STRONG FIELD ATOMIC PHYSICS AT GSI/FAIR: STATUS AND OUTLOOK

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GSI and University of Heidelberg

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG
PHYSIKALISCHES INSTITUT

sparc
Stored Particles Atomic Physics Research Collaboration

The Collaboration

Grenoble | Mainz | Paris | Frankfurt | Heidelberg

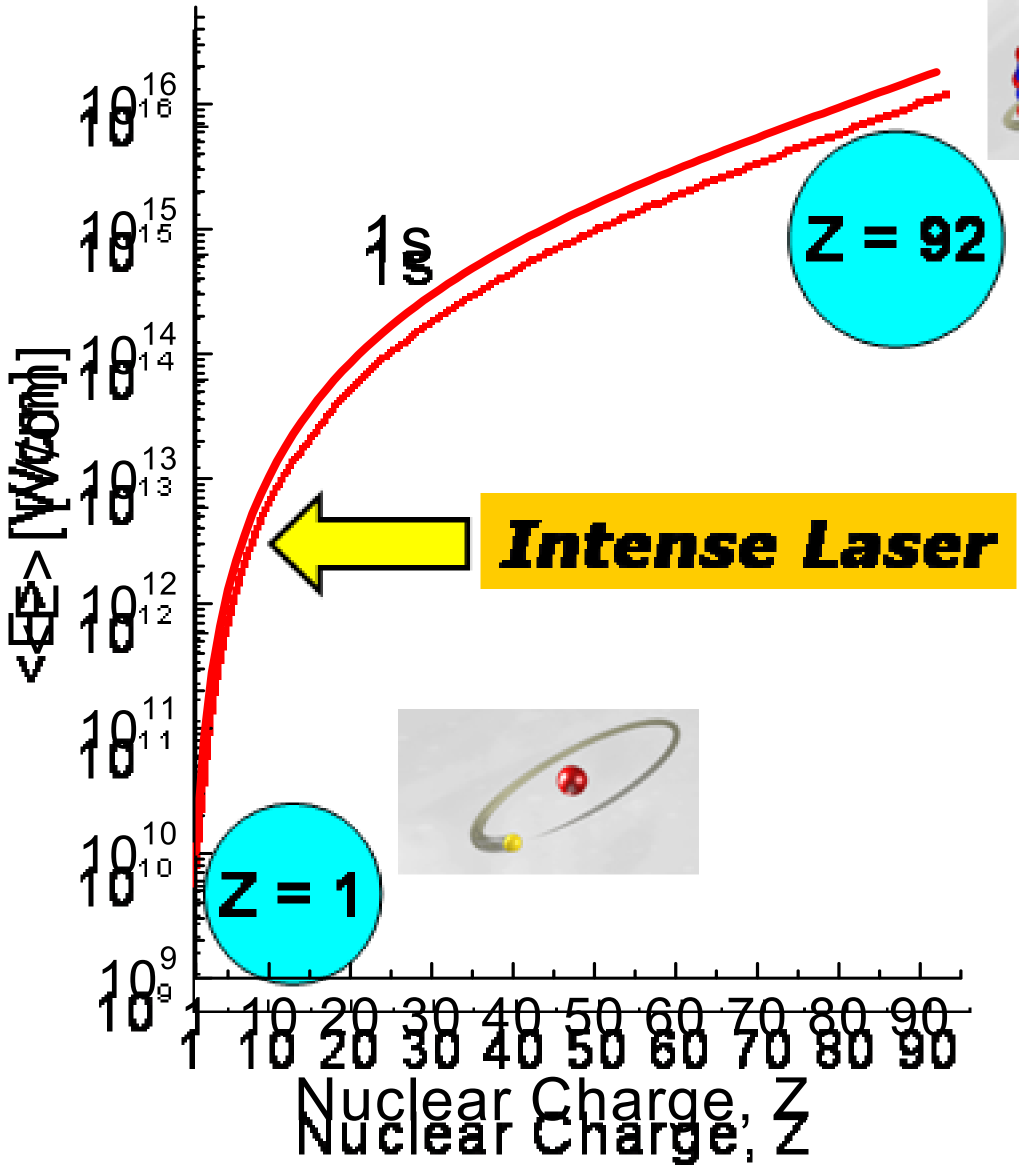
Lanzhou | Caen | Darmstadt | Jülich | Cracow

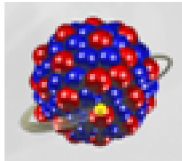
Madison | Jena | Greenbelt

D. Banas
G. Bednarz
C. Brandau
S. Geyer
A. Gumberidze
S. Hess
R. Maertin
R. Reuschl
D. Sierpowski
U. Spillmann
S. Tashenov
M. Trassinelli
S. Trotsenko
G. Weber

Theory: J. Eichler, S. Fritzsche, V. Shabaev, A. Surzhykov

Atomic Physics in Extremly Strong Coulomb Fields





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

ure at High-Z

um electrodynamics (QED)

on the atomic structure

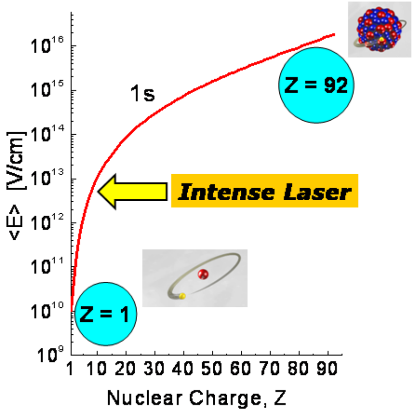
ı in the
strong fields

y induced strong field effect
econds (10^{-22} s < t < 10^{-18}s

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

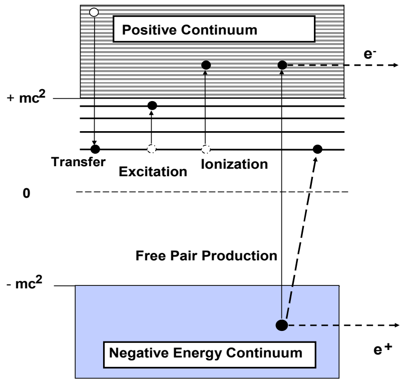
Atomic Physics in Strong Coulomb Fields

Structure Studies



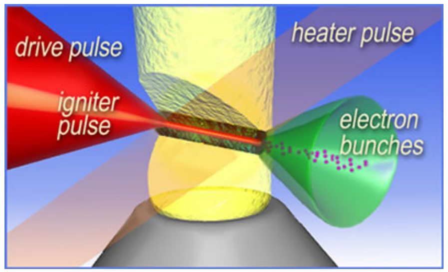
- bound state quantum electrodynamics (QED)
- nuclear effects on the atomic structure
- effects of relativity on the atomic structure
- electron correlation in strong fields
- supercritical fields

Dynamics



- dynamically induced strong field effects, sub-attoseconds (10^{-22} s < t < 10^{-18}s)
- correlated many body dynamics
- elementary atomic processes at high Z
- photon matter interaction, e.g. photon polarization correlation

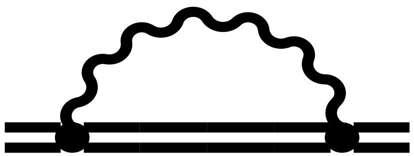
Applications



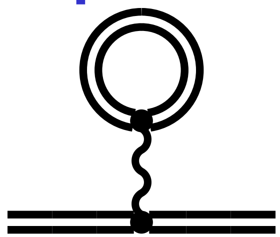
- ion cooling techniques
- storage and trapping techniques
- laser and spectrometer development
- photon, electron, ion detection techniques

Bound-State QED: 1s Lamb Shift at High-Z

Self energy



Vacuum polarization



U^{92+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

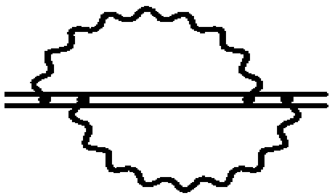
$$\Delta E = \alpha/\pi\ (\alpha Z)^4\ F(\alpha Z)\ m_e c^2$$

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

$F(\alpha Z)$: series expansion in αZ

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

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

Goal:  **±1 eV**

Test of QED in the Strong Field Regime

To proof the validity of QED at high-Z, a broad range of different experimental approaches is needed

1s-Lamb shift

g-factor

two-electron QED

hyperfine structure

2s2p in He-like ions

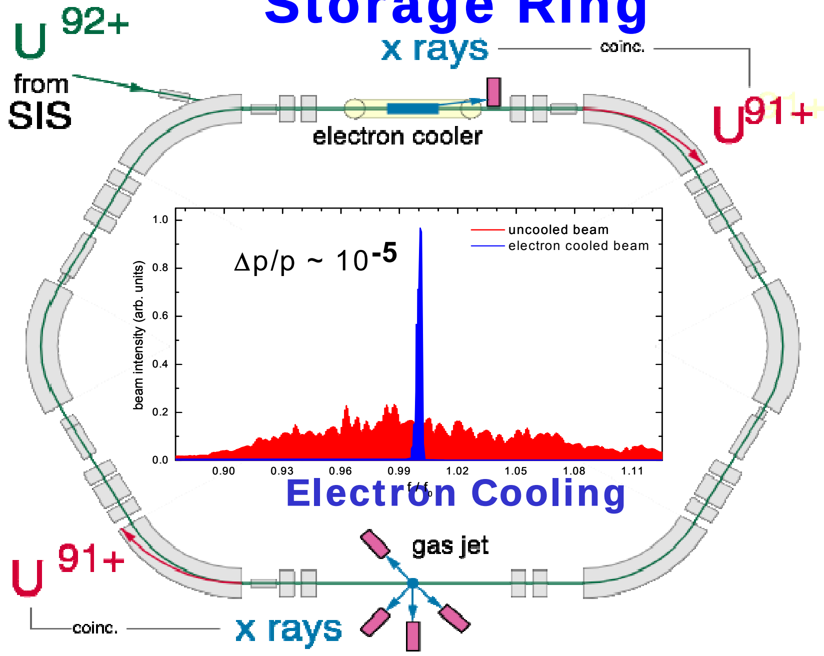
mass measurements

and ...

