X-Ray Emission in Atomic Collisions

(Decade of Experiments at the ESR)

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Contents

- Introduction

  - motivation of atomic physics experiments at GSI

  - historical remarks

- X-Ray Experiments at GSI (Jet-target Area of ESR)

- Electron Capture : Main Trigger of X-Ray Processes

  - Radiative Electron Capture and its angular distribution (spin-flip transitions)

  - strong alignment of REC populated states

  - nuclear effects ?

  - search for correlated two-electron capture

- Summary

GENERAL GUIDE-LINE of ATOMIC COLLISION EXPERIMENTS at GSI

- **HEAVY IONS (high Z , $\alpha * Z < 1$)**

  - strong internal fields
  - relativistic wavefunctions

- **HIGHLY CHARGED IONS**

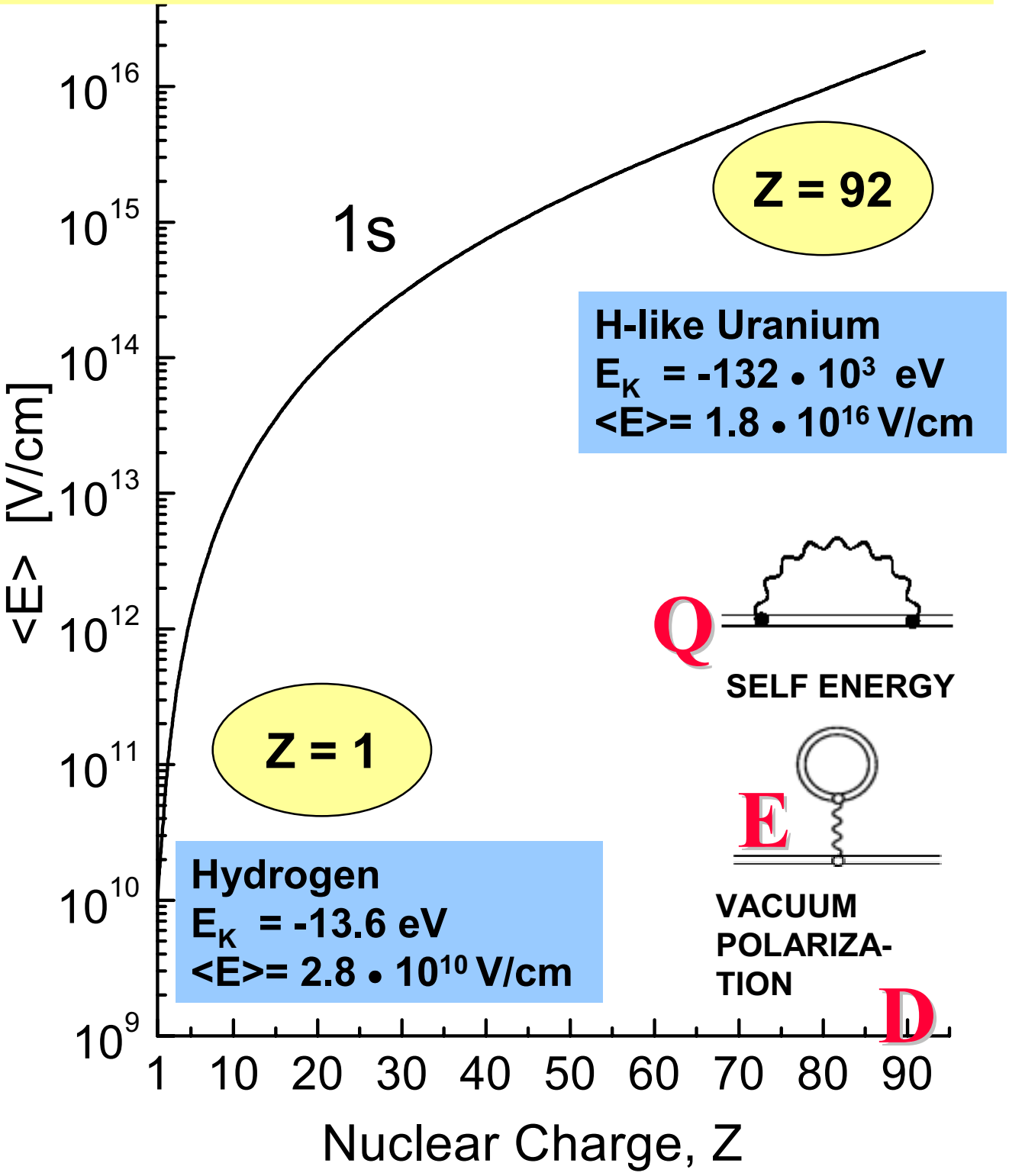
  - simple atomic systems
  - H- and He-like ions

- **FAST IONS ($0.4 < \beta < 0.7$)**

  - relativistic kinematics
    (Lorentz transformation between projectile and laboratory reference system)
  - relativistic dynamics of atomic processes

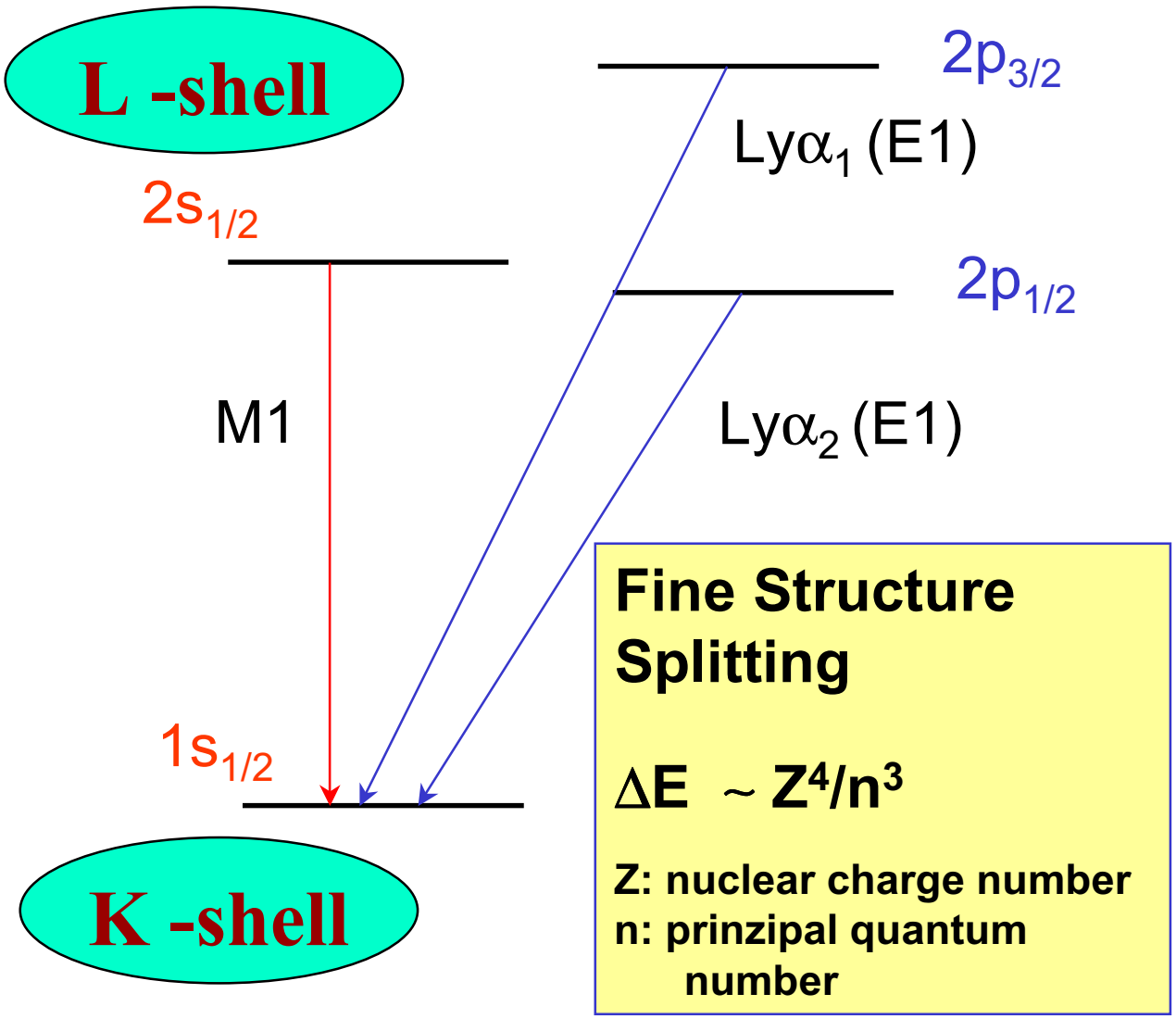
- **DECELERATION MODE**

Atomic Physics in Extremly Strong Coulomb Fields



1s-ground state: increase of the electric field strength by six orders of magnitude

