Structure and Dynamics of High-Z Ions Studied in Relativistic Atomic Collisions at the ESR Storage Ring

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- **Introduction**

  - **Experiments at the jet-target**
    Alignment studies: population of magnetic sublevels

    => Interference between E1 and M2 transition amplitudes

  - **Experiments at the electron cooler**

    Two-electron contribution to the K-shell ionization potential in He-like uranium

- **Summary and Outlook**

Collaboration

Experiment

H.F. Beyer, K. Beckert, G. Bednarz, F. Bosch, R.W. Dunford, B. Franzke, A. Gumberidze, S. Hagmann E. Kanter, O. Klepper, A. Krämer, C. Kozhuharov, D. Liesen, T. Ludziejewski, P.H. Mokler, X. Ma, A. Muthig, M. Steck, Z. Stachura, Th. Stöhlker, S. Toleikis, A. Warczak

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Institute for Nuclear Studies, Swierk, Poland
Argonne National Laboratory, Argonne, USA
Kansas State University, Kansas, USA
IMP, Lanzhou, China

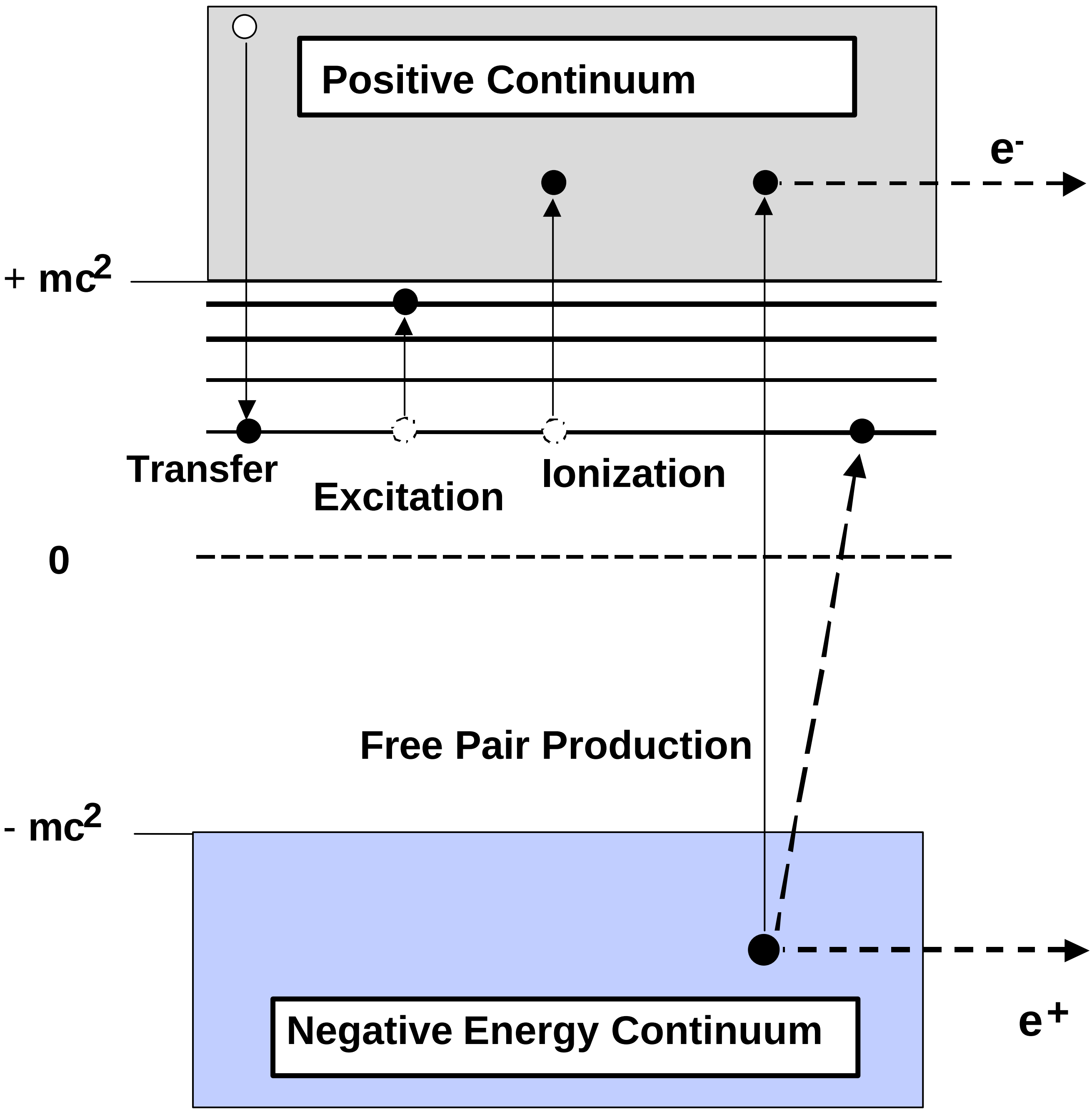
Theory

J. Eichler, S. Fritzsche A. Ichihara, D.C Ionescu, T. Shirai, A. Surzhykov

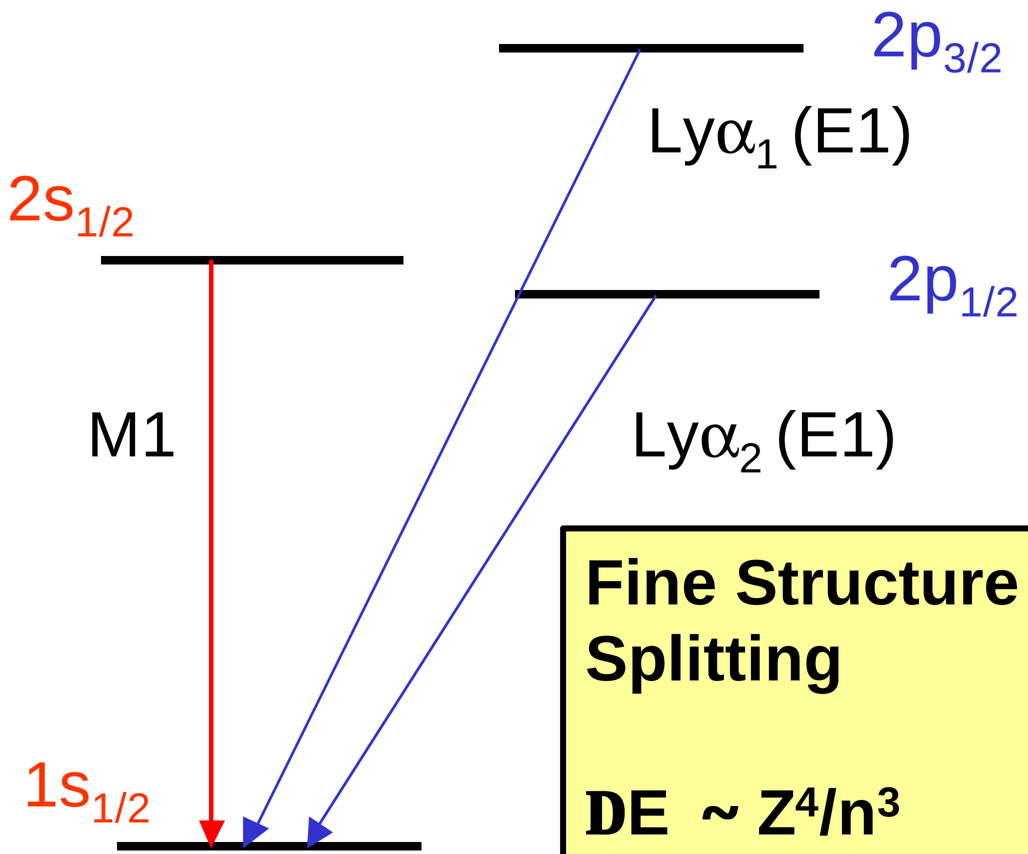
Theoretische Physik, HMI-Berlin, Germany
JAERI, Japan
TU-Dresden, Germany
GSI-Darmstadt, Germany
University of Kassel, Germany

Collision Dynamics of Relativistic Heavy Ions

Collision times in the sub-attosecond regime (10^{-19} s < t < 10^{-21}s)



The Structure of One-Electron Systems



Fine Structure Splitting

$DE \sim Z^4/n^3$

Z: nuclear charge number
n: prinzipal quantum number

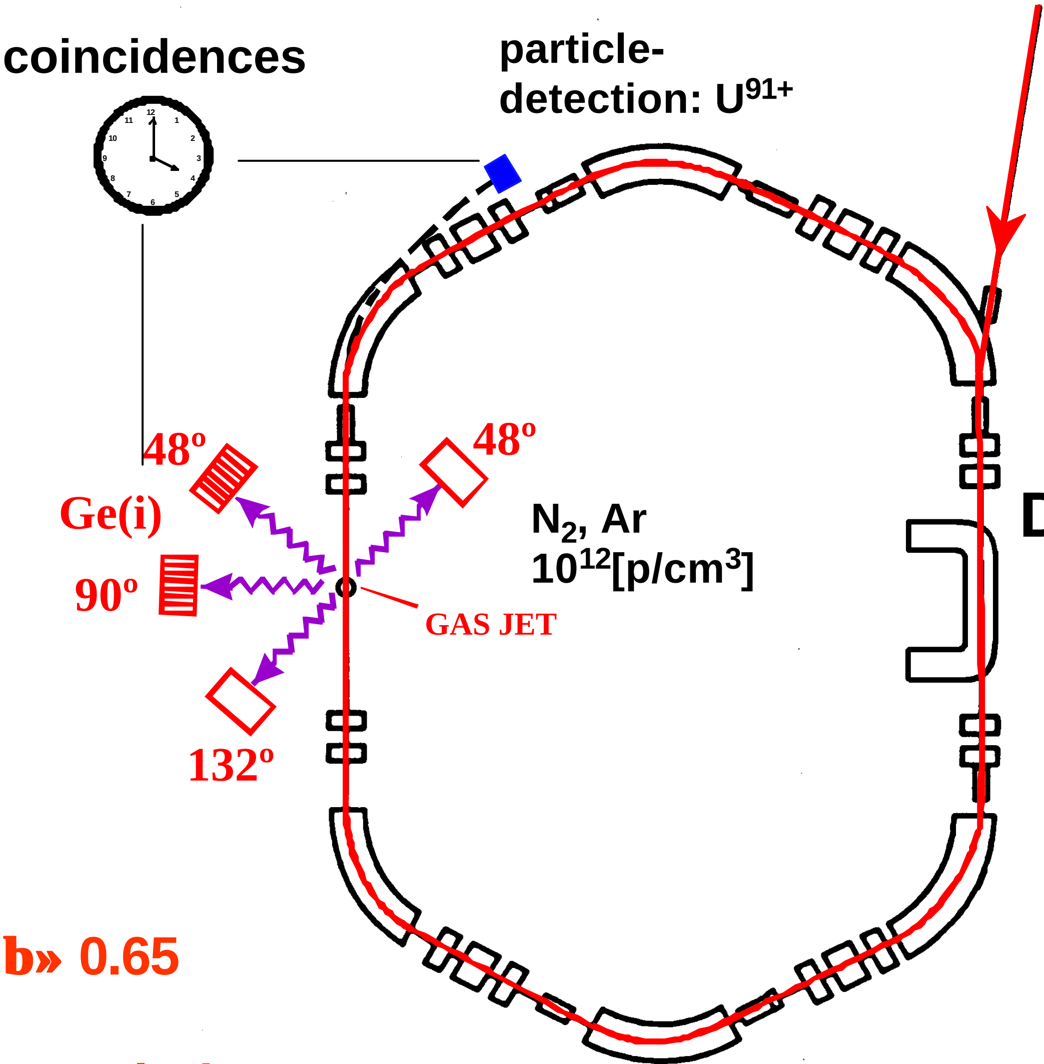
large shell and sub-shell splitting in high-Z systems

- ***photon emission enables to study dynamic atomic processes state selectively***

- ***Via angular distributions, even information about magnetic substates get accessible***