Production, Storage, and Cooling of HCI

Traps

Storage Ring



Cooling in Traps

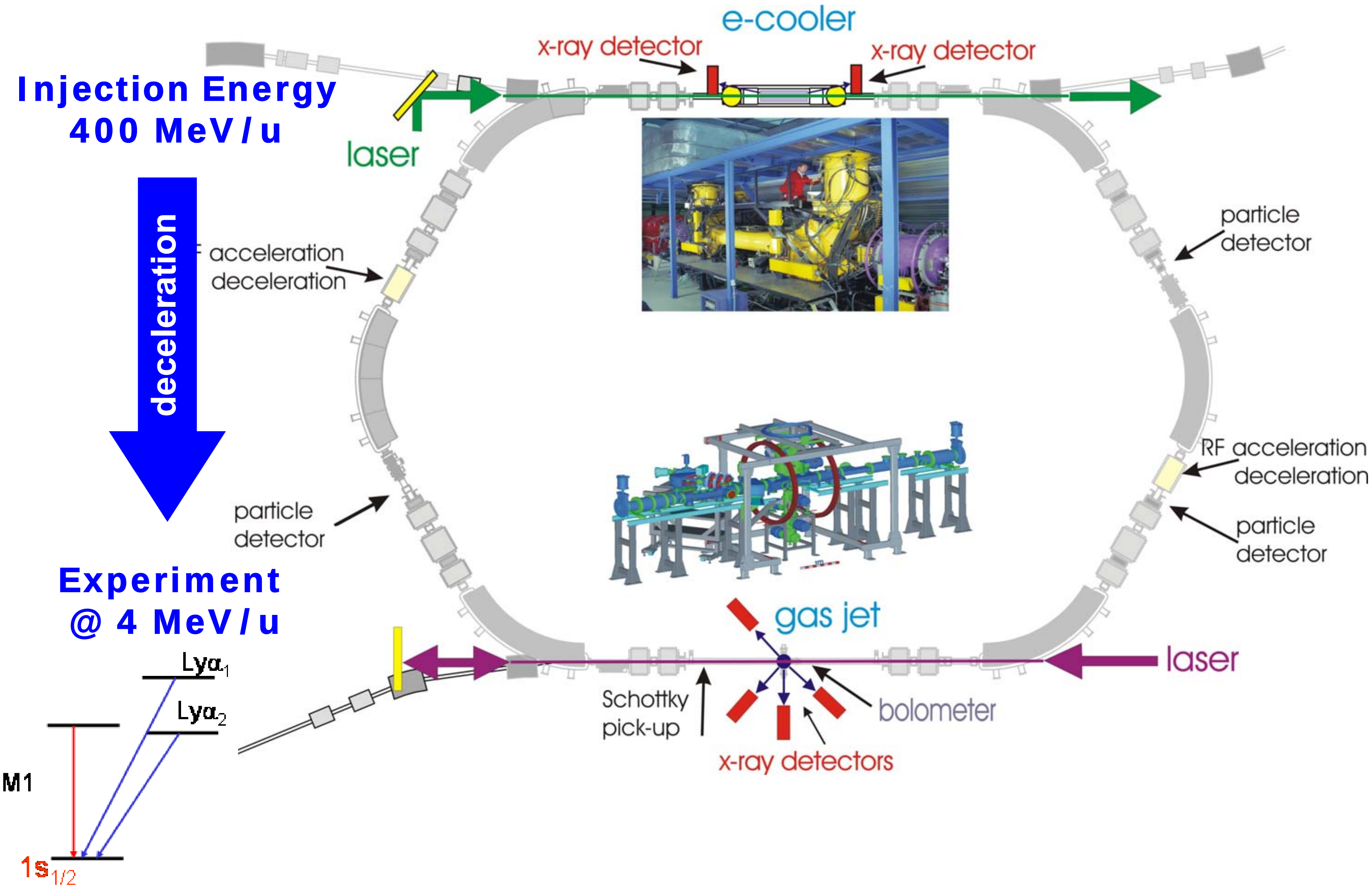
resistive cooling
evaporative cooling
laser cooling
electron cooling

Cooling in Storage Rings

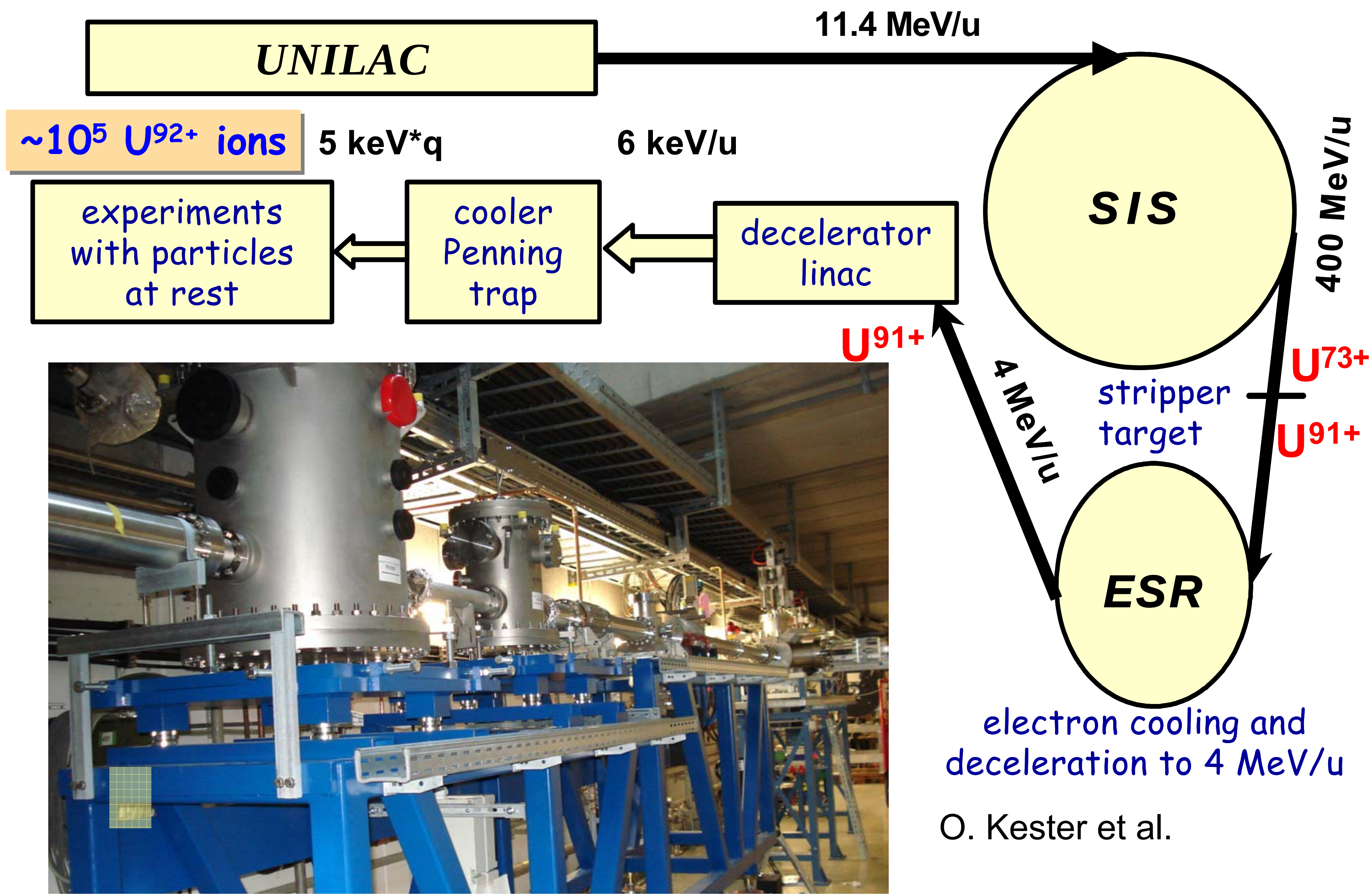
electron cooling
stochastic cooling
laser cooling

Storing and Cooling ist the key for precision

Precision Spectroscopy @ the ESR Storage Ring



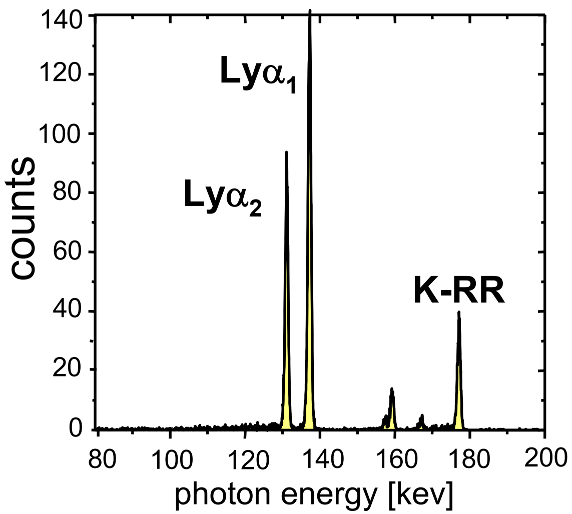
HITRAP Schematic Overview



O. Kester et al.

Test of Quantum Electrodynamics (1s-LS)

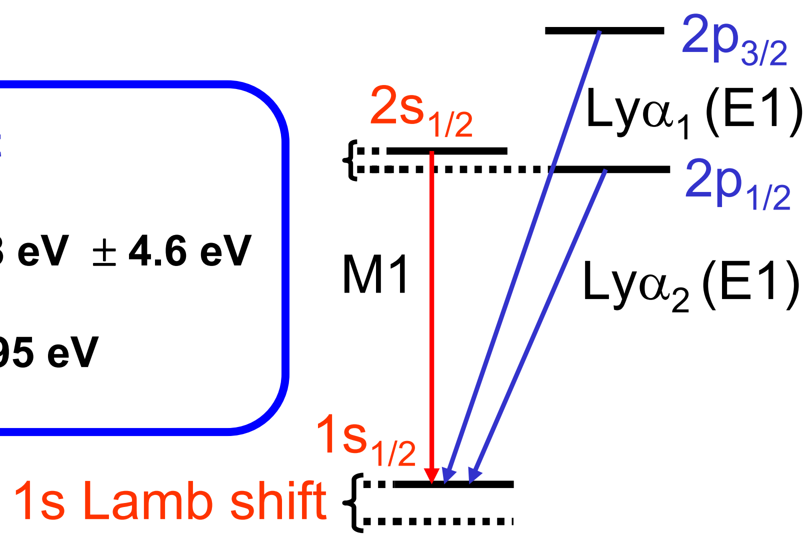
The 1s-LS in H-like Uranium

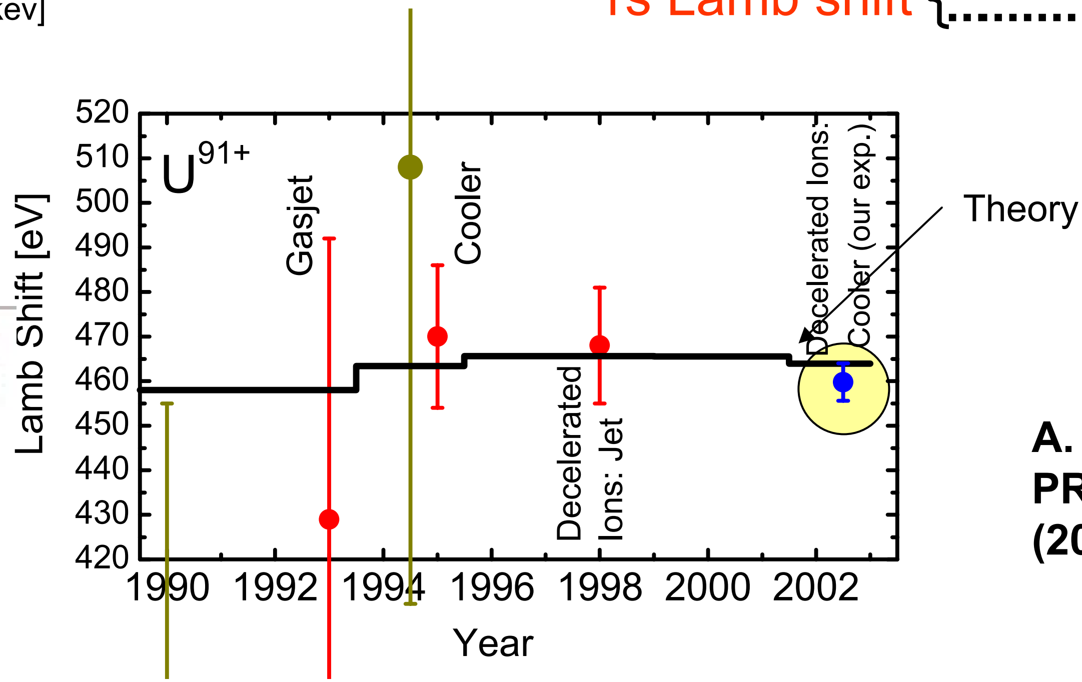


1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



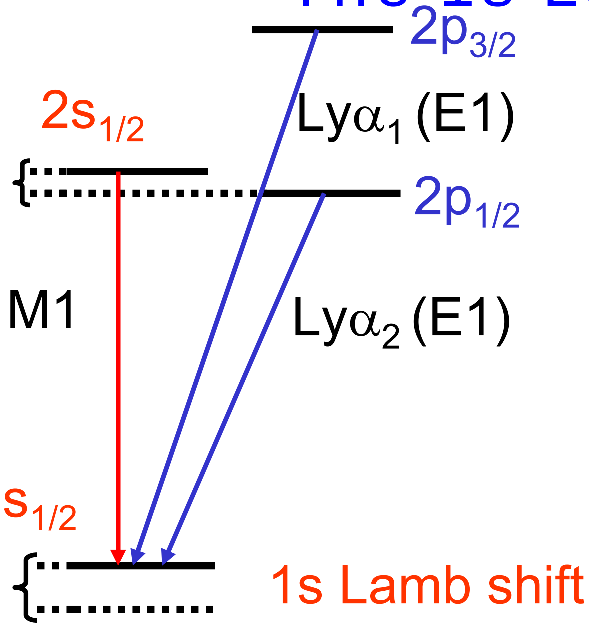


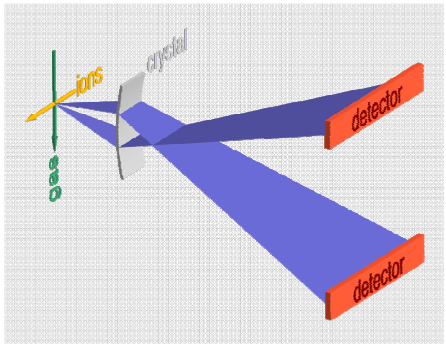
Research Highlights
Nature **435**, 858-859
(16 June 2005)

