

X-Ray Emission in Atomic Collisions

(Decade of Experiments at the ESR)

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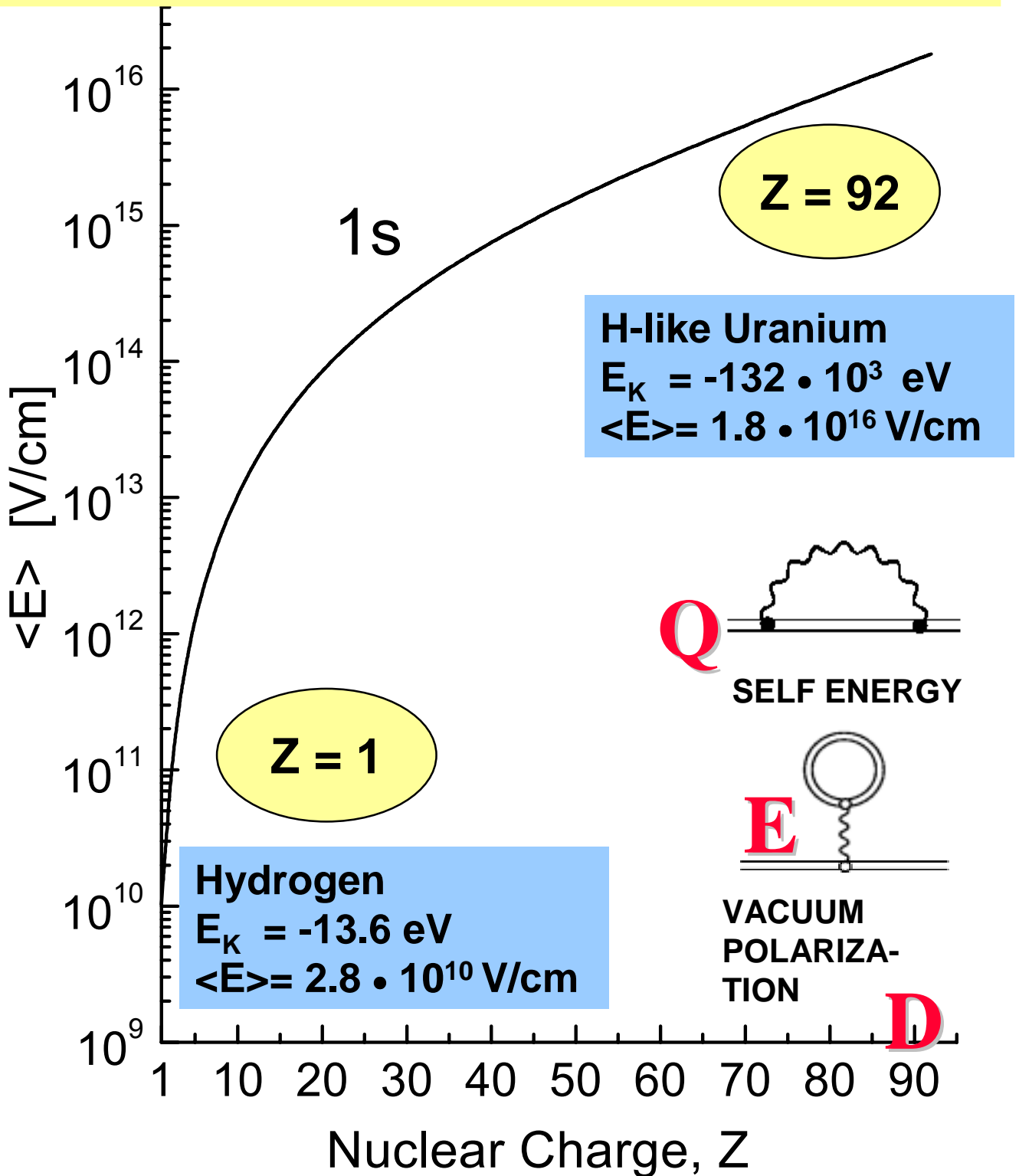
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 - **search for correlated two-electron capture**
- **Summary**

GENERAL GUIDE-LINE of ATOMIC COLLISION EXPERIMENTS at GSI

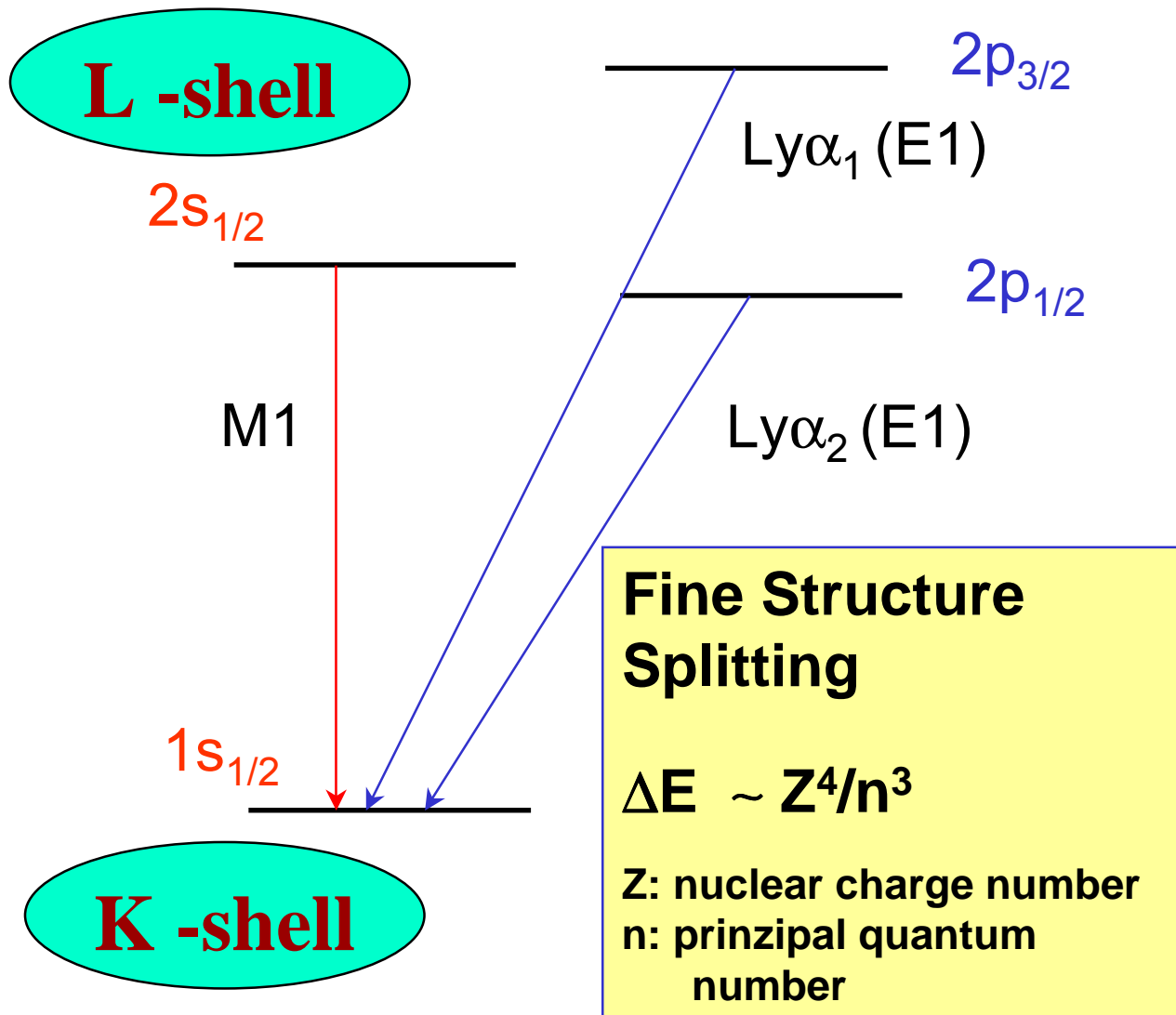
- **HEAVY IONS (high Z , $\alpha * Z < 1$)**
 - strong internal fields
 - relativistic wavefunctions
- **HIGHLY CHARGED IONS**
 - simple atomic systems
 - H- and He-like ions
- **FAST IONS ($0.4 < \beta < 0.7$)**
 - relativistic kinematics
(Lorentz transformation between projectile and laboratory reference system)
 - relativistic dynamics of atomic processes
- **DECELERATION MODE**