Th. Stöhlker, APAC Conference 2001

X-Ray Spectroscopy at the Jettarget



U^{92+}

300 MeV/u

Deceleration

20 MeV/u

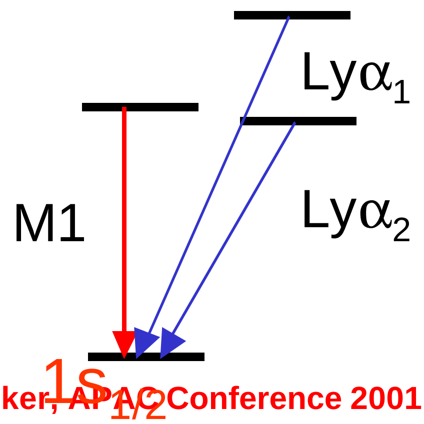
N_{Ion} » 10^8

b» 0.65

Revolution Frequency f: » 10^6 1/s

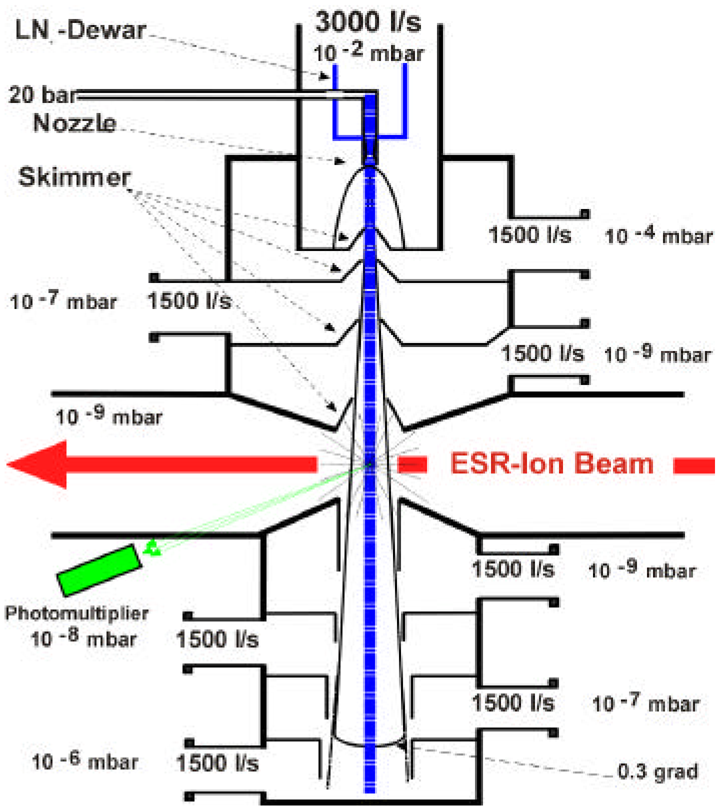
$$E_{lab} = \frac{E_{proj}}{\tilde{a} \bullet (1 - \hat{a} \bullet \cos\grave{e}_{lab})}$$

E_{lab}: Photon energy in laboratory system
E_{proj}: Photon energy in emitter system



The Jet-Target

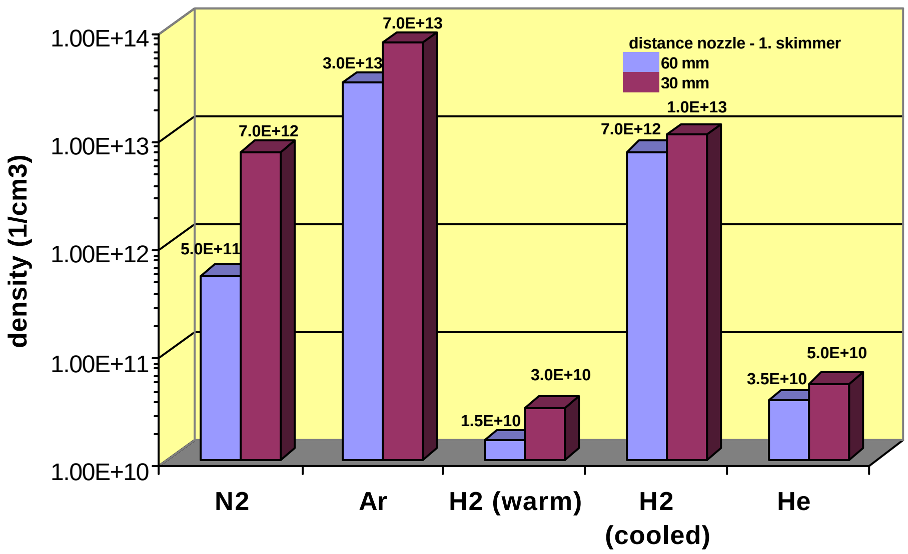
Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)



Target densities

10^{12} – 10^{14} p/cm^3

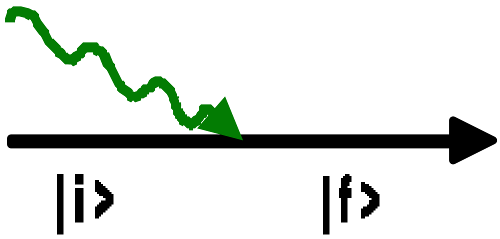
Single collision conditions

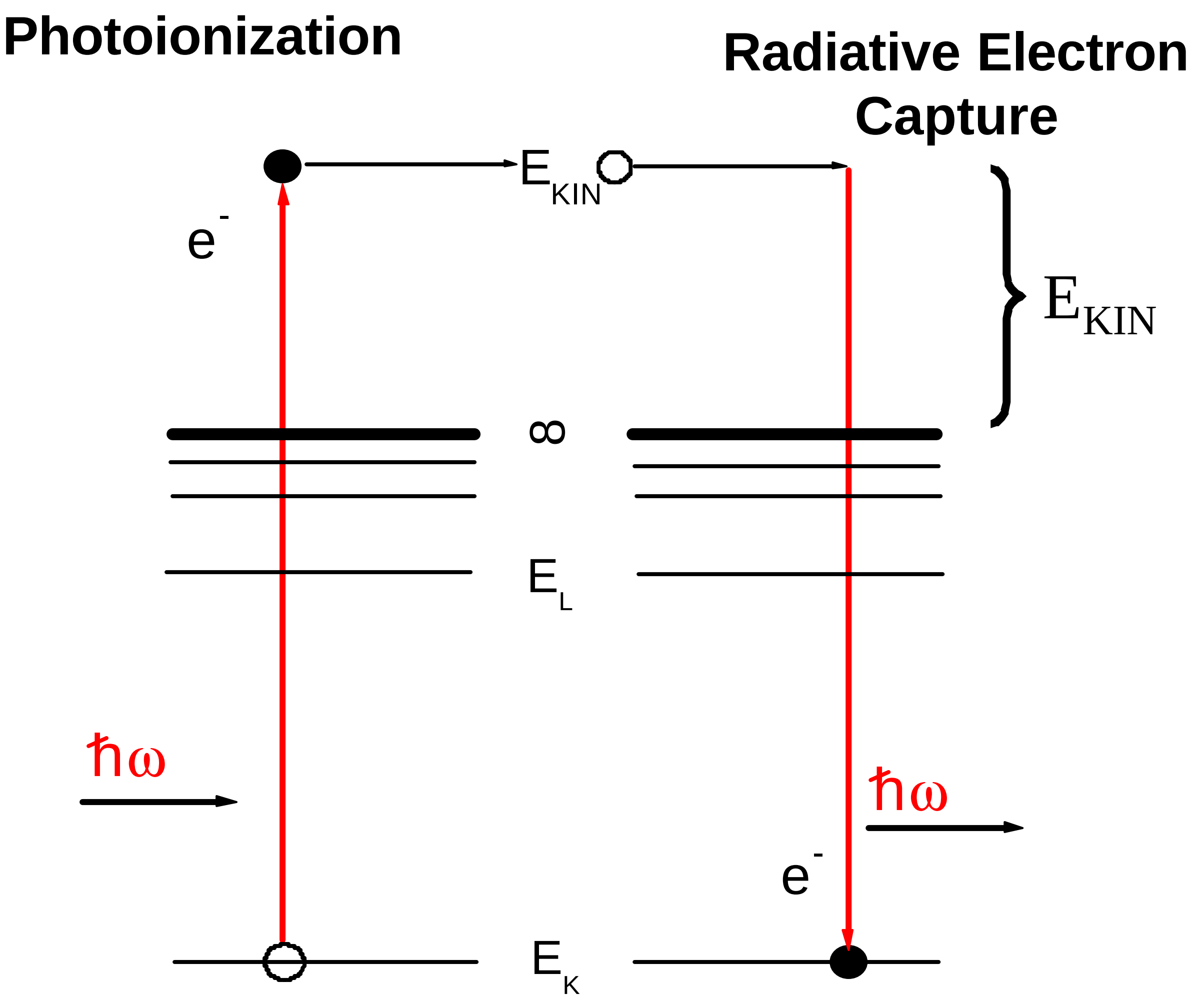


A. Krämer et al, NIM B 174. 205 (2001)

Th. Stöhlker, APAC Conference 2001

Photon-Matter Interaction in the Relativistic Regime:
Study of Photoionization of high-Z Ions





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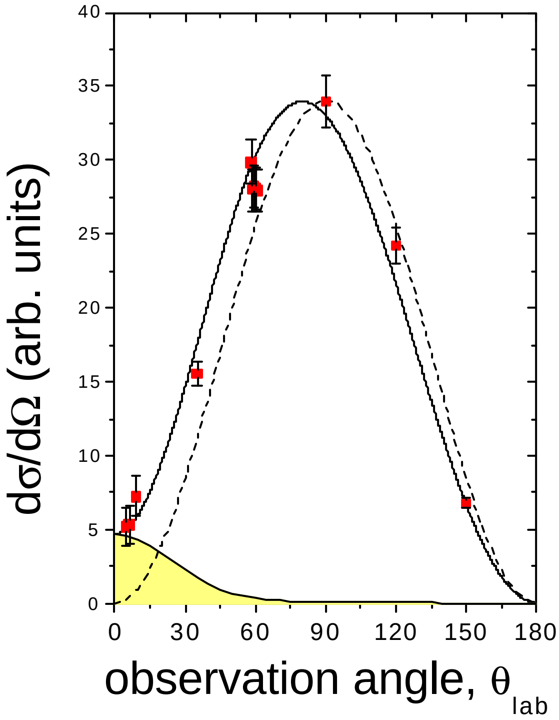
Angular Distribution