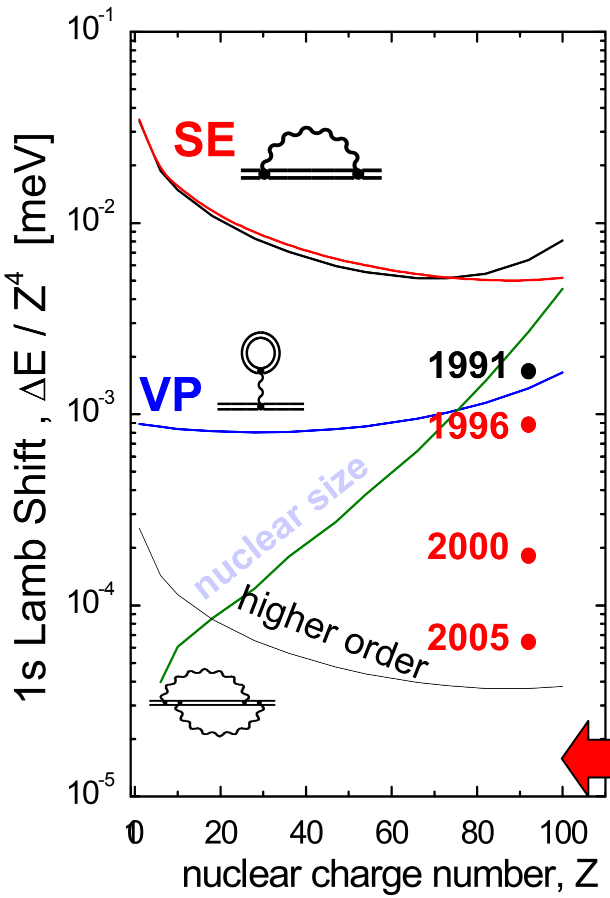
A. Gumberidze
PRL 94, 223001
(2005)

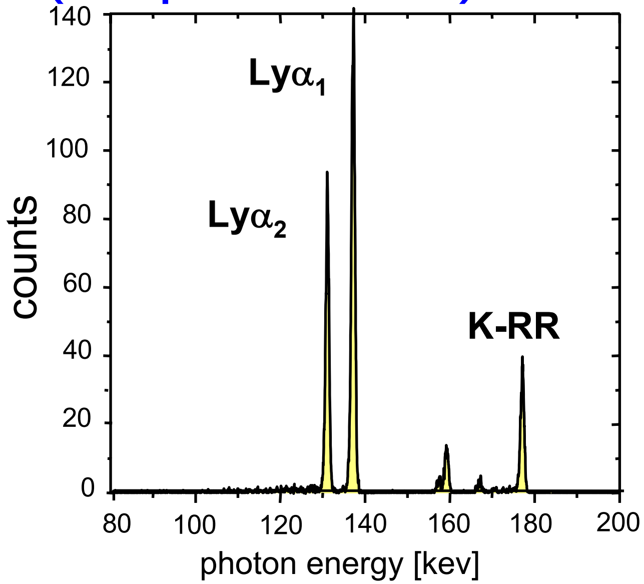
Test of Quantum Electrodynamics (1s-LS)

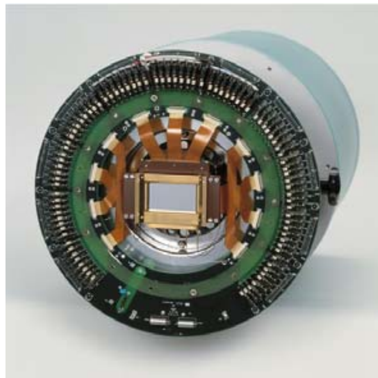
The 1s-LS in H-like Uranium (Exp. at GSI)











Goal: Accuracy of better 1 eV for the Lamb Shift in high-Z one-electron ions

What I left out !

- Dielectronic recombination
  (ESR/NESR: C. Brandau, C. Kozhuharov et al.,

  as tool to study bound state QED and/or nuclear radii (rare isotopes)

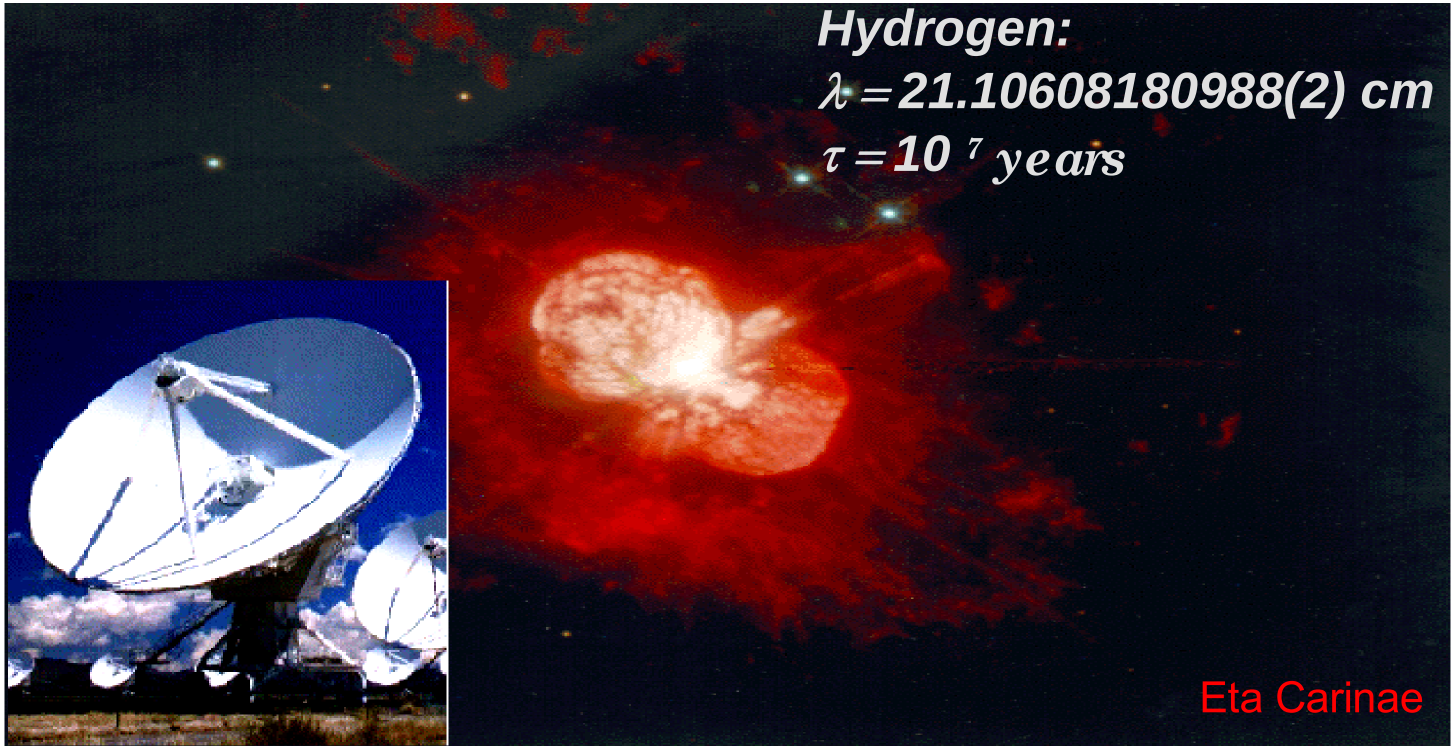
- Accurate mass measurements
  (HITRAP: K. Blaum et al.)

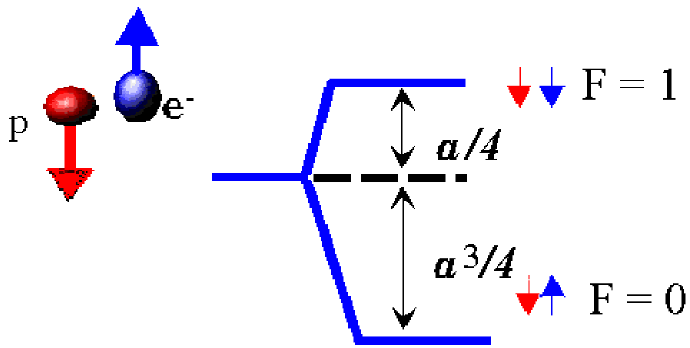
  $\delta m/m < 1\text{x}10^{-11} \rightarrow$
  $\delta mc^2 \approx 2$ eV $\rightarrow$
  'weighing' of Lamb shift

- g-factor measurements with HCIs
  (HITRAP: W. Quint et al.,)

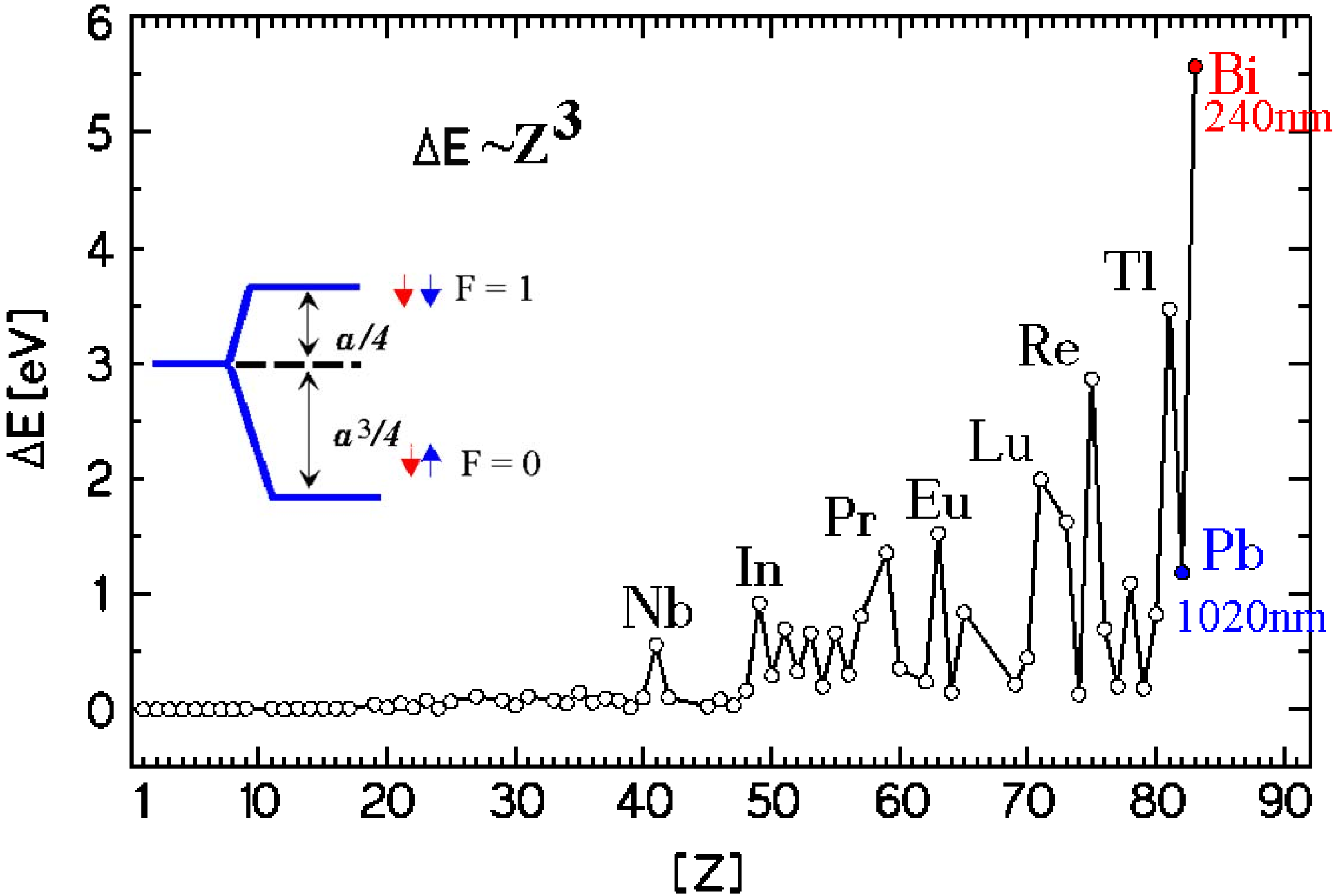
  low-Z: most accurate determination of the electron mass
  medium-Z: fine-structure constant a
  high-Z: test of QED

