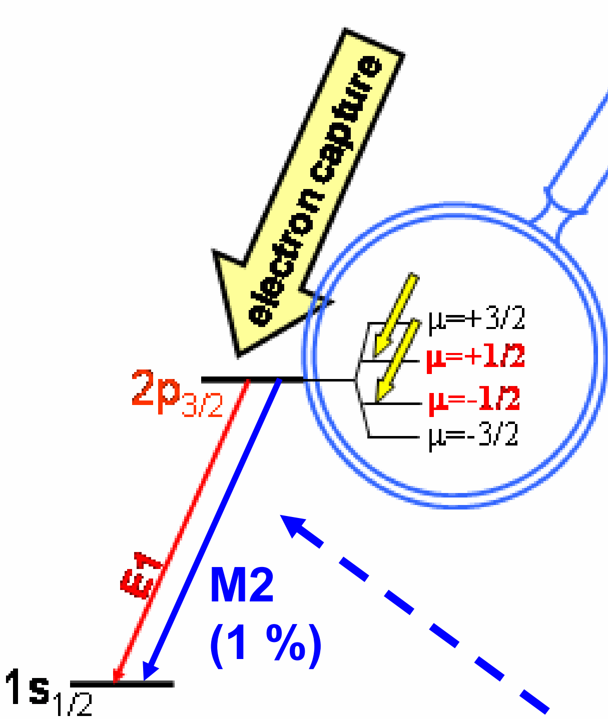


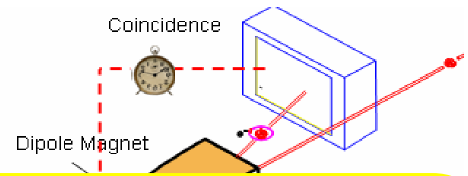
$$\sim \left|M\right|^2$$

No summation over polarization states !

Alignment Studies: Non-statistical population of magnetic sublevels

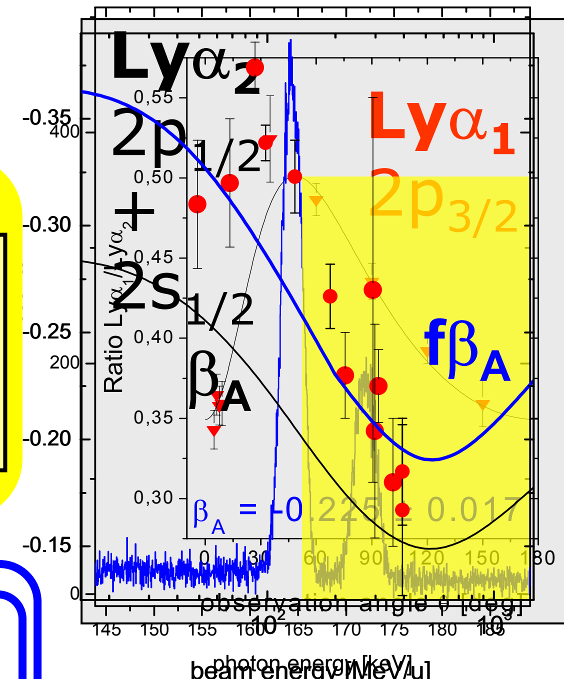
multipole mixing:
M2 contribution to the 2p3/2 decay





M2 contribution

$$\frac{\Gamma_{M2}}{\Gamma_{E1}} = 0.0062 \pm 0.001$$



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

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

Alignment Parameter

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

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

A. Orsic-Muthig PhD Thesis 2004

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

II Atomic Collisions of Cooled, Heavy Ions

Established

- **Total Electron Capture Cross Sections**

$$\sigma \sim \sum_{polarization} d\Omega |M|^2$$

- **Photon Angular Distributions**

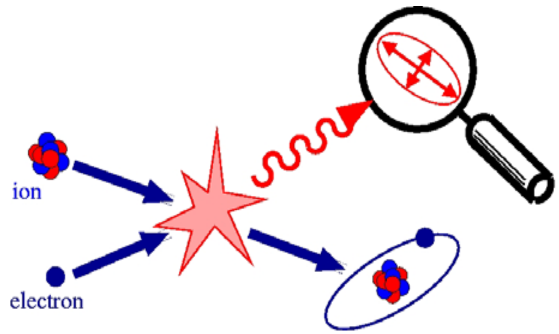
$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

New Directions

- **Alignment**

$$\sim |M|^2$$

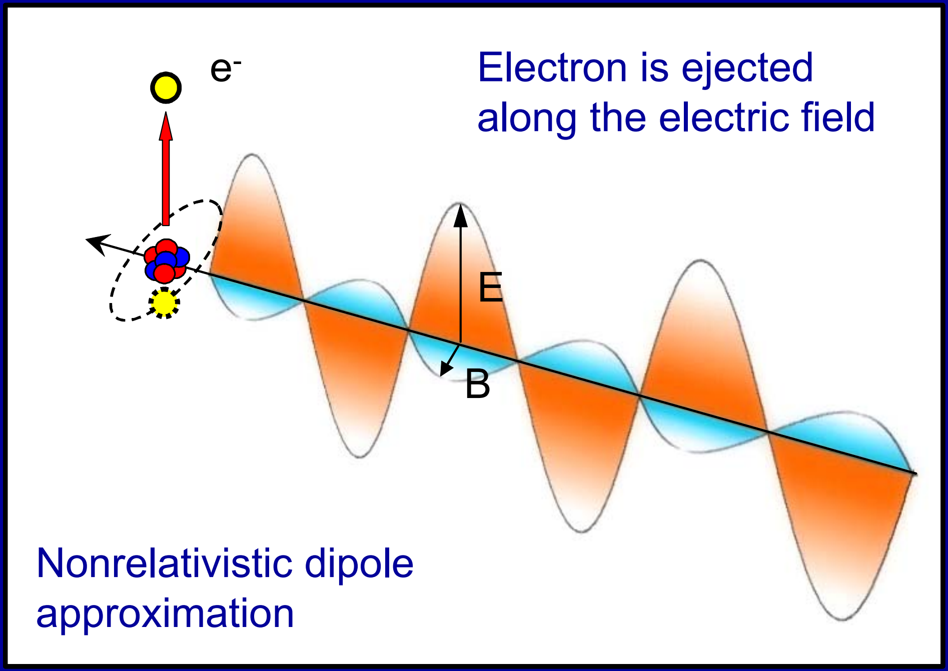
- **Polarization**



$$\sim |M|^2$$

No summation over polarization states !