radiative capture into U^{92+} and photoionization of U^{91+}

Time reversal

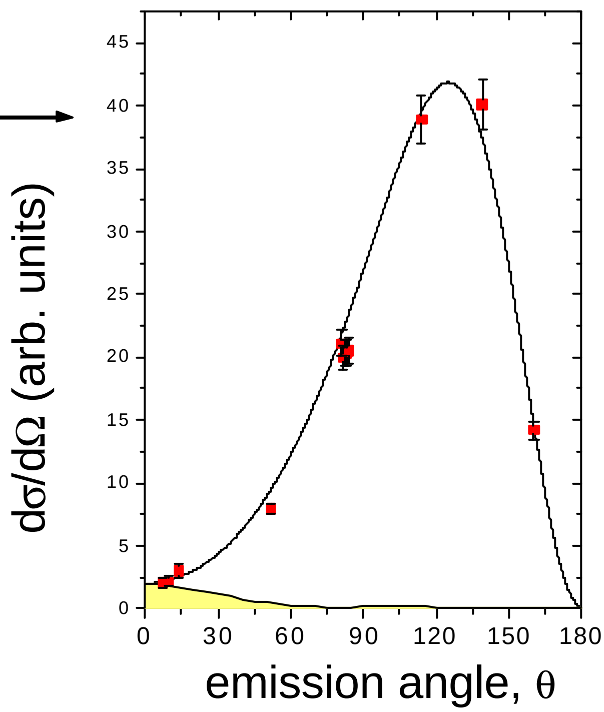
laboratory frame

$U^{92+} \Rightarrow N_2$, 88MeV/u



emitter frame

$e^- \Rightarrow U^{92+}$, 48 keV

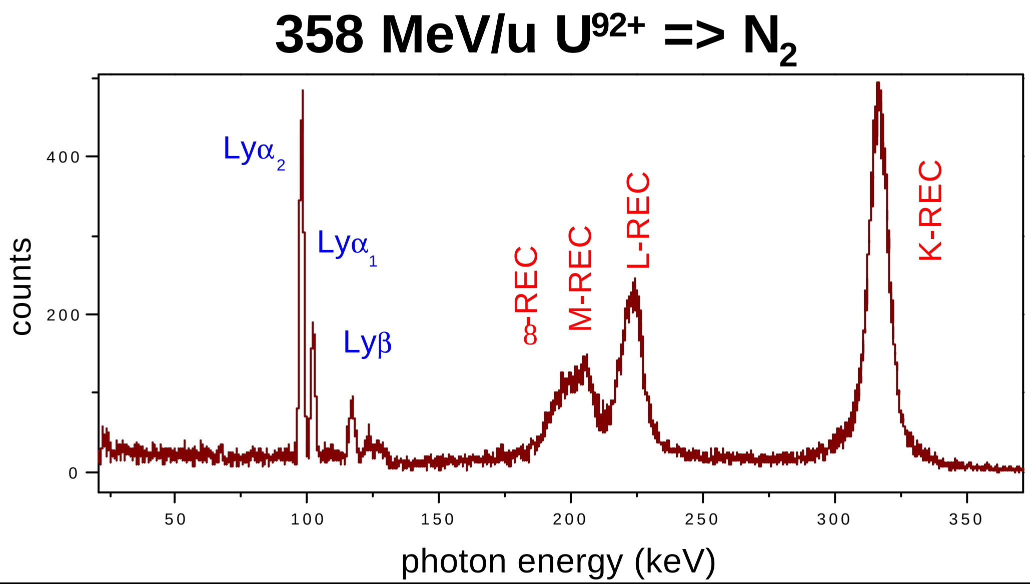


Theory: J. Eichler 1999

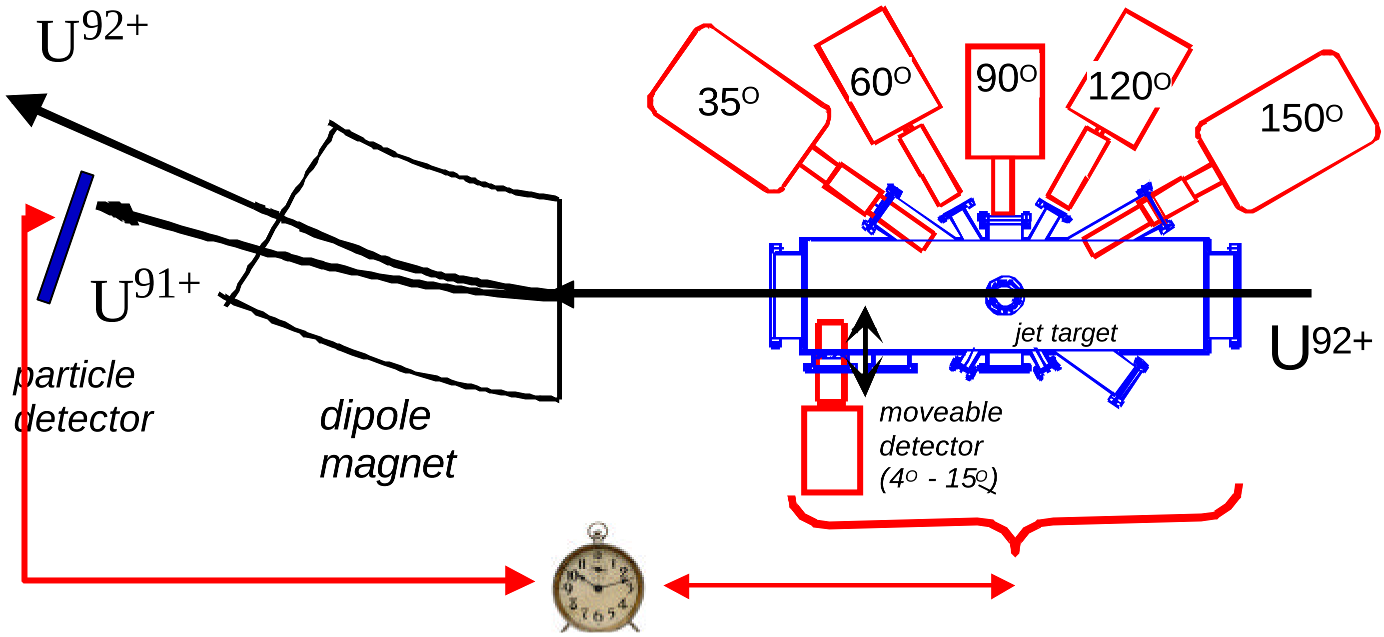
spin-flip contribution: 2%

Th. Stöhlker et al., PRL 82, 3232 (1999)
PRL 86, 983 (2001)

Angular Distribution Studies for the Time-Reversed Photoionization Process



Experimental Setup at the Gas-Jet Target



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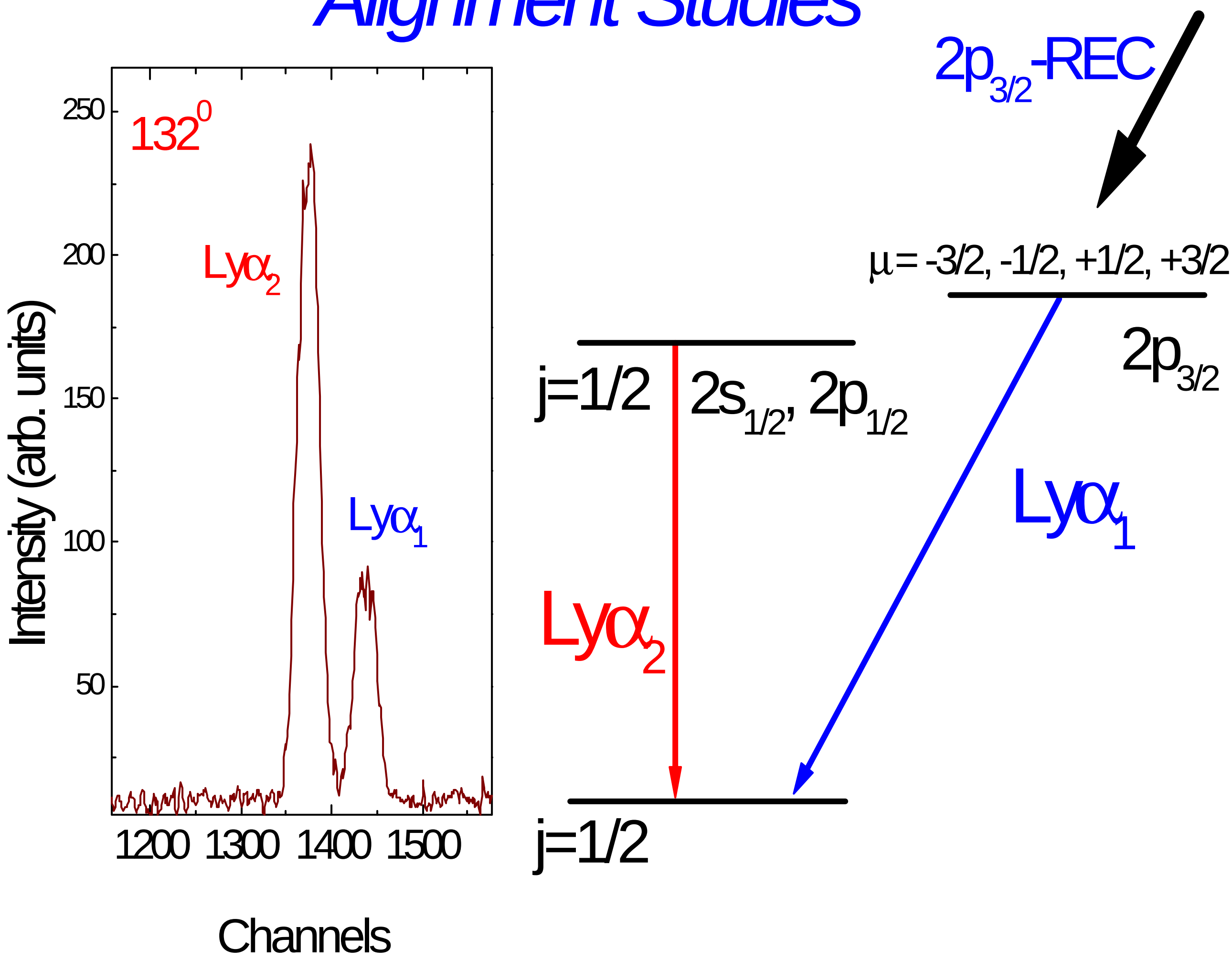
$2p_{3/2}$ transitions in high-Z ions produced by REC: a source of polarized high energy photons

Alignment Studies



Theory: J. Eichler Nucl. Phys. A572, 147 (1994)

Inverse of Two-Photon One-Electron Ionization

1st photon: resonant excitiation to the $2p_{3/2}$ state
+
2nd photon: ionization

$\Delta t \approx 10^{-17}$ s

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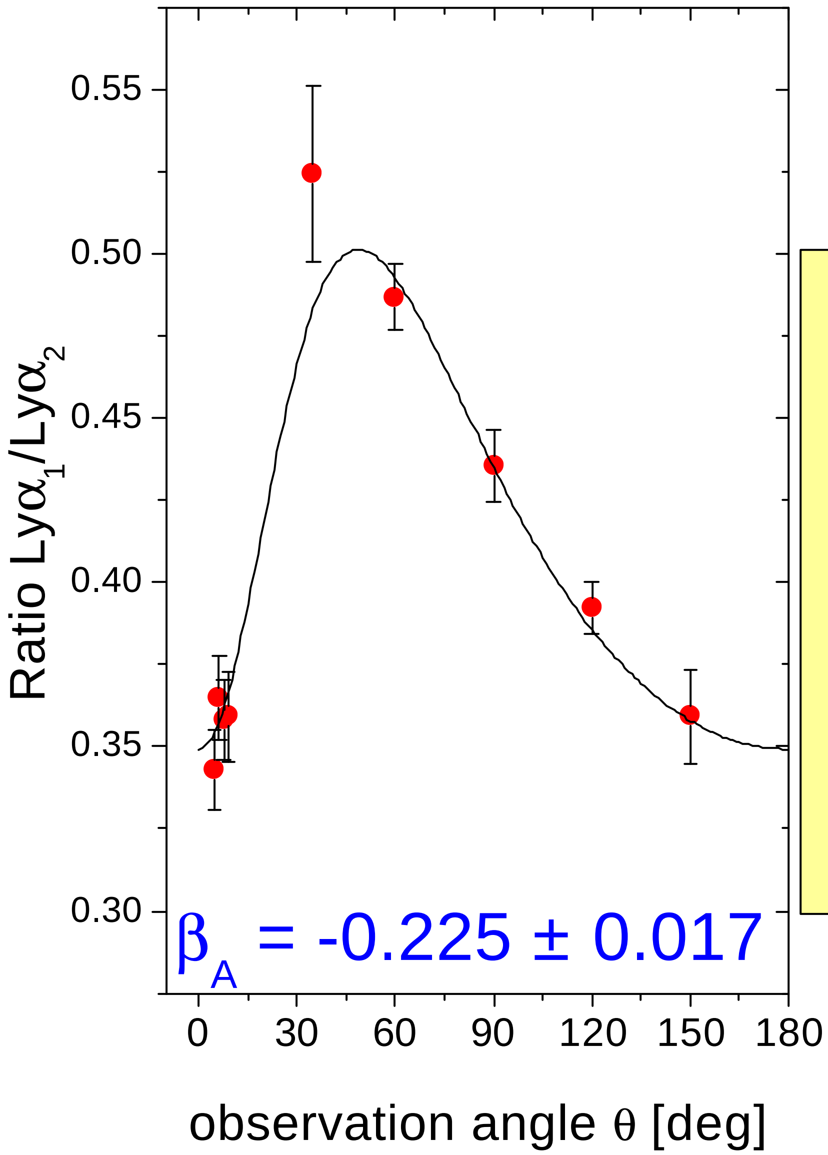