Atomic Physics in Extremely Strong Coulomb Fields



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

The Structure of One-Electron Systems

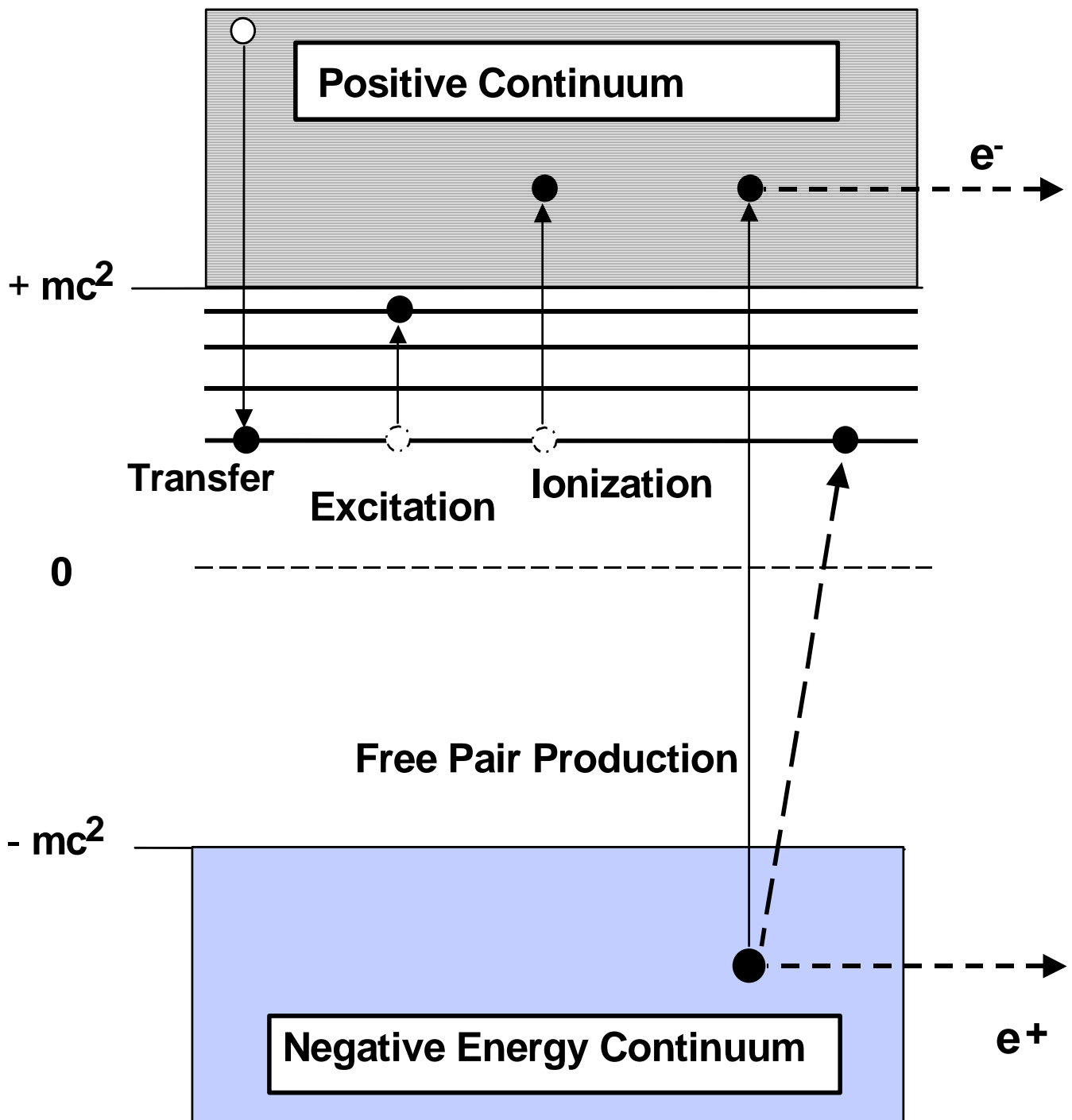


large shell and sub-shell splitting in high-Z systems

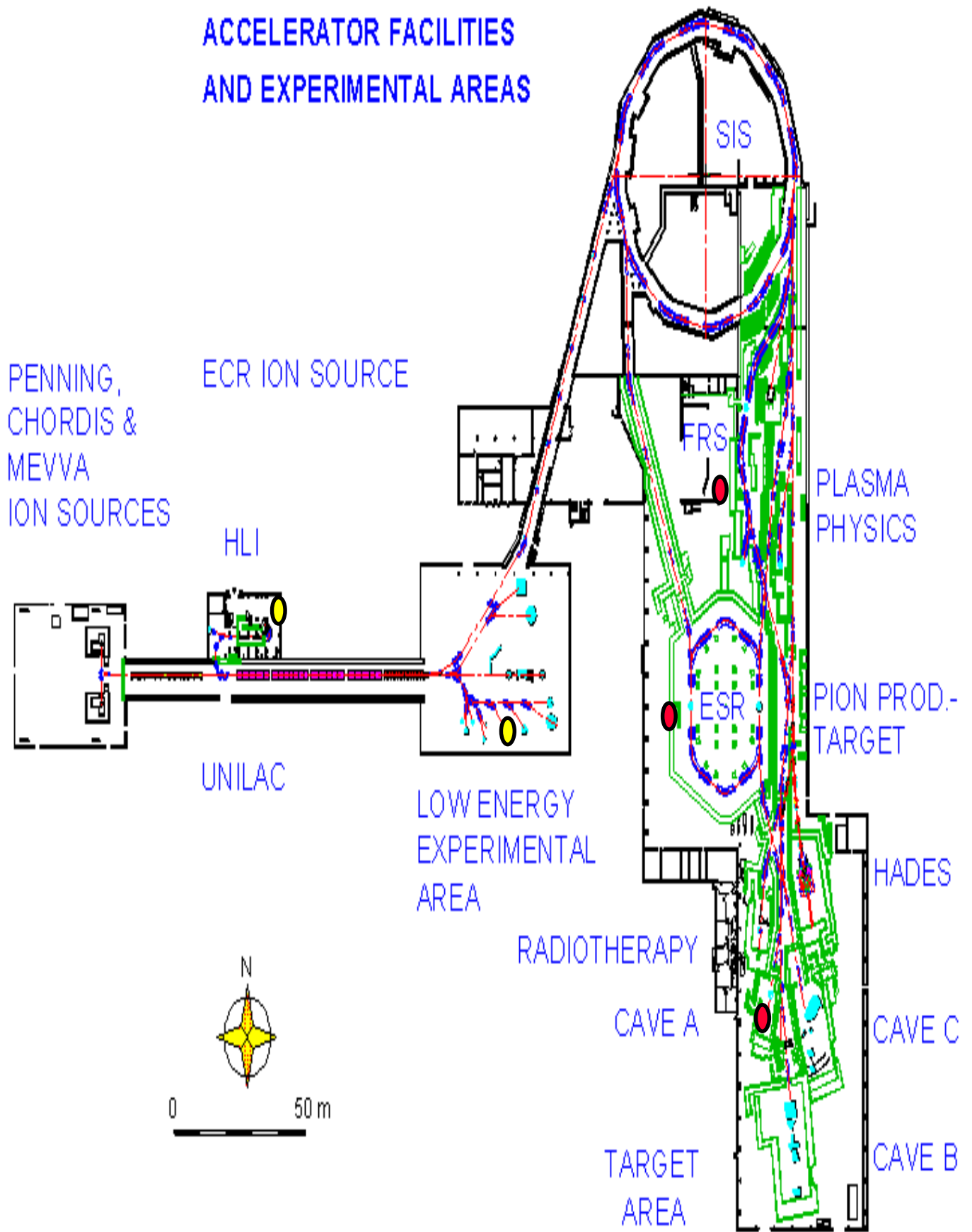
- *photon emission enables state selective study of atomic processes even with standard solid state detectors*

Collision Dynamics of Relativistic Heavy Ions

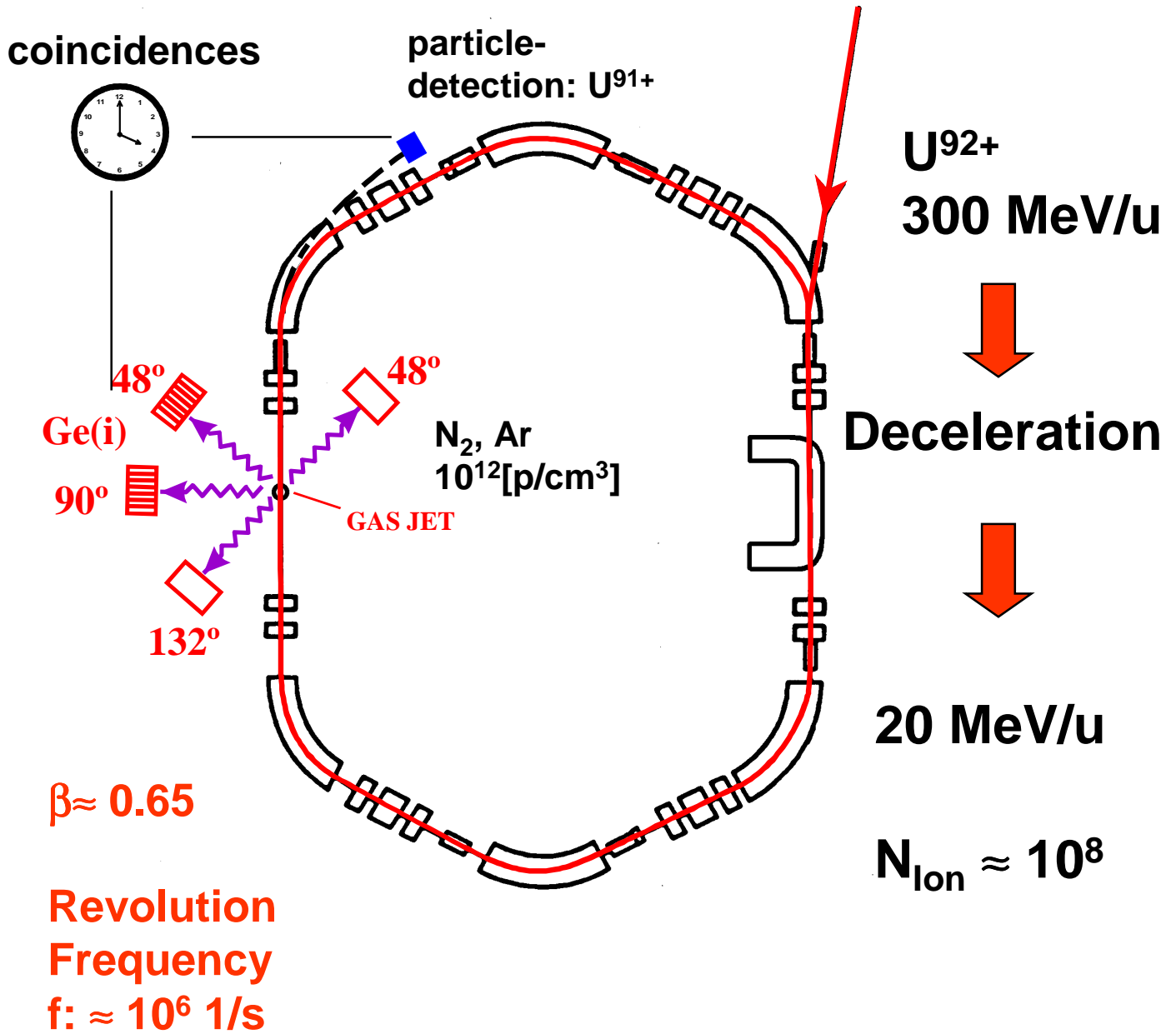
Collision times in the sub-attosecond regime
($10^{-19} \text{ s} < t < 10^{-21} \text{ s}$)



ACCELERATOR FACILITIES AND EXPERIMENTAL AREAS

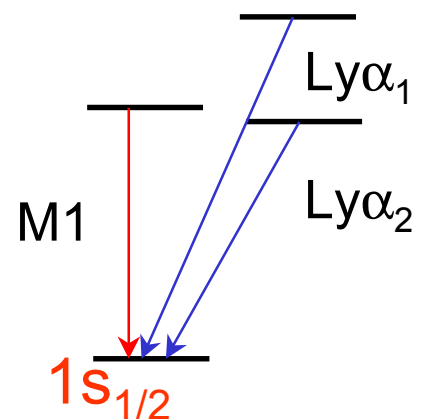


X-Ray Experiments at the Jet-Target



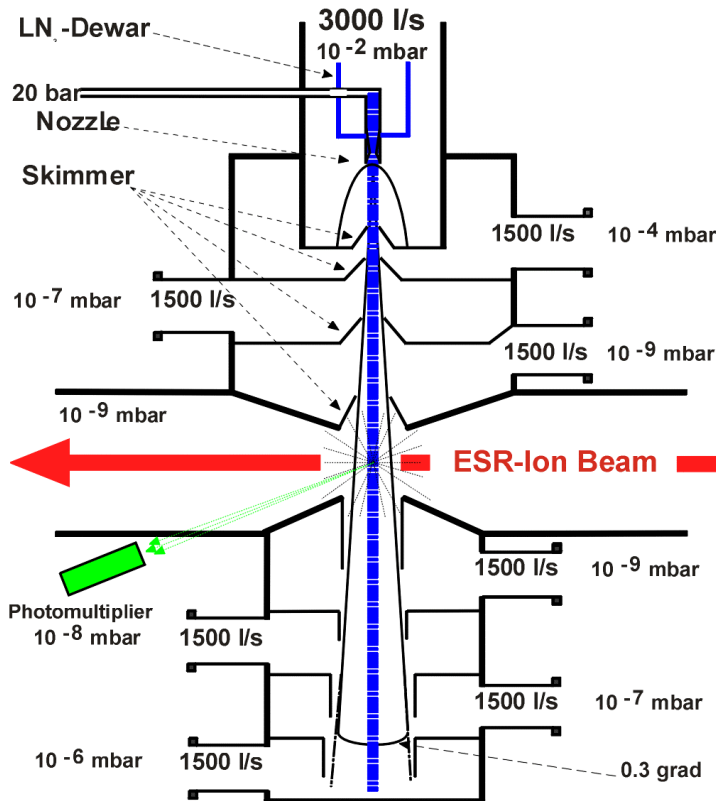
$$E_{lab} = \frac{E_{proj}}{\gamma \cdot (1 - \beta \cdot \cos\theta_{lab})}$$