Photon Polarization



Photoionization

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

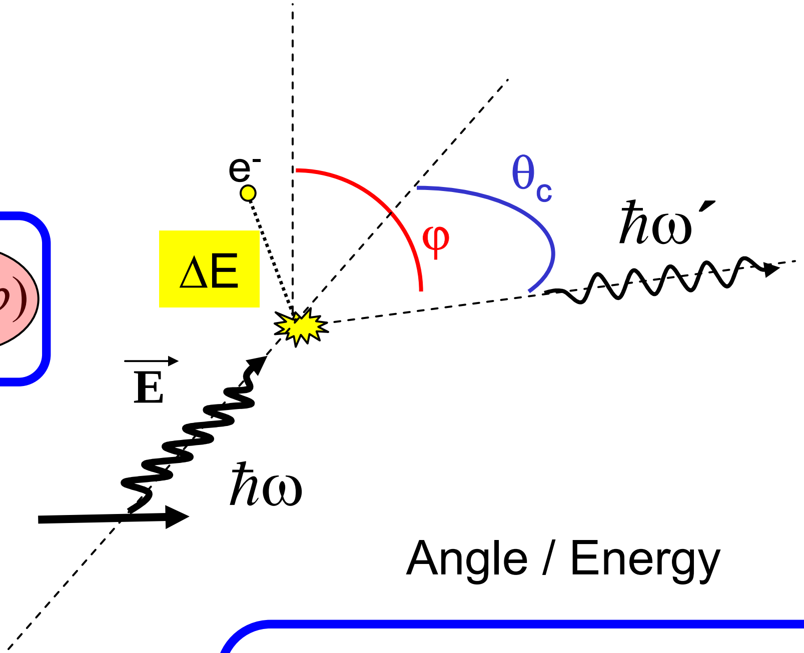
How to Measure Polarization for Hard X-Rays

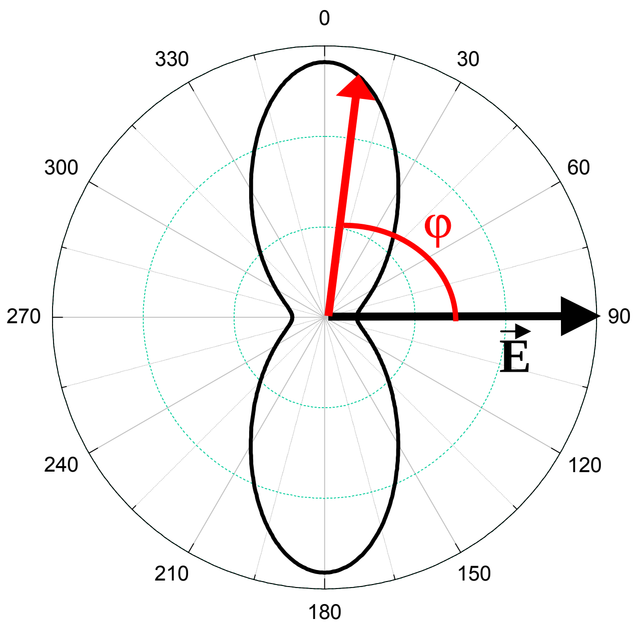
Polarization Measurement via Compton scattering

Linearly polarized radiation

Klein-Nishina equation

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





Angle / Energy

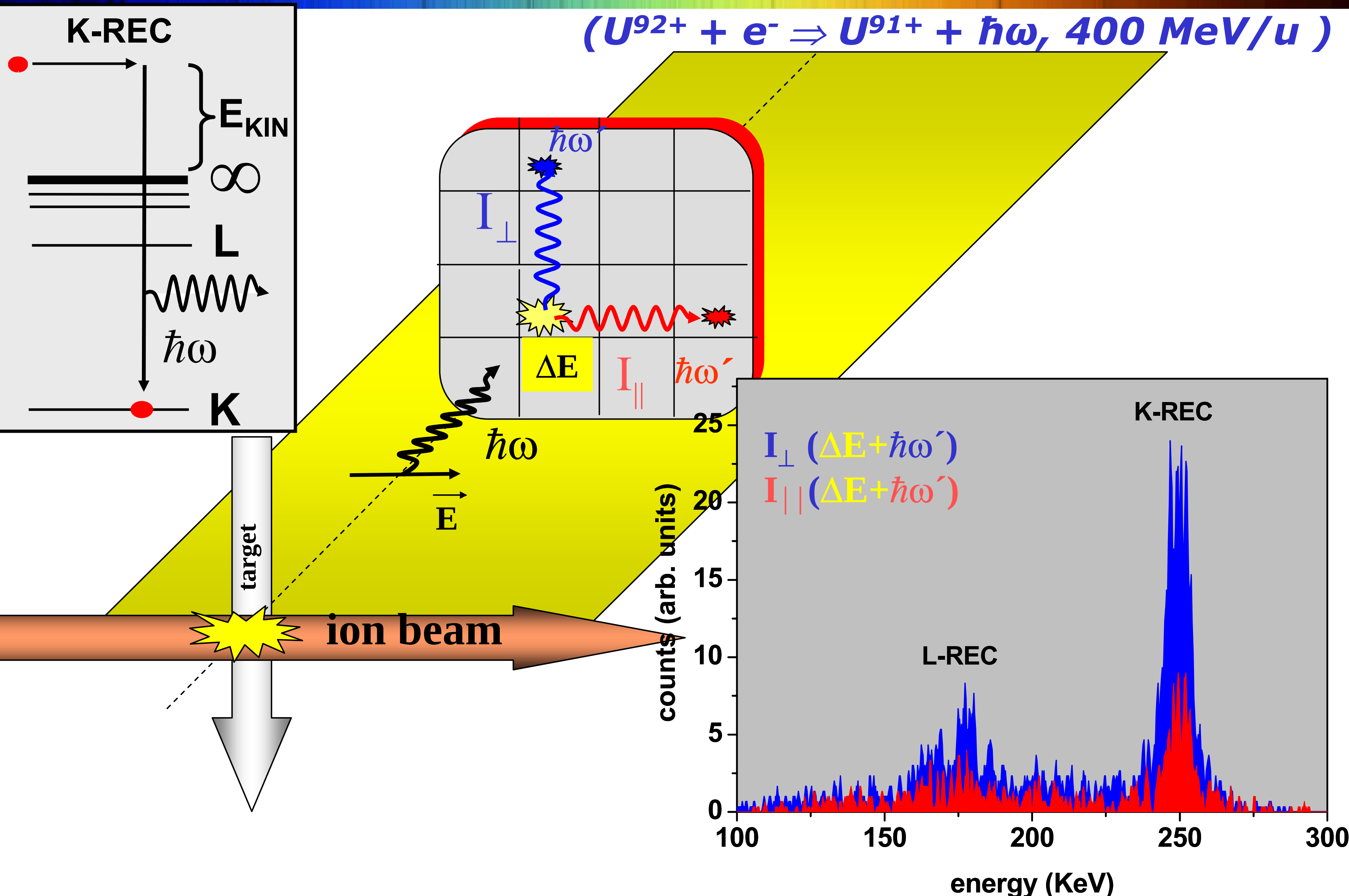
$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_e c^2}(1 - \cos\theta_c)}$$