Hyperfine Structure at High-Z

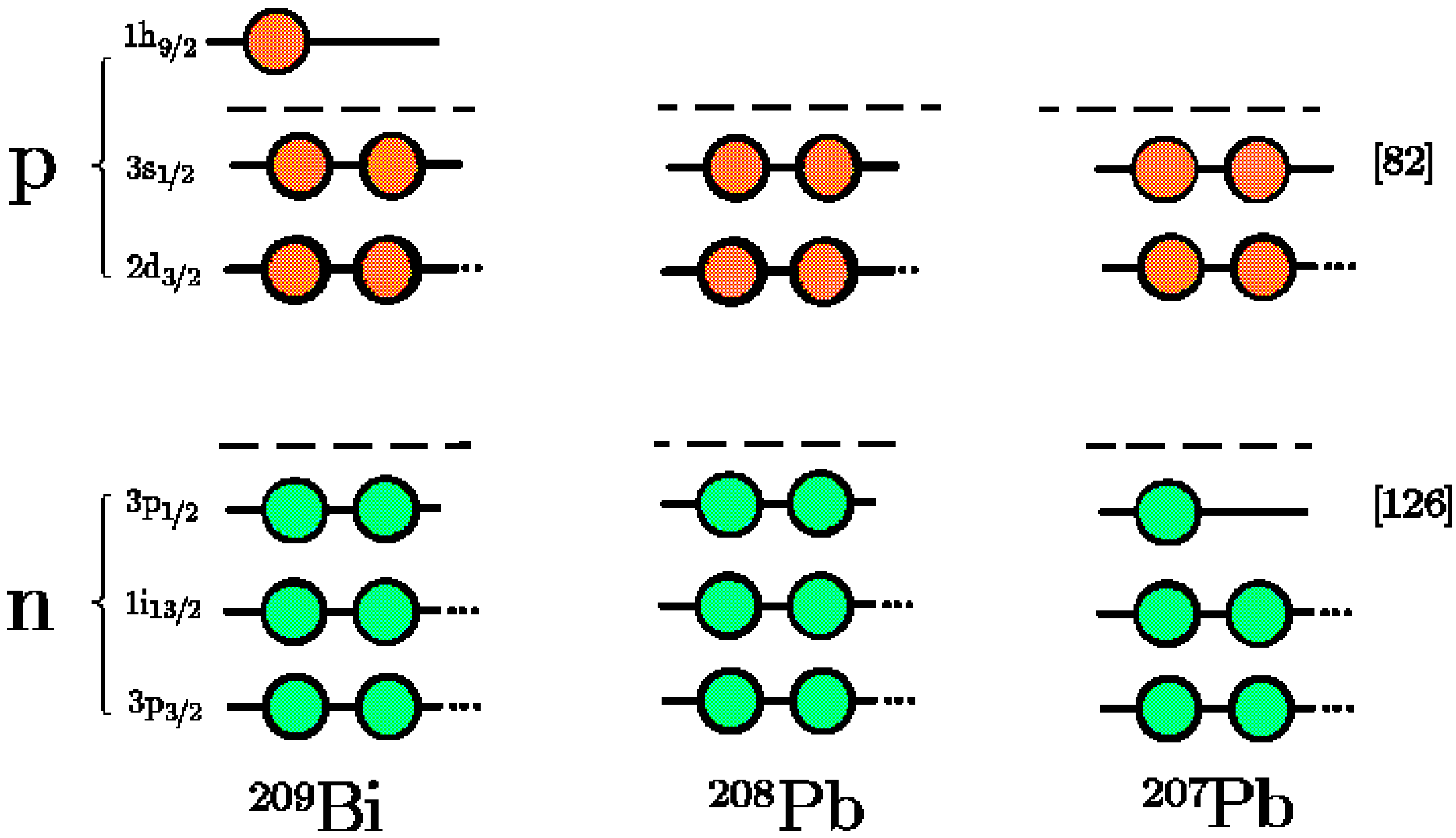




Hyperfine Structure at High-Z



Hyperfine Structure at High-Z



Hyperfine Structure

$^{209}Bi^{82+}$ $^{207}Pb^{81+}$

In the case of HFS, disagreement between experiment and atomic structure theory based on QED

Very similar findings:

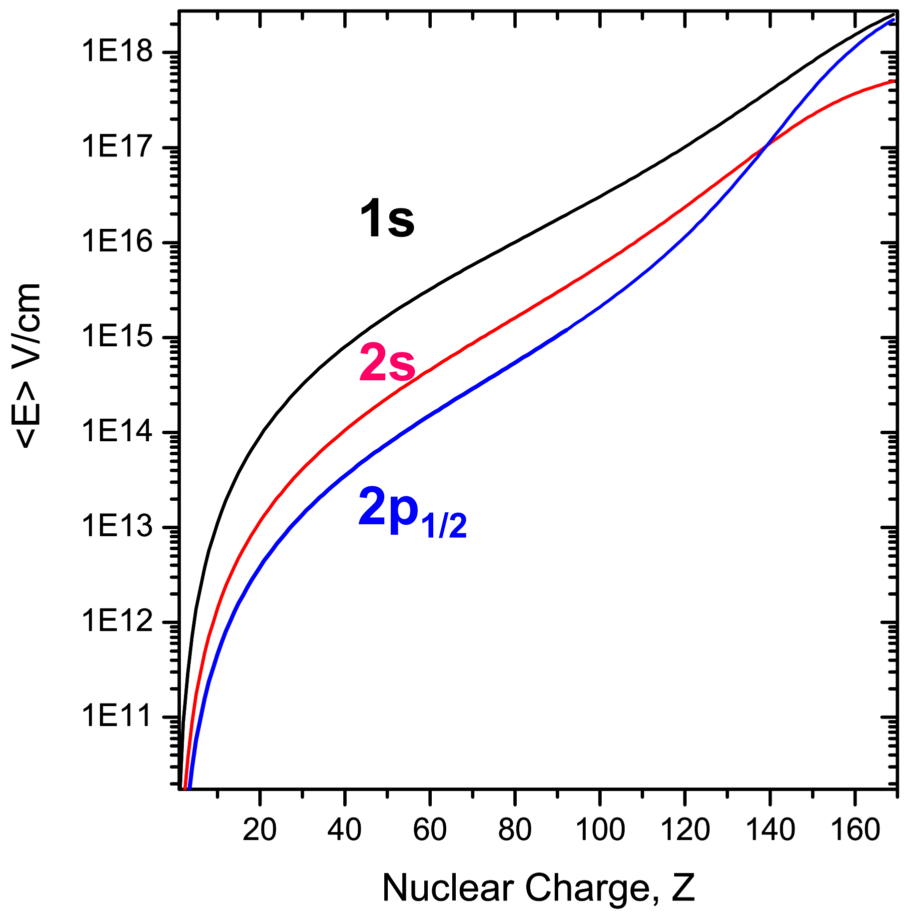
Experimenton the HFS will be continued in 2009 at the ESR, W. Noertershäuser et al.

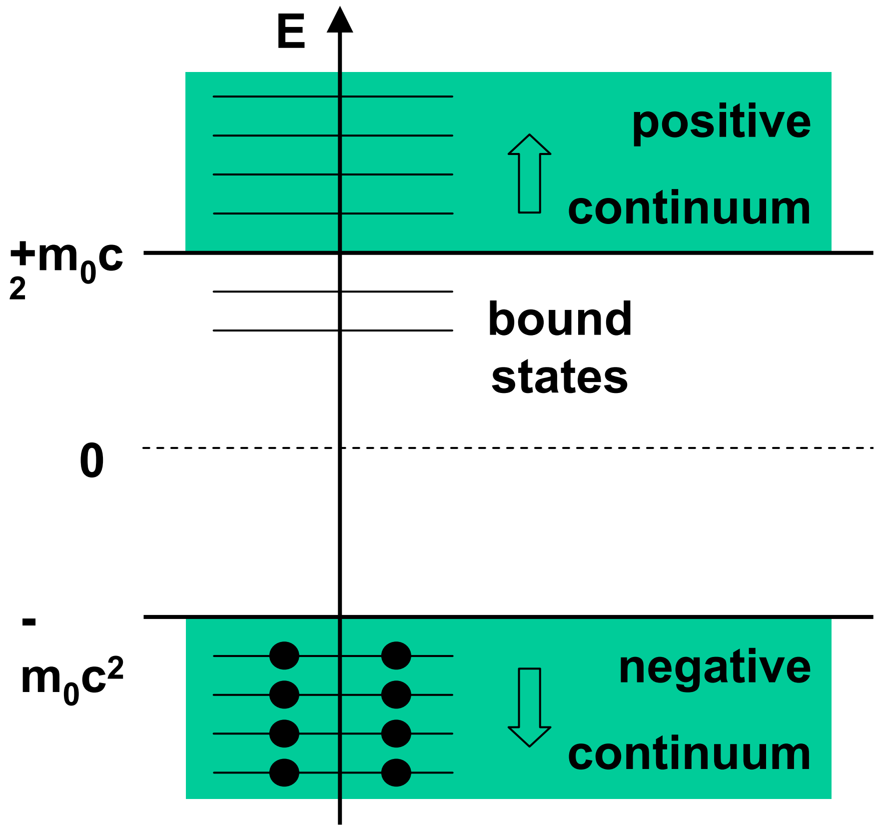
[Pb] Seelig et al., 1998

[Tl] Beiersdorfer et al., 2001

- **Conclusion**
  - **experiments on bound state QED at high-Z is very important part of A**

Critical- and Supercritical Fields





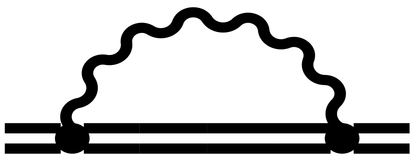
$U^{92+} \rightarrow U$ =>
U^{91+} + MO-X-Ray...
as function of
impact parameter

Requirements

Deceleration to About 6 MeV/u
10^7 Slow Extracted Ions
Large Solid Angle X-Ray Detectors
Monolayer Target (Uranium)
Position Sensitve Particle Detectors