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



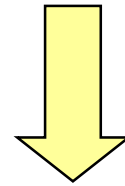
Jet-Target

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

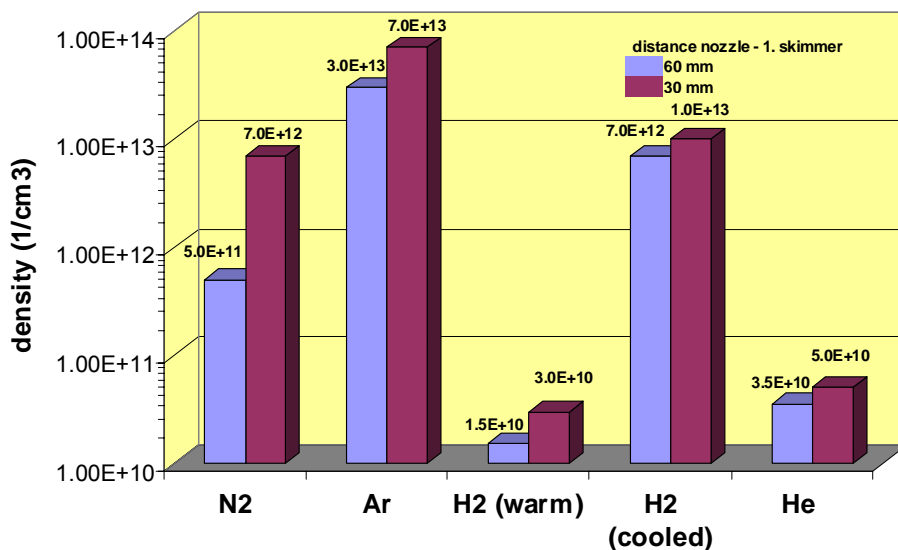


Target densities

$10^{12} - 10^{14}$ p/cm³



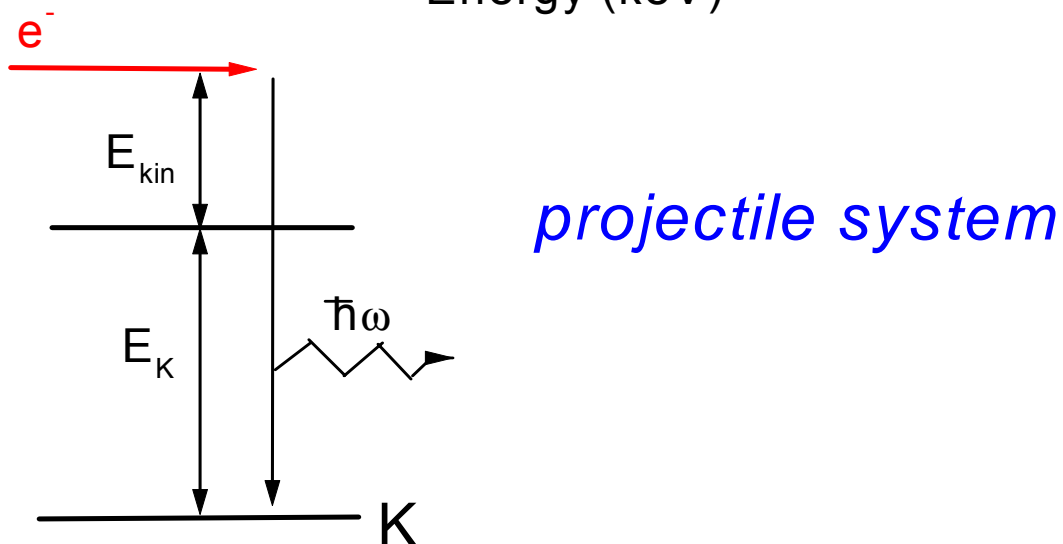
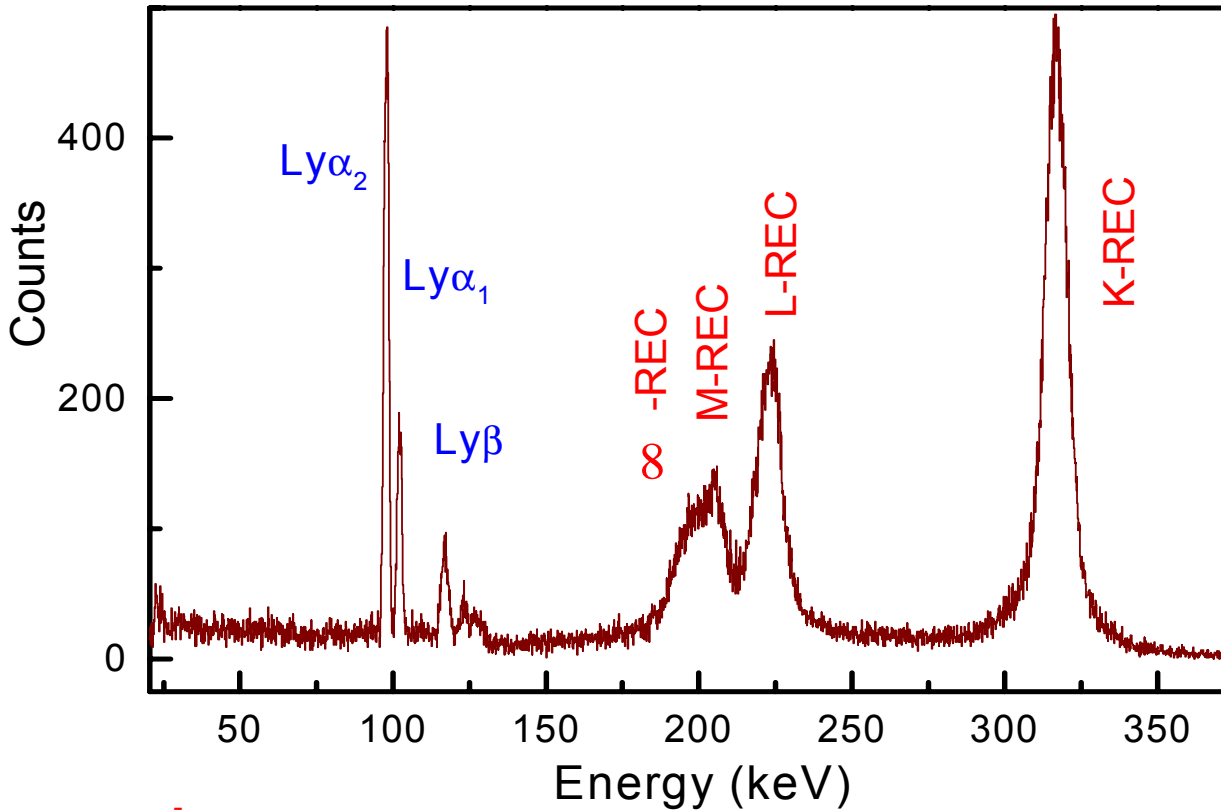
Single collision conditions



X-Ray Spectrum of H-like Uranium

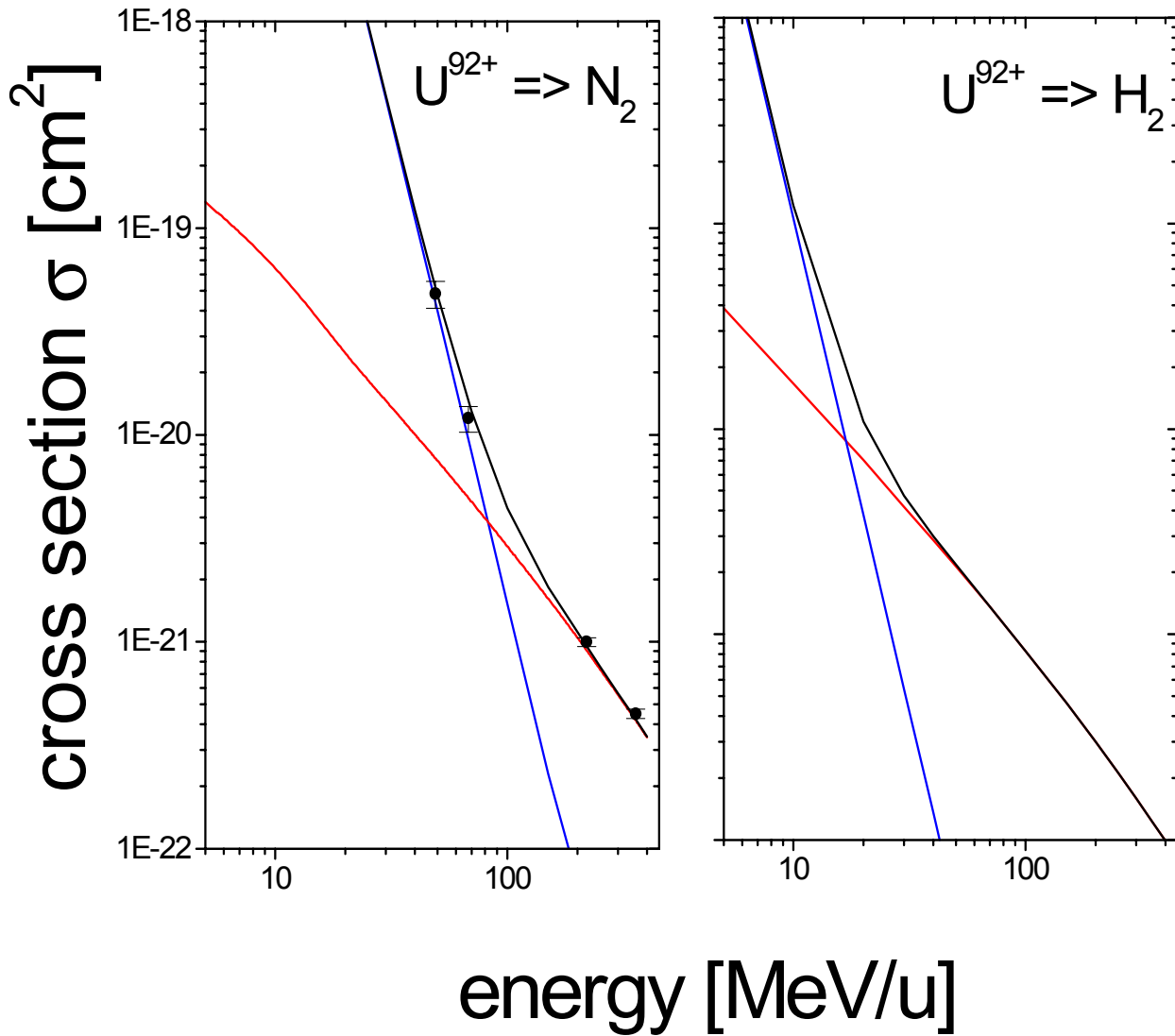
358 MeV/u $U^{92+} \Rightarrow N_2$

$\theta_{lab} = 132 \text{ deg}$



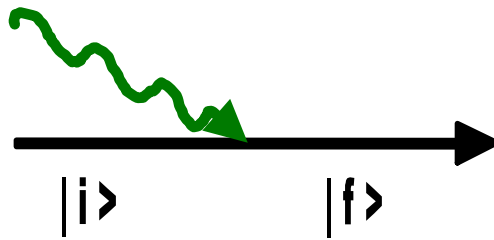
$$E_{REC} = E_K + m_e c^2 (\gamma - 1) + \gamma (p_i v_0 - E_T^B)$$