The Structure of One-Electron Systems

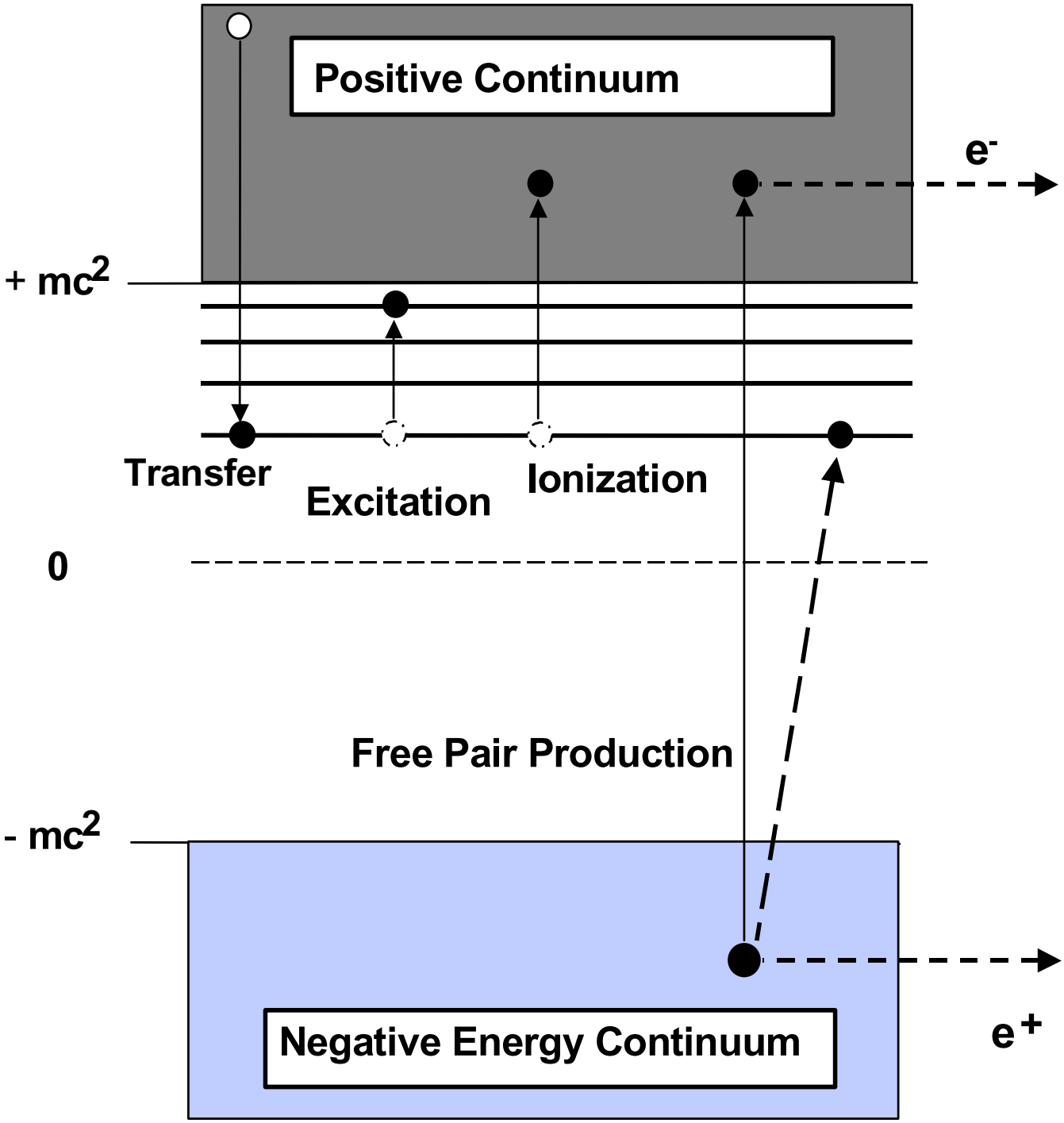


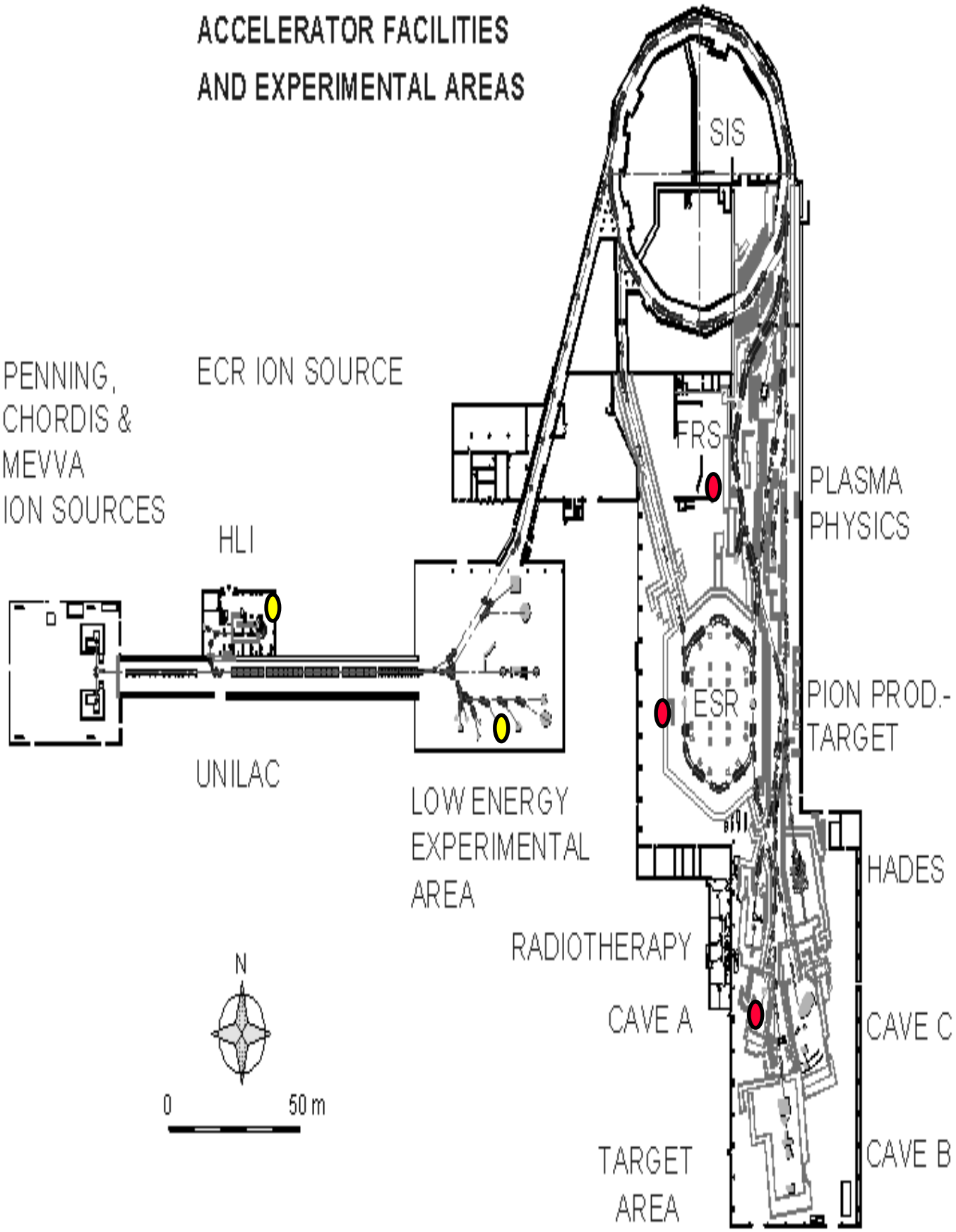
large shell and sub-shell splitting in high-Z systems

- ***photon emission enables state selective study of atomic processes even with standard solid state detectors***

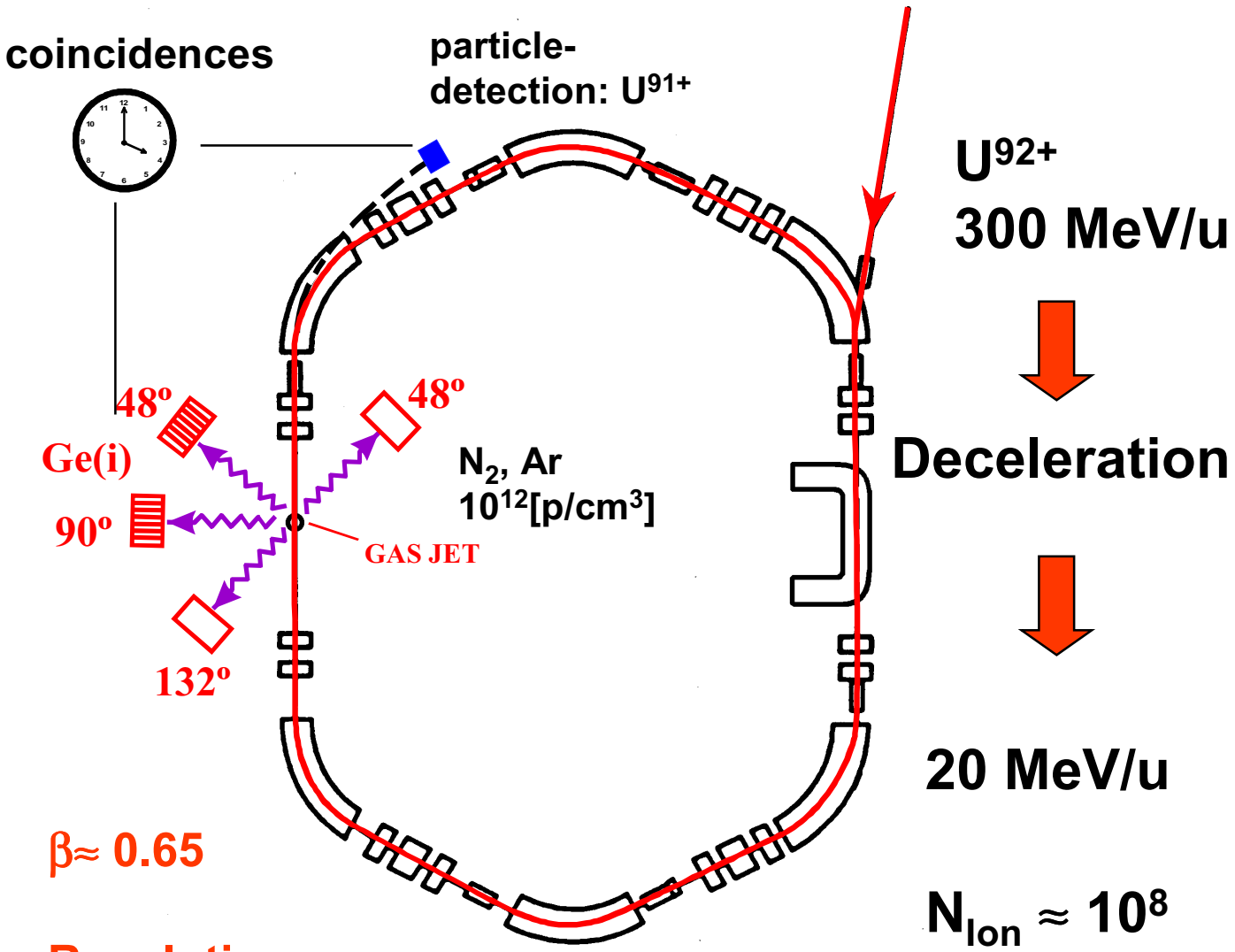
Collision Dynamics of Relativistic Heavy Ions

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



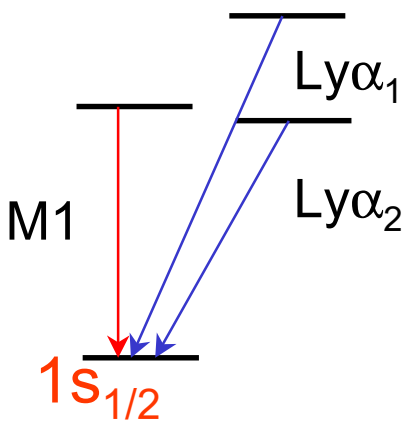

ACCELERATOR FACILITIES
AND EXPERIMENTAL AREAS
SIS
PENNING,
CHORDIS &
MEVVA
ION SOURCES
ECR ION SOURCE
FRS
PLASMA
PHYSICS
HLI
ESR
PION PROD.-
TARGET
UNILAC
LOW ENERGY
EXPERIMENTAL
AREA
HADES
RADIOTHERAPY
CAVE A
CAVE C
CAVE B
TARGET
AREA
N
0
50 m

X-Ray Experiments at the Jet-Target



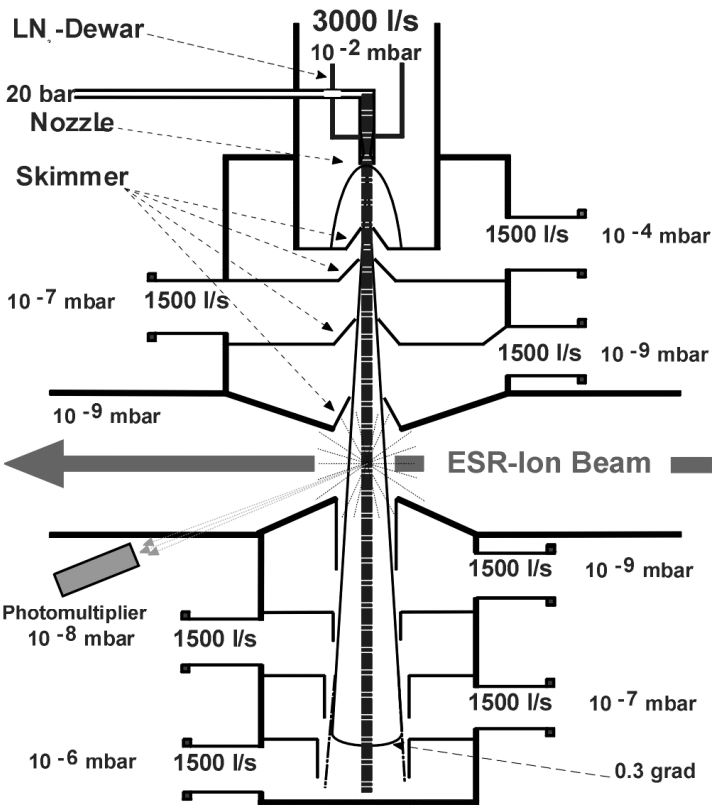
$$E_{lab} = \frac{E_{proj}}{\gamma \bullet (1 - \beta \bullet \cos\theta_{lab})}$$

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



Jet-Target

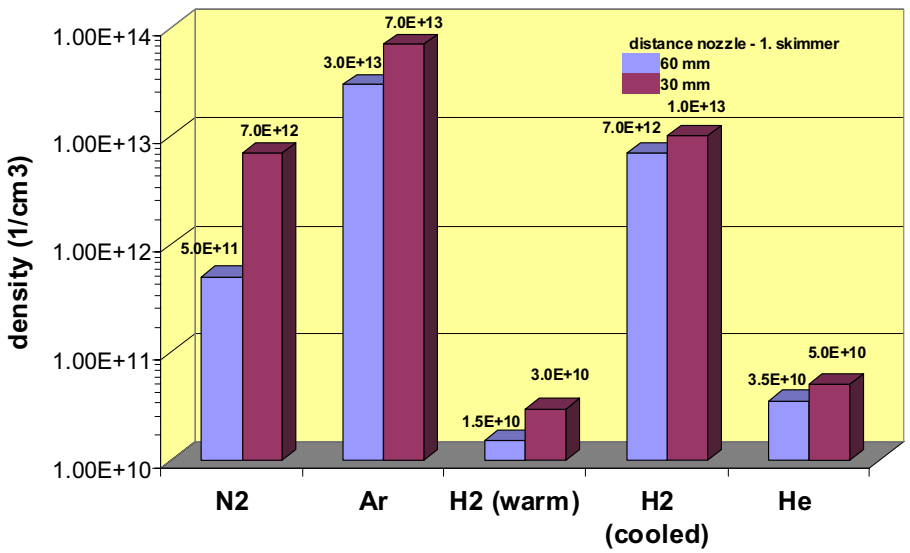
Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)