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

ΔE : electron recoil energy

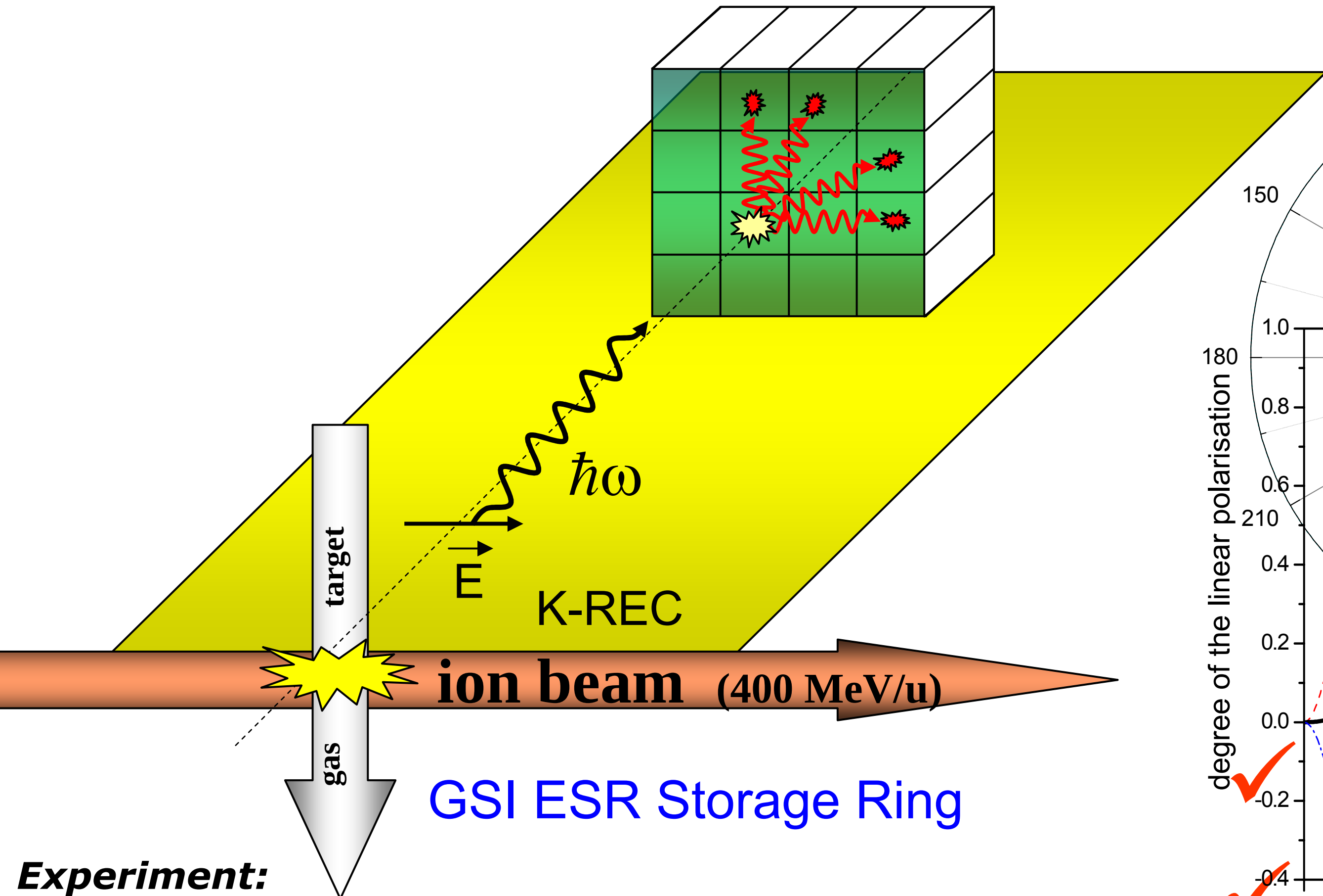
Polarization Experiment

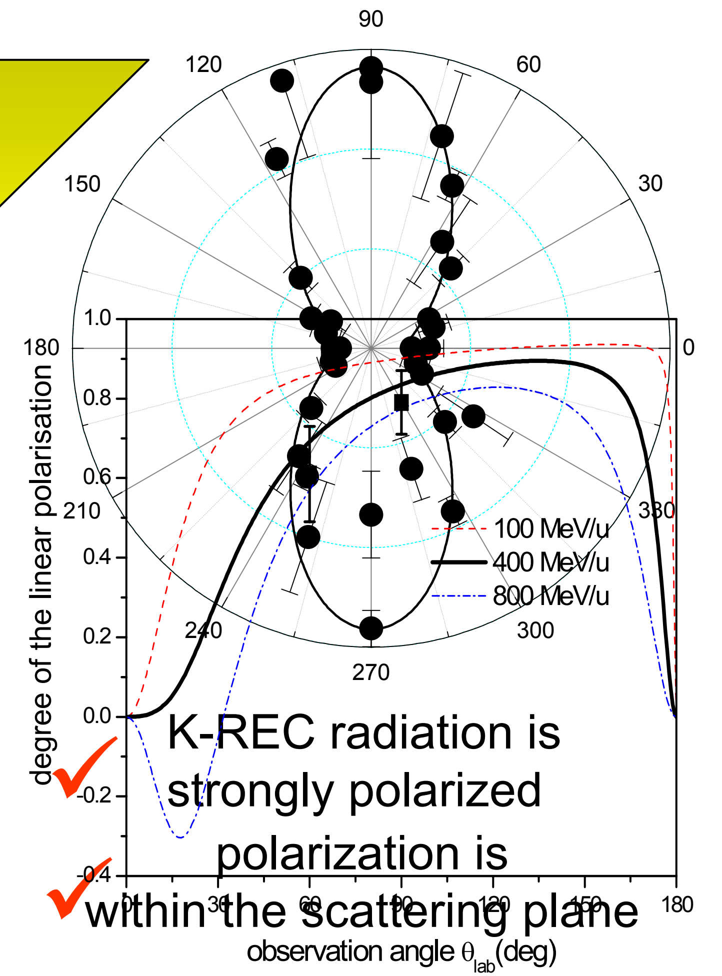
($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$, 400 MeV/u)



Experiment

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





✓ K-REC radiation is strongly polarized

✓ polarization is within the scattering plane

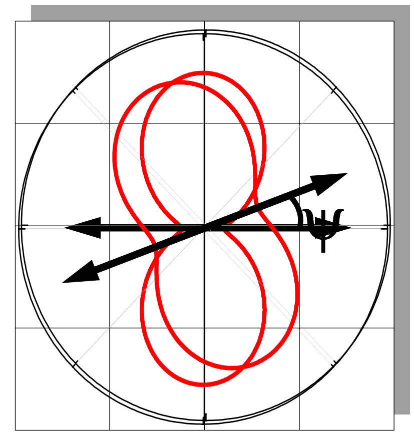
Experiment:
Tachenov et al.,
PHD Thesis 2005
Submitted to PRL, 2006

Exact Relativistic Treatment
Eichler et al., PRA, 2002
Surzykov et al., PRA, 2002

Spin Polarized Ion Beams

for spin polarized ions, the polarization plane and scattering plane are not equal for spin aligned ion beams