Choice of the collision system preferring REC charge-exchange channel



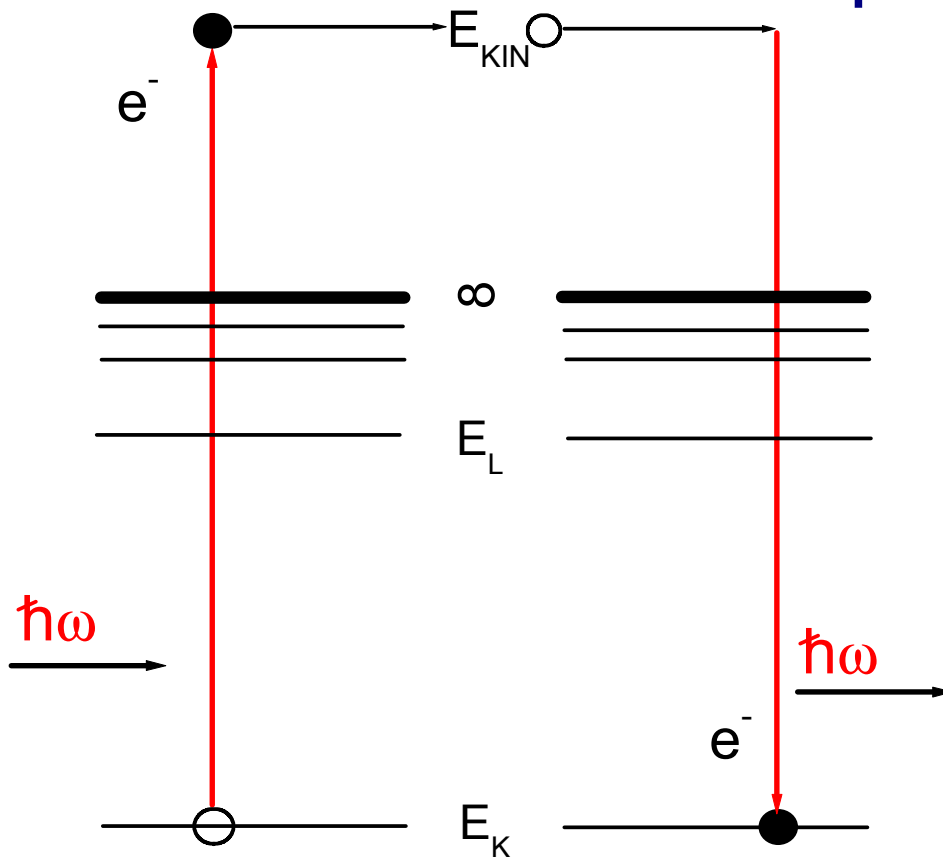
— NREC
— REC

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



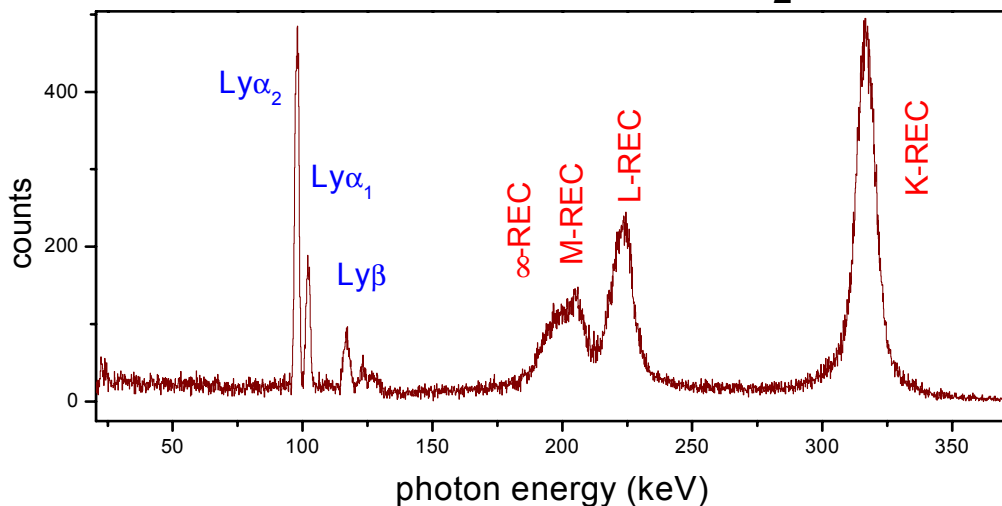
Photoionization

Radiative Electron Capture

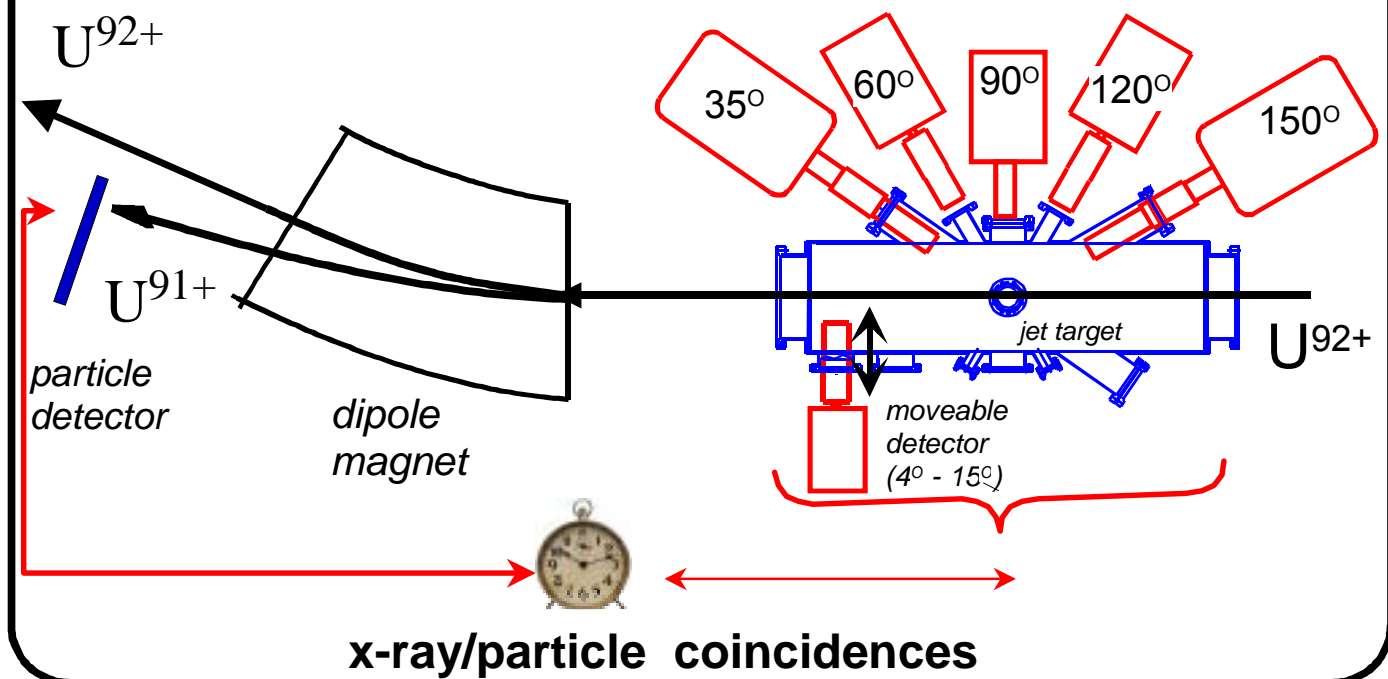


Angular Distribution Studies for the Time-Reversed Photoionization Process

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



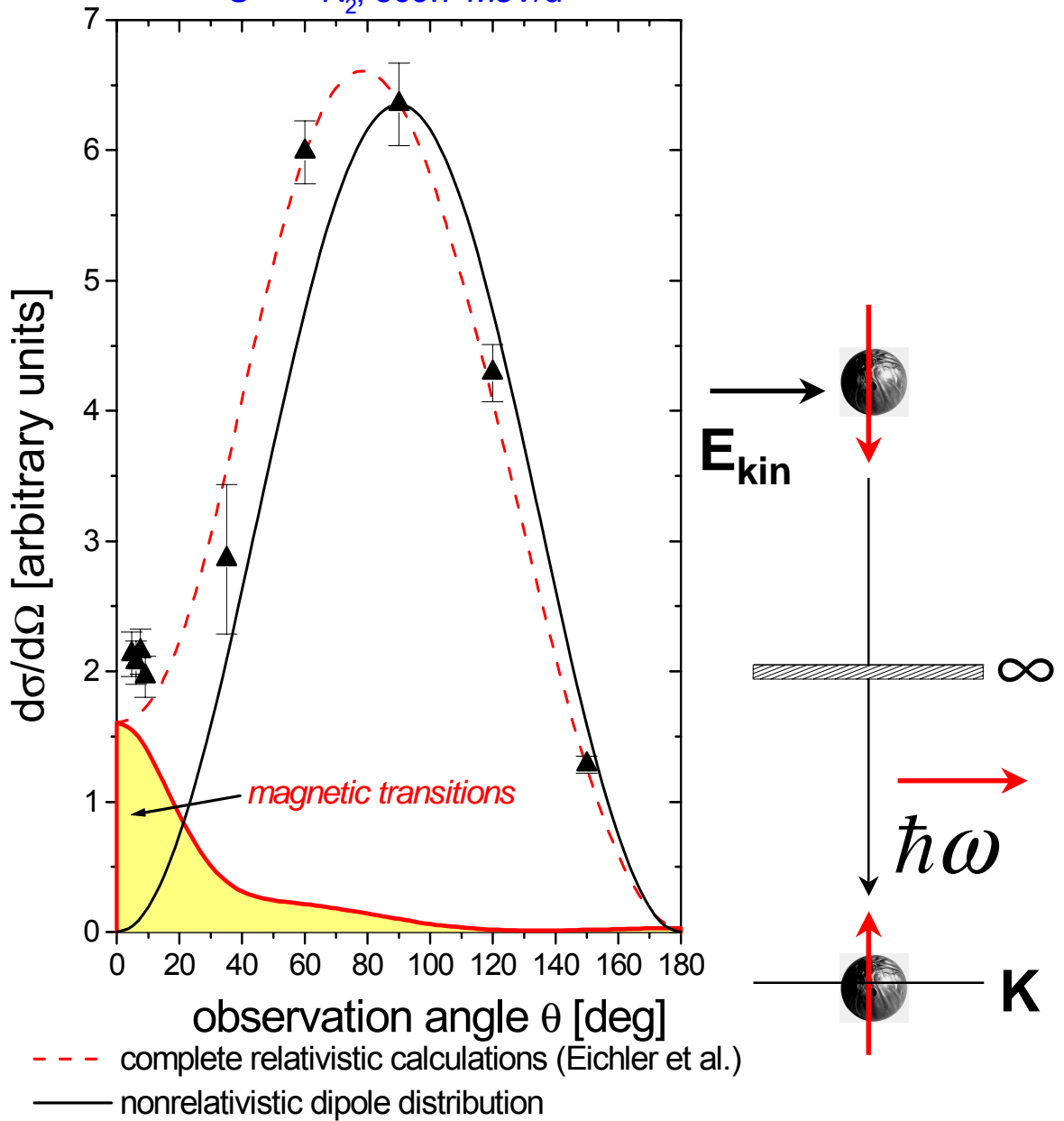
Experimental Setup at the Gas-Jet Target



Radiative Capture into the K-Shell

laboratory frame

$U^{92+} \Rightarrow N_2, 309.7 \text{ MeV/u}$

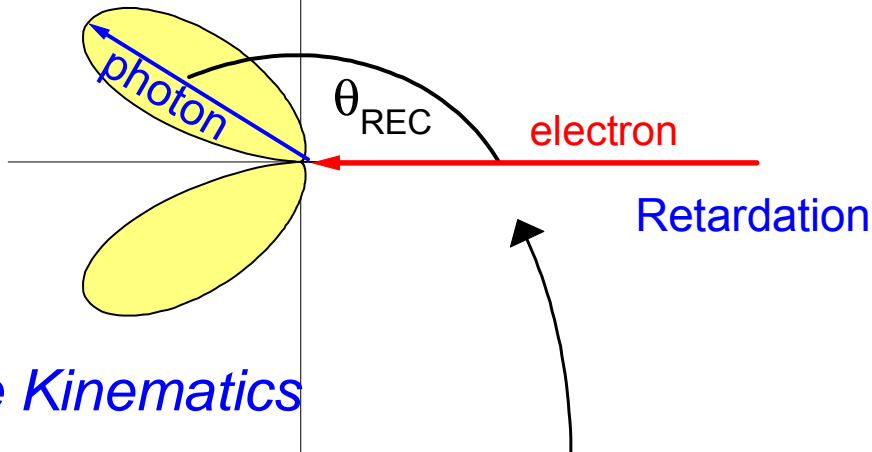


zero degree emission of electric radiation by
 electron capture into s-orbitals is forbidden
 by angular momentum conservation laws