Lyα$_1$ transitions at 310 MeV/u

Direct capture into the $2p_{3/2}$ state populates almost exclusively the magnetic sublevels with

$$|m_j| = \frac{1}{2}$$

Alignment → Alignment Parameter

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

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

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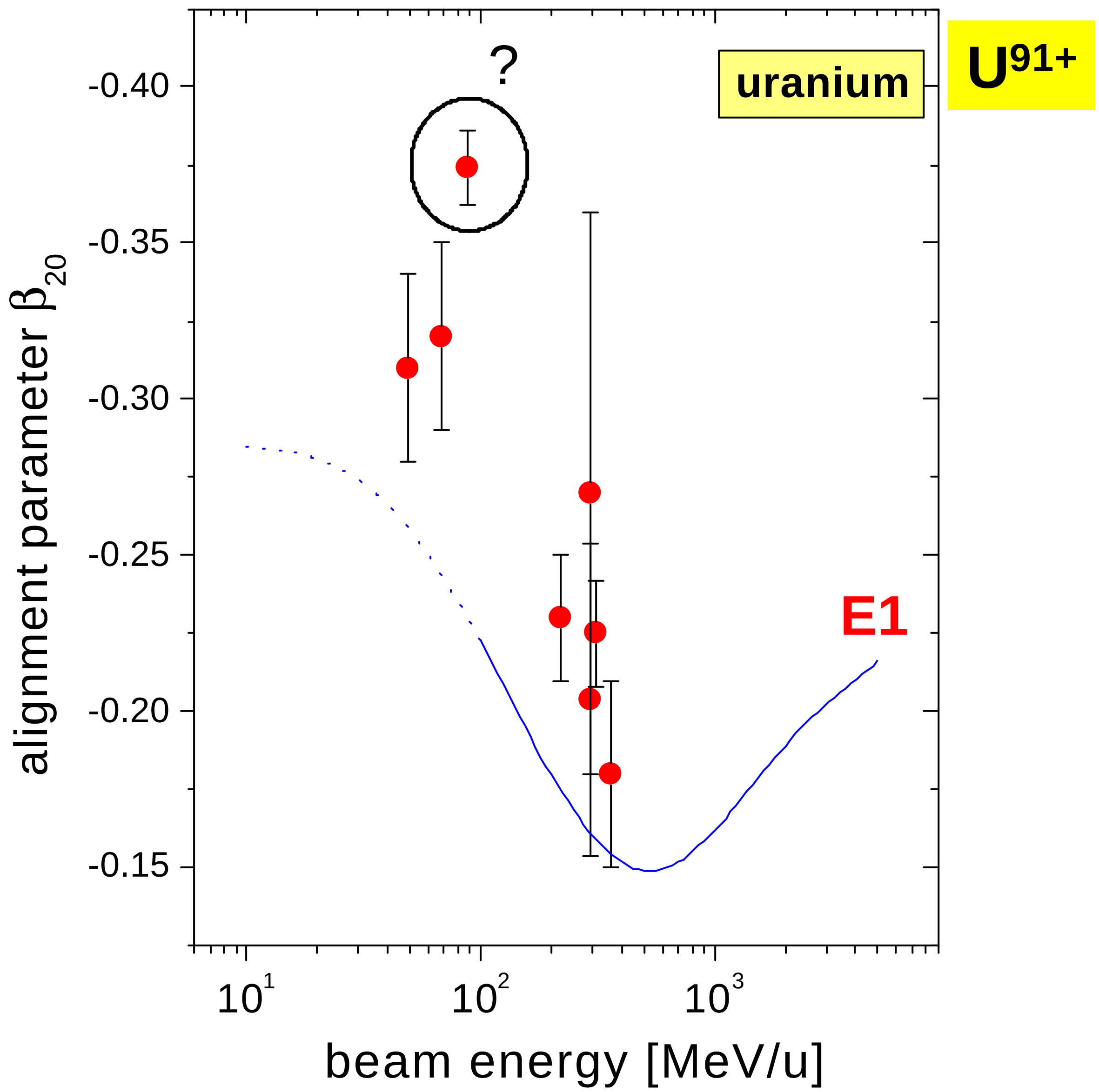
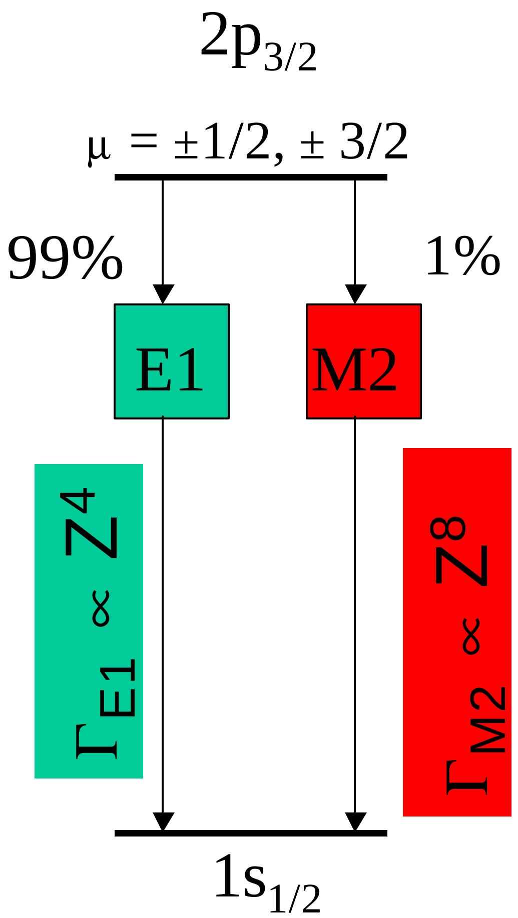
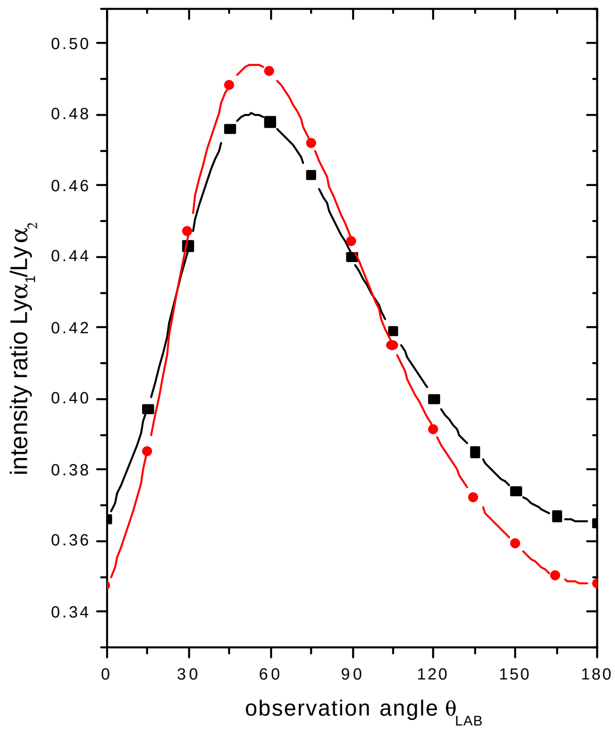


Strong alignment observed for REC into the $2p_{3/2}$ state but data deviate markedly from theory

(Th. Stöhlker et al., PRL 79, 3270 (1997))

Interference between the E1 and M2 transition amplitudes leads to a disturbed angular distribution for the $2p_{3/2}$ decay



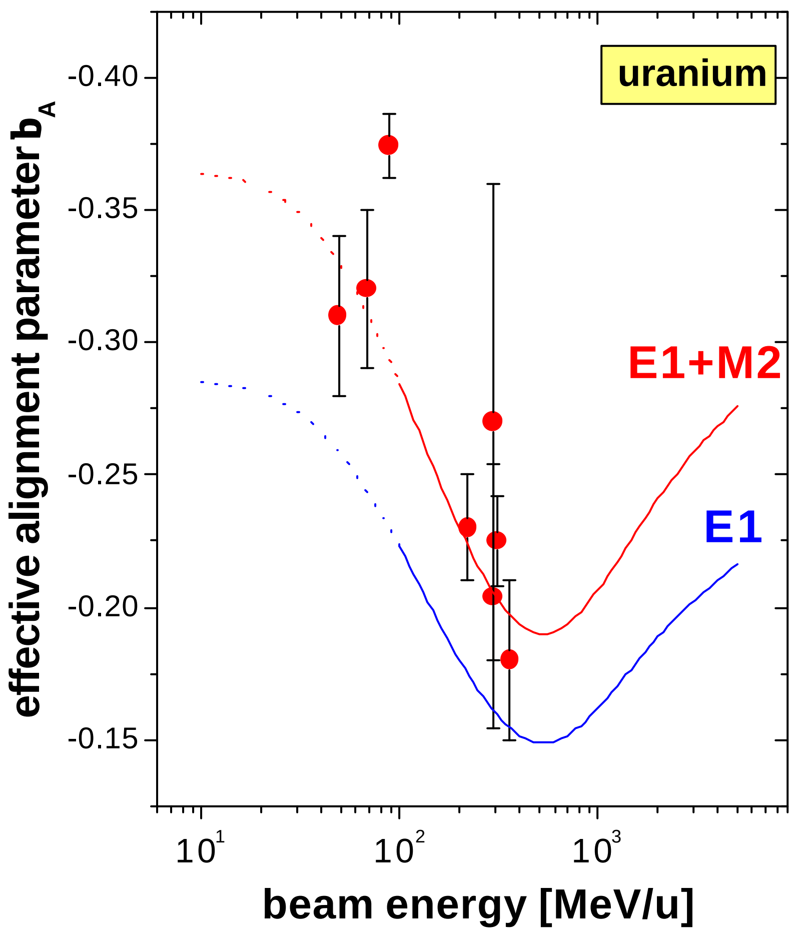


Photon angular distribution of the decay of the $2p_{3/2}$ state in H-like ions

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

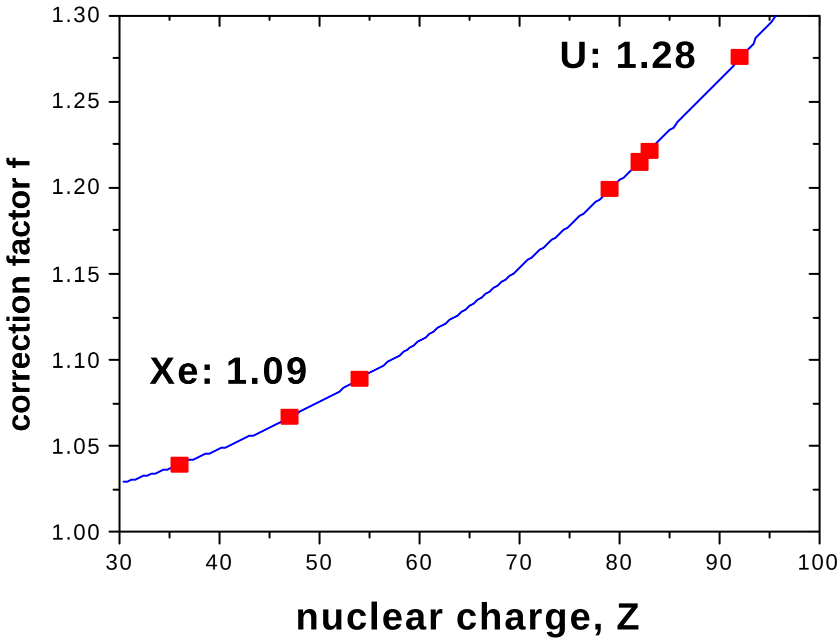
for Z=92 $\quad f\left(\frac{a_{E1} \cdot a_{M2}}{a_{E1}^{2}}\right) = 1.28$