Target densities

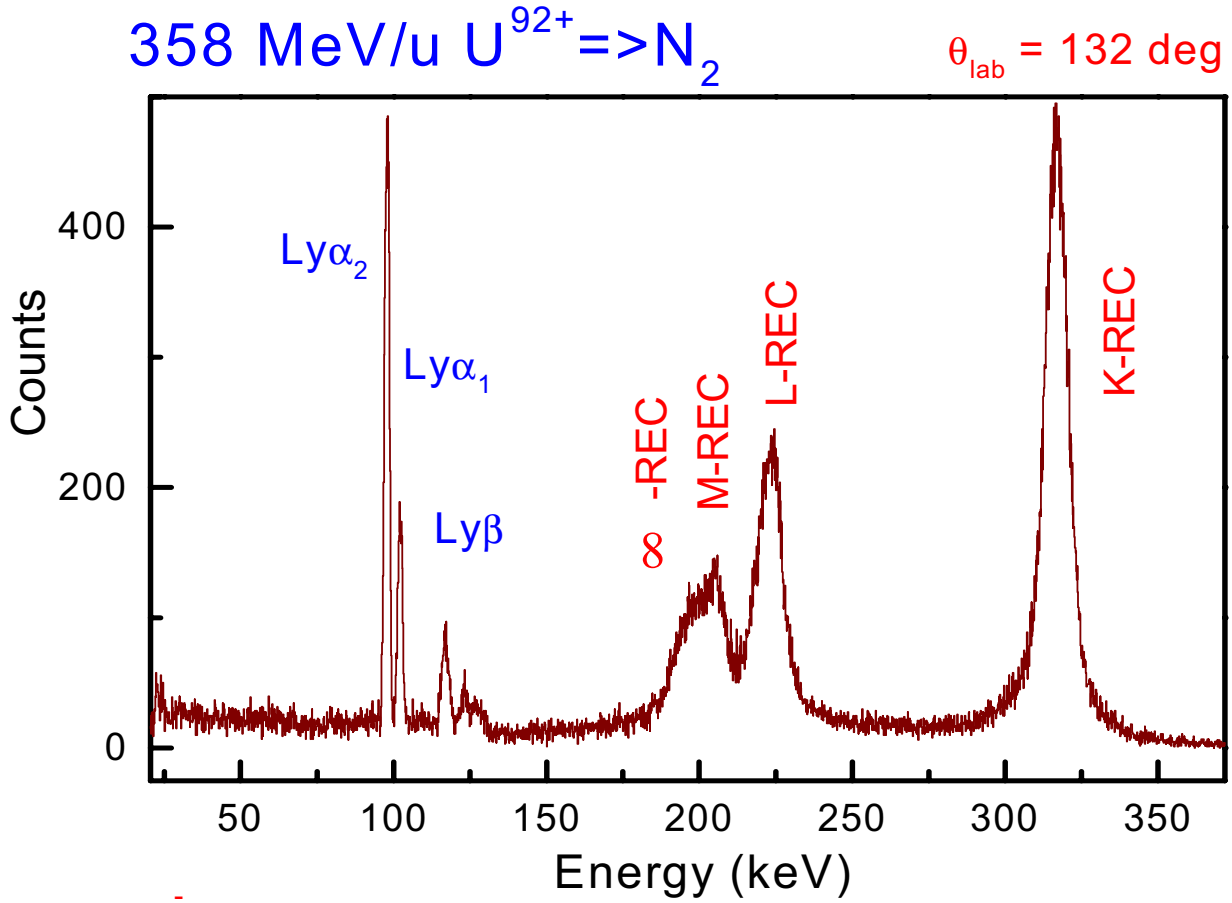
10^{12} – 10^{14} p/cm^3

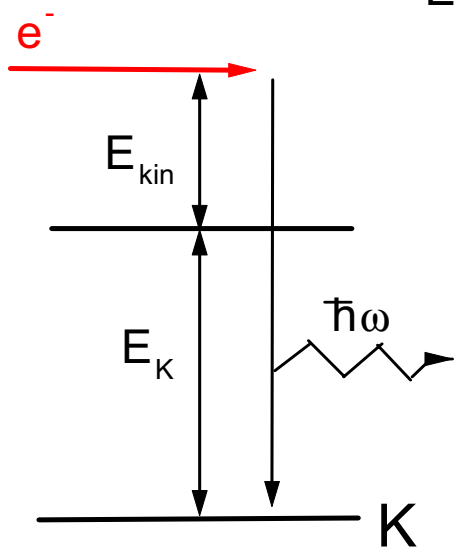
Single collision conditions



H. Reich et al., Nucl. Phys. A 626 (1997) 417c.

X-Ray Spectrum of H-like Uranium

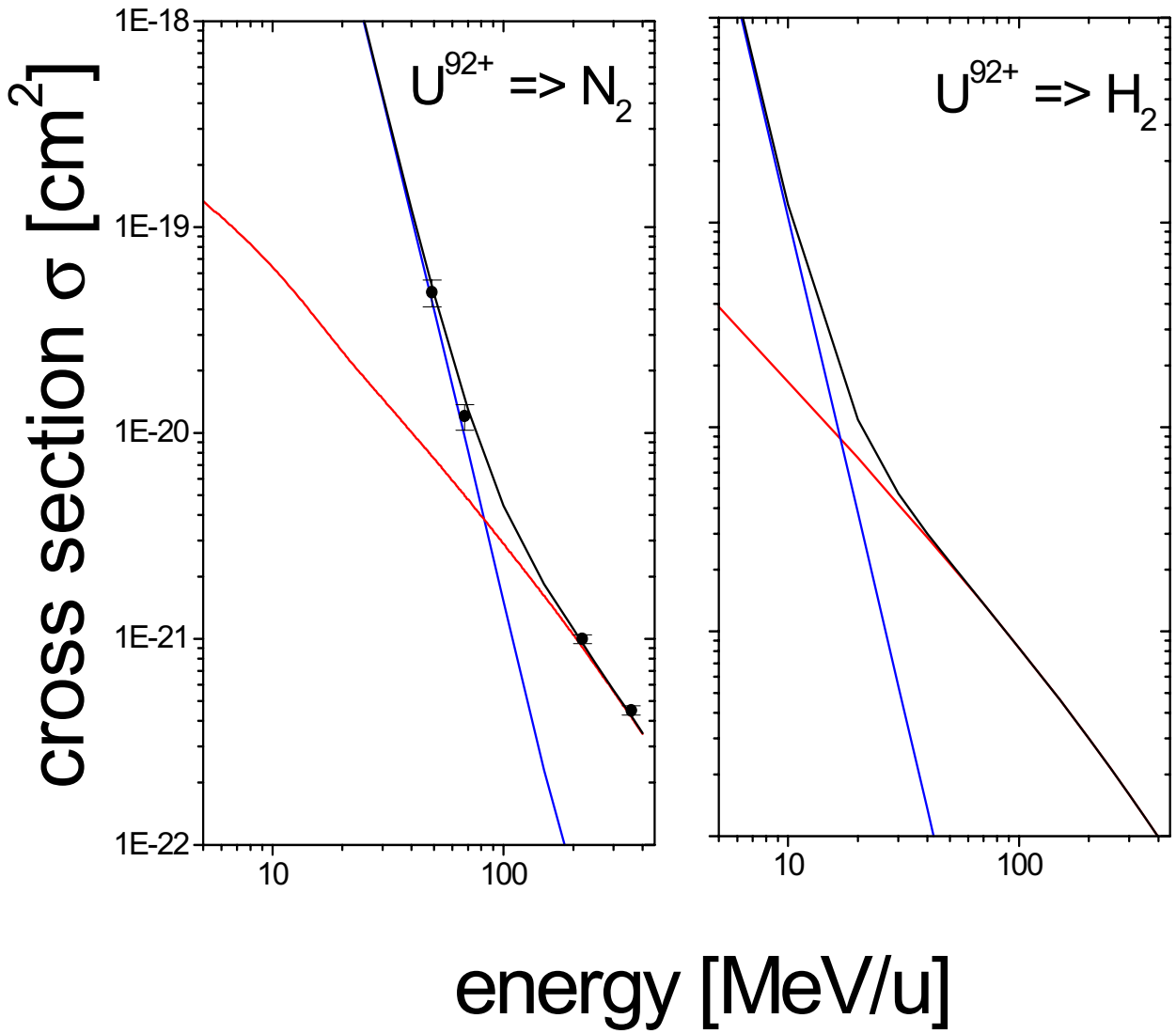




projectile system

$$E_{REC} = E_K + m_e c^2 (\gamma - 1) + \gamma (p_i v_0 - E^B_T)$$

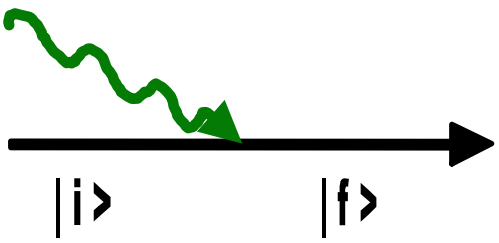
Choice of the collision system prefering REC charge-exchange channel