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

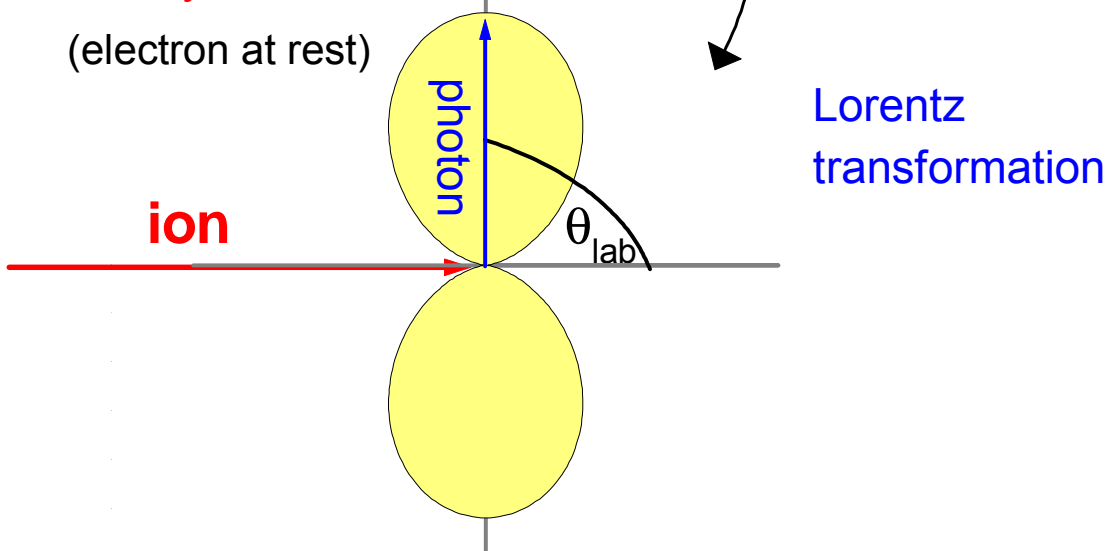
Transition matrix element
 $\langle \psi_i | \alpha u_+ \exp(-ikr) | \psi_f \rangle$

projectile frame (REC)



laboratory frame

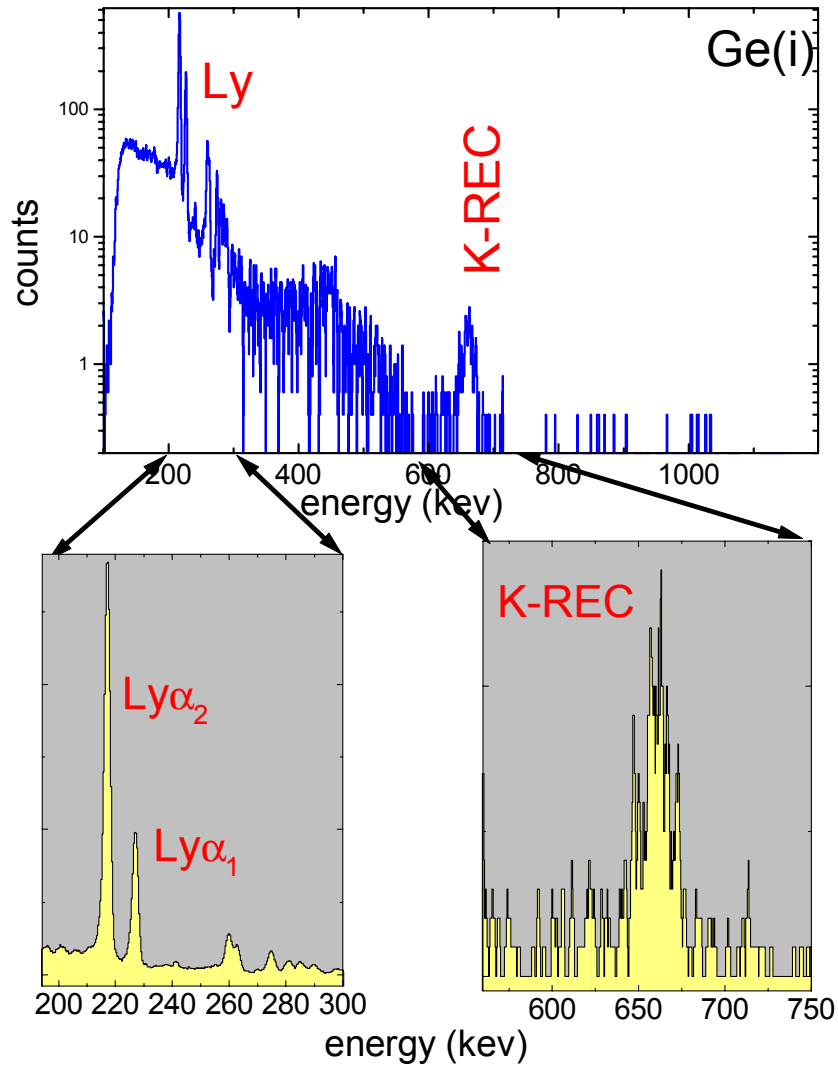
(electron at rest)



Using nonrelativistic wavefunctions, complete cancellation between retardation and Lorentz transformation occurs

(verified by Anholt for $197 \text{ MeV/u Xe}^{54+} \Rightarrow \text{Be}$)

Photon emission close to zero degree



Normalization to the $\text{Ly}\alpha_2 + \text{M1}$ intensity:

almost all systematic uncertainties cancel out completely

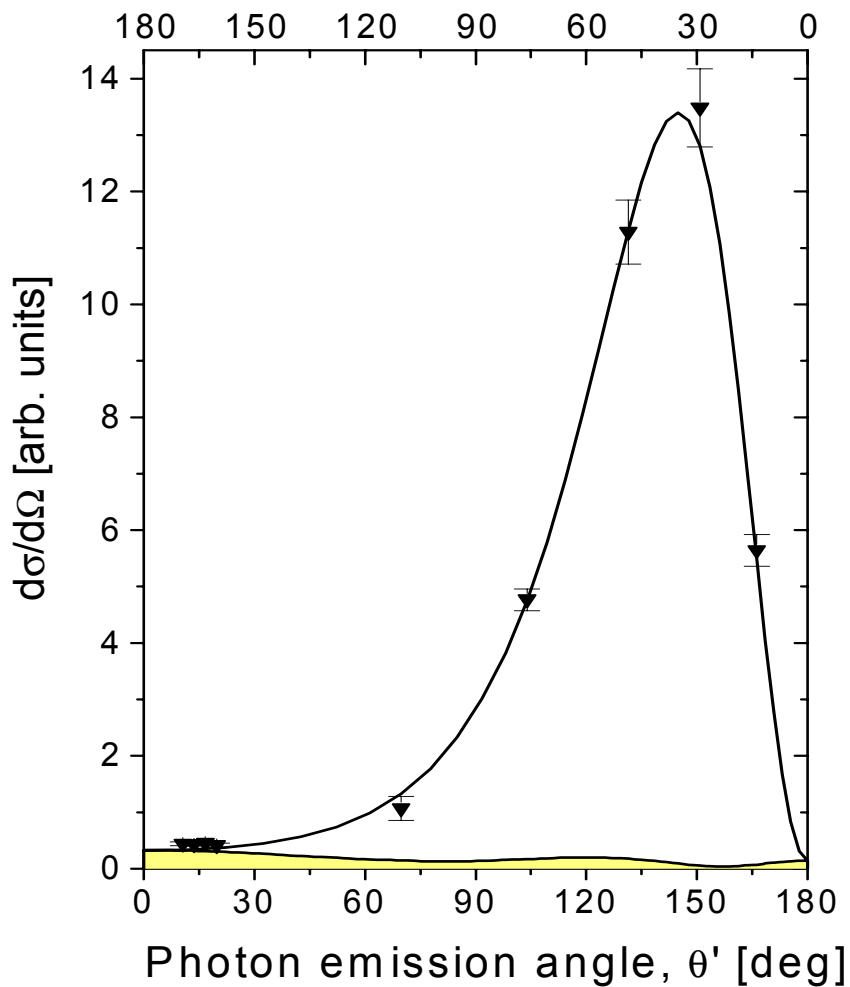
From the REC distribution in the emitter frame the electron angular distribution for photionization is obtained by the simple transformation

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

Emitter frame

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

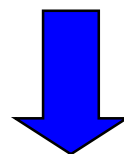
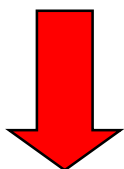
Electron emission angle, $\pi - \theta'$ [deg]



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+}



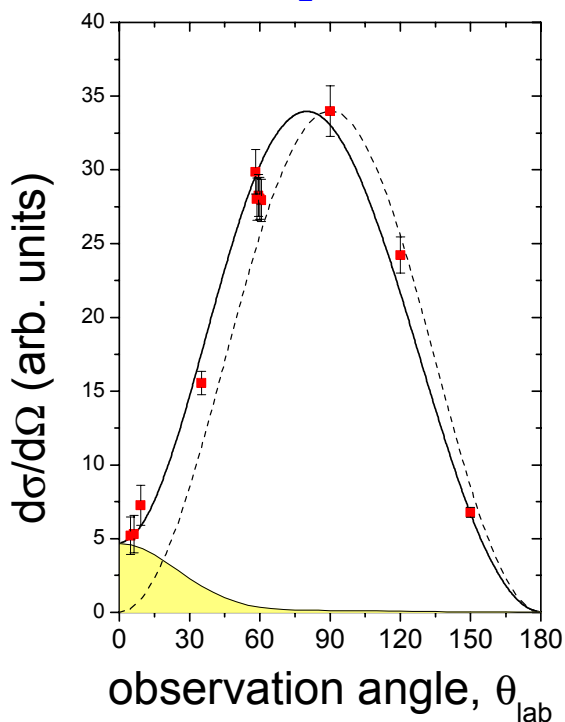
Time reversal

laboratory frame

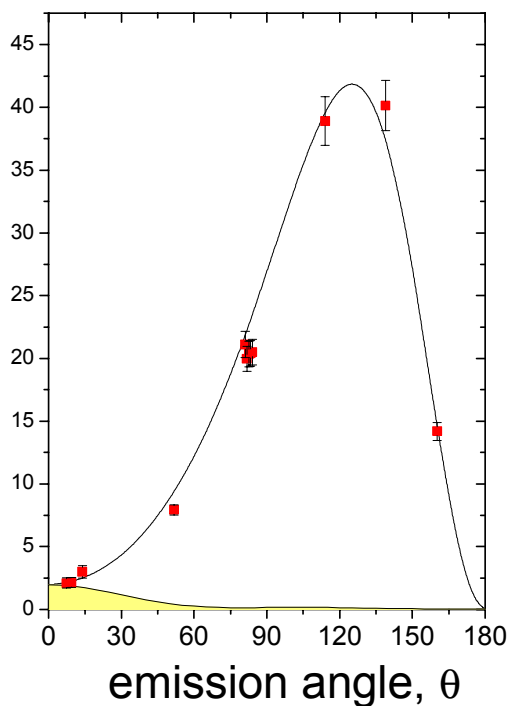
emitter frame

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

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



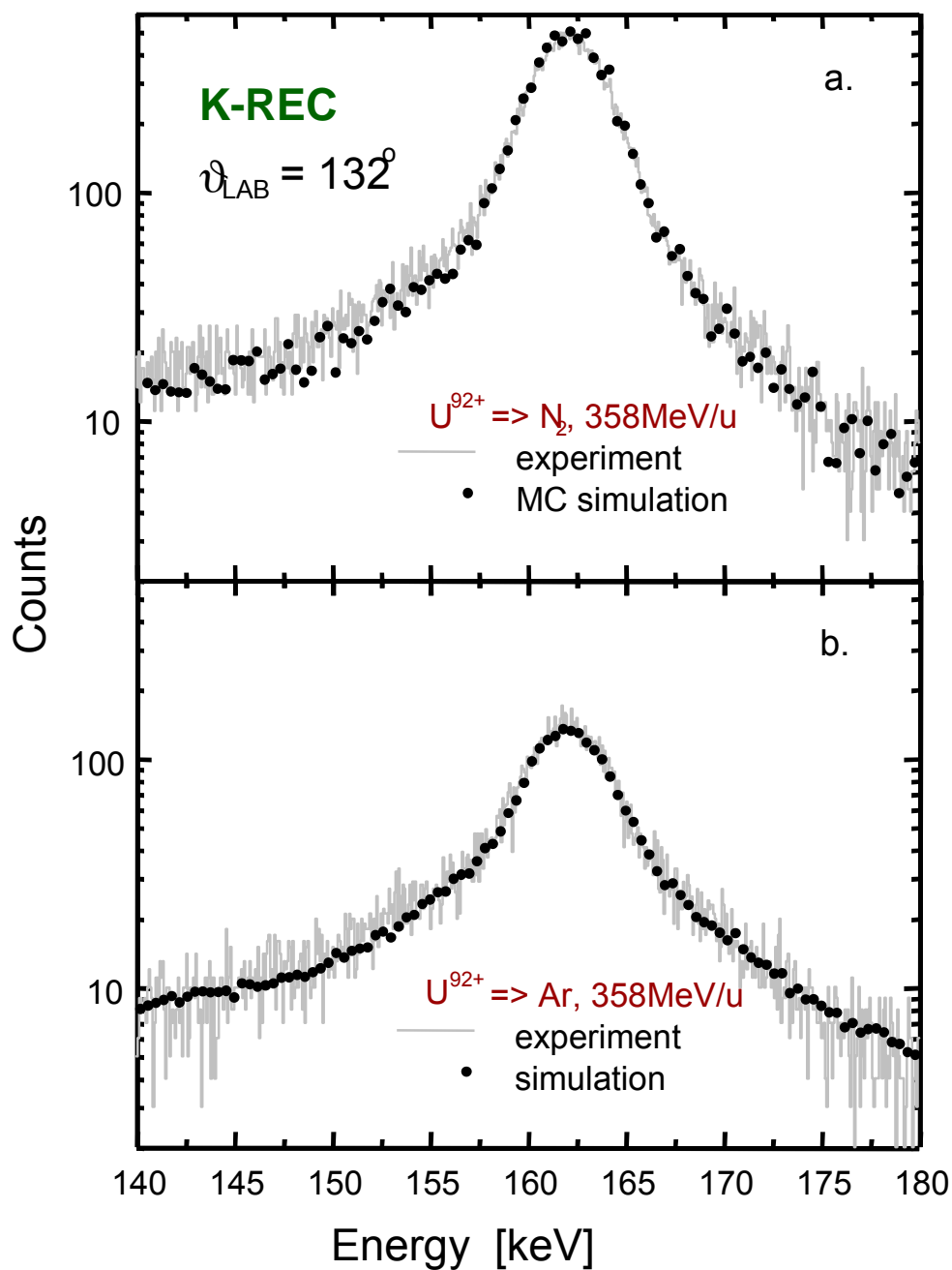
$d\sigma/d\Omega$ (arb. units)