Prediction by S. Fritzsche und A. Surzhykov, 2001



U^{91+}

$$f\left(\frac{a_{E1} \cdot a_{M2}}{a_{E1}^{\;2}}\right) = 1.28$$



$$f\left(\frac{a_{E1} \cdot a_{M2}}{a_{E1}^{\;2}}\right) \propto Z^2$$

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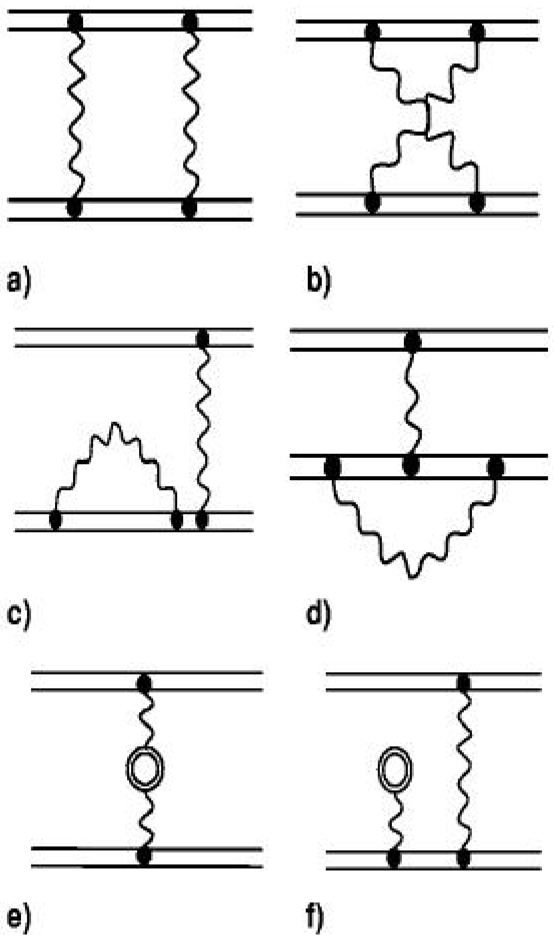
Electron-Electron Interaction in Strong Fields

Measurement of the 2eQED for Uranium at the ESR

Accuracy:
2 eV; $\Delta E/E \approx 0.1\%$

Z=92

Two-Electron Contribution: 2246.0 eV



a,b) Non-Radiative QED
+1.3 eV [U^{90+}]
0.06%

c,d) Two-Electron Self Energy
-9.7 eV [U^{90+}]
0.4%

e,f) Two-Electron Vacuum Polarization
+2.6 eV [U^{90+}]
0.1%

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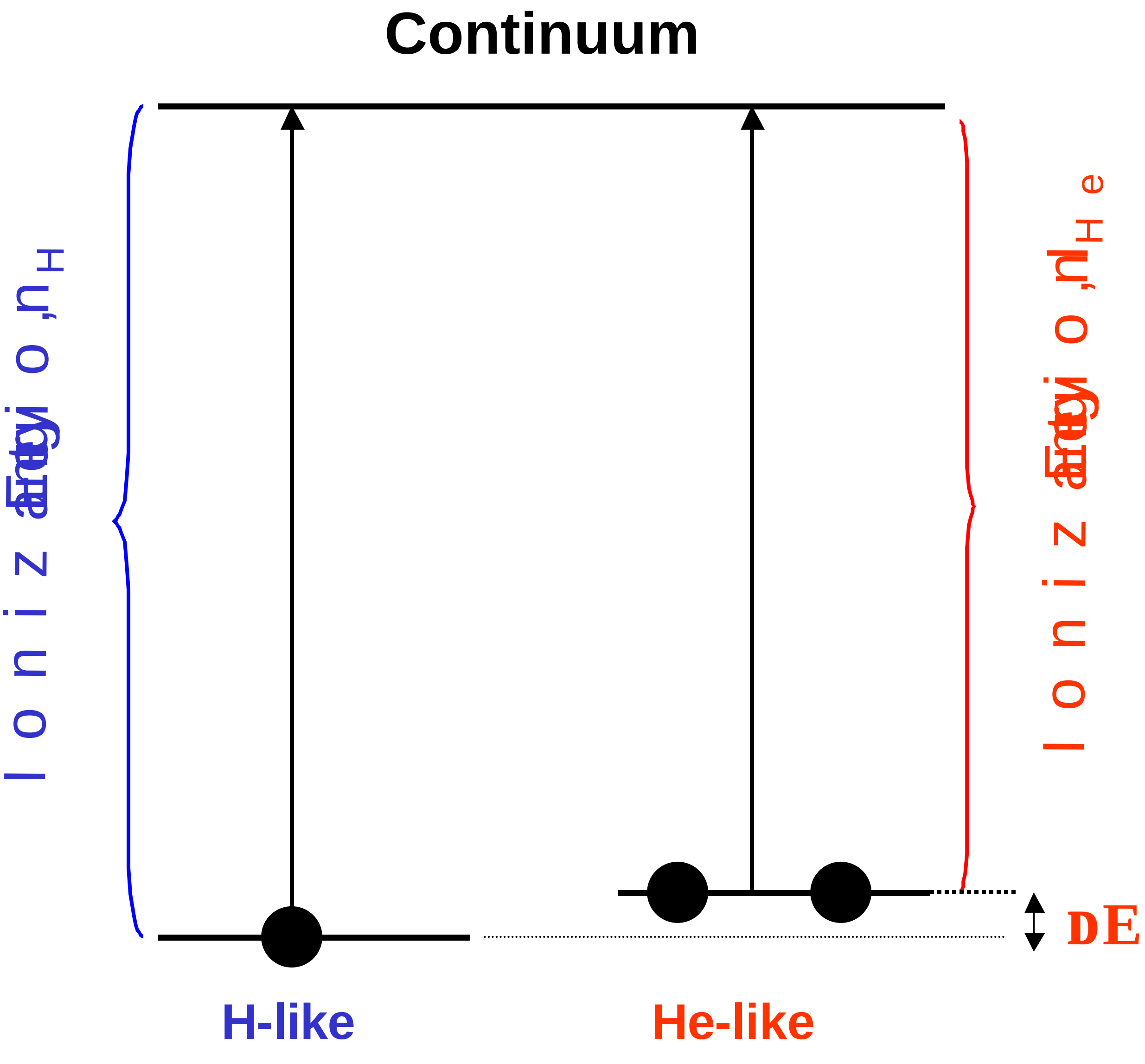
Electron-Electron Interaction in Strong Fields



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

ΔE: ***Two-Electron Contribution to the Binding Energy in the He-like System***

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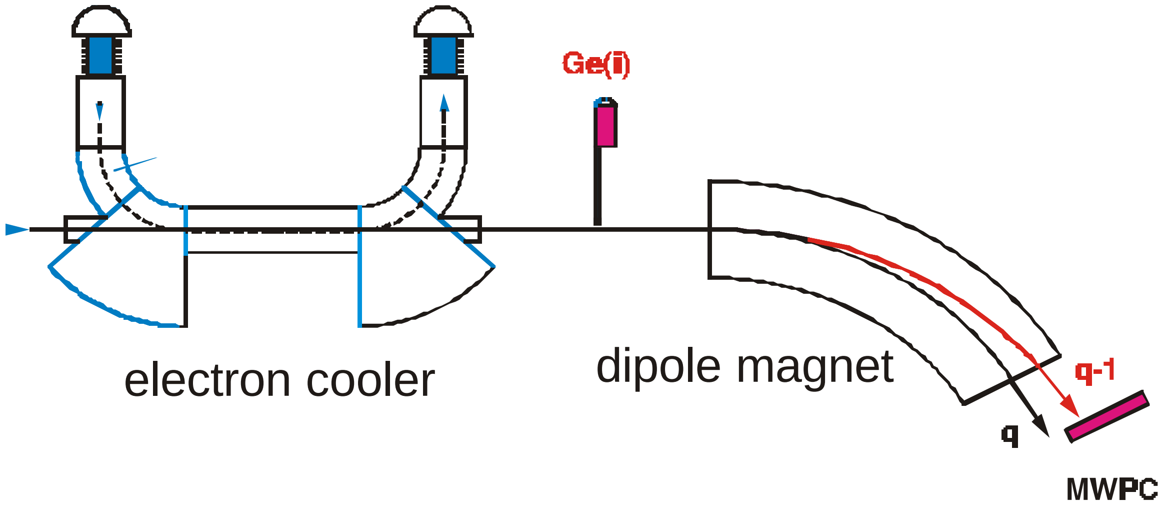
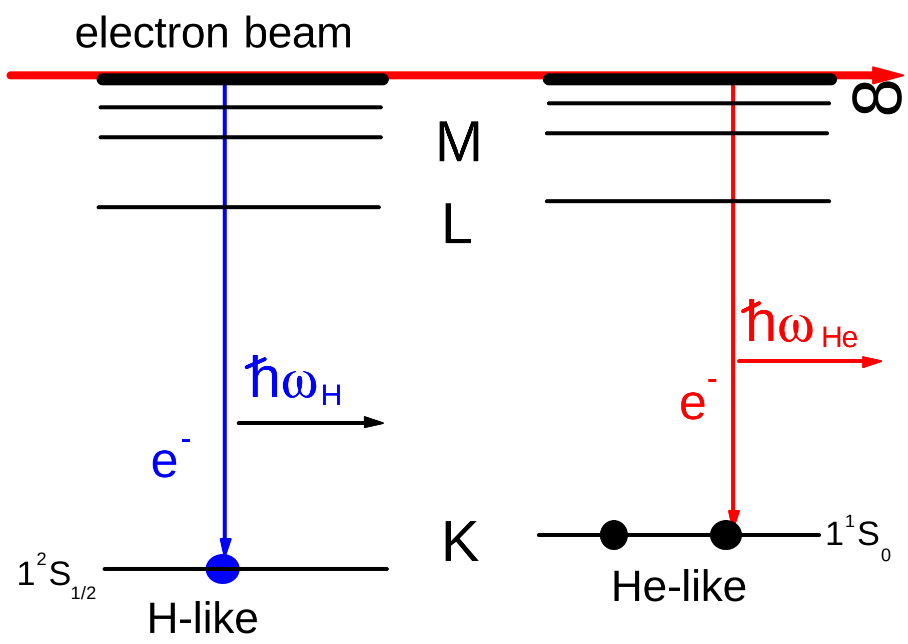
Goal of the experiment

To probe the first time higher order QED (in a) corrections in the domain of high-Z systems