NREC

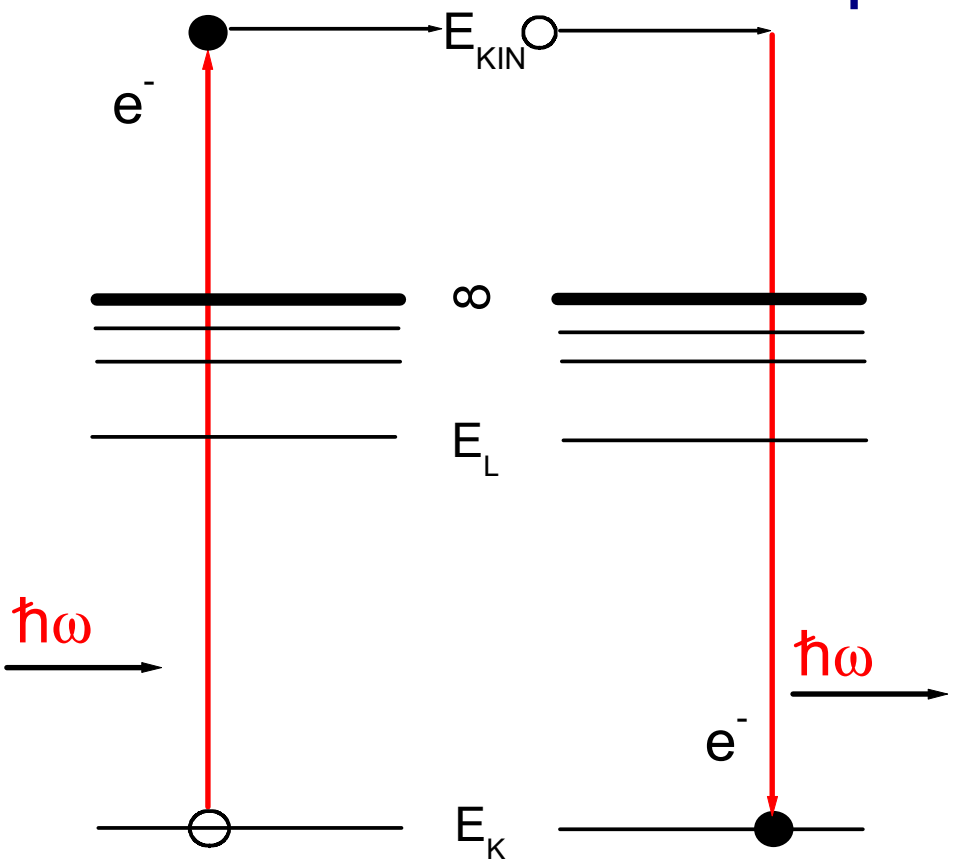
REC

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

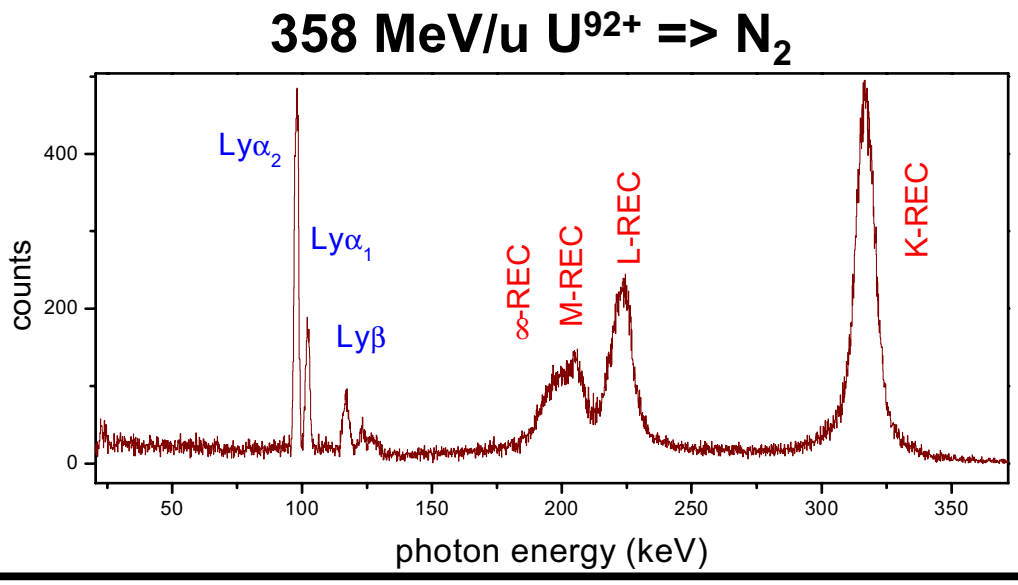


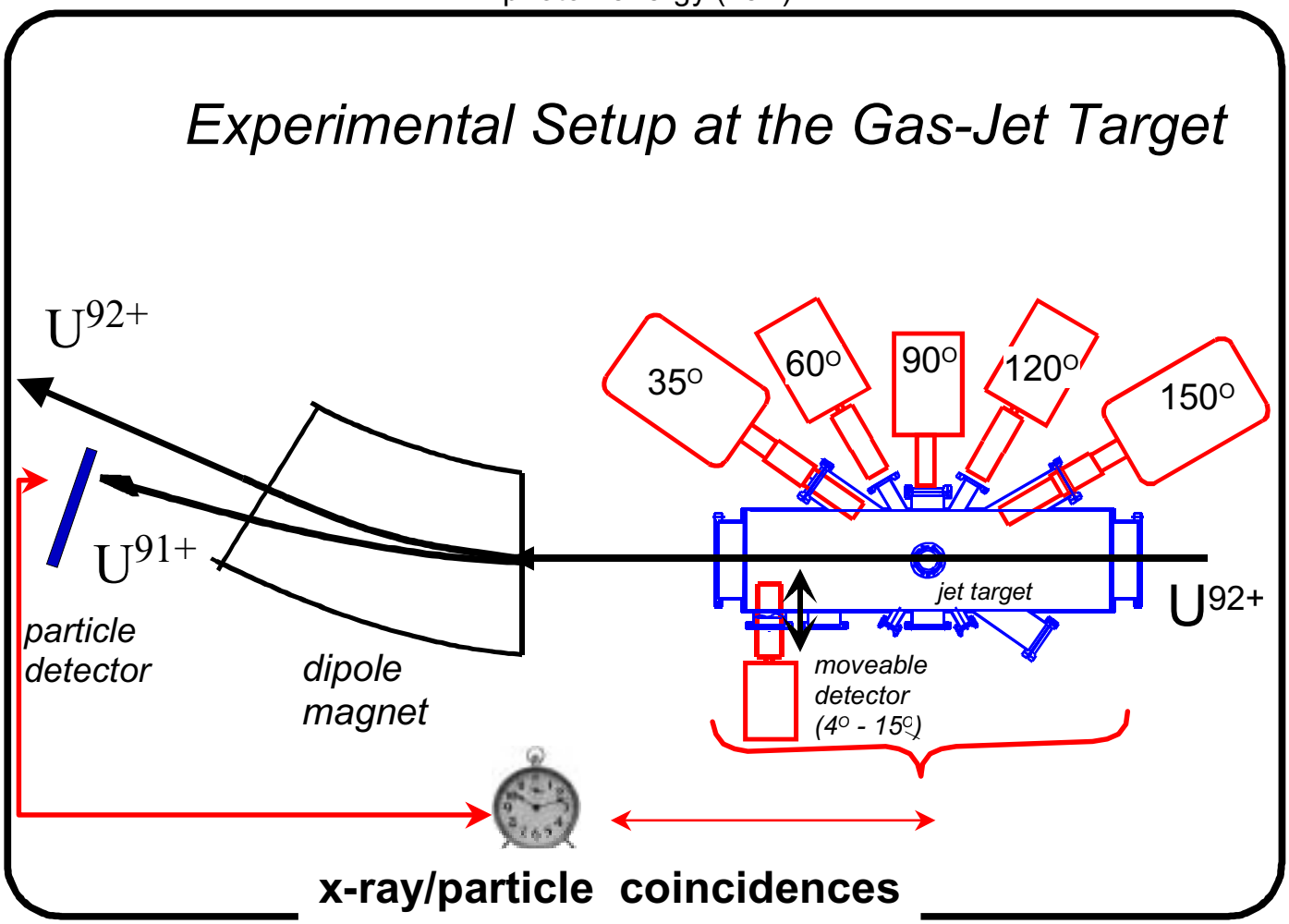
Photoionization

Radiative Electron Capture



Angular Distribution Studies for the Time-Reversed Photoionization Process

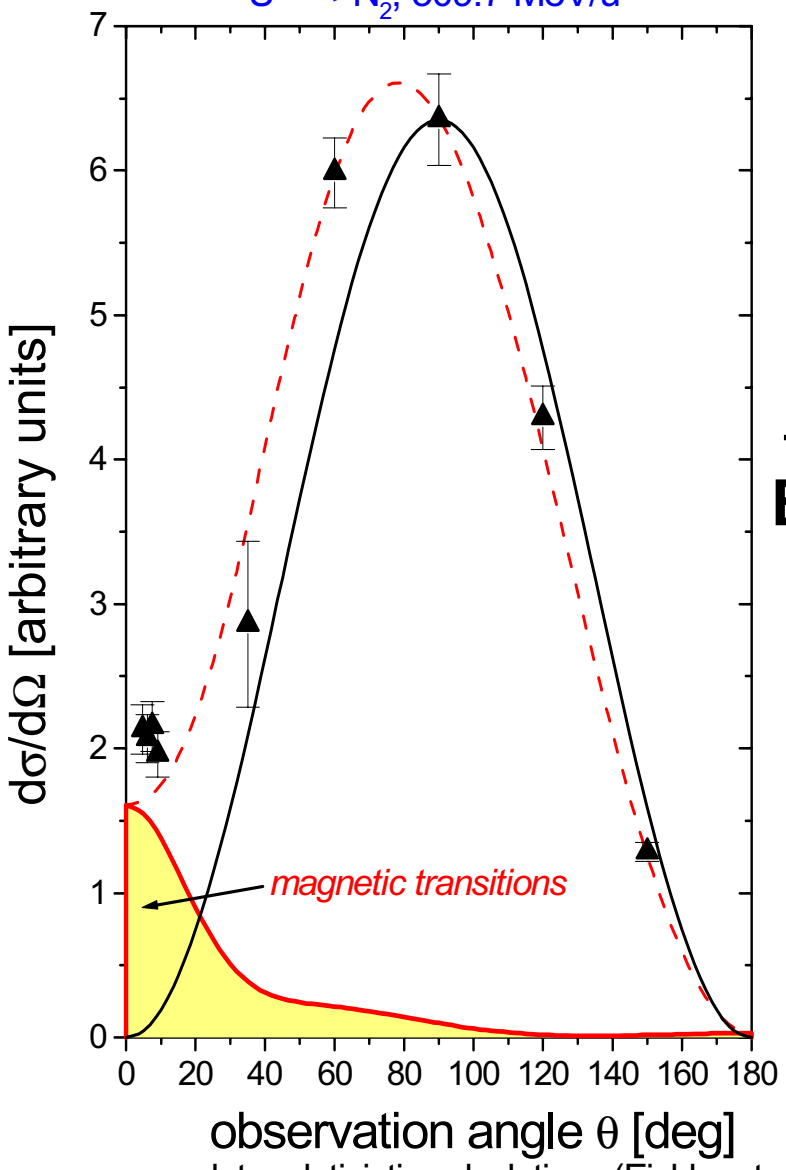


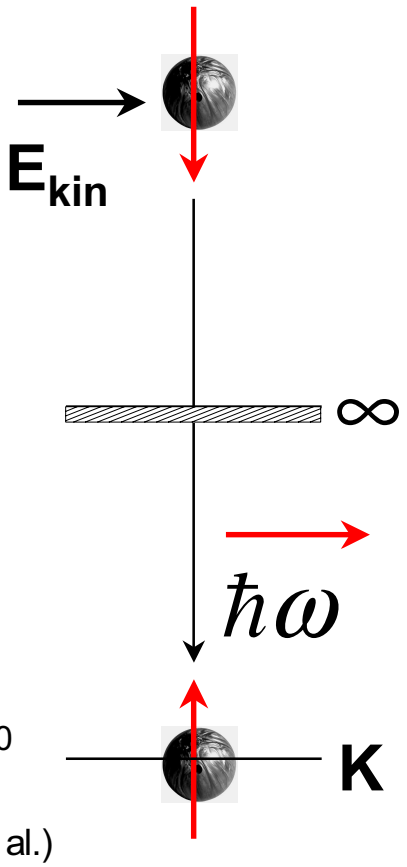


Radiative Capture into the K-Shell

laboratory frame

U^{92+}=>N_2, 309.7 MeV/u





- - - complete relativistic calculations (Eichler et al.)

——— nonrelativistic dipole distribution

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zero degree emission of electric radiation by electron capture into s-orbitals is forbidden by angular momentum conservation laws

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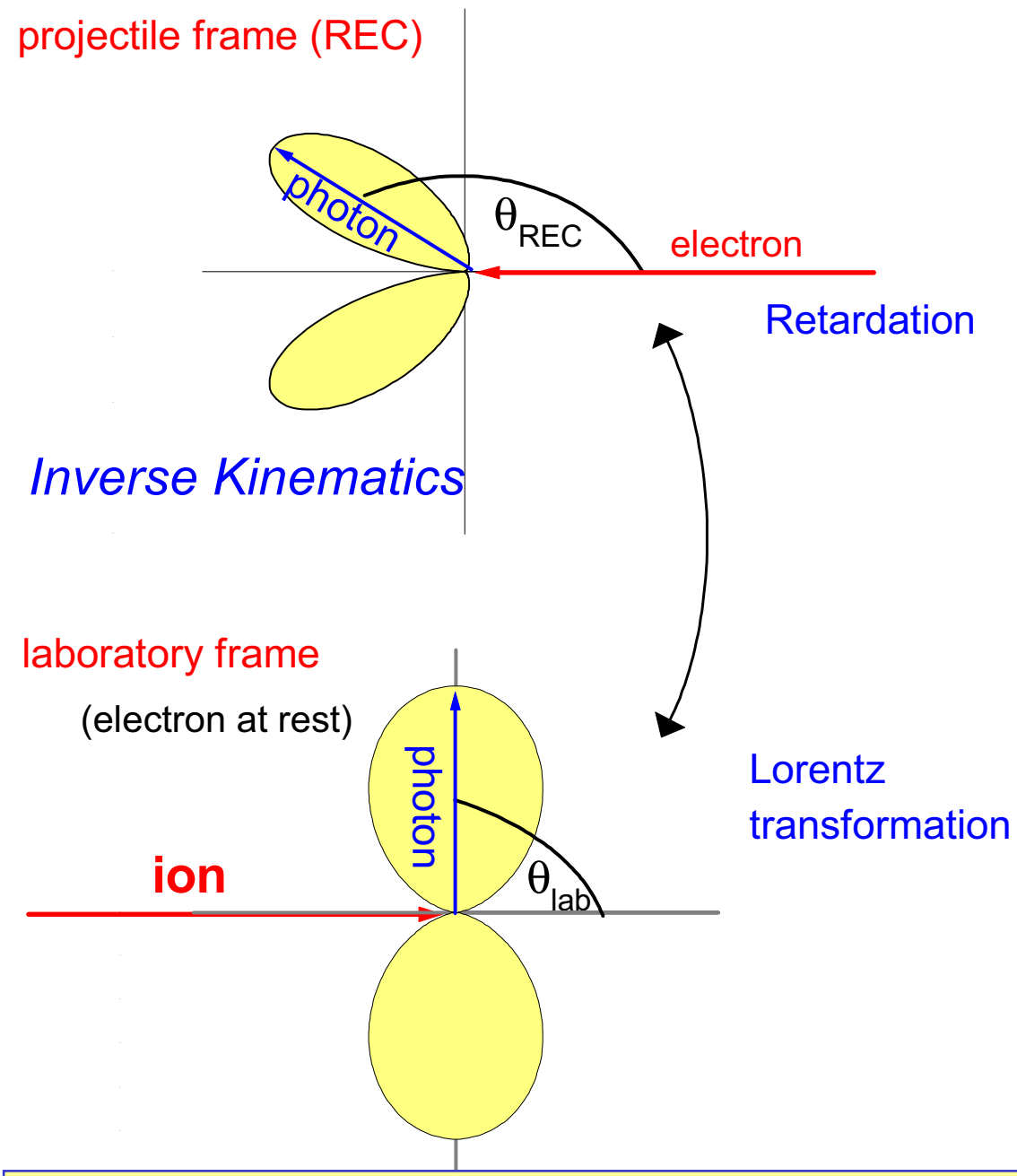
zero degree emission: $(\alpha Z)^2$ correction to the magnetic emission

Th. Stöhlker et al., Phys. Rev. Lett 82, 3232 (1999).

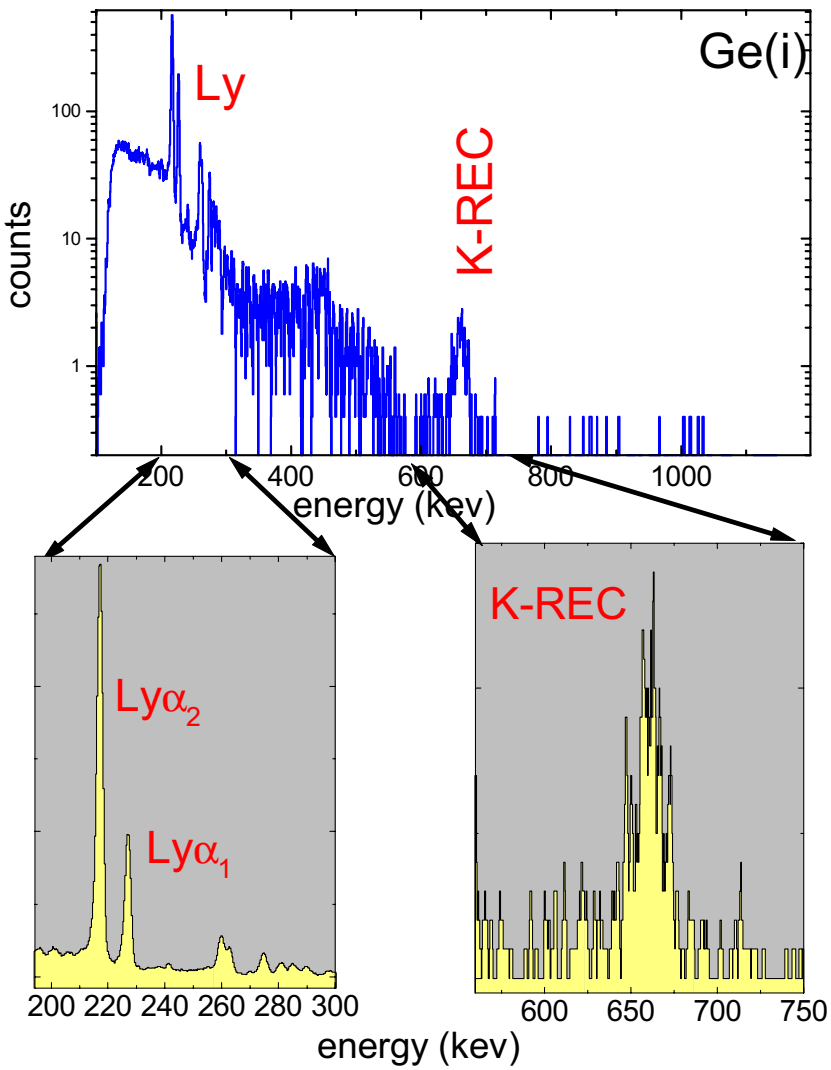
Transition matrix element

$$\langle \psi_i | \alpha \; u_+ \exp(-i\mathbf{kr}) | \psi_f \rangle$$



Using nonrelativistic wavefunctions, complete cancellation between retardation and Lorentz transformation occurs
(verified by Anholt for 197 MeV/u $Xe^{54+} \Rightarrow$ Be)

Photon emission close to zero degree



Normalization to the Lyα_2+M1 intensity:

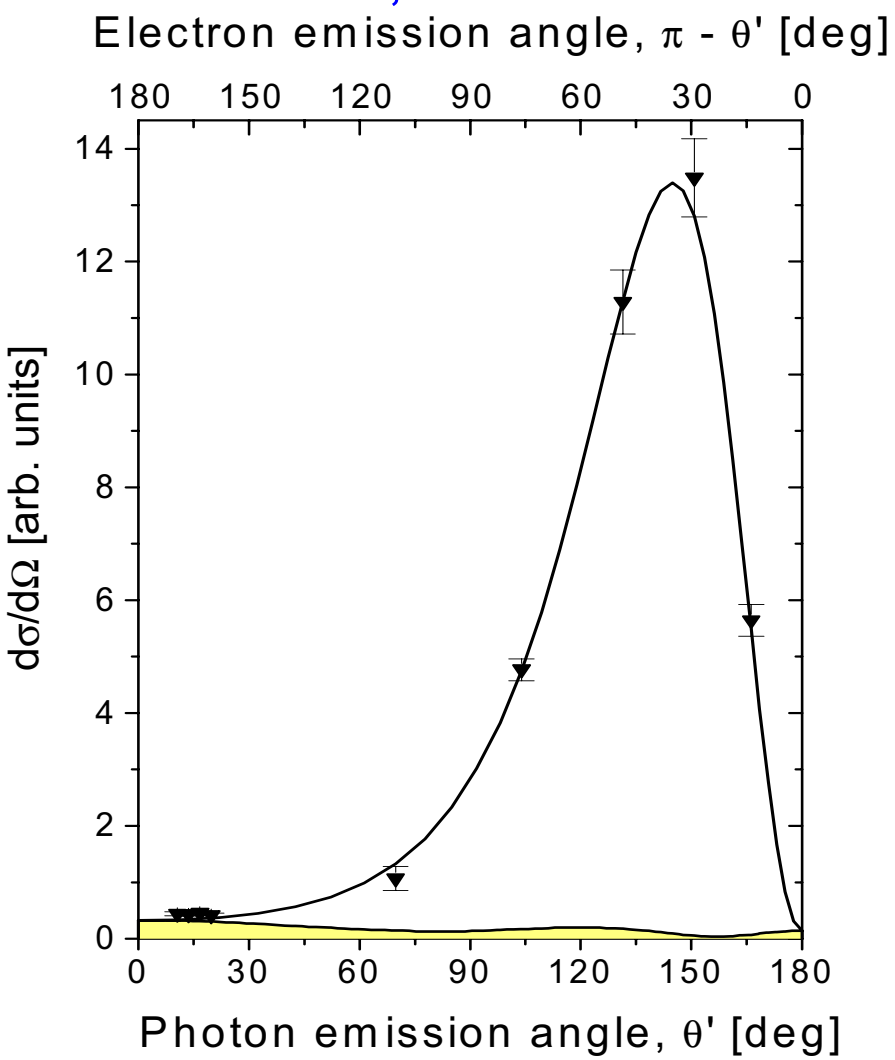
almost all systematic uncertainties cancel out completely

From the REC distribution in the emitter frame the electron angular distribution for photonization is obtained by the simple transformation

$$\theta' \Rightarrow \pi - \theta'$$

Emitter frame

$e^- => U^{92+}$, $\hbar\omega = 301.7$ keV



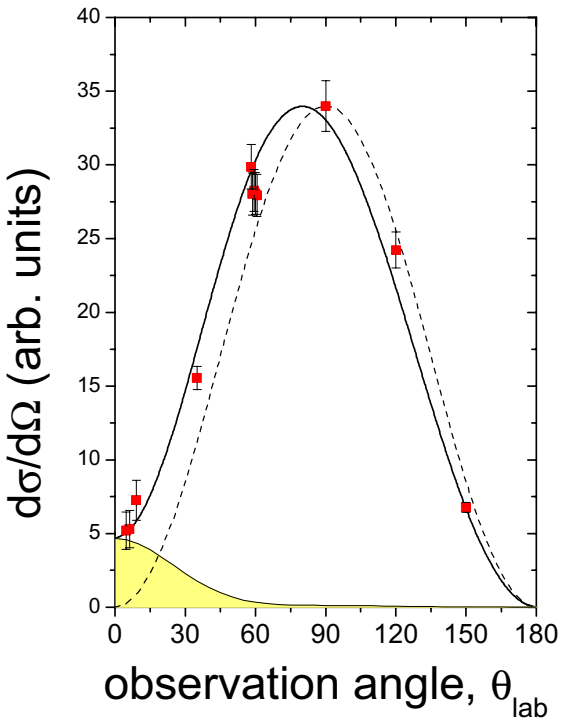
The experiment confirms, that at high energies the shape of the distribution is almost the same for H-like ions and neutral elements.

Angular Distribution

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

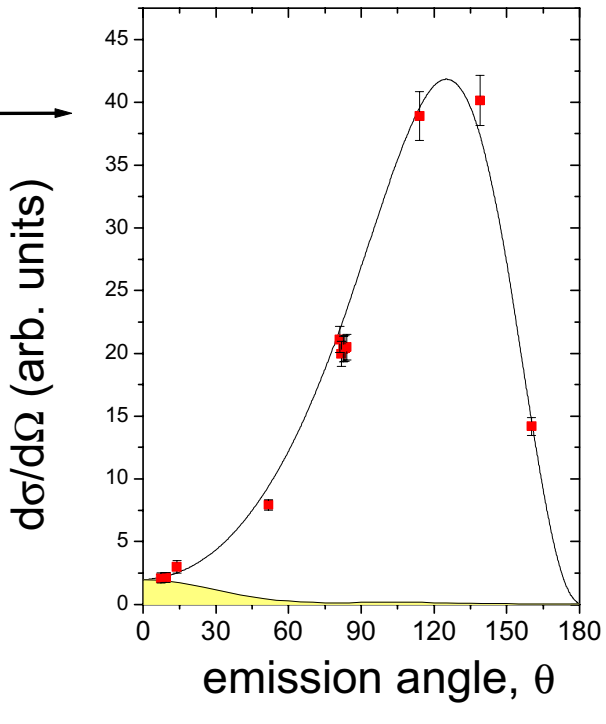
laboratory frame

U^{92+} => N_2, 88MeV/u



emitter frame

e^- => U^{92+}, 48 keV

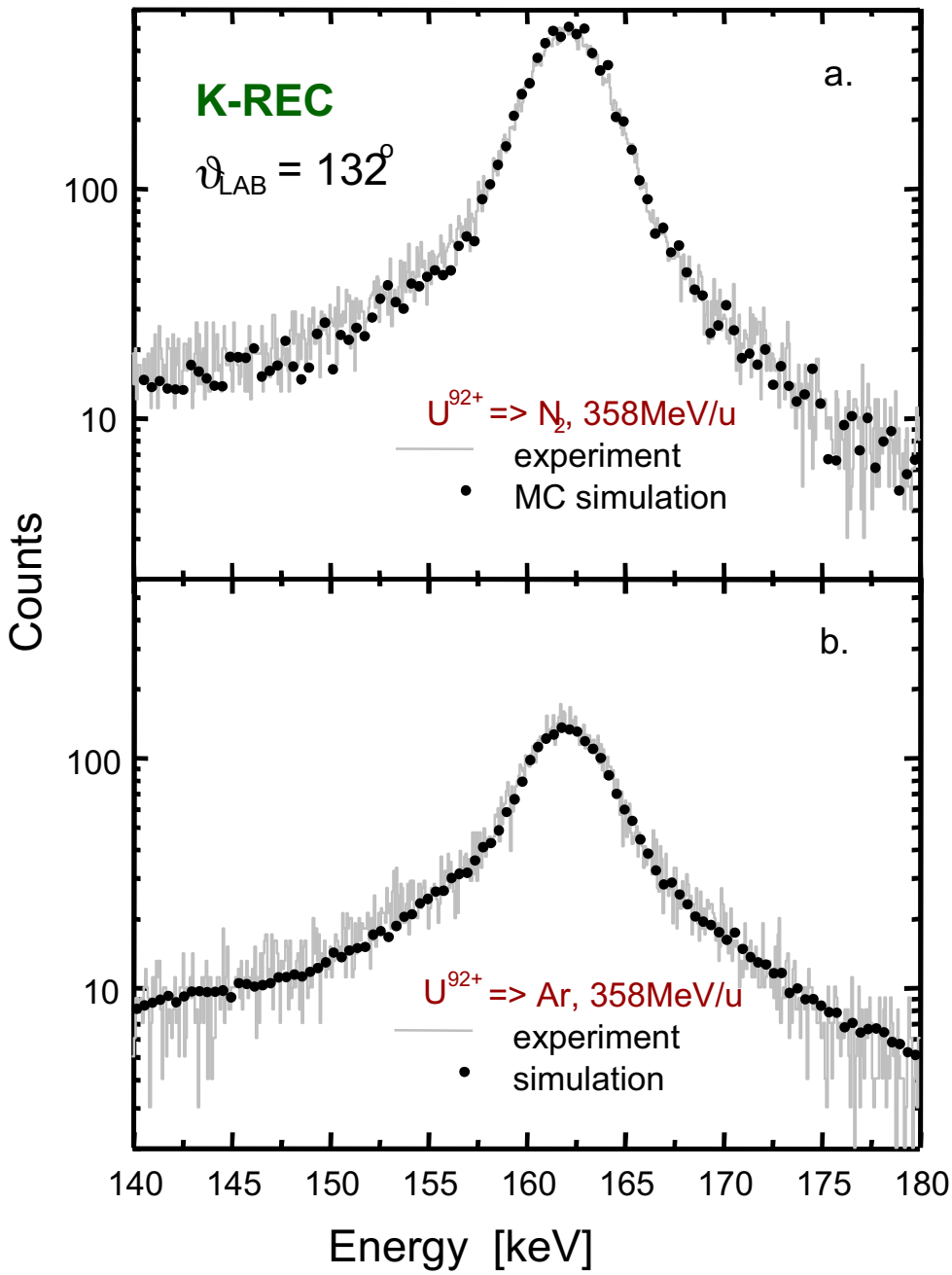


Theory: J. Eichler 1999

spin-flip contribution: 2%

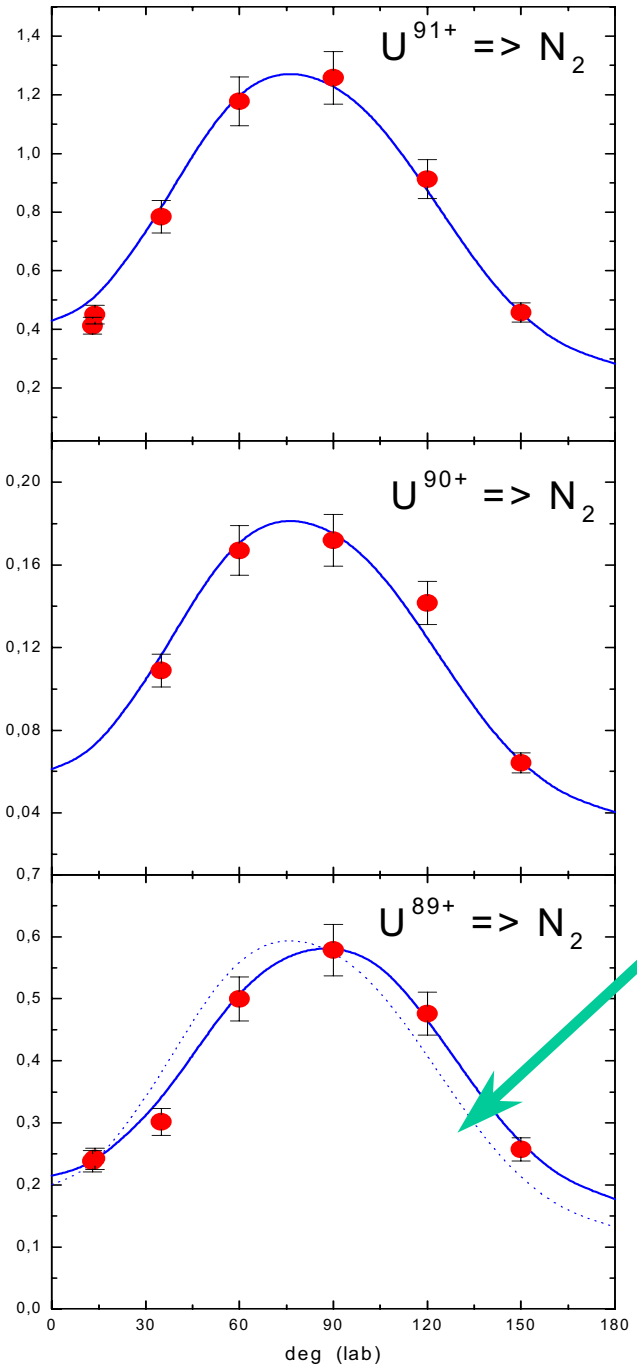
Th. Stöhlker et al., Phys. Rev. Lett 86, 983 (2001).