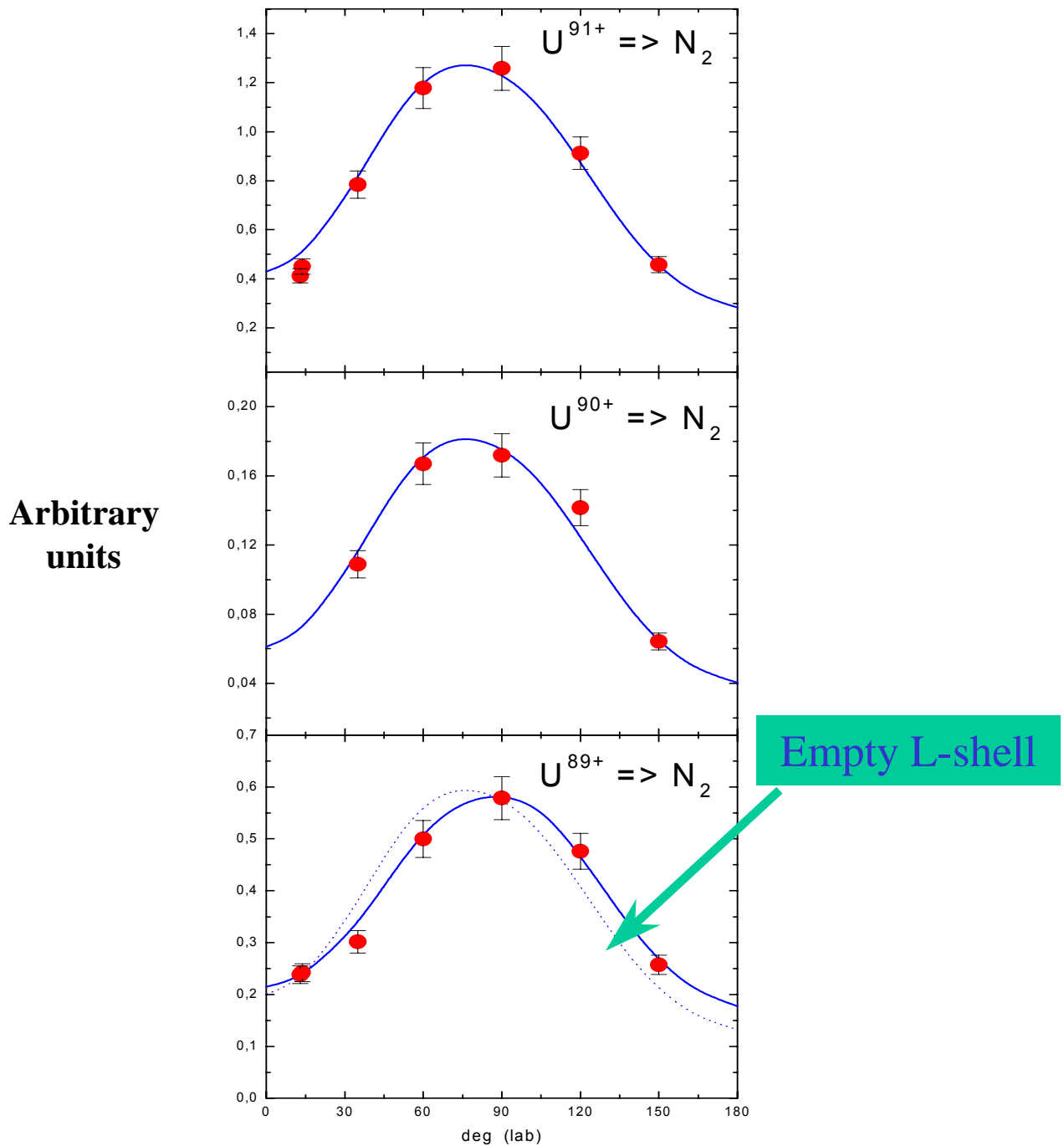
Theory: J. Eichler 1999

spin-flip contribution: 2%

Comparison of Experimental and Monte Carlo Simulated Spectra



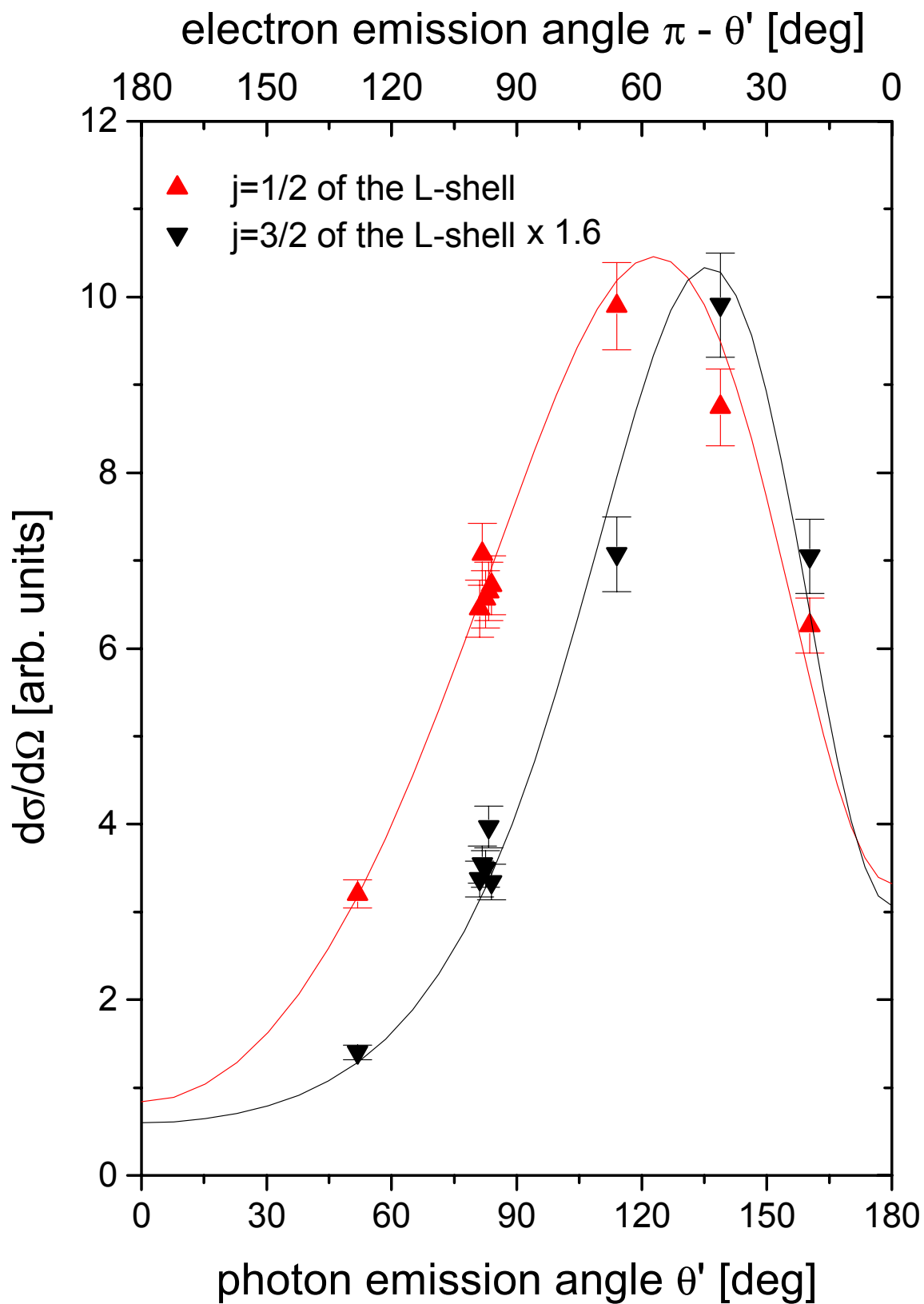
L-REC in 216 MeV/u collisions of H-, He-, and Li-like U-ions with nitrogen target



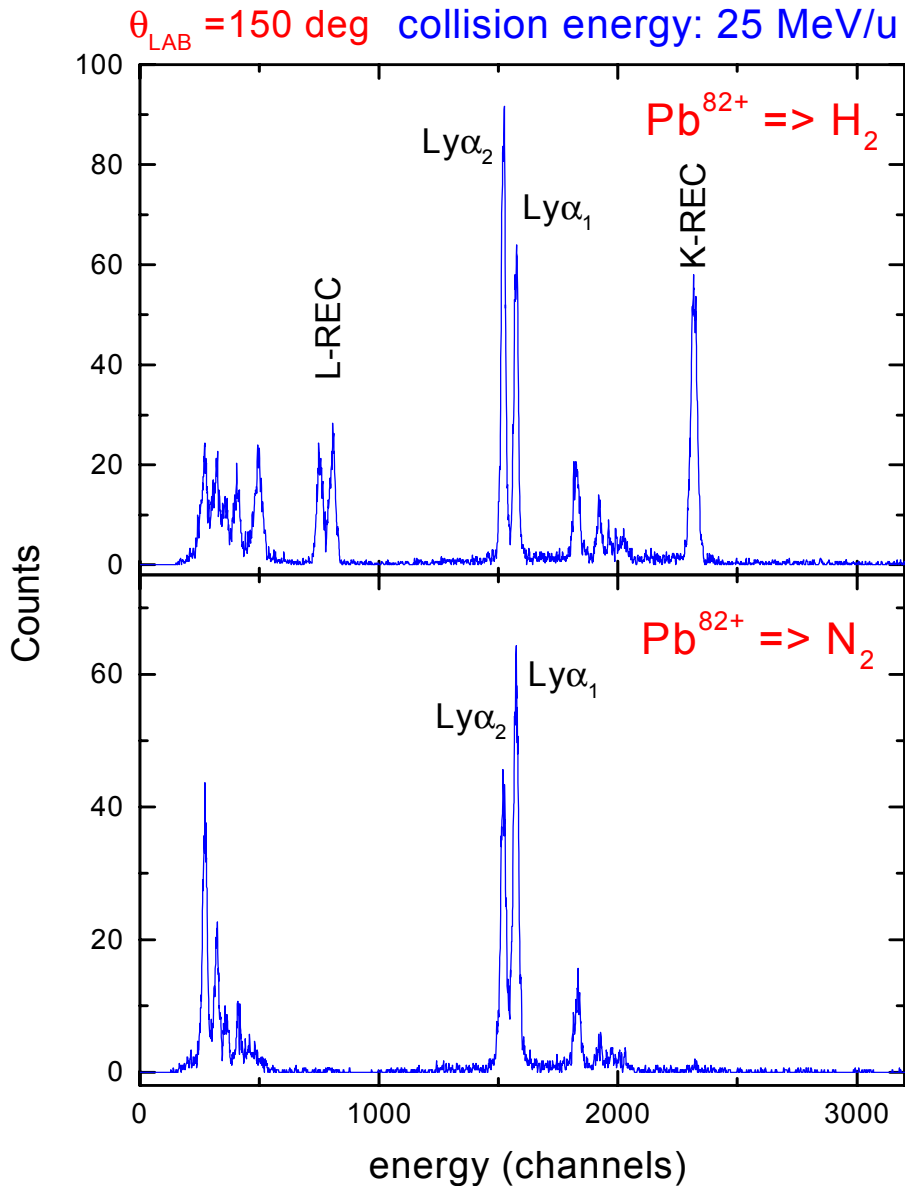
One electron added into the projectile L-shell provides a very sensitive test of theoretical prediction for L-REC