$E_{KIN} + I_H = \hbar\omega$ $\qquad$ $E_{KIN} + I_{He} = \hbar\omega$

$$\Delta E(\hbar\omega - \hbar\omega) = I_H - I_{He}$$

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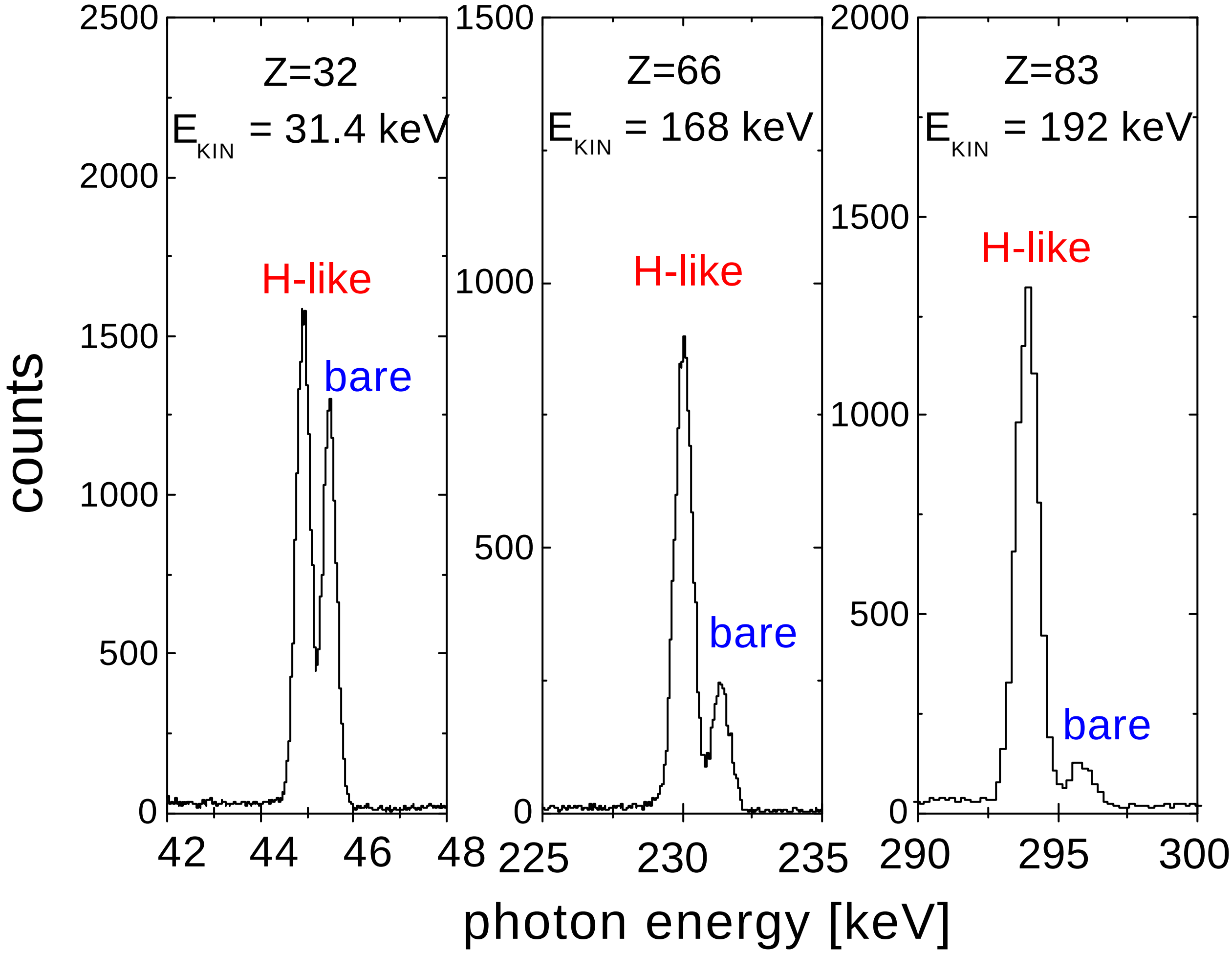
result



Z	32	54	66	74	76	83
Exp. [eV]	562.6 ±1.6	1027.2 ±3.5	1341.6 ±4.3	1568.9 ±15	1608 ±20	1876 ±14
ΔE/E	2.8 x 10^{-3}	3.4 x 10^{-3}	3.0 x 10^{-3}	1 x 10^{-2}	1.2 x 10^{-2}	0.7 x 10^{-3}

Results are only limited by counting statistics

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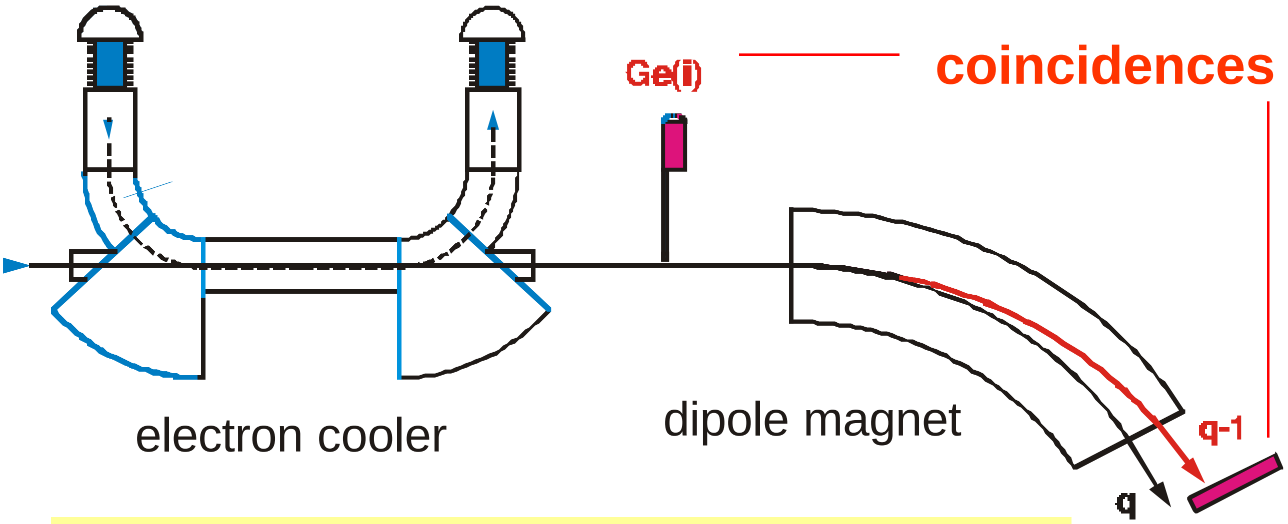
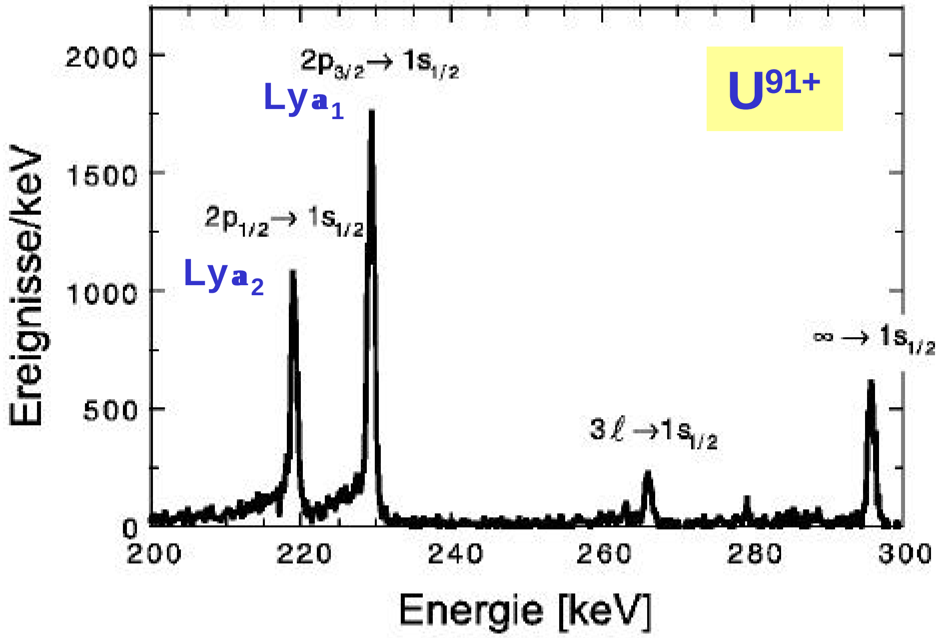


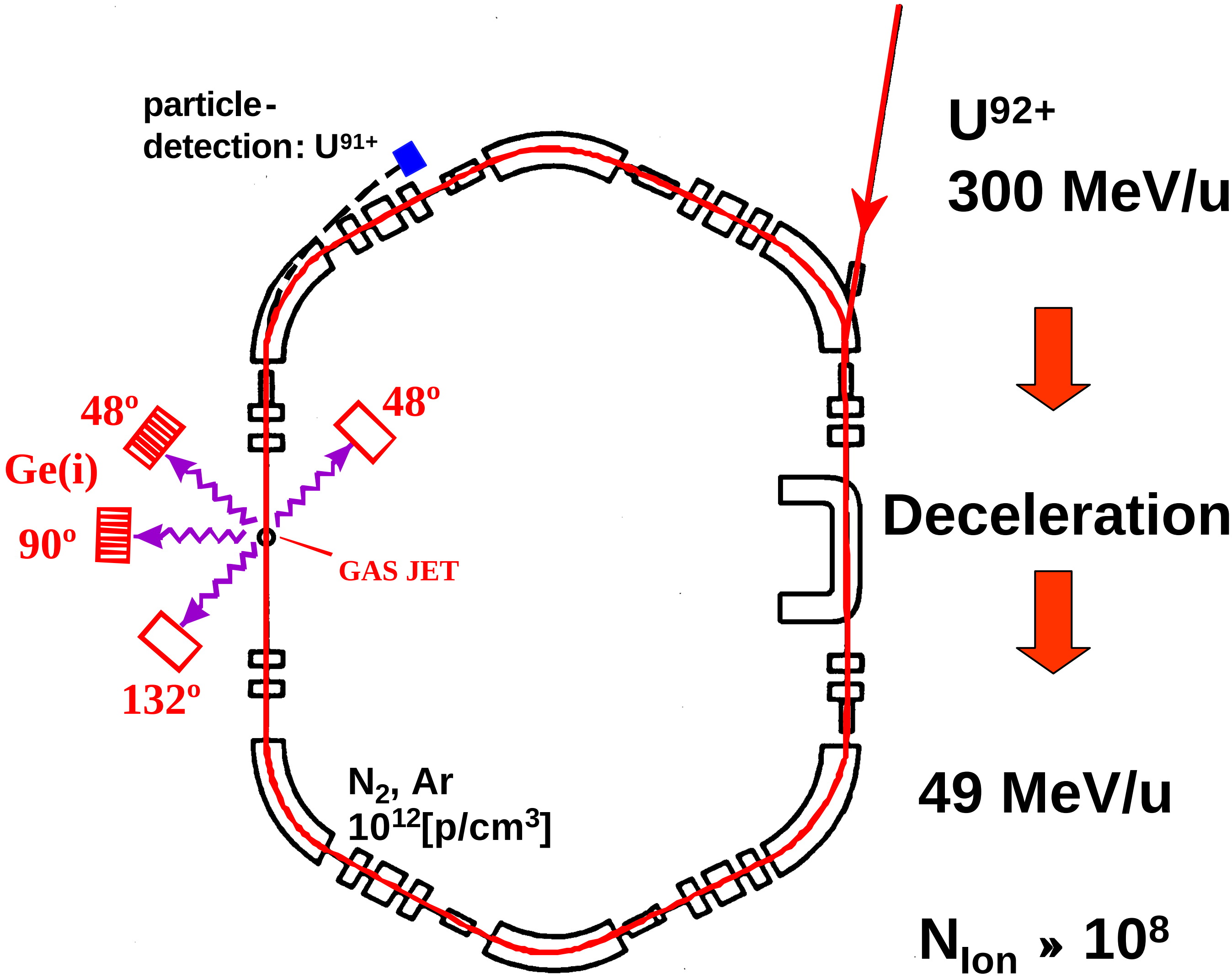
0^{o} Spectroscopy at the Electron Cooler

- strongest blue shift
  $\beta \approx 0.65 \Rightarrow E_{lab} \approx 2.2 \times E_{proj}$
- $\Delta\theta_{LAB}$ not critical, Doppler width has its minimum
- Uncertainty is caused by $\Delta\beta$



H.F. Beyer et al., 1995

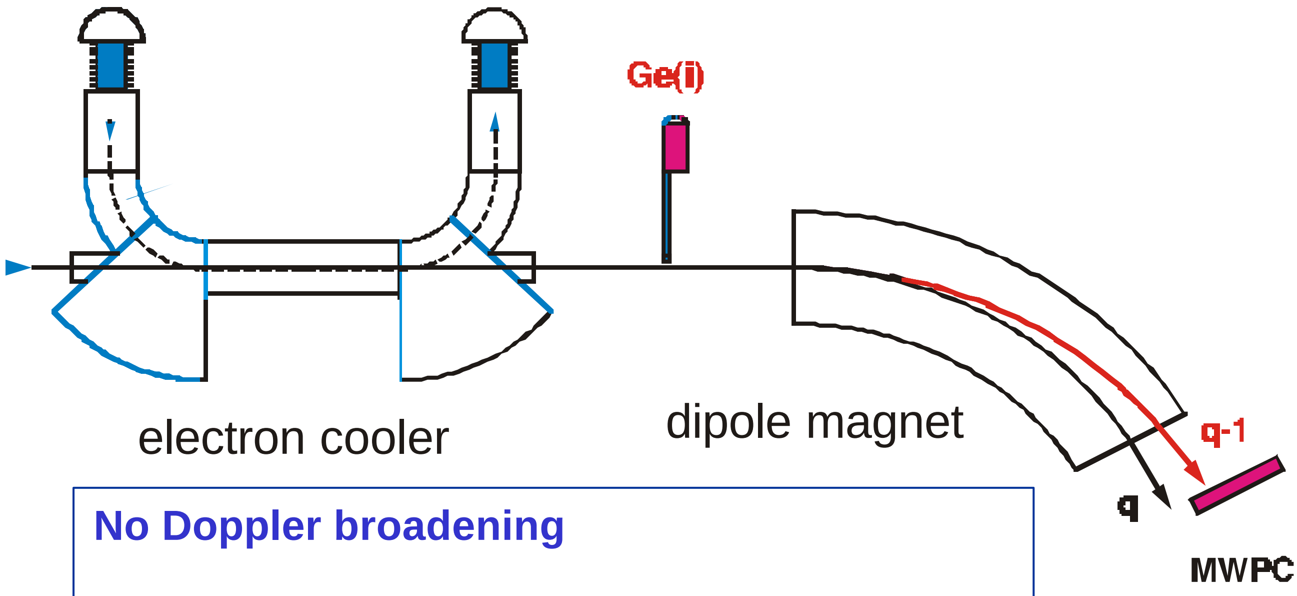
X-Ray Spectroscopy at the Jettarget



$$E_{lab} = \frac{E_{proj}}{\tilde{a} \bullet (1 - \hat{a} \bullet \cos\grave{e}_{lab})}$$