Test of Bound-State QED at high-Z

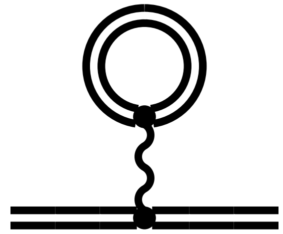
Self Energy



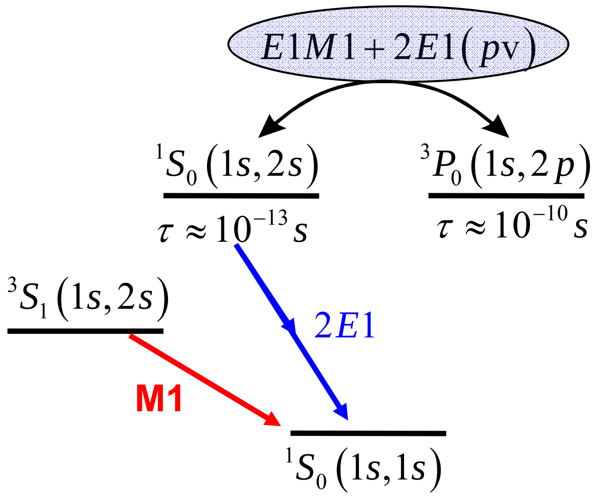
Experiments

- **1s Lamb Shift**
- **2eQED for He-like ions**
- **2s-2p transitions in He- and Li-like heavy ions**
- **hyperfine-structure**
- **g-factor of bound electrons**

Vacuum Polarization



Parity Violation in Highly Charged Ions
Helium-like Uranium



Parity admixture

$$\eta = \frac{\left\langle 2\ ^3P_0 \left| \frac{G_F}{2\sqrt{2}} \left(1 - 4\sin^2\Theta_w - \frac{N}{Z}\right) \rho_{el}\gamma_5 \right| 2\ ^1S_0 \right\rangle}{E\left(2\ ^3P_0\right) - E\left(2\ ^1S_0\right)}$$

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

G_F: Fermi constant,

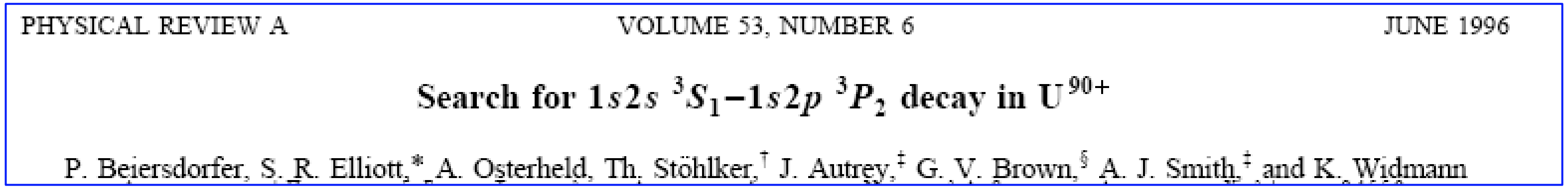
N: neutron number,

Θ_w: Weinberg angle

Z: proton number

ρ_{el}: electric charge densit

First observation of the $\Delta n=0$ $^3P_2 \rightarrow {}^3S_1$ transition in He-like uranium: Experiment at the ESR

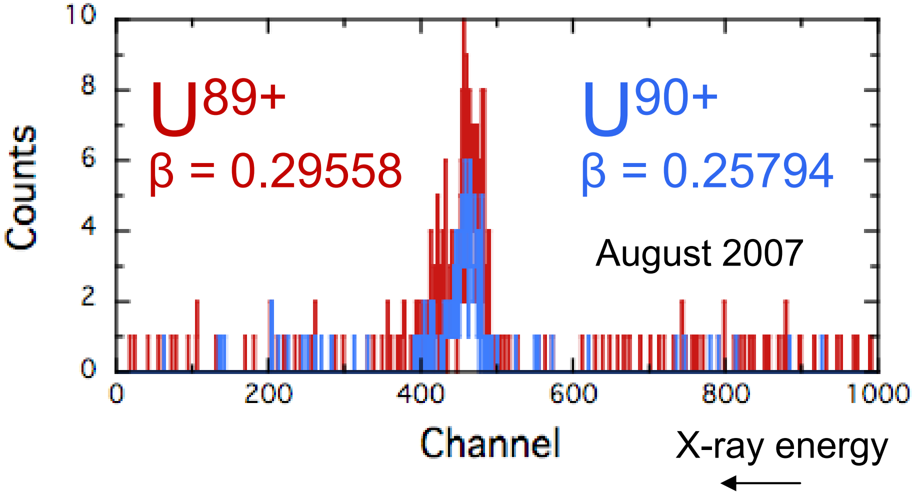

PHYSICAL REVIEW A VOLUME 53, NUMBER 6 JUNE 1996

Search for $1s2s\ {}^3S_1 - 1s2p\ {}^3P_2$ decay in U^{90+}

P. Beiersdorfer, S. R. Elliott,* A. Osterheld, Th. Stöhlker,† J. Autrey,‡ G. V. Brown,§ A. J. Smith,‡ and K. Widmann

$$\Delta E = E^{lab}_{He} - E^{lab}_{Li}$$

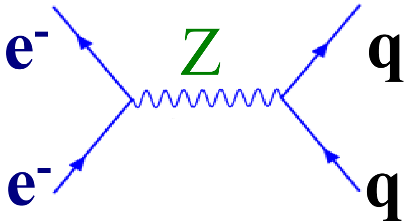
preliminary

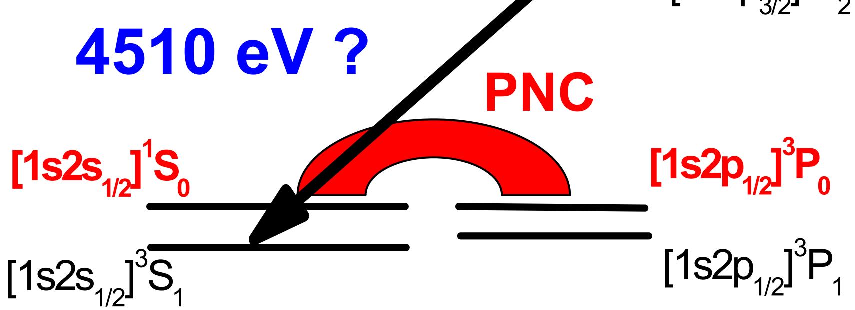


Relative measurement

He-like ⇔ Li-like (well-known)

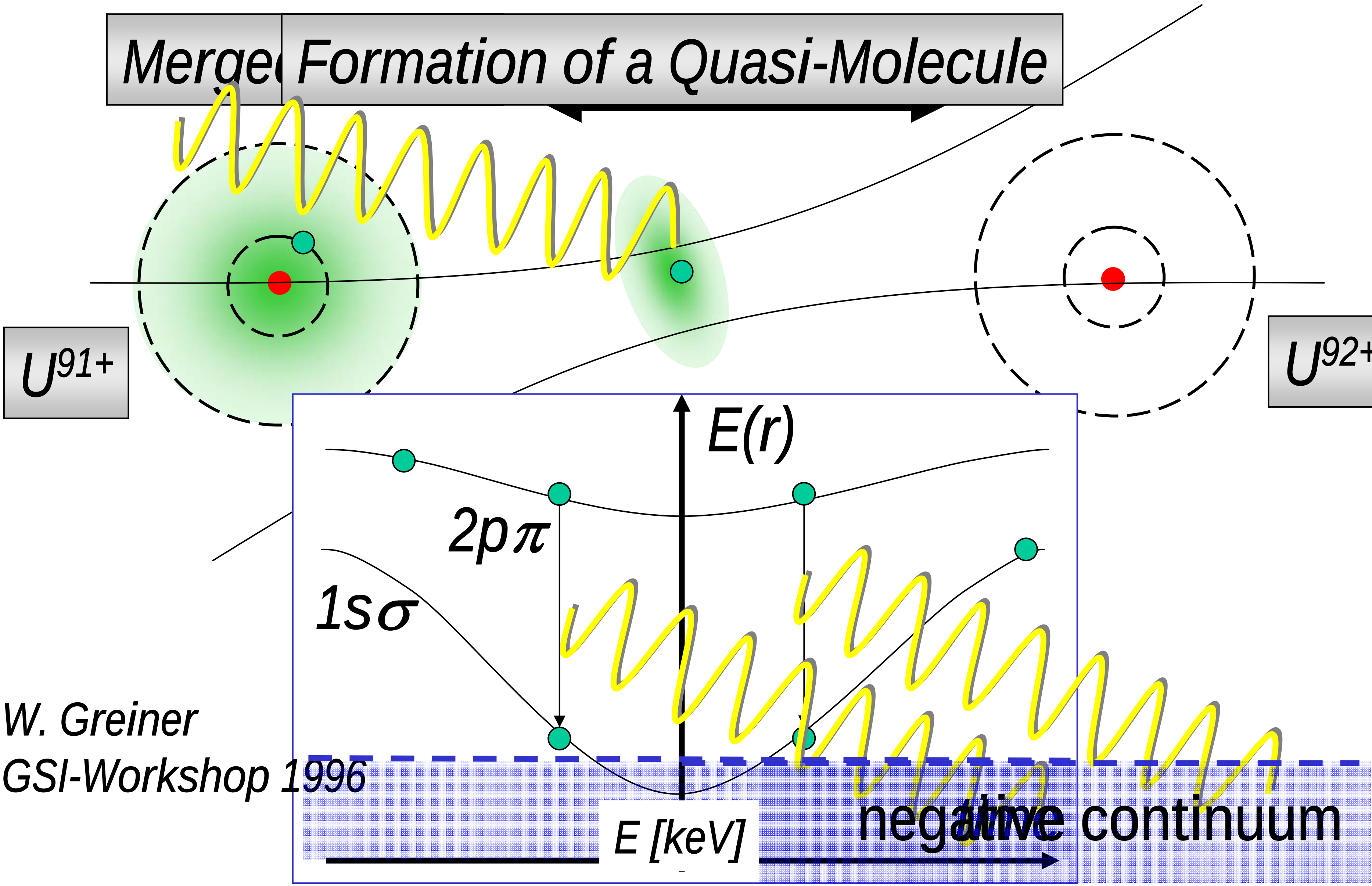
Accuracy goal: 0.5 eV





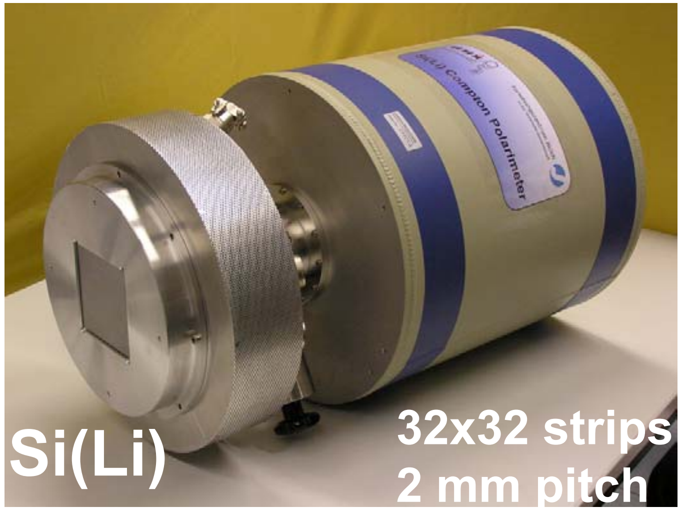
M. Trassinelli et al. (2008), in preparation for PRL