Comparison of Experimental and Monte Carlo Simulated Spectra



P. Swiat et al., Physica Scripta Vol. T80, 326 (1999)

L-REC in 216 MeV/u collisions of H-, He-, and Li-like U-ions with nitrogen target



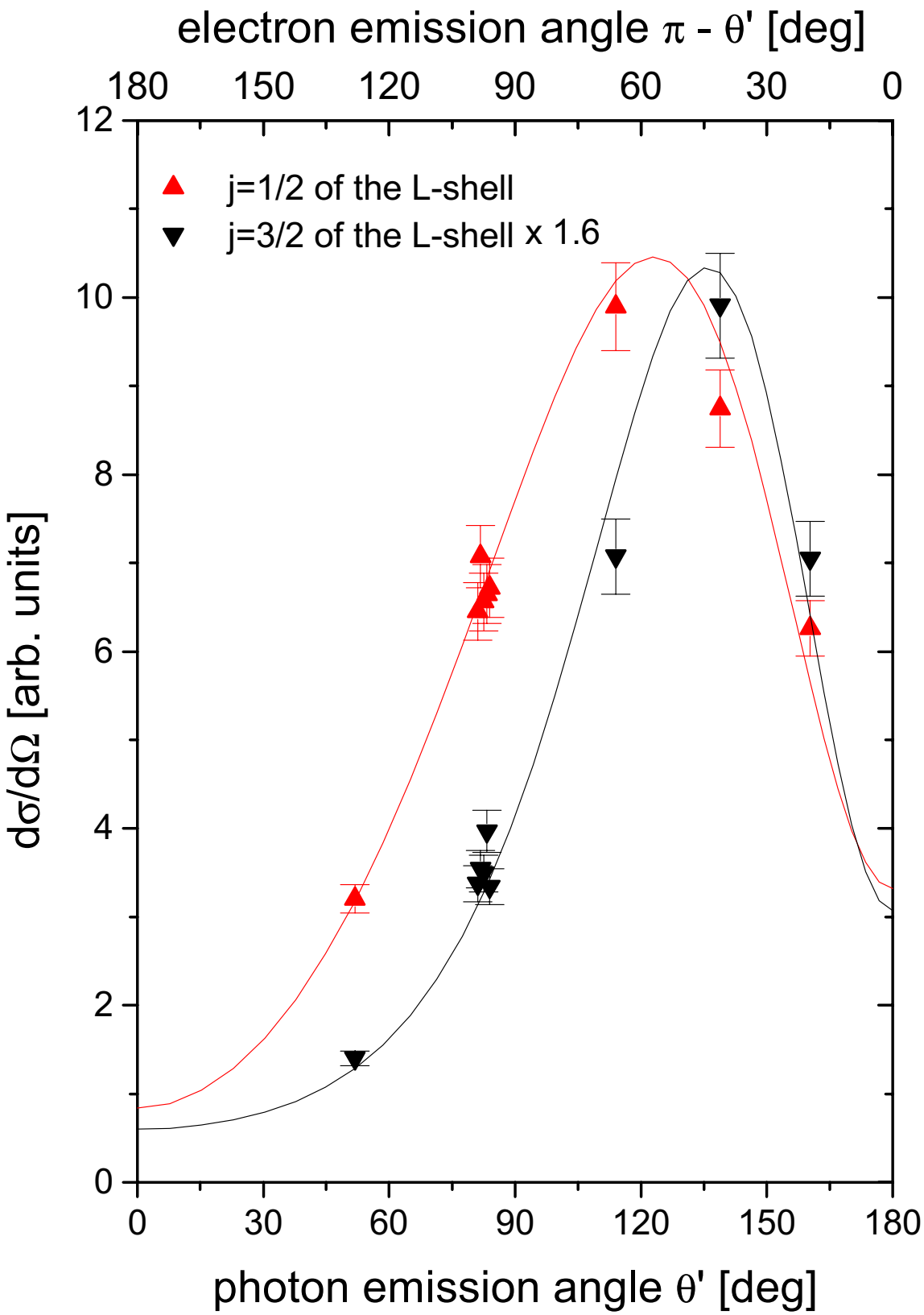
Empty L-shell

One electron added into the projectile L-shell provides a very sensitive test of theoretical prediction for L-REC

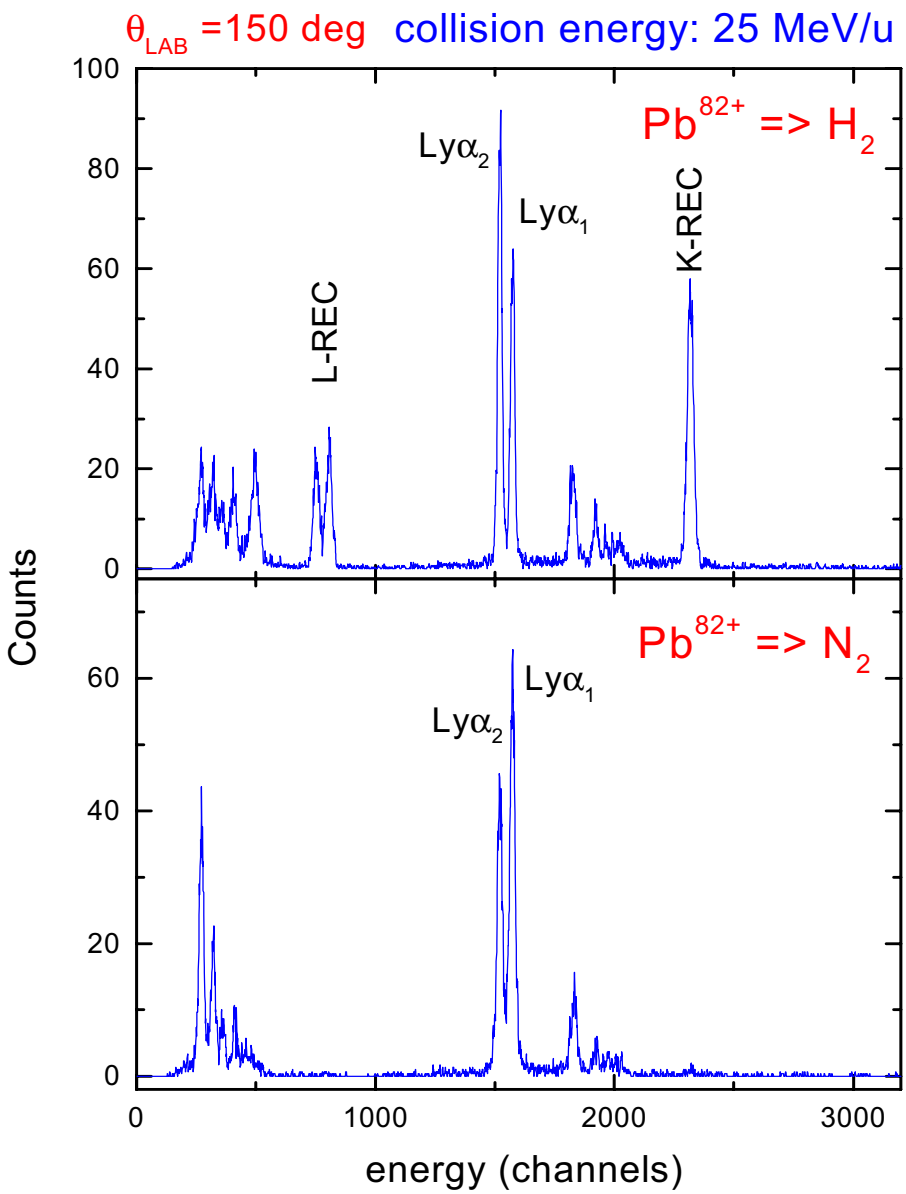
A.Ichihara et al.., Phys.Rev. **A49** 1875(1994)

G. Bednarz et al., GSI Annual Report 2000.

REC into excited states of H-like uranium



First test experiment with an H_2-target: bare Pb ions at 25 MeV/u

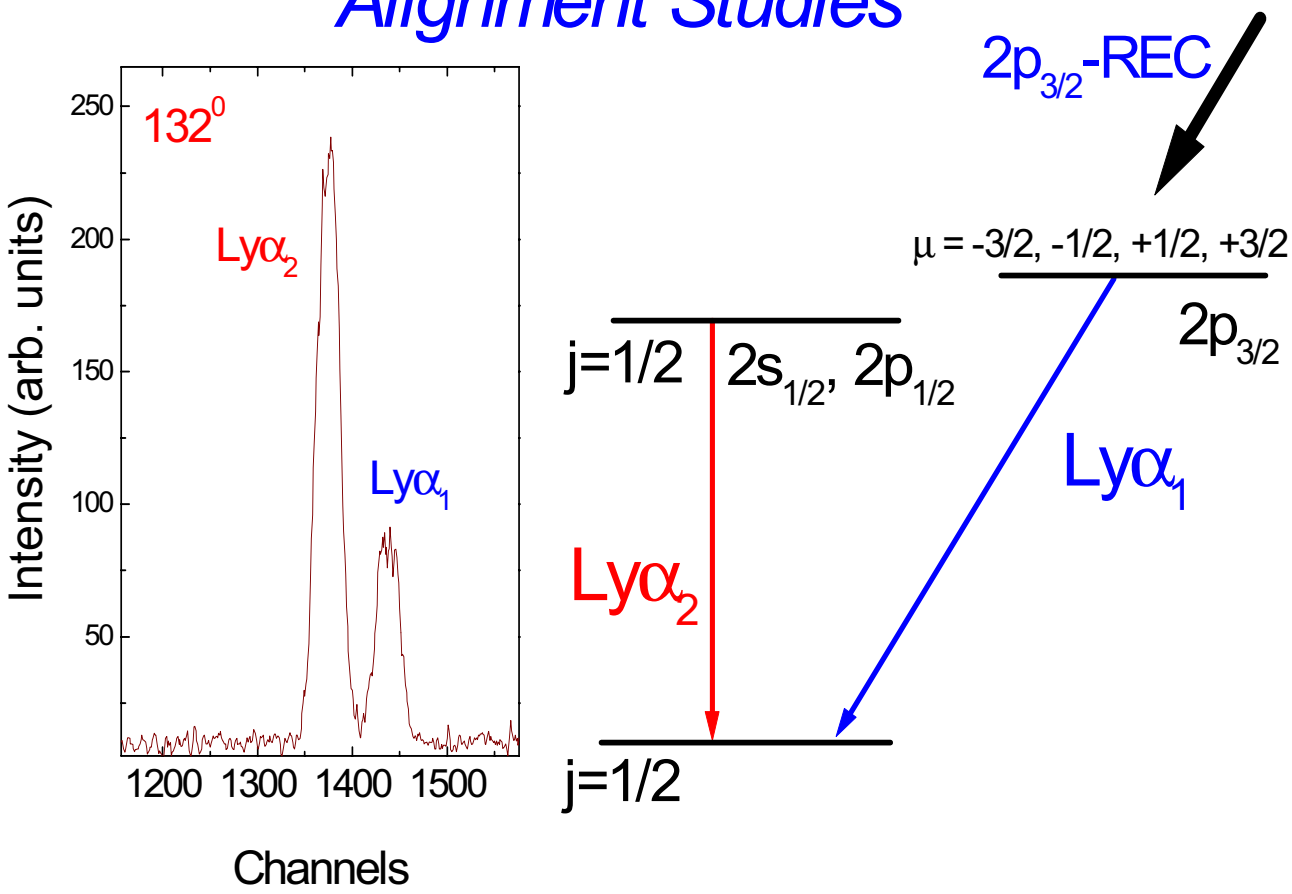


- narrow Compton profile
- strong REC

A. Krämer et al., NIM B174, 205 (2001)

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

Alignment Studies

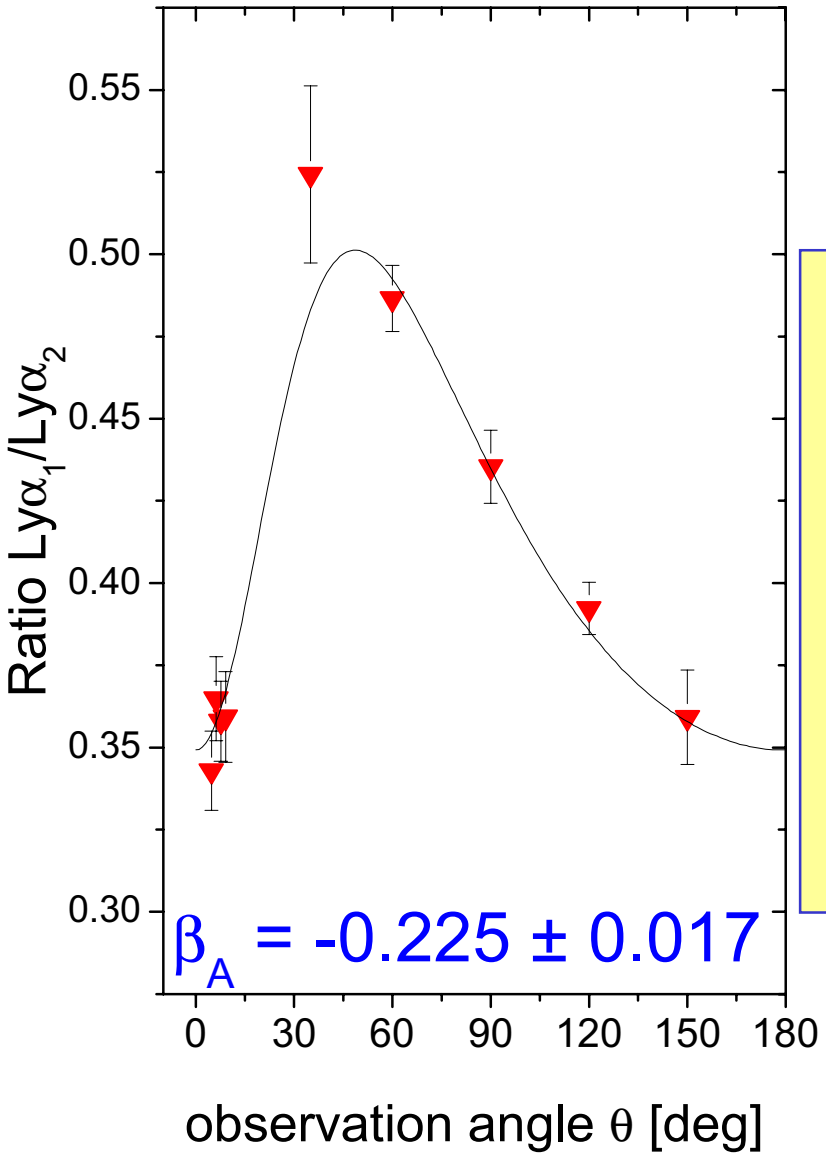


$U^{92+} \rightarrow N_2$ - target

(80-350) MeV/u

Th. Stöhlker et al., Phys. Rev. Lett 79, 3270 (1997).