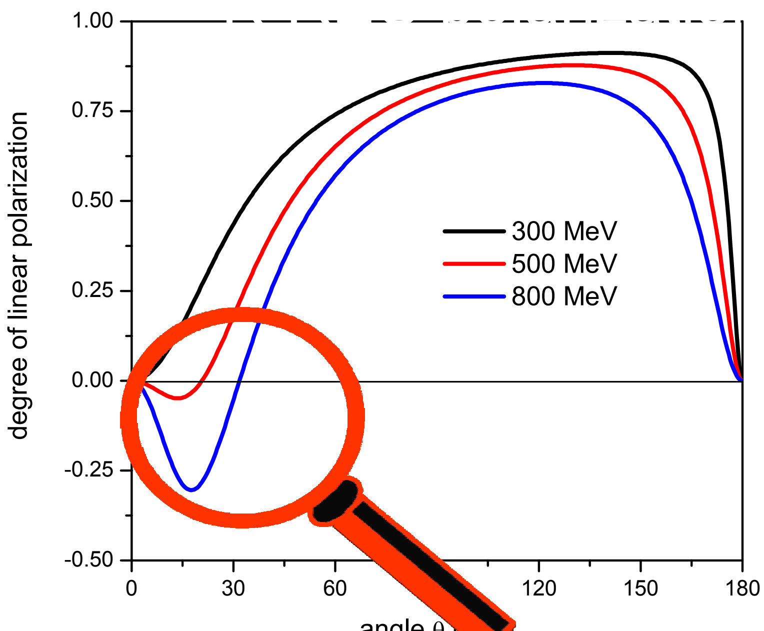
predictions by A.Surzhykov et al., PRL 94, 203202 (2005)



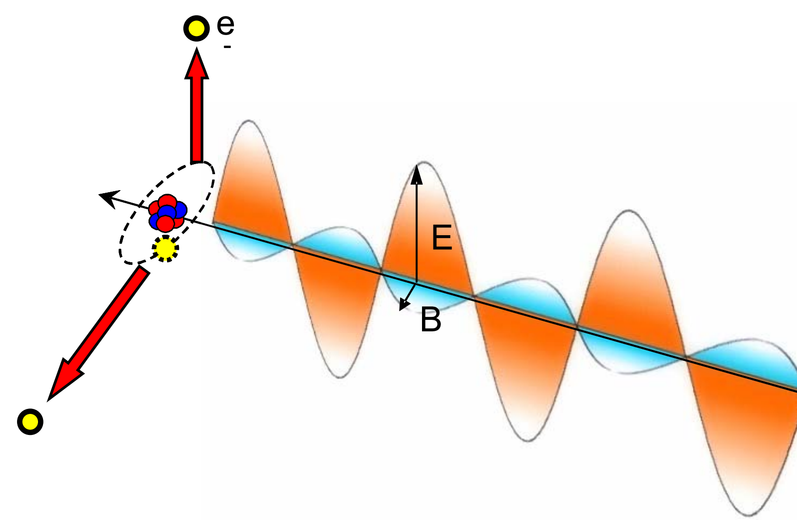
<spin polarized ion beam>

$\psi \Rightarrow$ degree of beam polarization

Crossover Phenomena



Photoionization



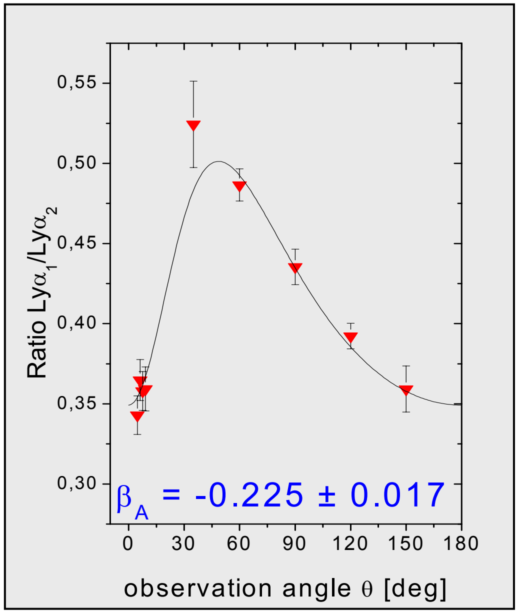
Polarization Spectroscopy of Photon-Matter Interaction

main photon matter interaction processes with distinct photon polarization features

Synchrotron Radiation, Bremsstrahlung, Recombination, Inverse Compton Scattering

Atomic Structure (bound-bound transitions)

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

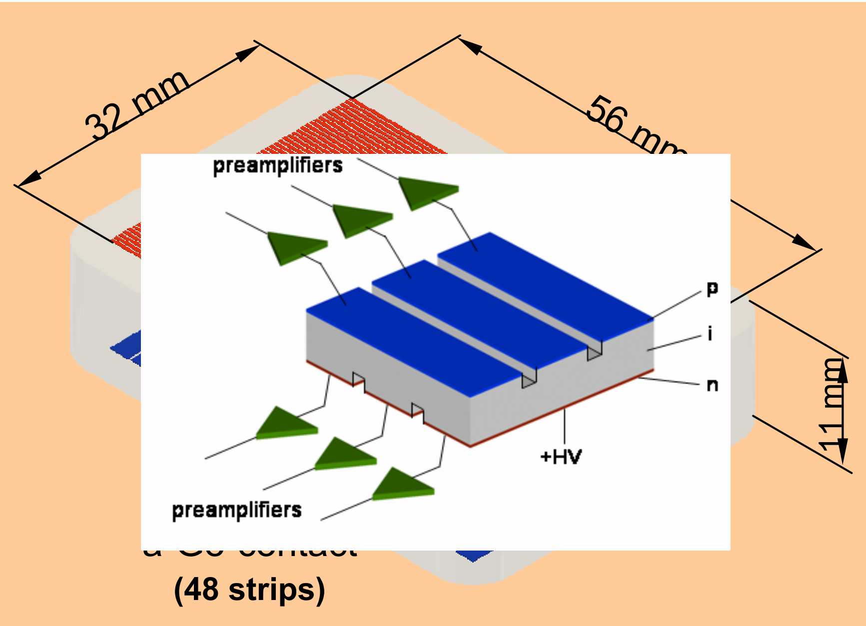


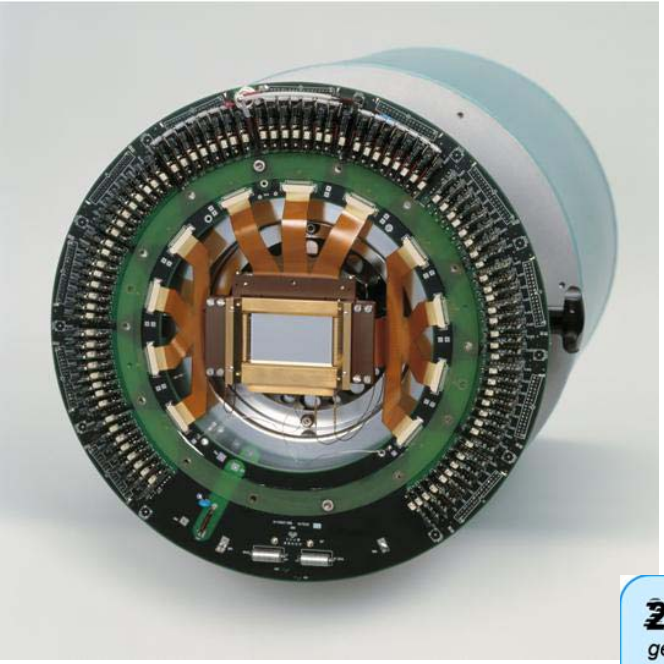
III Development of Position Sensitive X-Ray Detectors

How accurately can we measure linear polarization ?