Supercritical fields

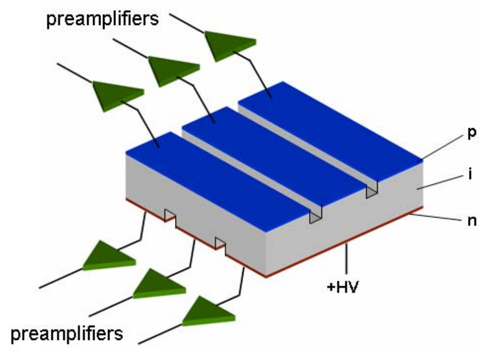


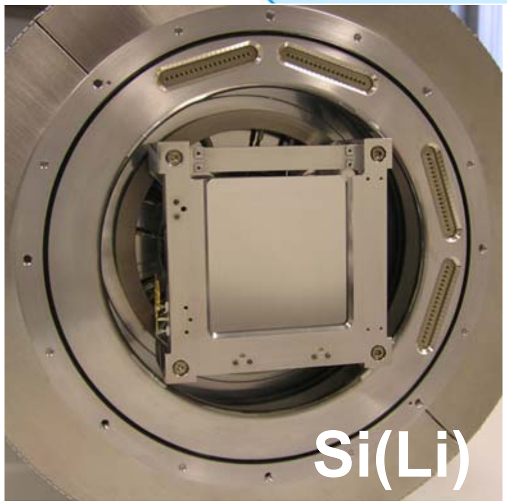
W. Greiner
GSI-Workshop 1996

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



Si(Li) and Ge(i) based Compton polarimeter



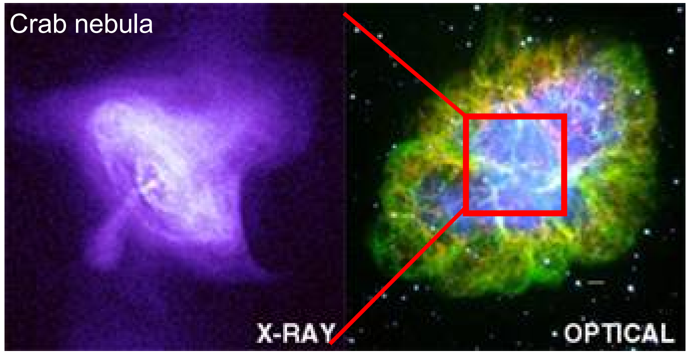


crystall size: 4" x 4"

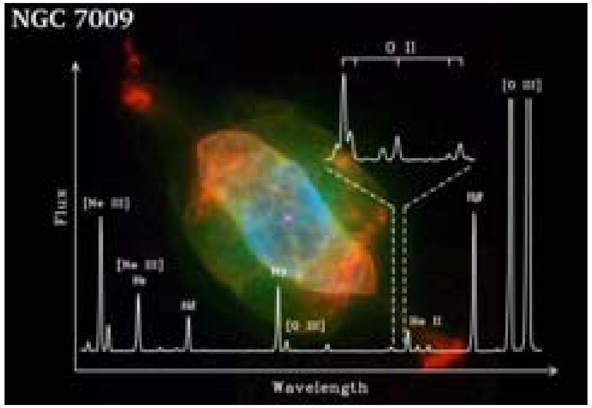
energy resolution – timing - 2D/3D position sensitivity – multihit

Application to high precision spectroscopy based on transmission spectrometer (50 to 100 keV)

Polarization Spectroscopy



Direct insight into celestial plasmas



Spectra provide knowledge of temperature, density, element abundance, etc.

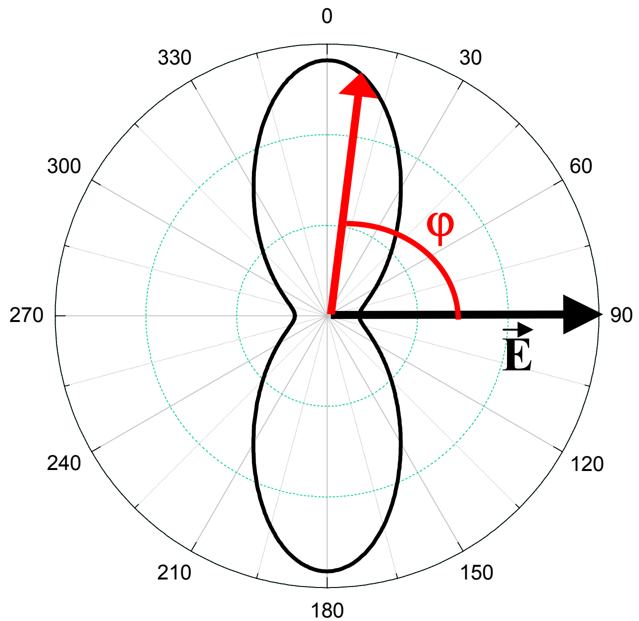
Radiative processes: **Main photon matter interaction processes exhibit distinct photon polarization features (Synchrotron Radiation, Bremsstrahlung, Recombination, Inverse Compton Scattering)**

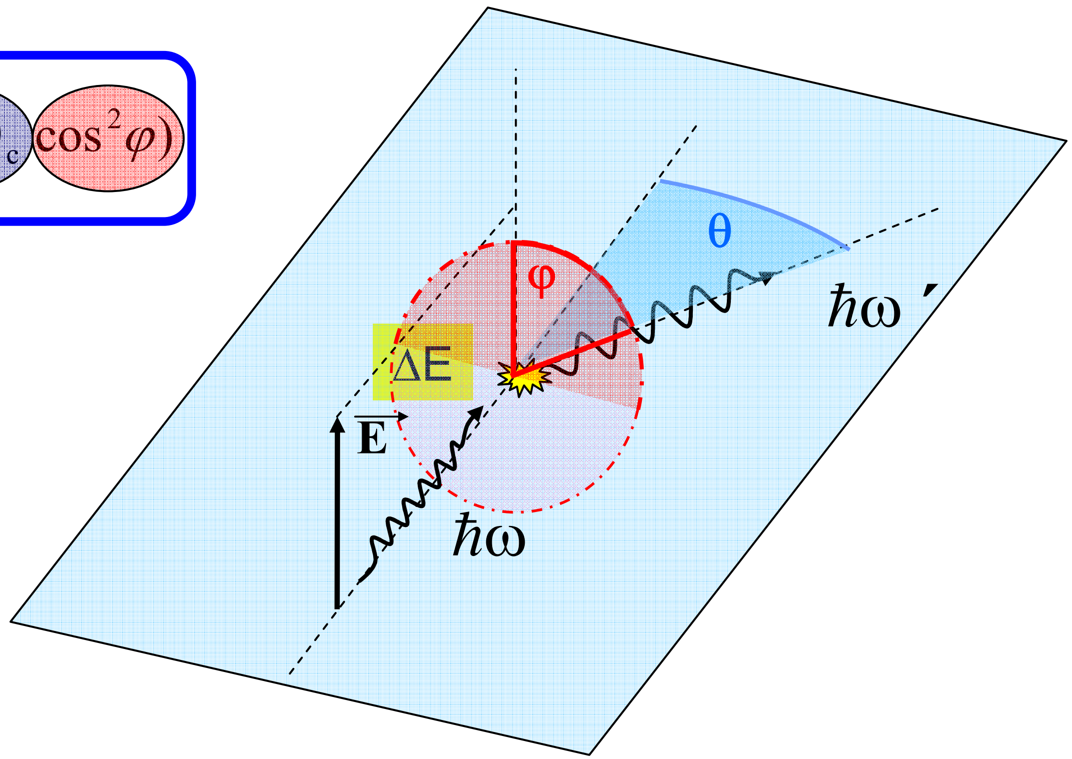
Polarization Measurement via Compton Scattering

Linearly polarized radiation

Klein-Nishina equation

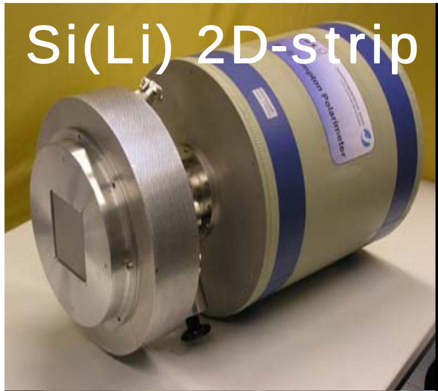
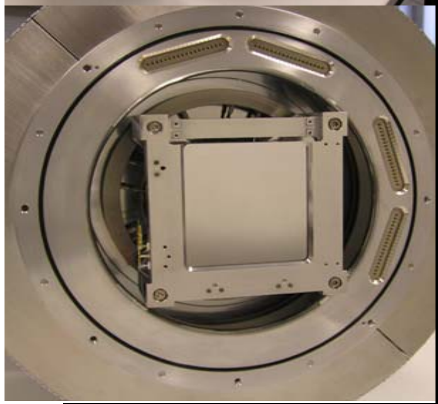
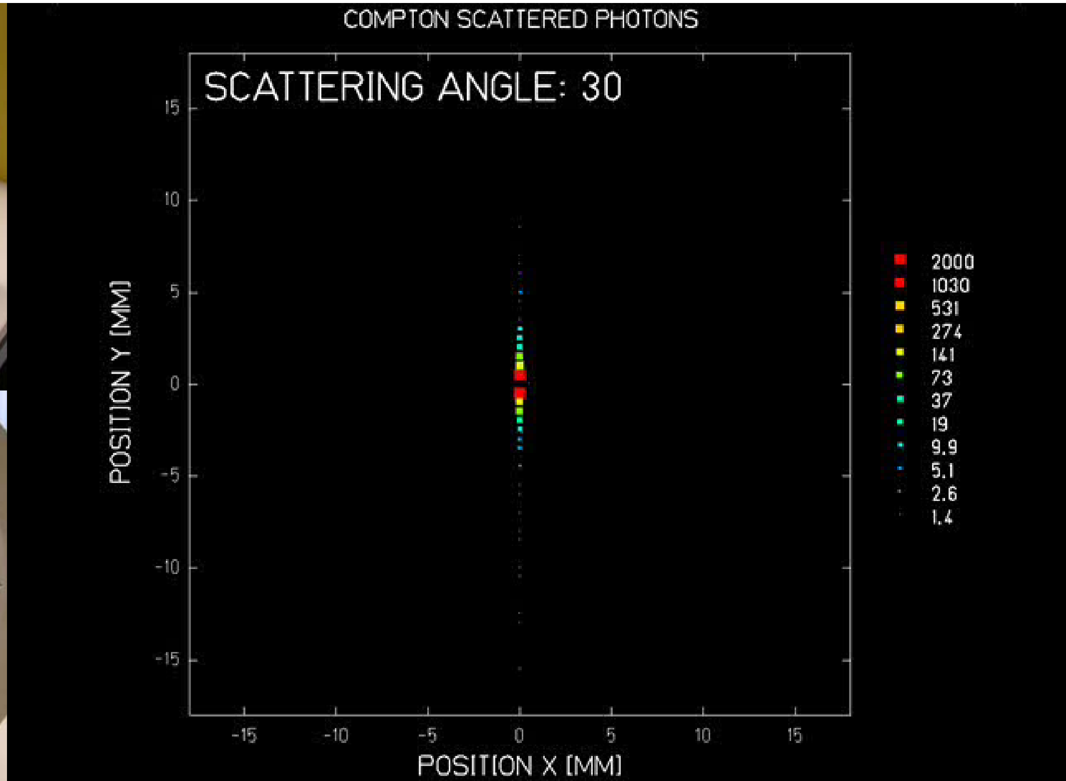
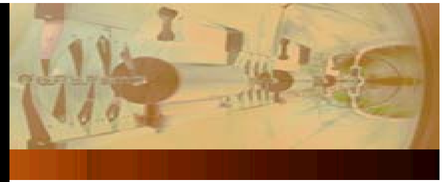
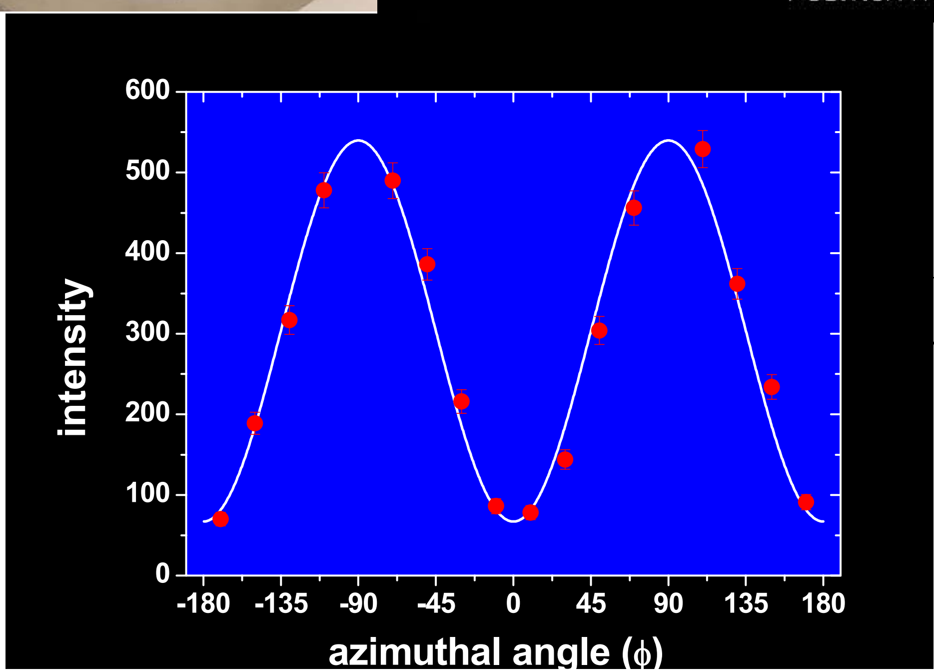
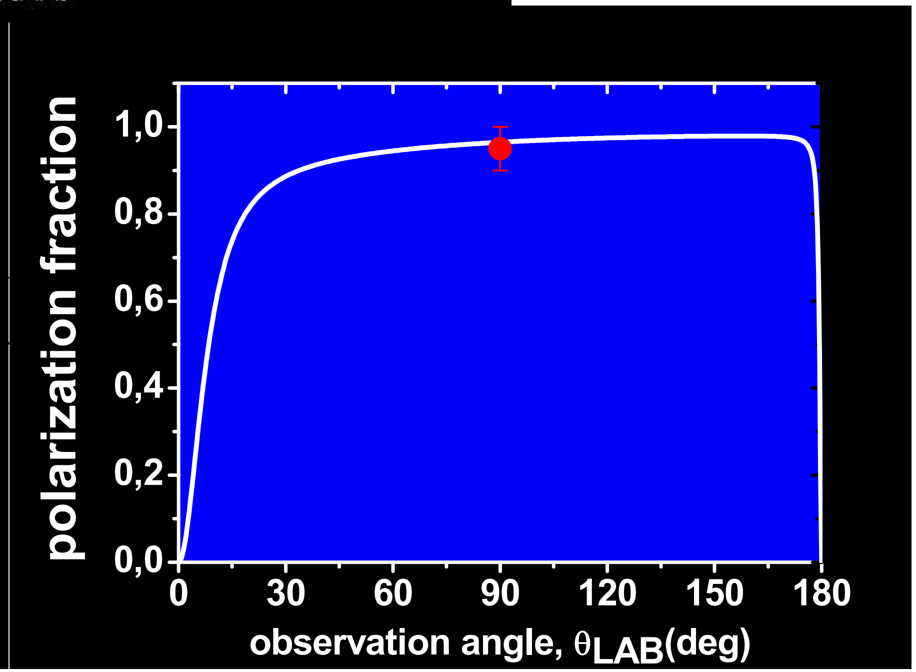
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta_c \cos^2\varphi\right)$$