Lyα_1 transitions at 310 MeV/u



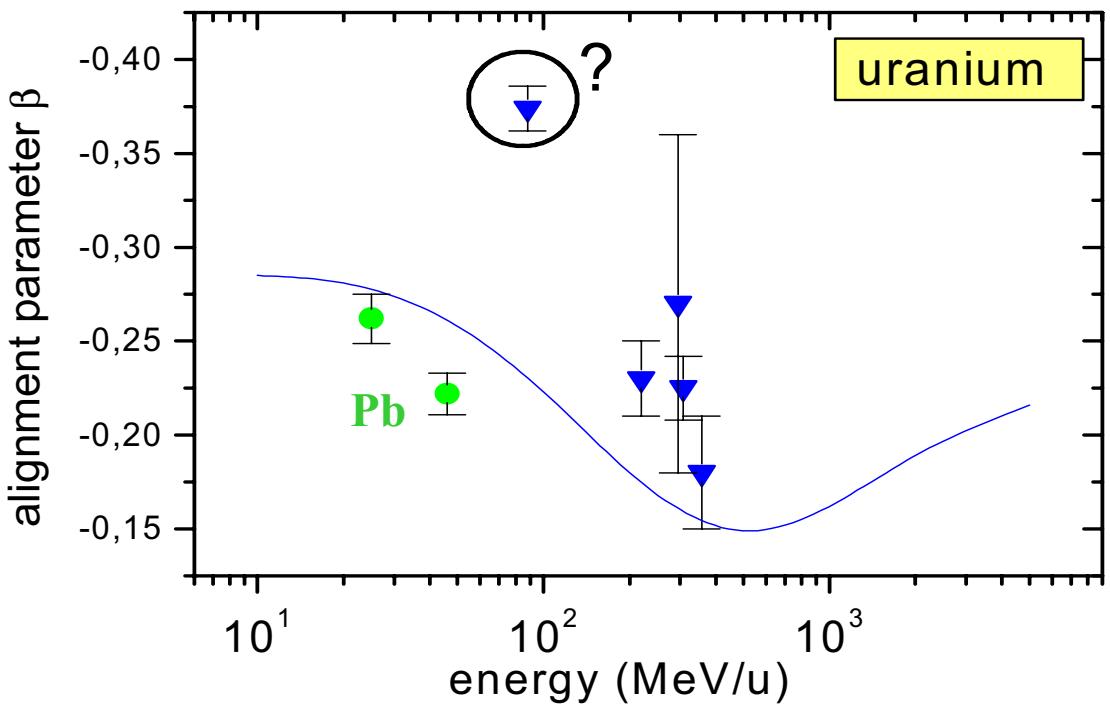
Direct capture into the 2p3/2 state populates almost exclusively the magnetic sublevels with

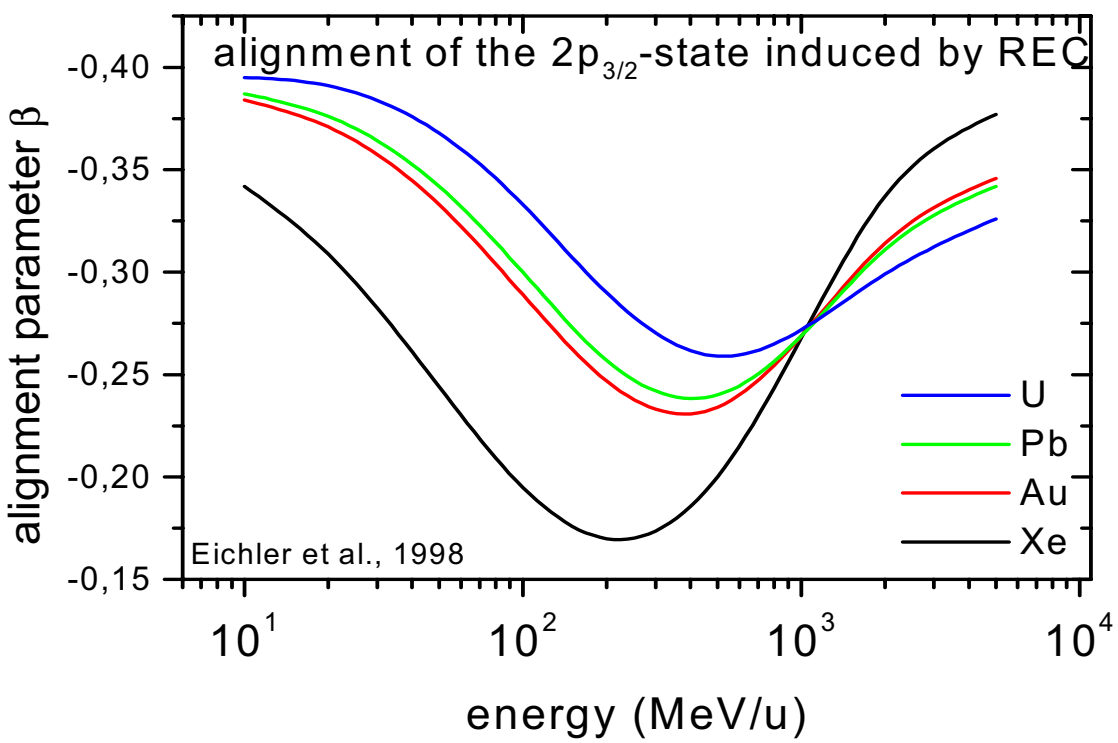
$$|m_j| = \frac{1}{2}$$

Alignment → Alignment Parameter

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

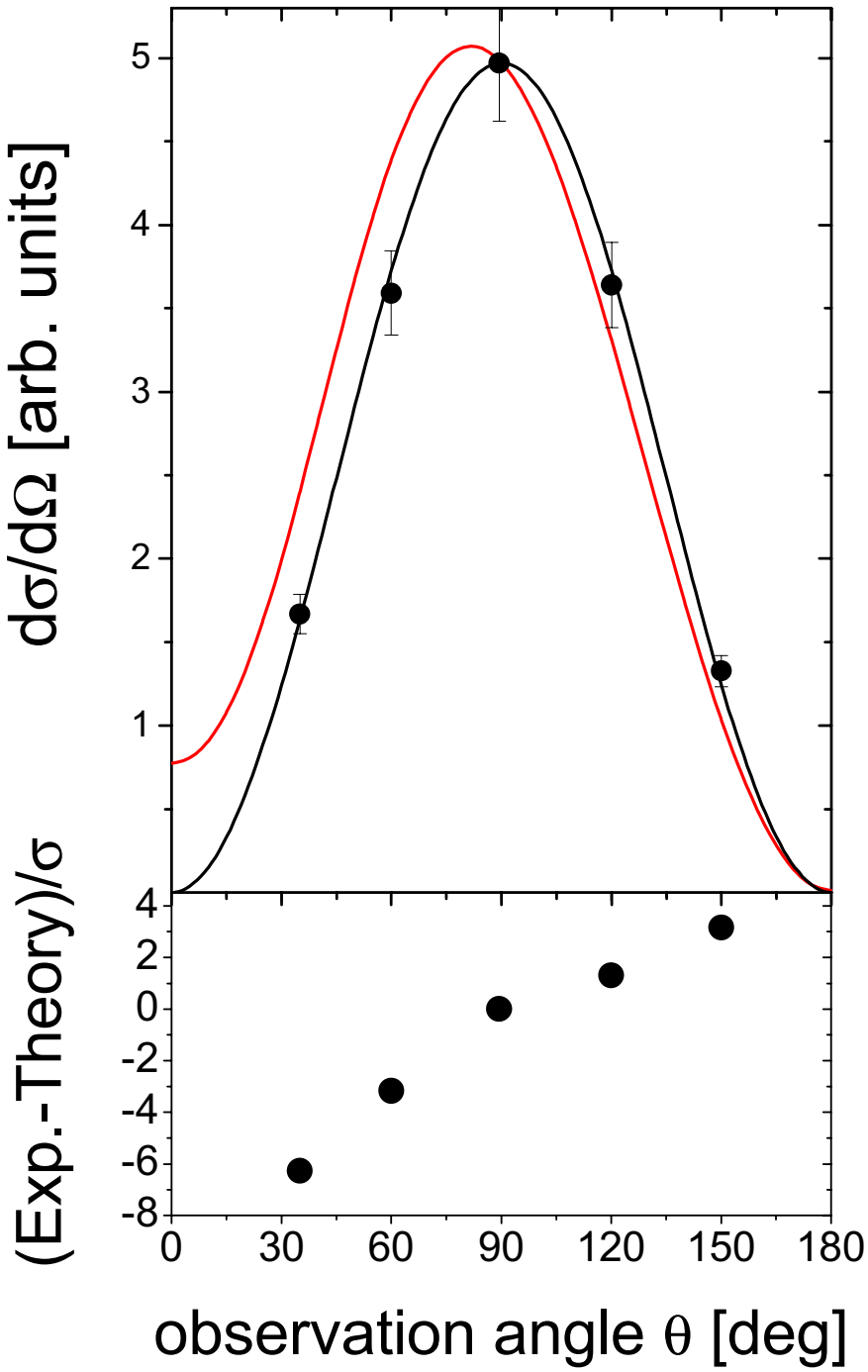
$$\beta_A = \frac{1}{2} \frac{\sigma\left(\frac{3}{2}\frac{3}{2}\right) - \sigma\left(\frac{3}{2}\frac{1}{2}\right)}{\sigma\left(\frac{3}{2}\frac{3}{2}\right) + \sigma\left(\frac{3}{2}\frac{1}{2}\right)}$$


uranium
?
Pb
alignment parameter β
-0,40
-0,35
-0,30
-0,25
-0,20
-0,15
10^1
10^2
10^3
energy (MeV/u)


alignment of the 2p3/2-state induced by REC
alignment parameter β
-0,40
-0,35
-0,30
-0,25
-0,20
-0,15
U
Pb
Au
Xe
Eichler et al., 1998
10^1
10^2
10^3
10^4
energy (MeV/u)

Nuclear spin and the atomic photoionization process

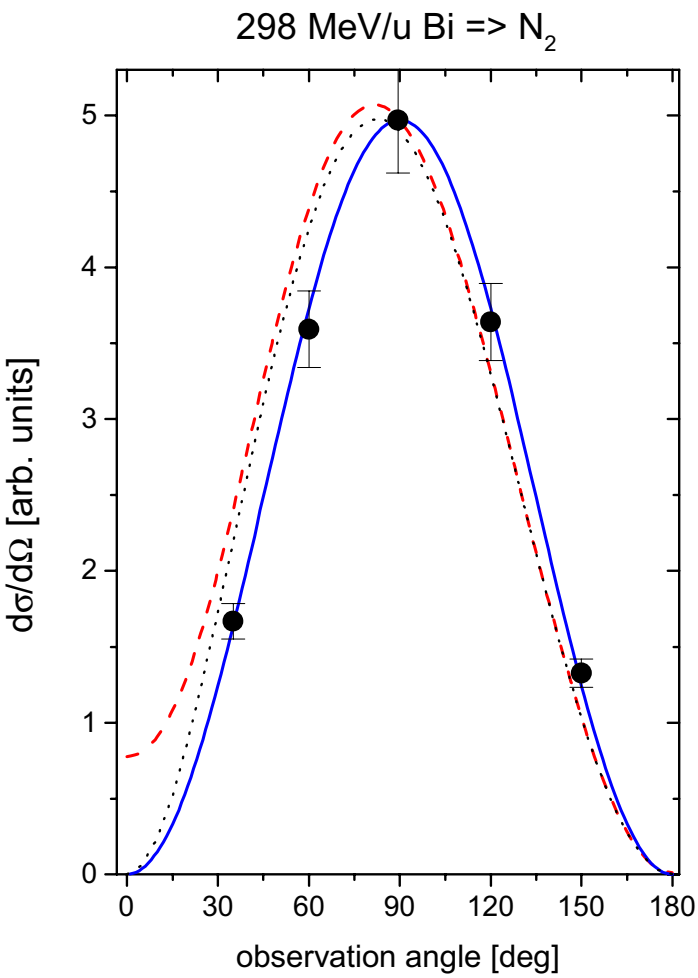
Strong deviations from theory observed for Bi^{83+}, a nucleus with large nuclear spin