E_{lab}: Photon energy in Laboratory system
E_{proj}: Photon energy in emitter system

0 deg spectroscopy at the electron cooler



No Doppler broadening

practically, no uncertainties introduced by the geometry of the set-up

X-ray projectile coincidences

The relative measurement can be performed in sequential steps by changing frequently between bare and H-like uranium

Application of the deceleration mode of the ESR

→ **strongly reduced bremsstrahlung**
uncertainty in ь not critical

To probe the QED corrections for the ground state in helium like uranium, a relative accuracy of only $\Delta E/E \approx 10^{-3}$ is required

For uranium, we like to measure the 2.2 keV energy splitting with an accuracy of better 5 eV (DE/E »2x10^{-3})

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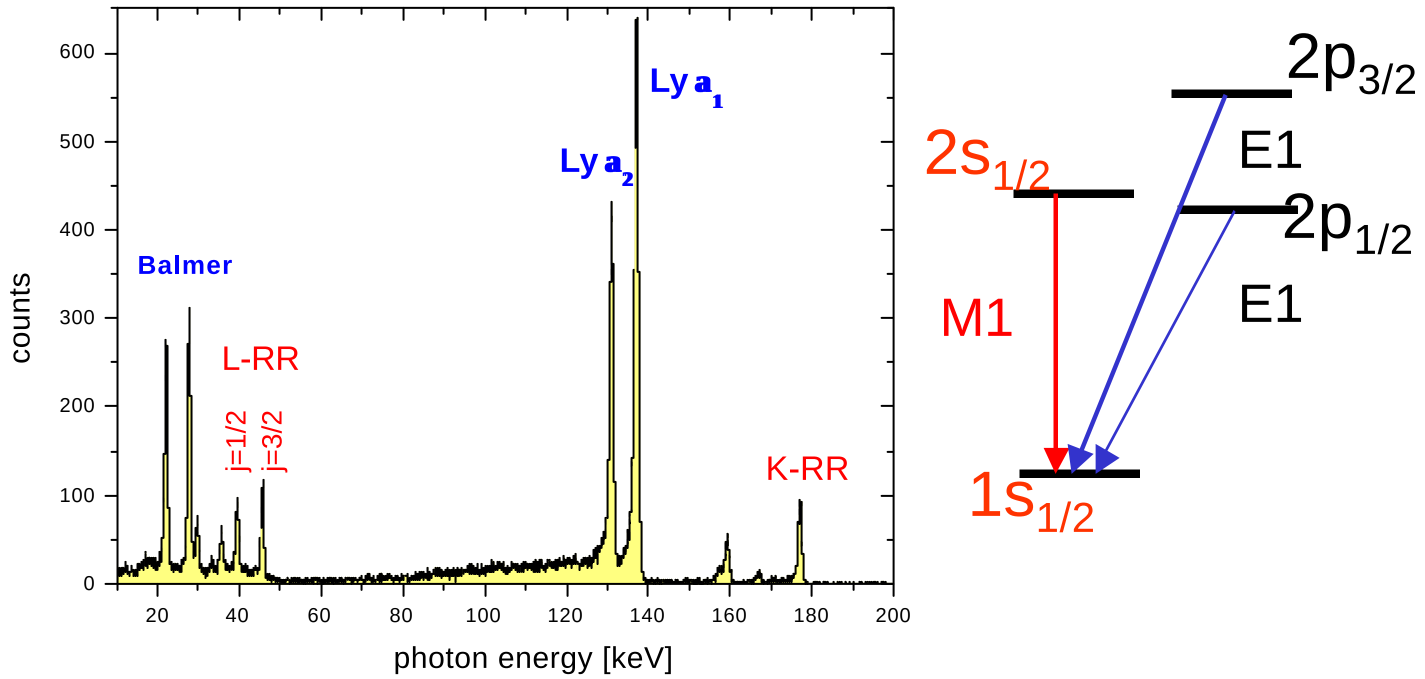
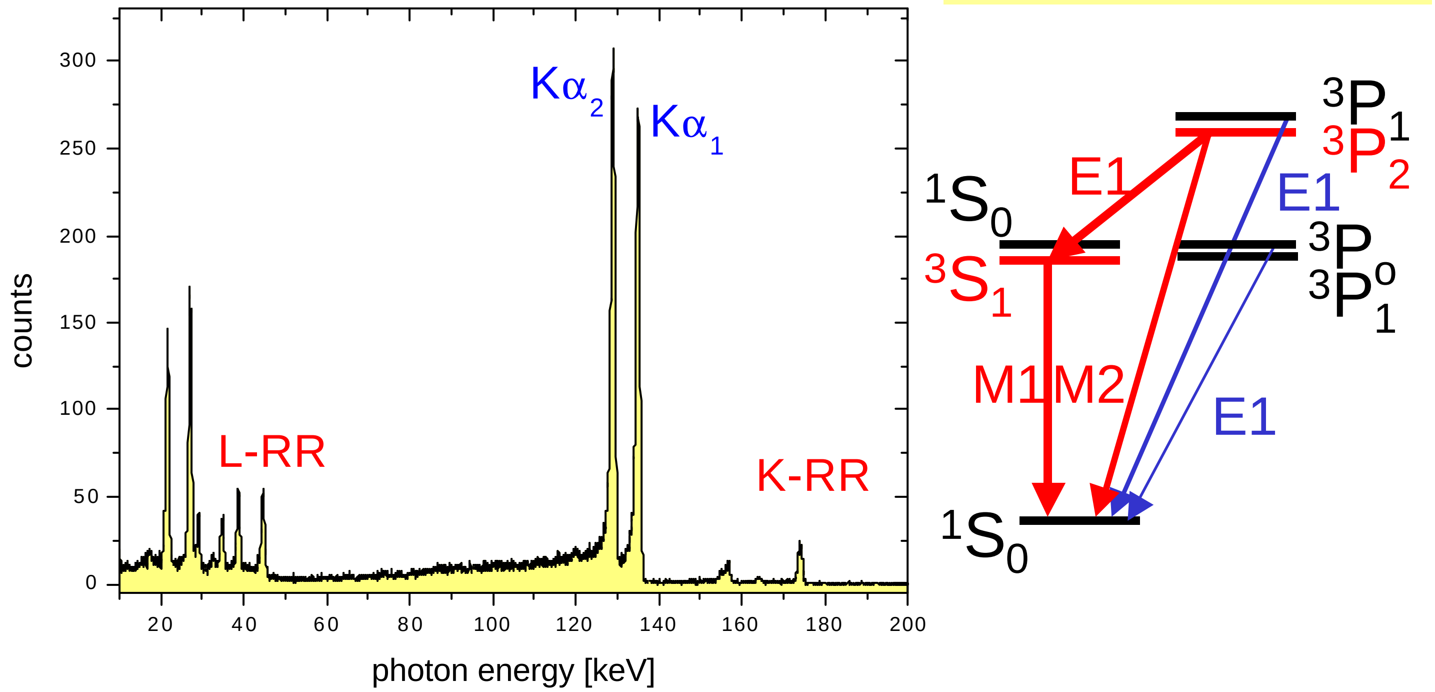
H-like uranium



He-like uranium



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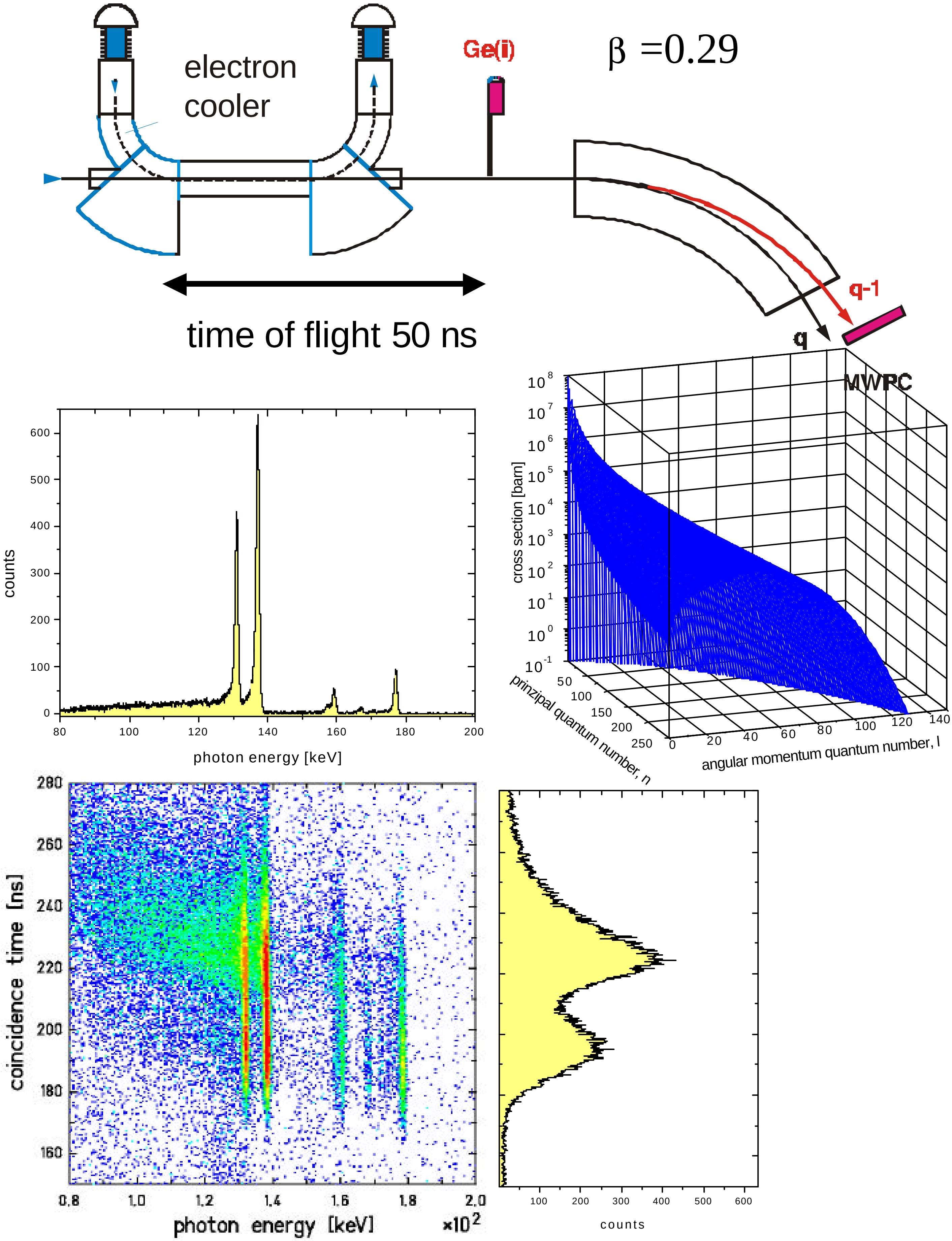