2D μSTRIP planar detector systems for future precision experiments and Compton polarimetry

energy resolution – timing - 2D/3D position sensitiviy (100 μm)





Front: 128 strips pitch ~250μm

Back: 48 strips pitch ~1167μm

Equivalent to 6144 pixel

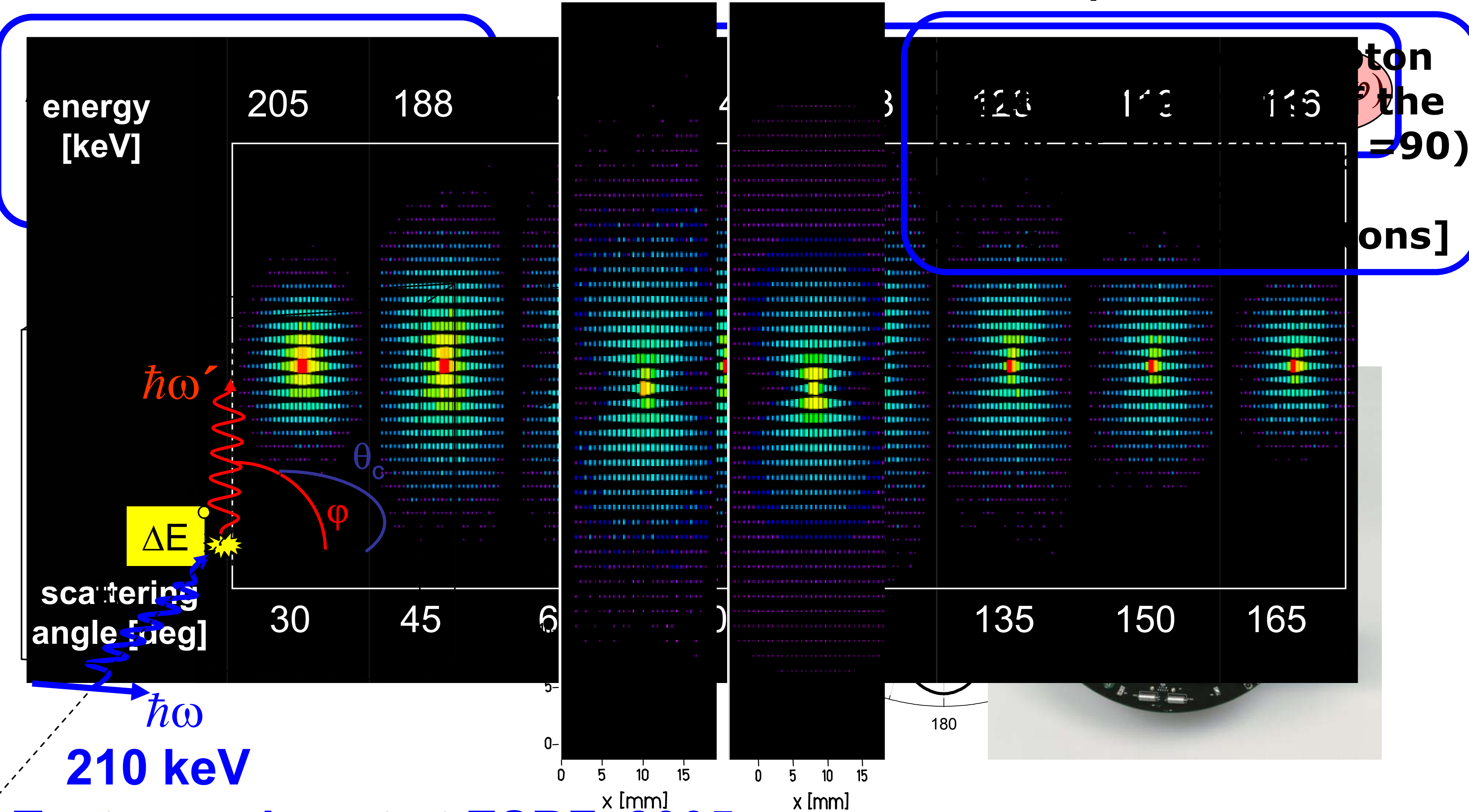
2D μSTRIP germanium detector

GSI

Polarization Spectroscopy of Photon-Matter Interaction

Angle / Energy

Experiment Theory Klein-Nishina equation



Test experiment at ESRF, 2005

Compton Imager and Polarimeter for Hard X-Rays

Similar projects based on planar position sensitive germanium and Si(Li) detectors

Compton imager and polarimeter at Naval Research Lab. and LBL
(space missions,
Kroeger et al., Burke et al.)

Compton imager
(medical imaging,
Valenta et al.)

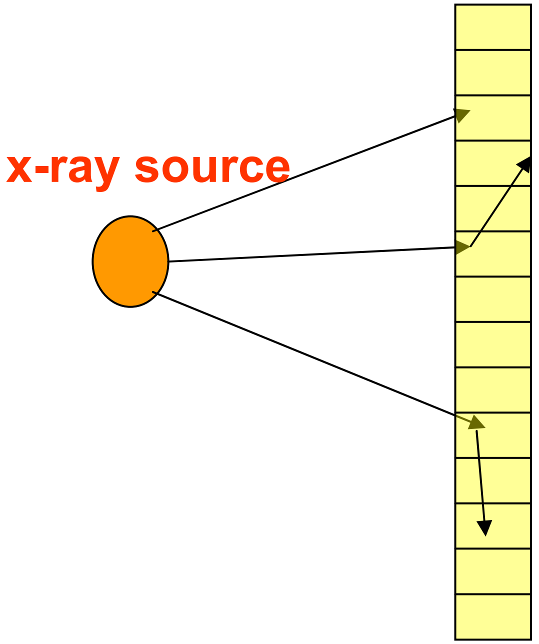
Compton imager at LLNL
(γ-ray imaging,
K. Vetter et al.)