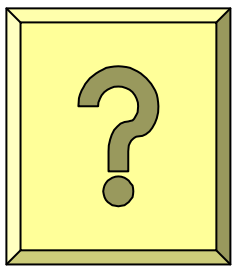


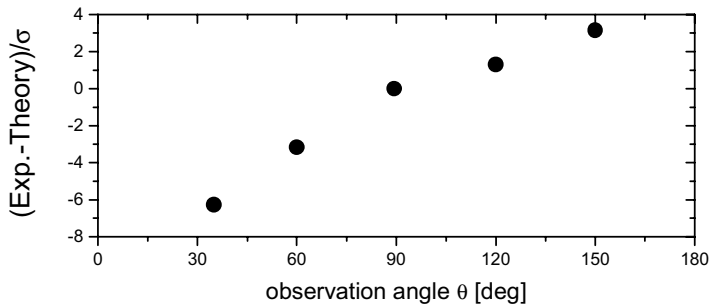
1s-REC for
209 Bi^{83+}
at 298 MeV/u

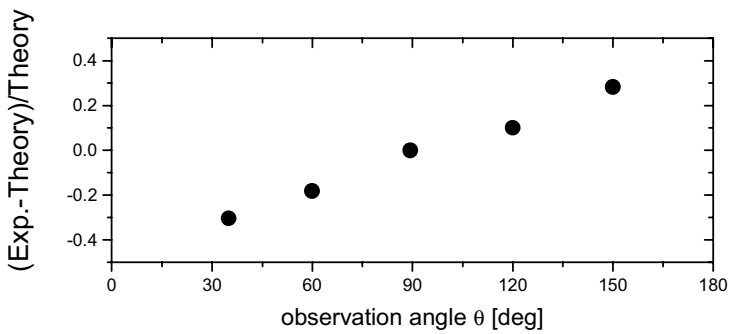
Nuclear spin of bismuth I=9/2

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


298 MeV/u Bi => N2
dσ/dΩ [arb. units]
observation angle [deg]
0
1
2
3
4
5
0
30
60
90
120
150
180

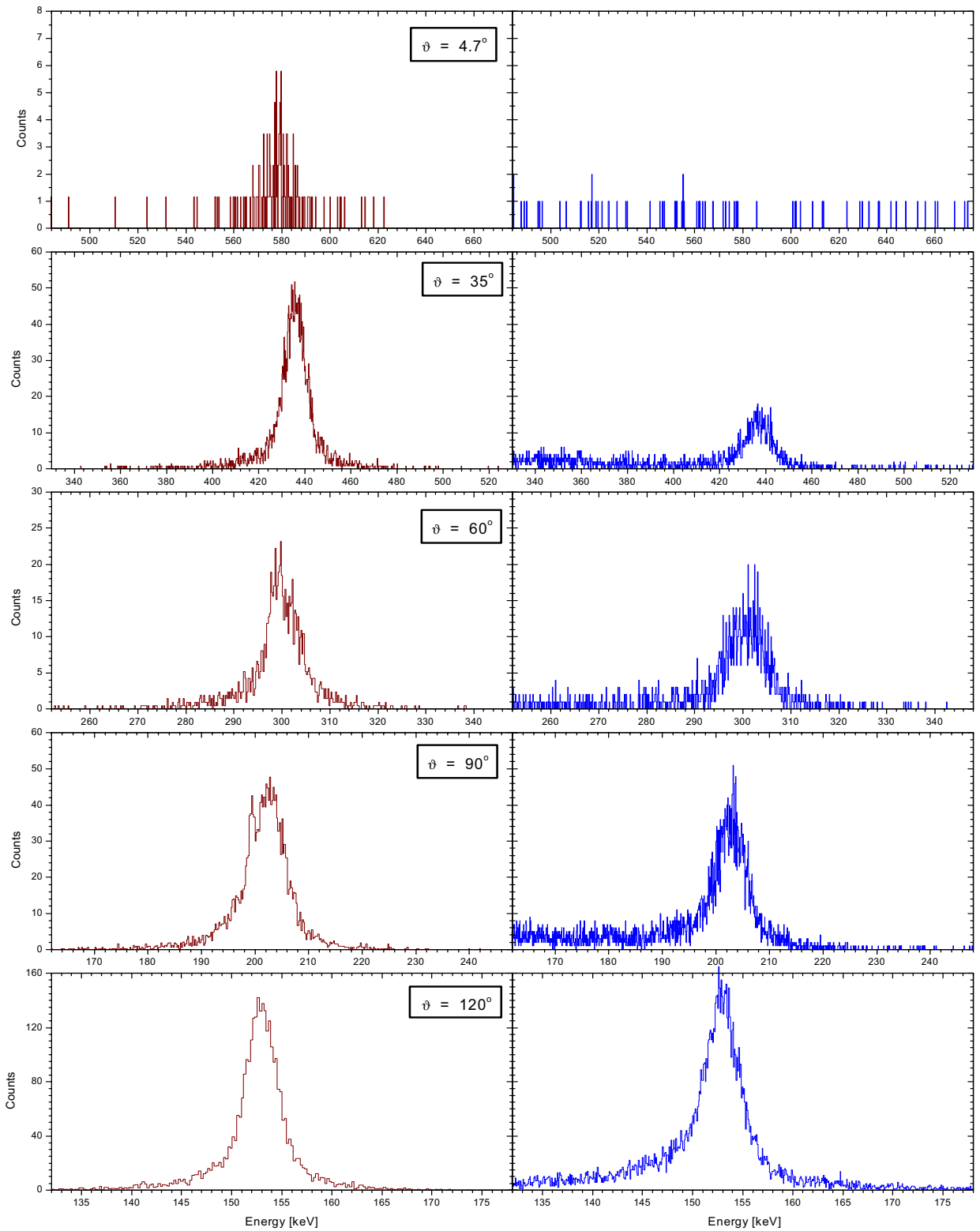



(Exp.-Theory)/σ
observation angle θ [deg]
4
2
0
-2
-4
-6
-8
0
30
60
90
120
150
180


(Exp.-Theory)/Theory
observation angle θ [deg]
0.4
0.2
0.0
-0.2
-0.4
0
30
60
90
120
150
180

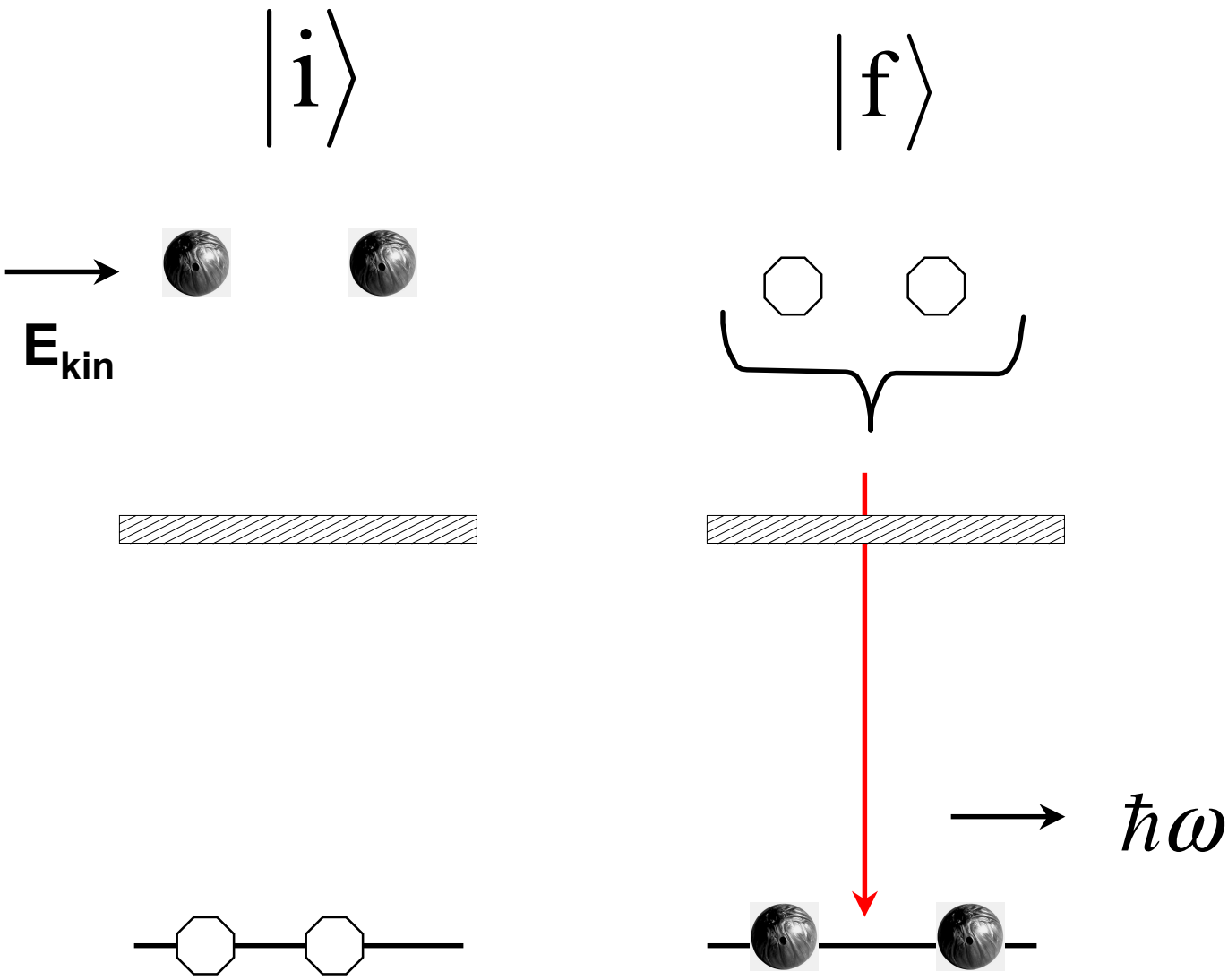
K-REC in 298 MeV/u $^{209}Bi^{83+} \longrightarrow N_2$

Monte Carlo simulation | Experiment



P. Swiat et al., Physica Scripta Vol. T80, 326 (1999)

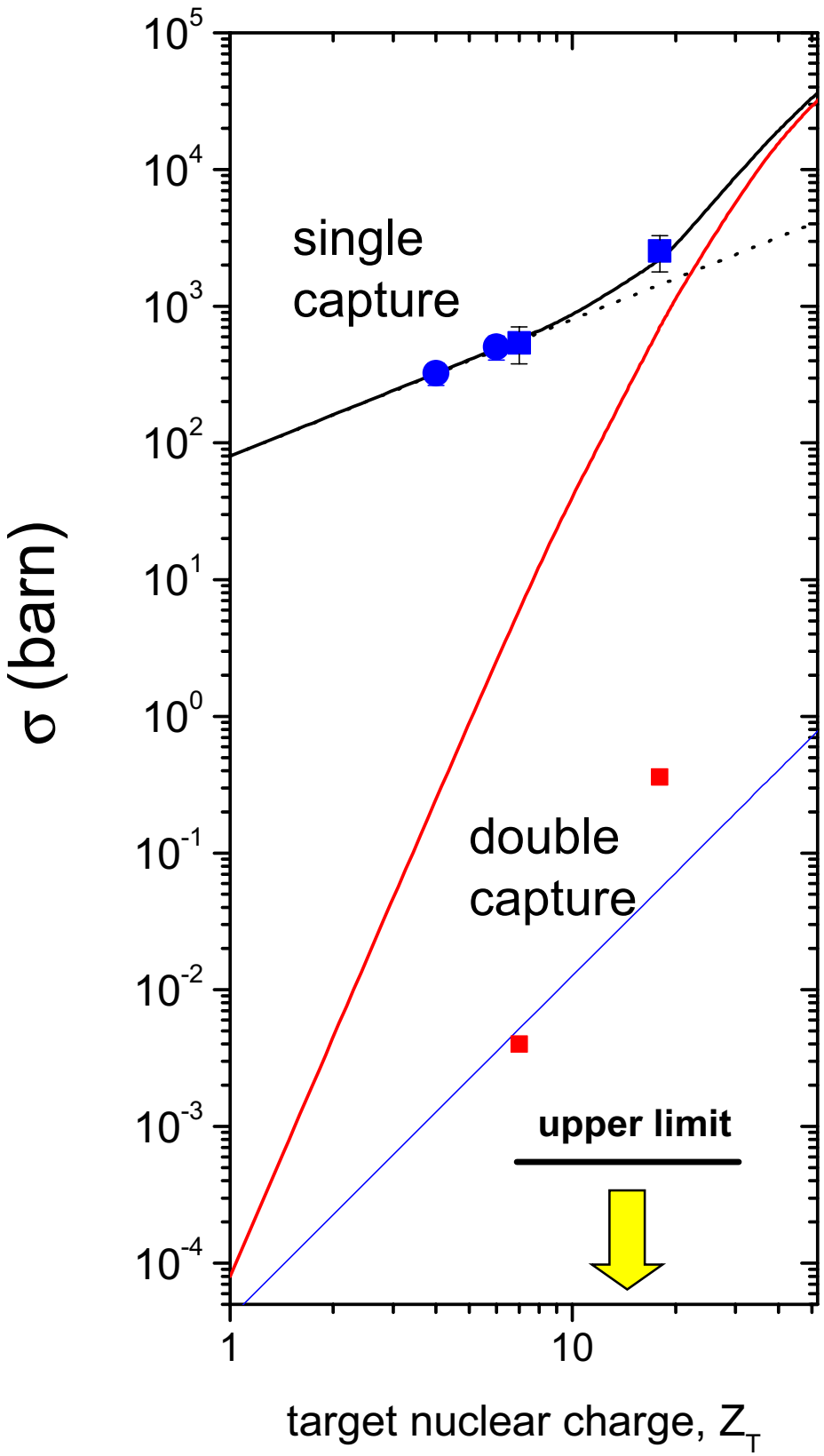
Search for Correlated Two-Electron Capture



Time reversed double photoionization

Due to relativistic corrections, strong cross-section enhancement expected

A. Warczak et al., Nucl. Instr. Meth. B98, 303 (1995)



Correlated two-electron capture

G. Bednarz, Physica. Scripta, in print 2001.

Summary

• Storing and cooling of highly charged ions delivers brilliant beams for experiments

•Single collision conditions at the jet-target (no solid state effects)

• The ESR provides ideal conditions for precise x-ray studies of atomic collision processes:

- fotoionization study for highly charged high-Z ions via time reversal (REC)

- cross-section studies on the level of 1 mbarn (Radiative Double EC)

- population of magnetic substates (alignment)