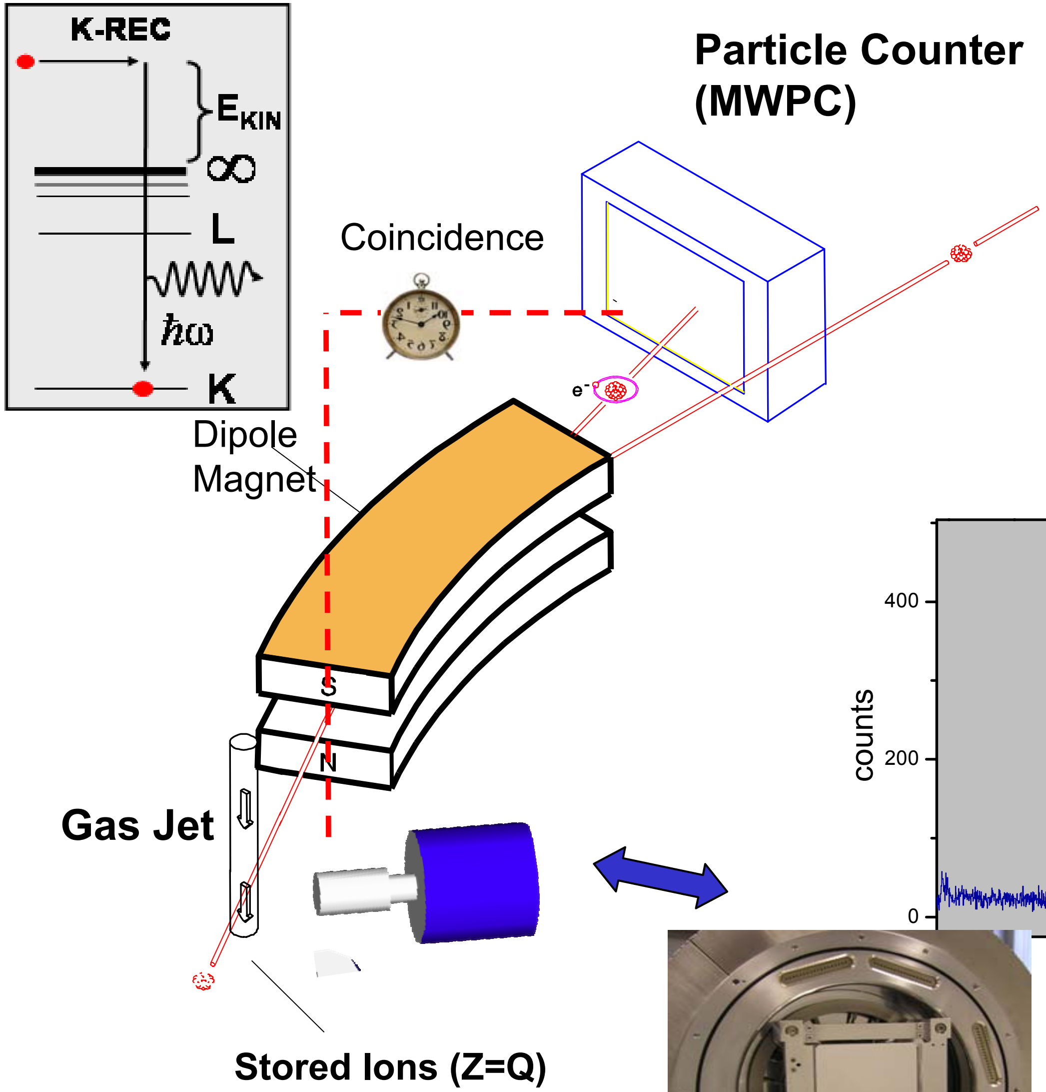


$$\hbar\omega = \hbar\omega' + \Delta E$$

ΔE : electron recoil energy

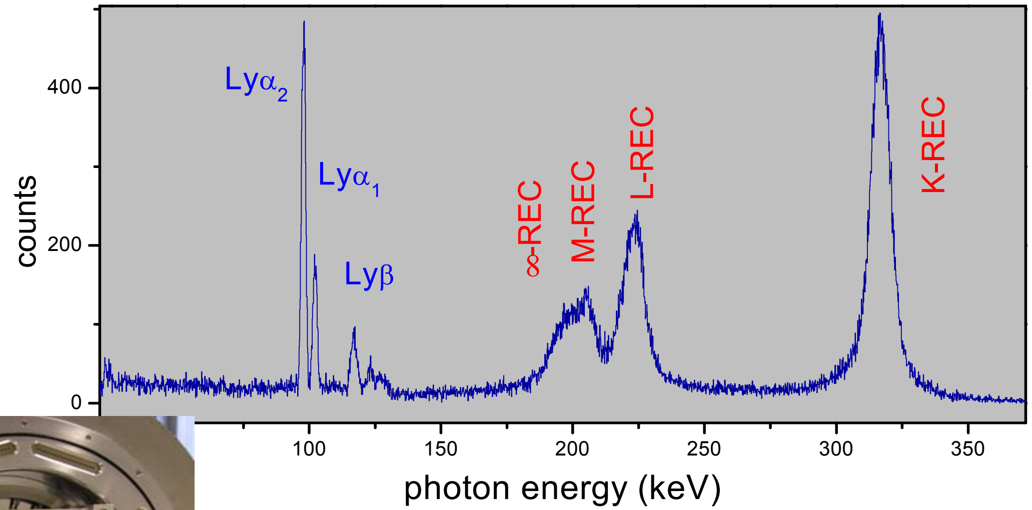

Si(Li) 2D-strip


COMPTON SCATTERED PHOTONS
SCATTERING ANGLE: 30
POSITION Y [MM]
POSITION X [MM]
2000
1030
531
274
141
73
37
19
9.9
5.1
2.6
1.4


intensity
azimuthal angle (ϕ)
0
100
200
300
400
500
600
-180
-135
-90
-45
0
45
90
135
180

polarization fraction
observation angle, θ_{LAB}(deg)
0,0
0,2
0,4
0,6
0,8
1,0
0
30
60
90
120
150
180

Experiments at the Jet-Target



Electron transfer from the target atom into the HCI

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

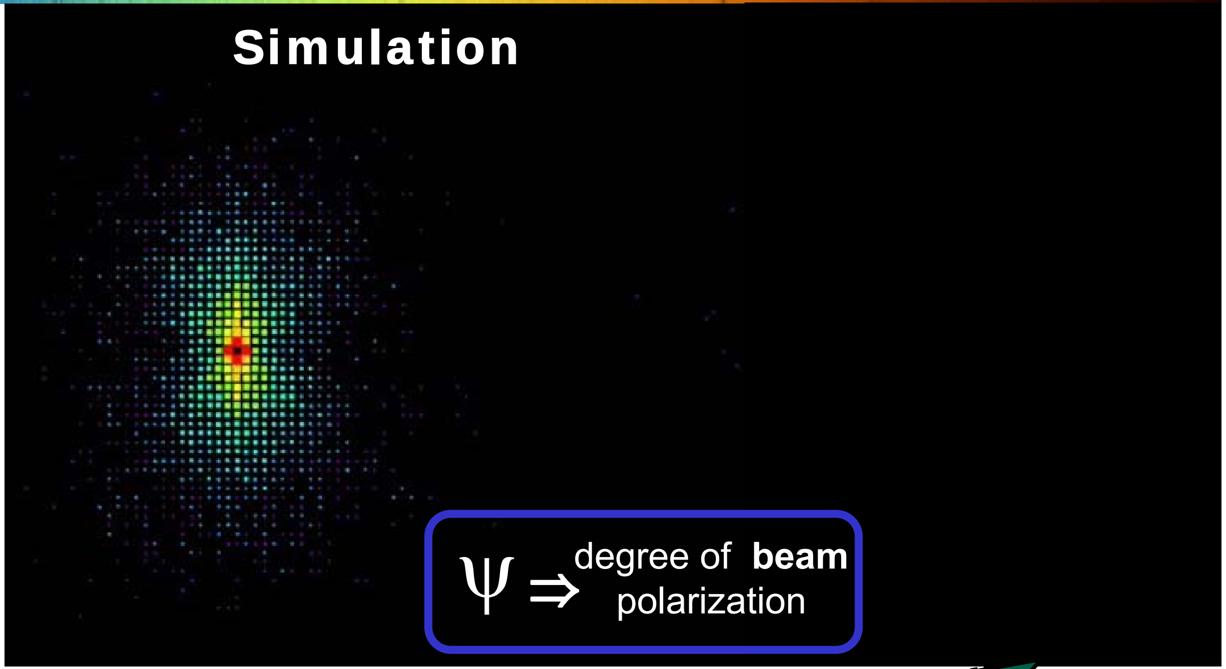


Recombination: spin polarization of particles
(ion or electron beam)