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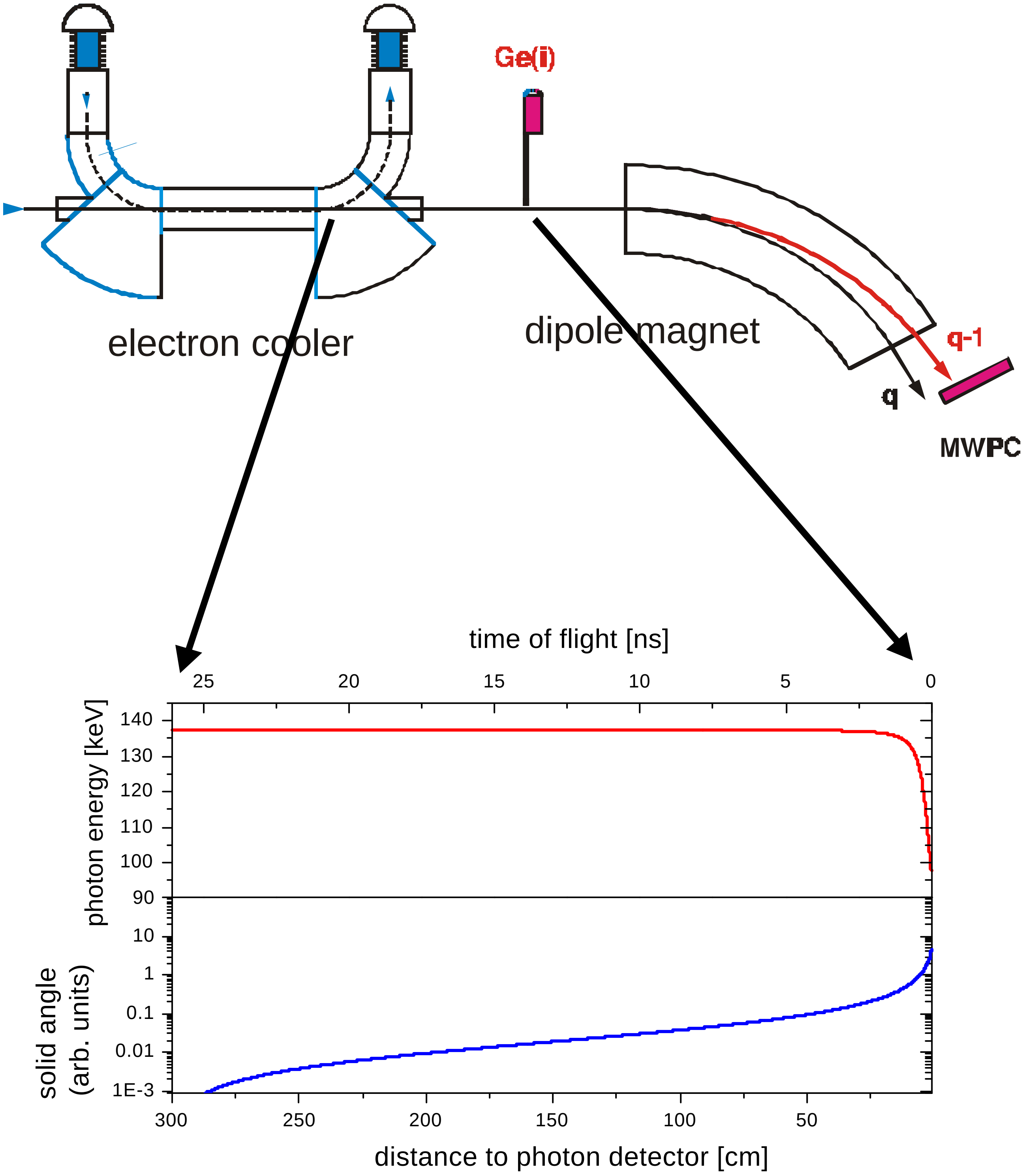

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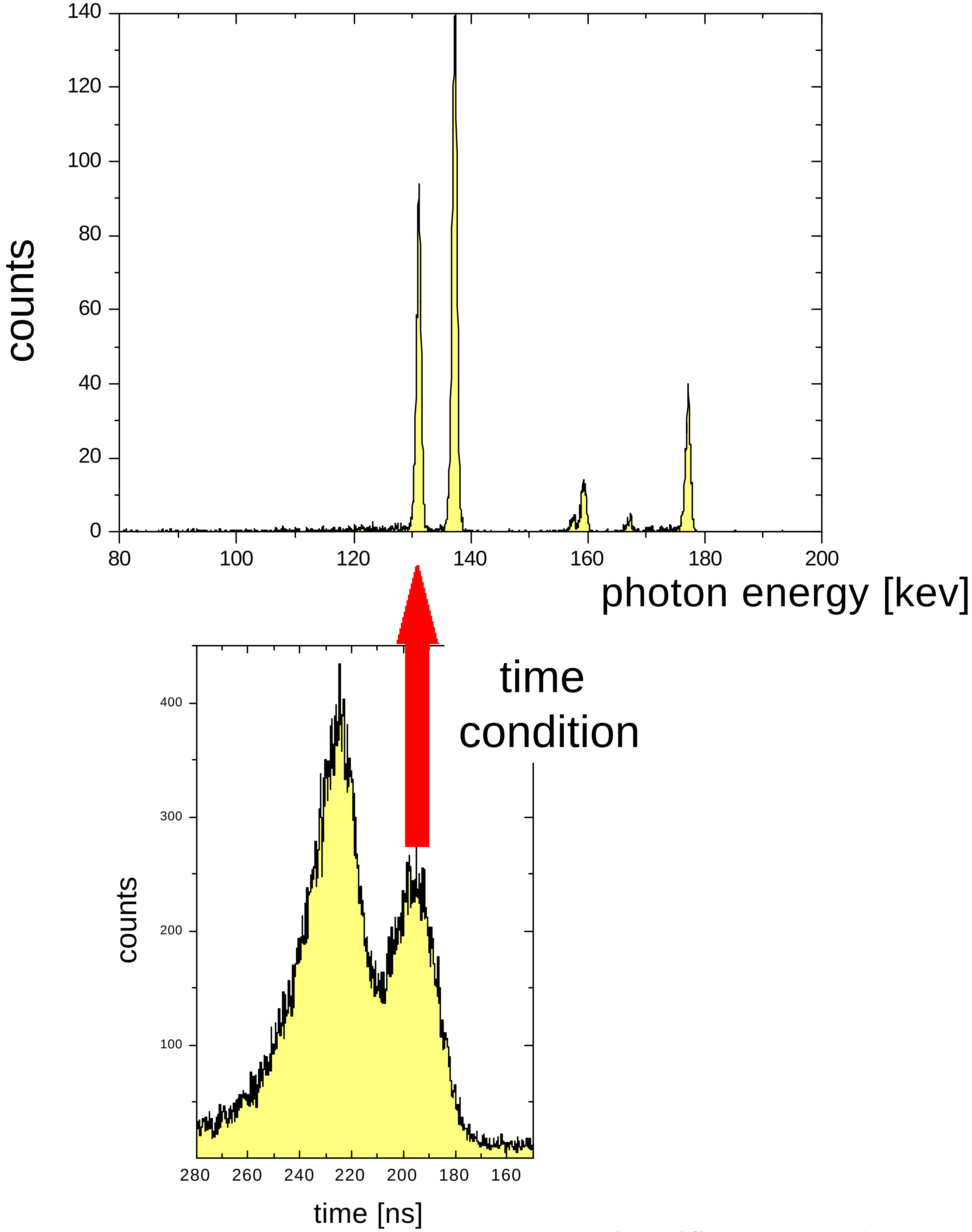

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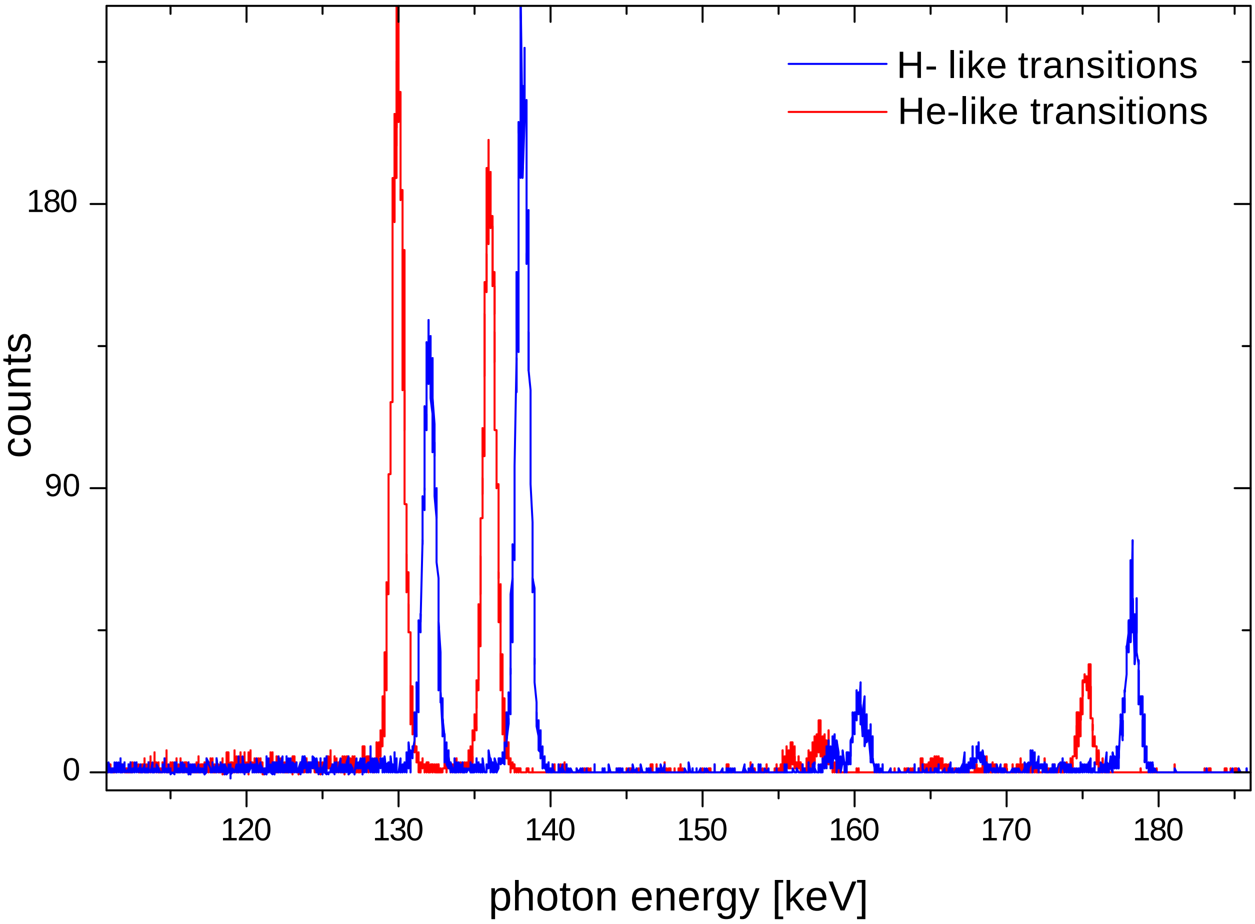
Relative measurement at electron cooler for decelerated ions



Estimated statistical uncertainty
for RR into H- and He-like uranium: $\approx$ 9 eV

Uncertainty caused by doppler
shift:

Additional systematic errors: ?

Summary

- **The ESR provides ideal conditions for precise studies of the atomic structure and collision of high-Z ions (at the jet target as well as at the electron cooler)**

    - ***determination of relative ionization potentials***

    - ***Lamb shift experiments***

- **The study of elementary atomic processes for highly-charged heavy ions via their time-reversal**

    - ***identification of spin-flip transitions for photoionization***
    - ***interference between E1 and M2 transition amplitudes***

Outlook

- **Decelerated ions**
- **photon correlation spectroscopy**
- **polarisation studies**
- **Recoil momentum spectroscopy and electron spectroscopy**
- **Combination of electron and photon spectroscopy**
- **Laser assisted experiments**