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

REC into excited states of H-like uranium



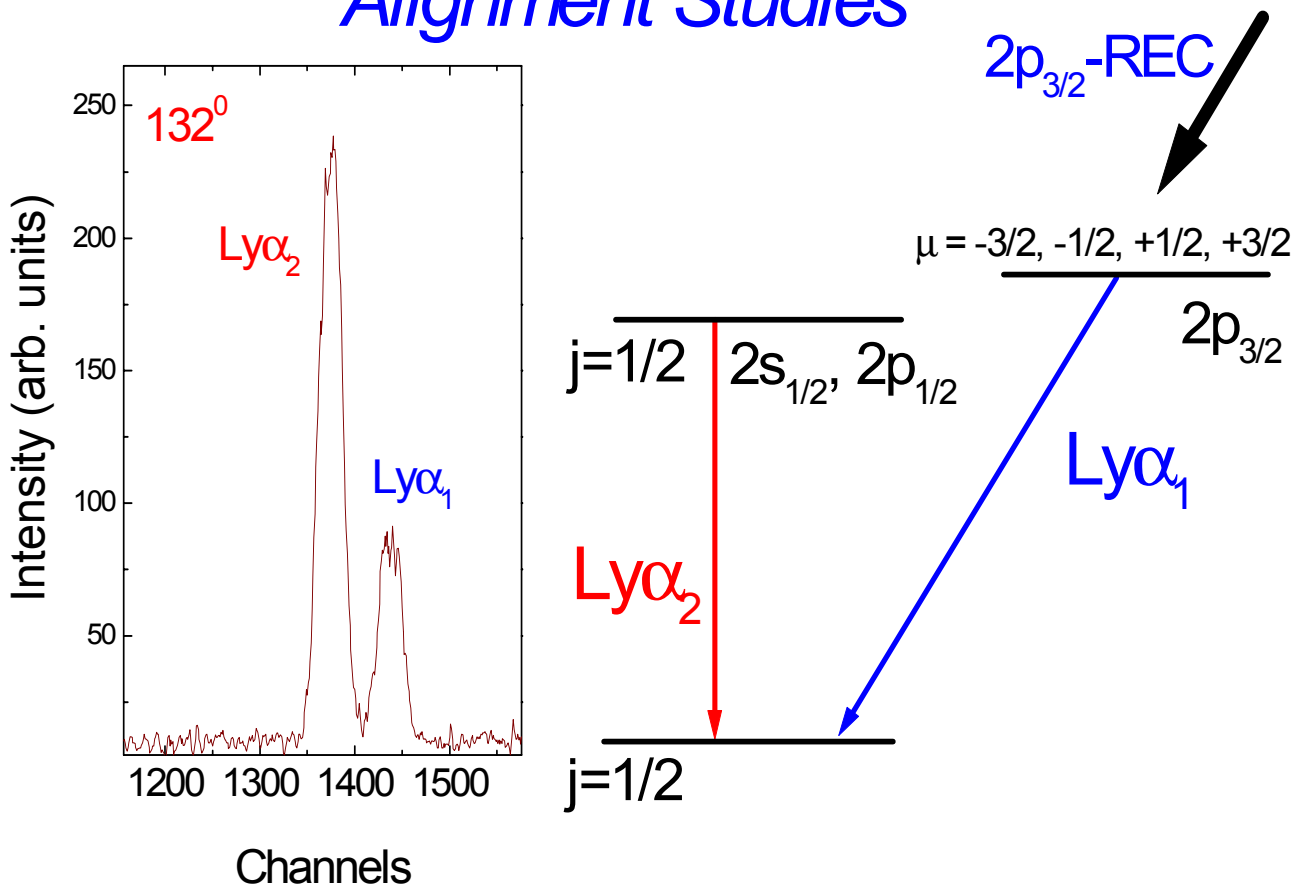
First test experiment with an H₂-target: bare Pb ions at 25 MeV/u



- ➔ narrow Compton profile
- ➔ strong REC

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

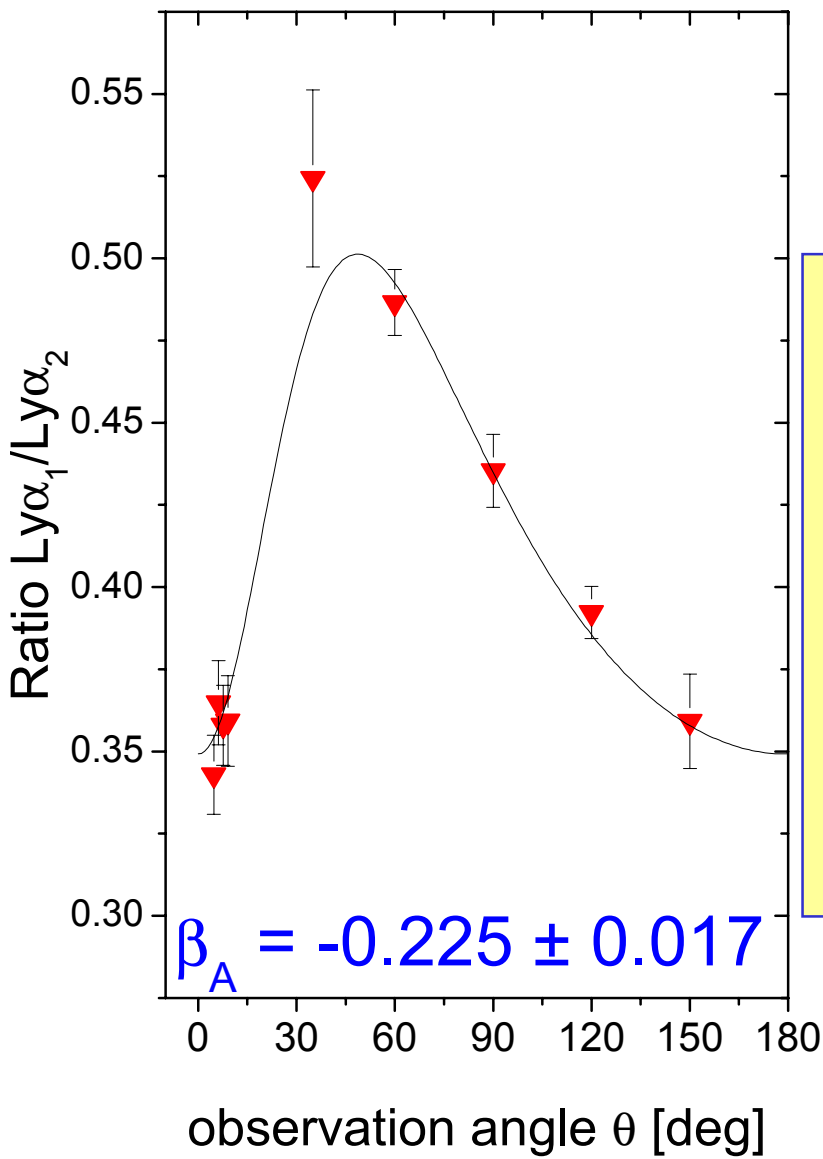
Alignment Studies



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

(80-350) MeV/u

Ly α_1 transitions at 310 MeV/u



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

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

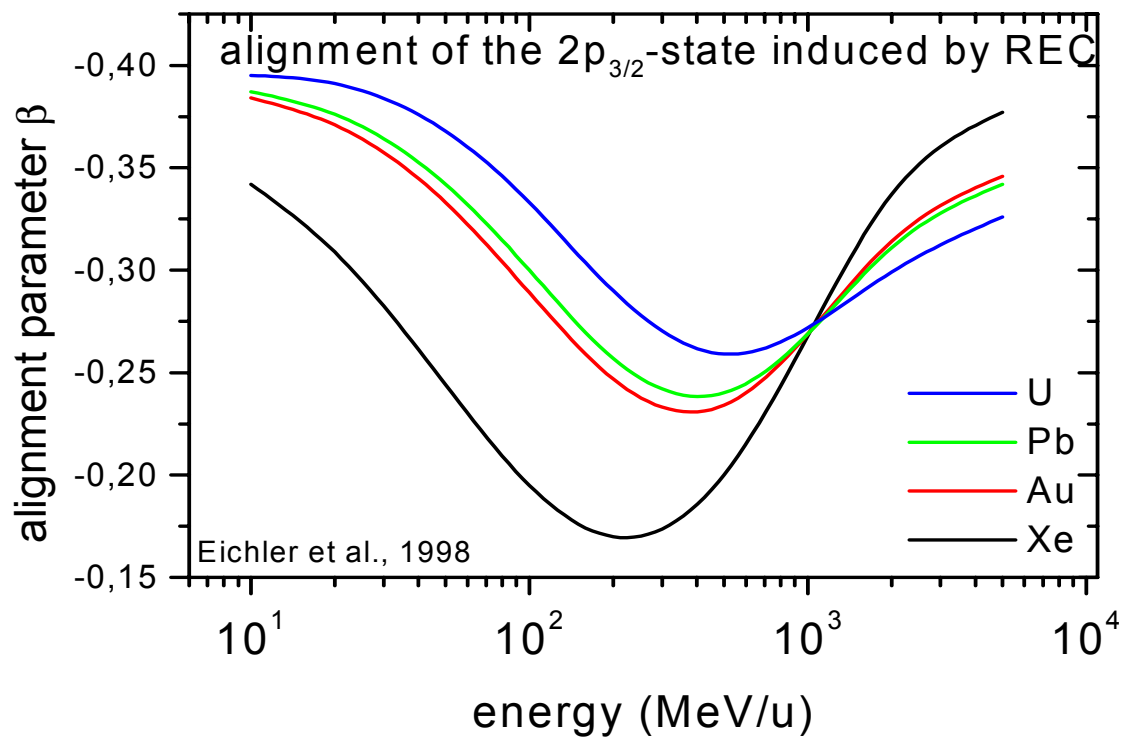
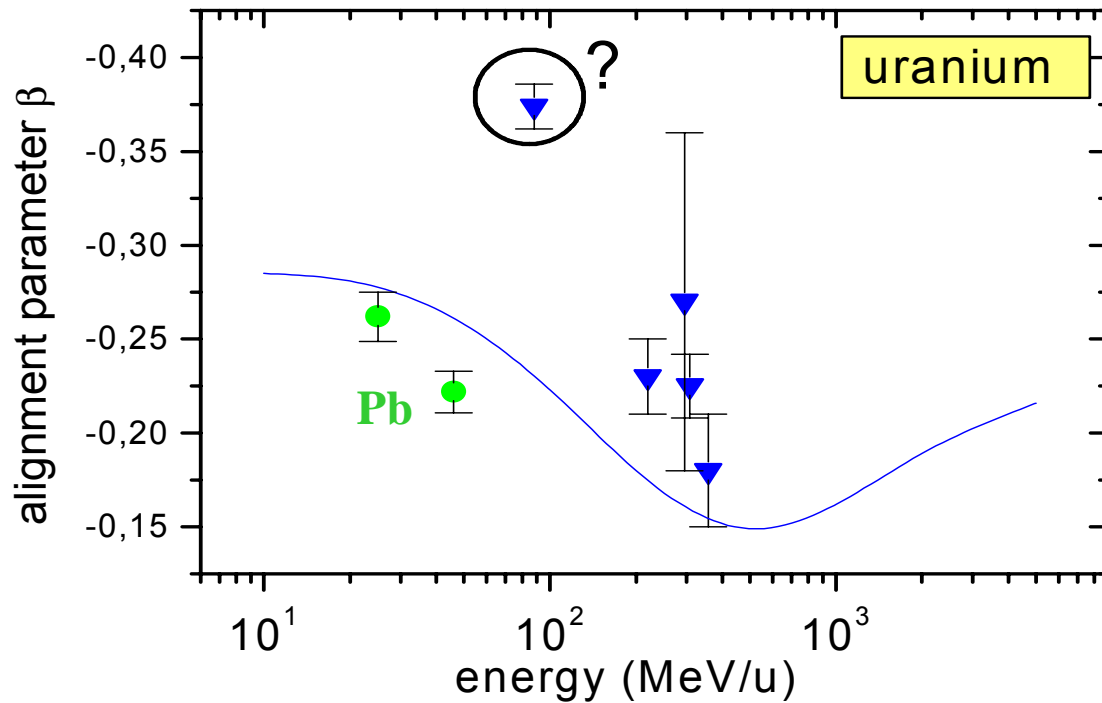
Alignment