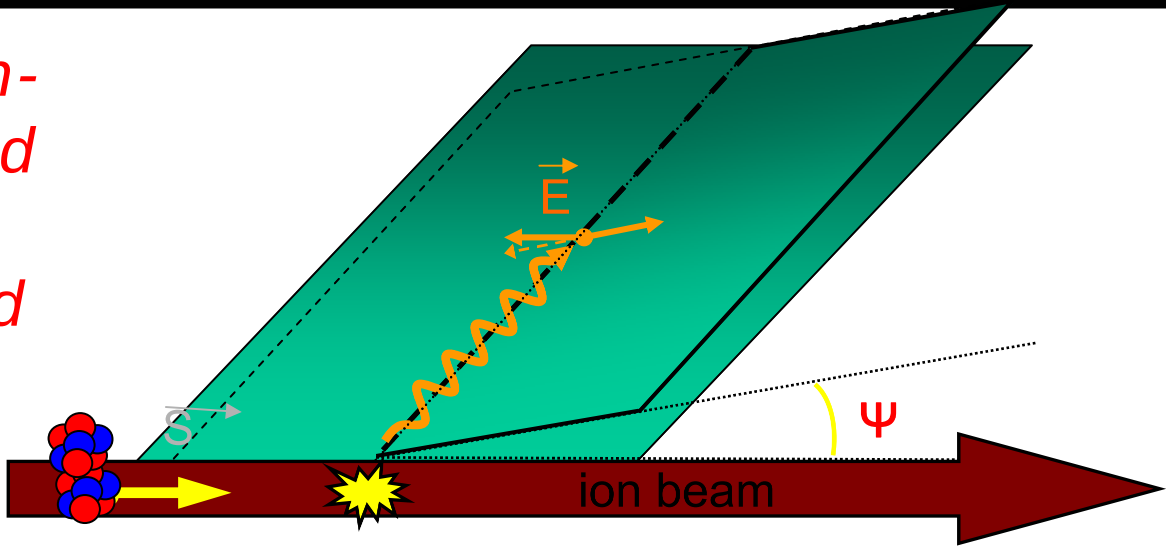
Spin Polarized Ion Beams

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)

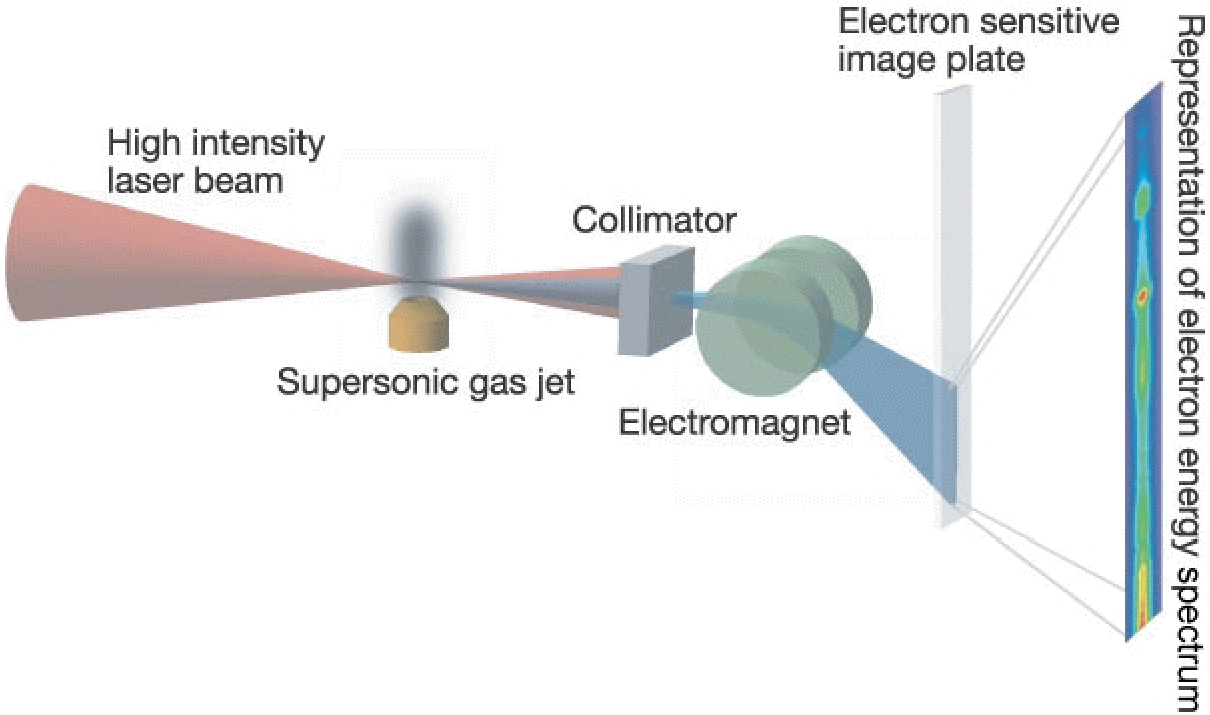


control over the spin-polarization of stored ions:
required for EDM and PNC experiments



Laser-Acceleration of Electrons

typical setup for electron
laser acceleration studies:

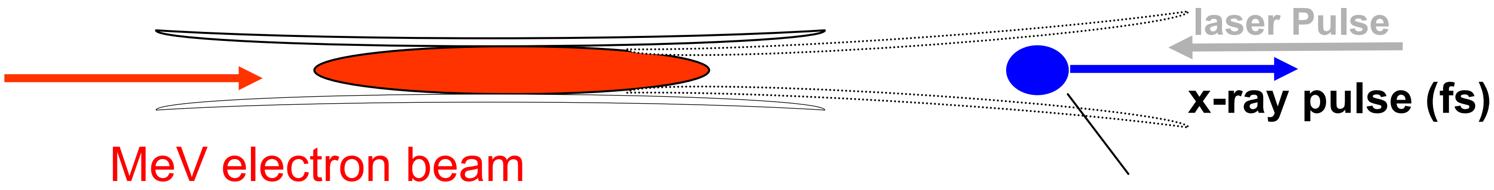


Nature 431 (Sept. 2004):

3 groups report on laser acceleration
of (low-emittance) electron beams with
(quasi-monochromatic) 70-200 MeV

Hard x-ray generation using Thomson scattering off laser accelerated electron bunches

Collaboration with the l'OASIS Group@LBNL
(supported by NSF,DAAD)



E.g. $E_{x\text{-}ray}$ (360keV) = 4 · γ^2(for 150MeV e^-) · E_{Photon}(1eV)

Laser pulse
1 TW, τ = 50 fs, λ=800 nm

electron pulse
~50 MeV,
(energy spread (2 to 4%)

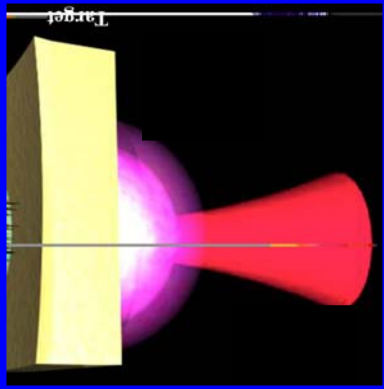
X-ray pulse
$\hbar\omega$~60 keV, ~10 ps
10mrad divergence

First phase of experiment
- determination of x-ray background
- optimization of x-ray signal, e.g. laser intensity, target density, pulse duration

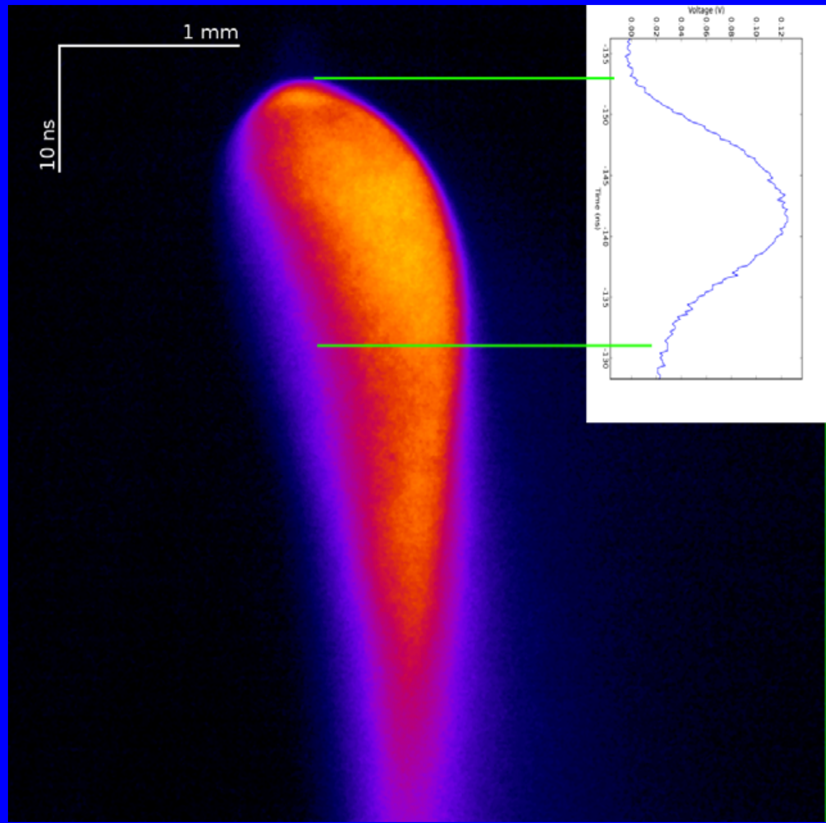
Second phase of experiment
- determination of the x-ray polarization

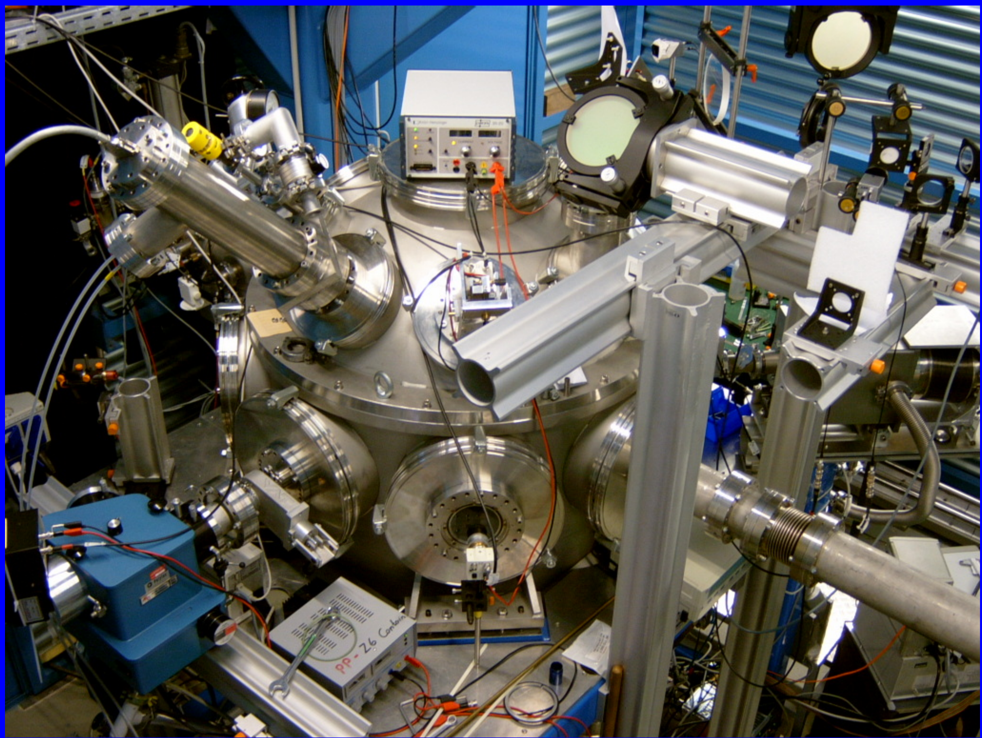
High Intensity Laser PHELIX

- UNILAC ion beam: 5 MeV/u S^{15+}
- heating laser: Phelix,
  15 ns, 150 J



Time Profile





Challenges and Opportunities

- *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