Collimator-Free Compton Camera

- use several interaction points to reconstruct incident angle without use of a collimator

Advantages

- Enhanced efficieny
- Good energy and position resolution
- 3D tomography with a single detector



Summary

Atomic Structure at High-Z

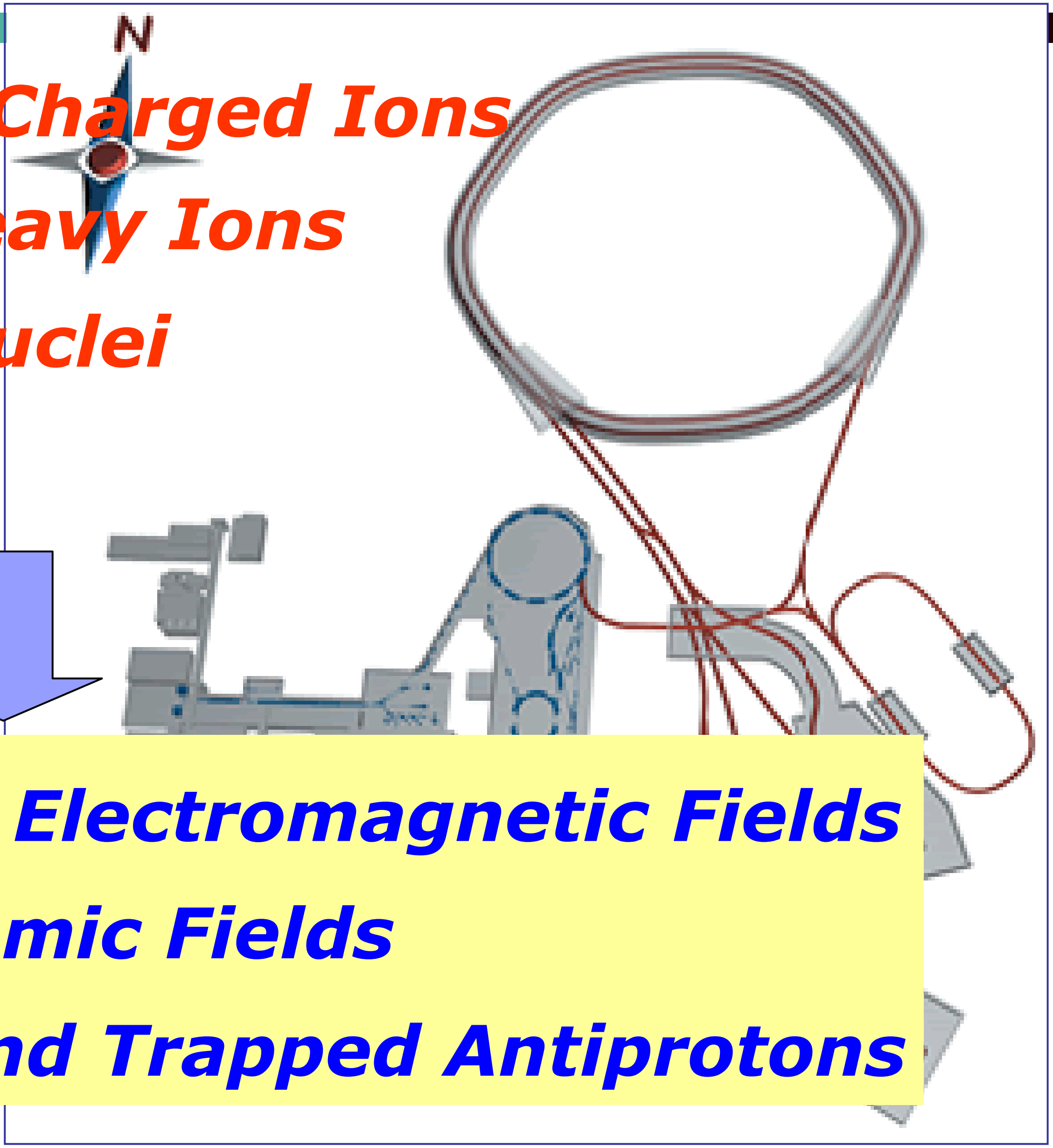
- 1s LS in H-like uranium confirmed on a level of 1%
- further progress towards an absolute accuracy of 1 eV can be expected from high-resolution spectroscopy techniques
- for He-like uranium, a sensitivity on the level of two-electron QED contributions has been achieved
- Dielectronic Recombination has been found to be a precise tool for atomic structure studies
- $\Delta n=0$ resonances are in particular sensitive to nuclear size corrections and may serve as a model independent test of nuclear parameters

Atomic Collisions at High-Z

- elementary atomic processes can uniquely be studied by their time reversal in inverse kinematics
- recombination process reveal structure properties
- basic photon matter interactions can be investigated
- segmented solid state detectors, an excellent tool for polarization studies in the hard x-ray regime
- first polarization studies for radiative recombination studies show that REC is a source of strongly polarized radiation
- using Si(Li) strip detectors, such studies can be extended to inner-shell transitions

Challenges and Opportunities: Atomic Physics at FAIR

- *Heavy Highly Charged Ions*
- *Relativistic Heavy Ions*
- *Radioactive Nuclei*
- *Antiprotons*

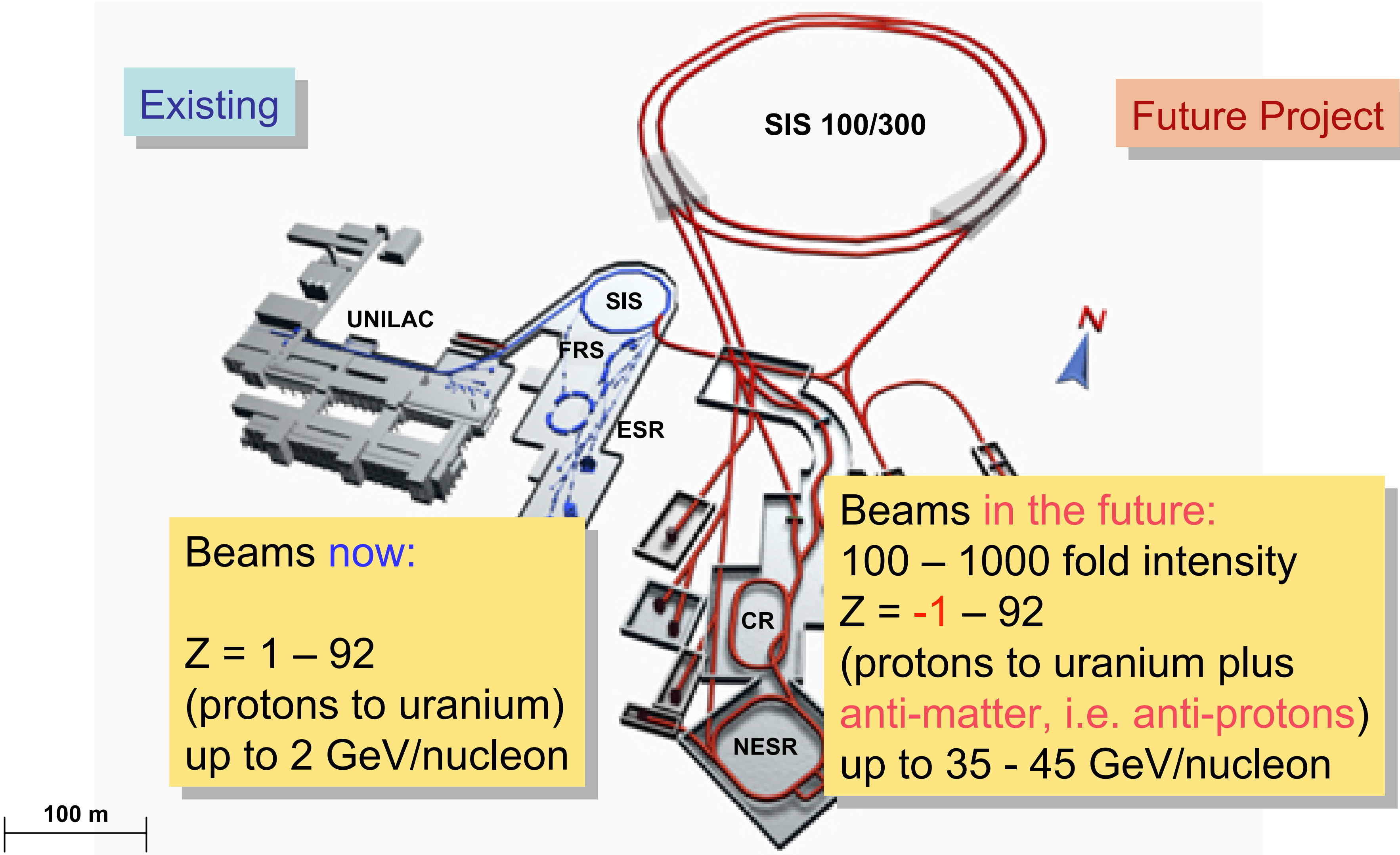


I. Extreme Static Electromagnetic Fields

II. Extreme Dynamic Fields

III. Ultra-Slow and Trapped Antiprotons

The Future International Facility at GSI: Beams of Ions and Antiprotons



Beams now:

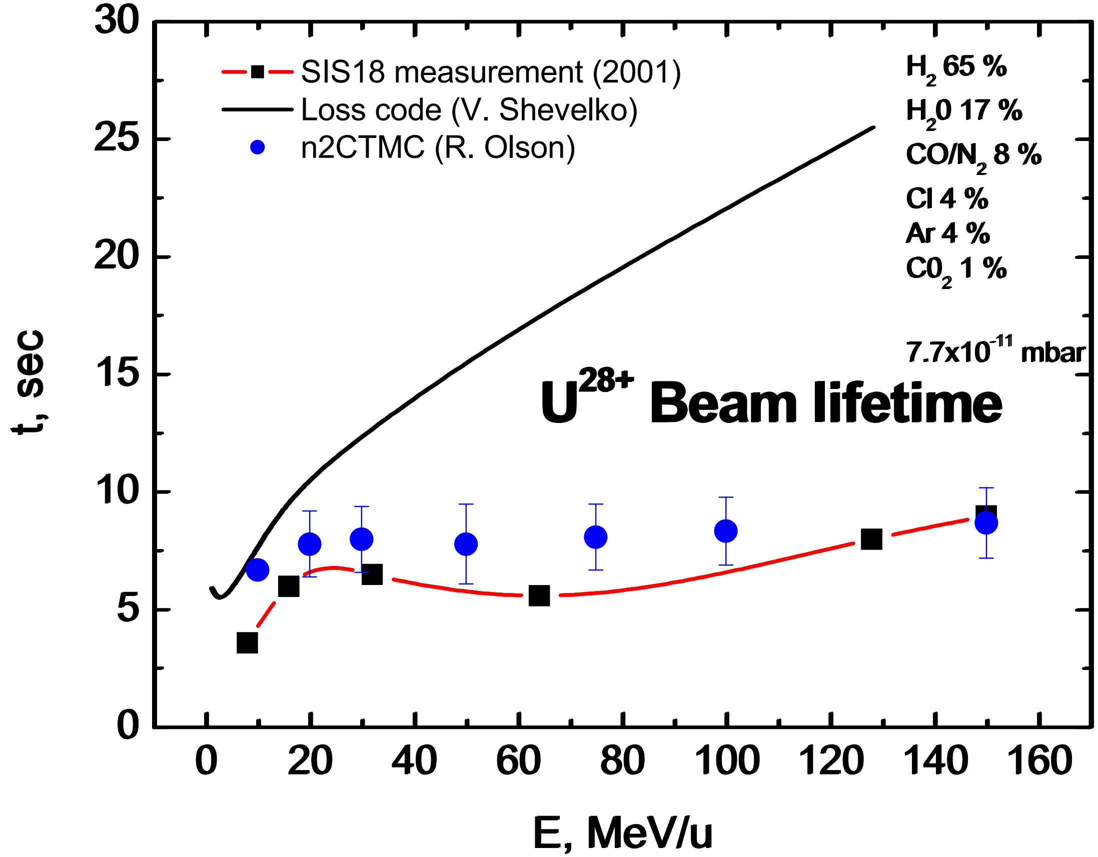
Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon

Beams in the future:
100 – 1000 fold intensity
Z = -1 – 92
(protons to uranium plus anti-matter, i.e. anti-protons)
up to 35 - 45 GeV/nucleon

Accelerator Issues: Charge Changing Collisions

data are needed for

heavy ion driven fusion
RHIC
GSI



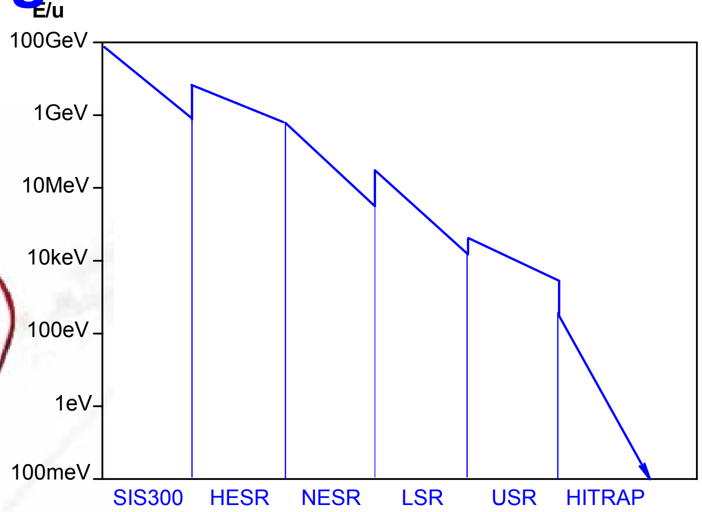
related projects

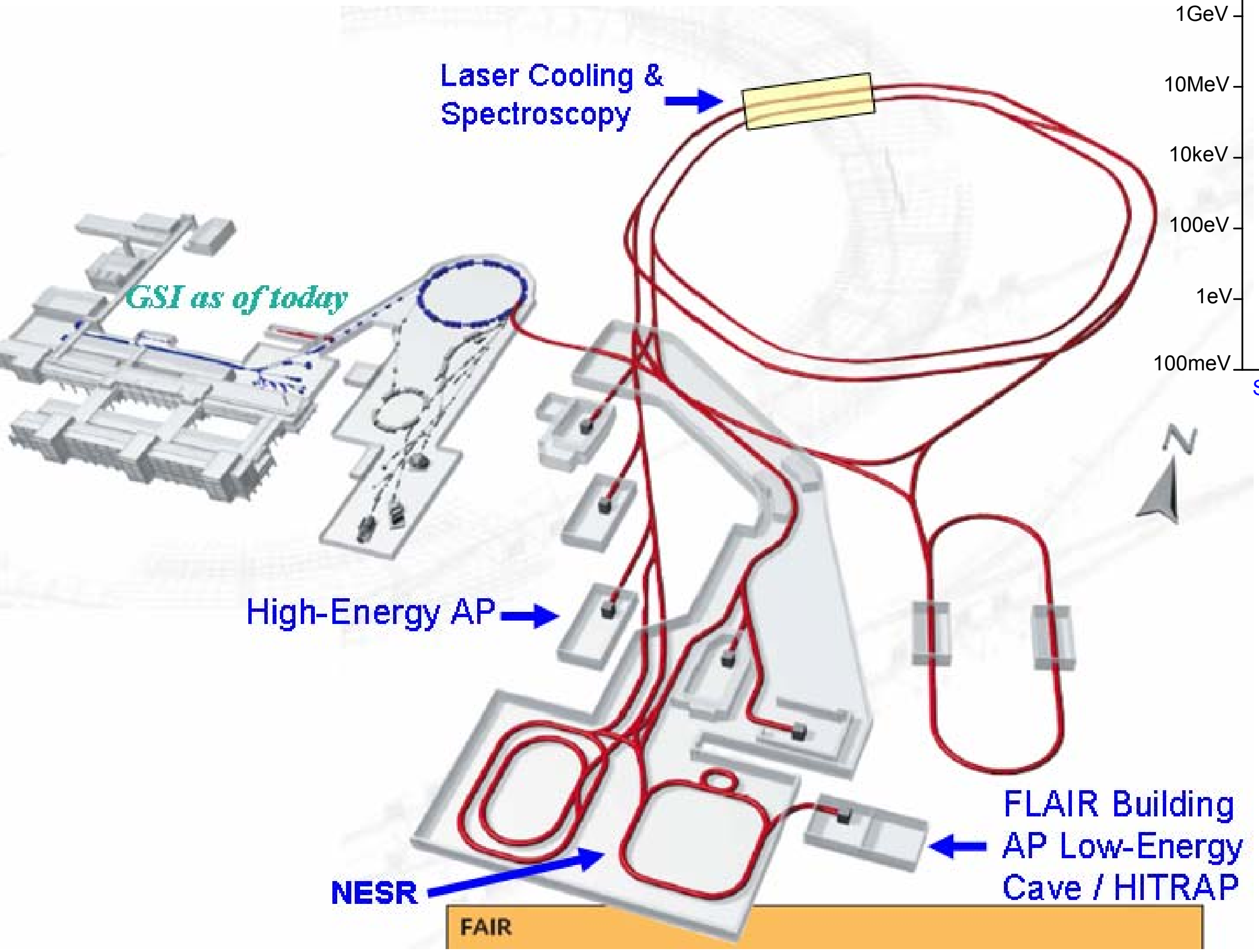
charge state distributions for relativistic ions

luminosity for radioactive ion beams at storage rings

The Facilities for Atomic Physics @ FAIR

From Highly Relativistic Energies to Rest

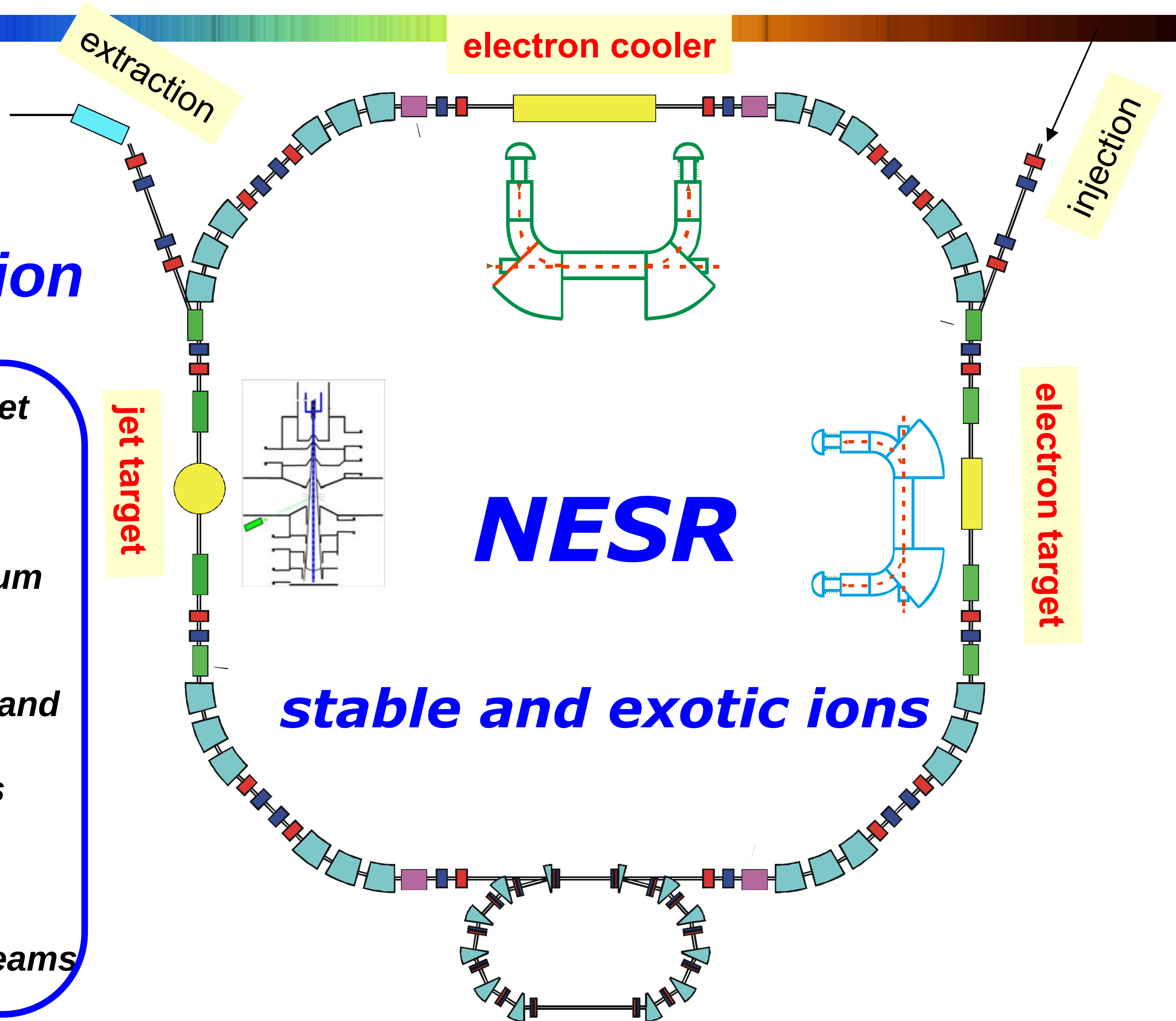




The New Experimental Storage Ring NESR

Novel Instrumentation

- *Ultracold Electron Target*
- *Micro-Jet Target*
- *In-Ring Recoil Momentum Microscope*
- *High Resolution X-Ray and Electron Spectrometers*
- *X-Ray Laser*
- *Highly Intense Laser Beams*



The SPARC-Collaboration: Atomic Physics with Heavy Stable and Radioactive Ions

SPARC
Stored Particle Atomic Research Collaboration

The FLAIR-Collaboration: Atomic Physics with Slow Antiprotons

FLAIR
Facility for Low-Energy Anti-Protons and Ion Research

Challenges and Opportunities - Atomic Physics at FAIR