Alignment Parameter

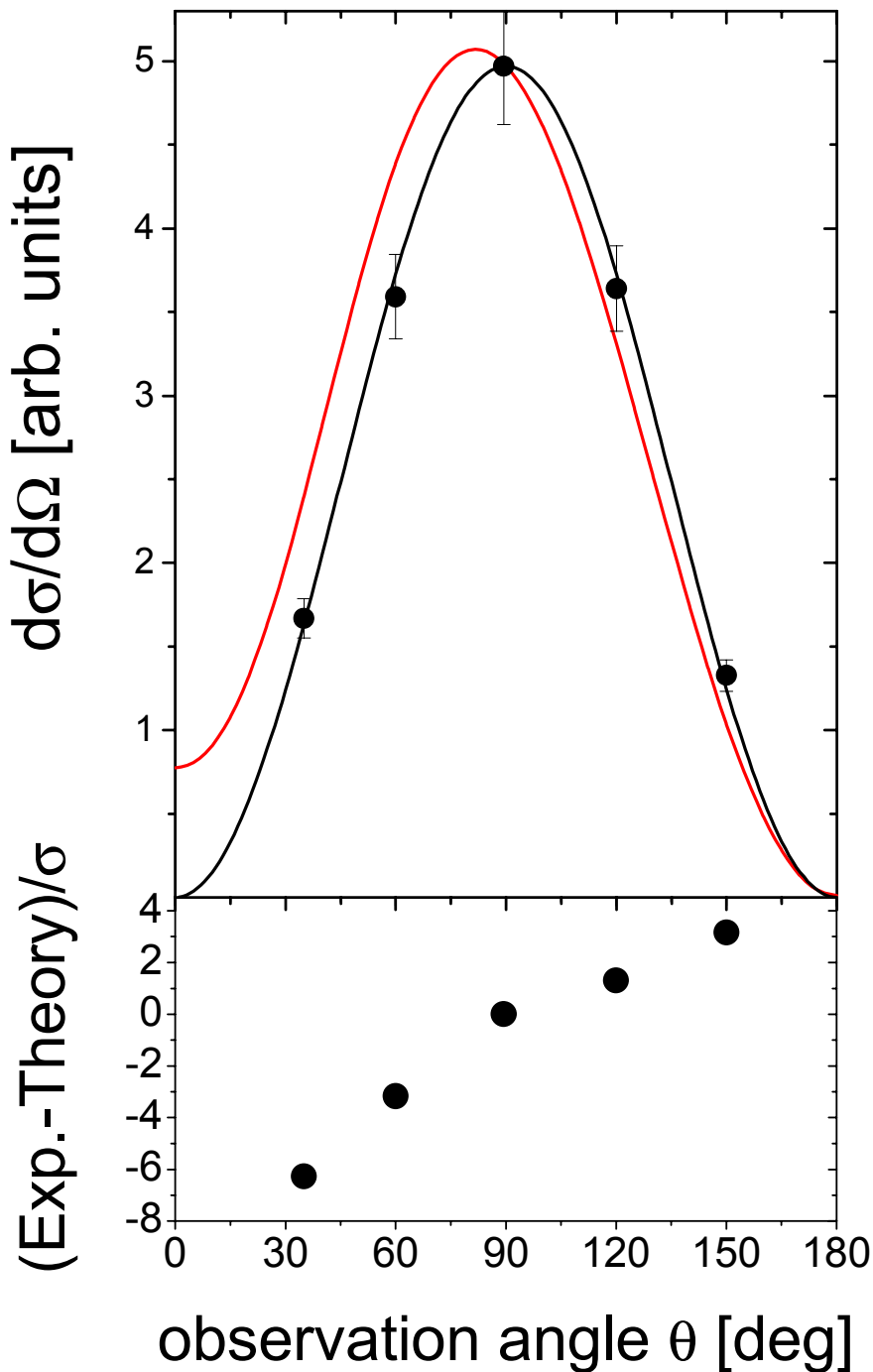
$$W(\theta) \propto 1 + \beta_A \left[1 - \frac{3}{2} \sin^2 \theta \right]$$

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



Nuclear spin and the atomic photoionization process

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

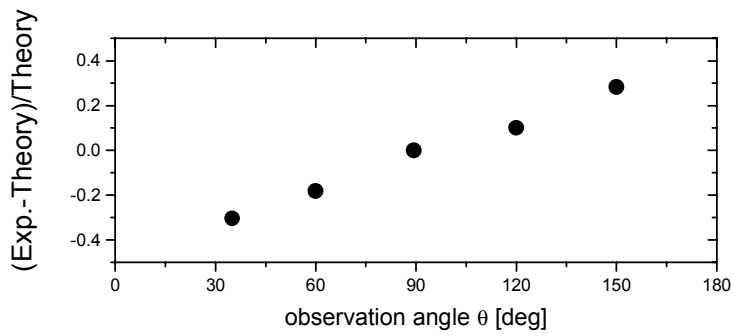
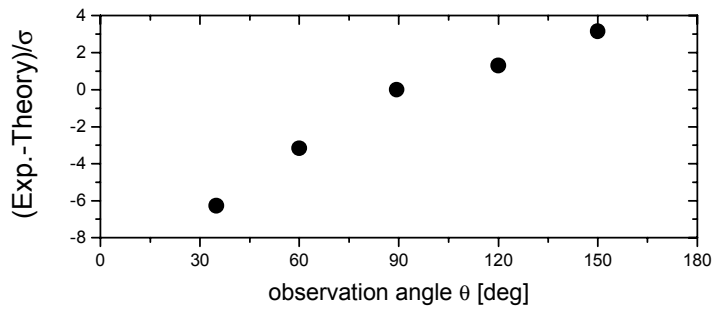
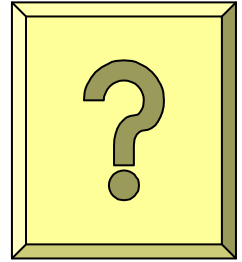
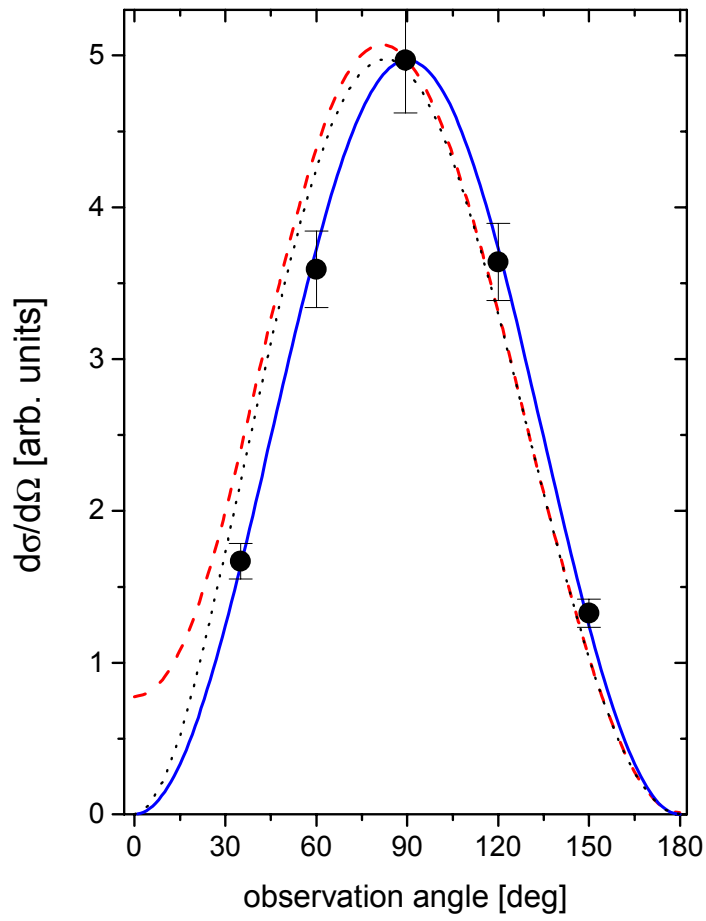


1s-REC for
209 Bi⁸³⁺
at 298 MeV/u

Nuclear spin
of bismuth
 $I=9/2$

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

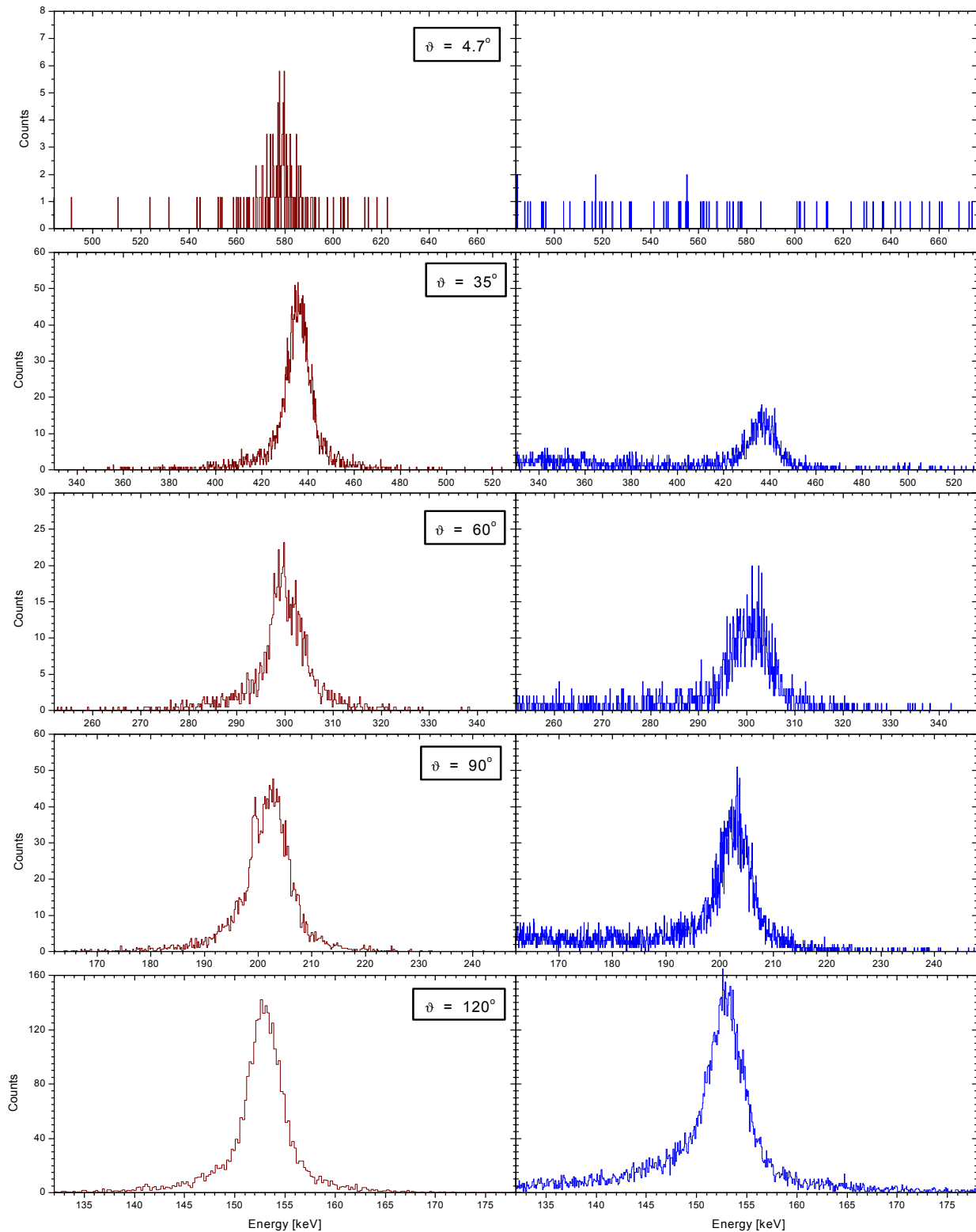
298 MeV/u Bi => N₂



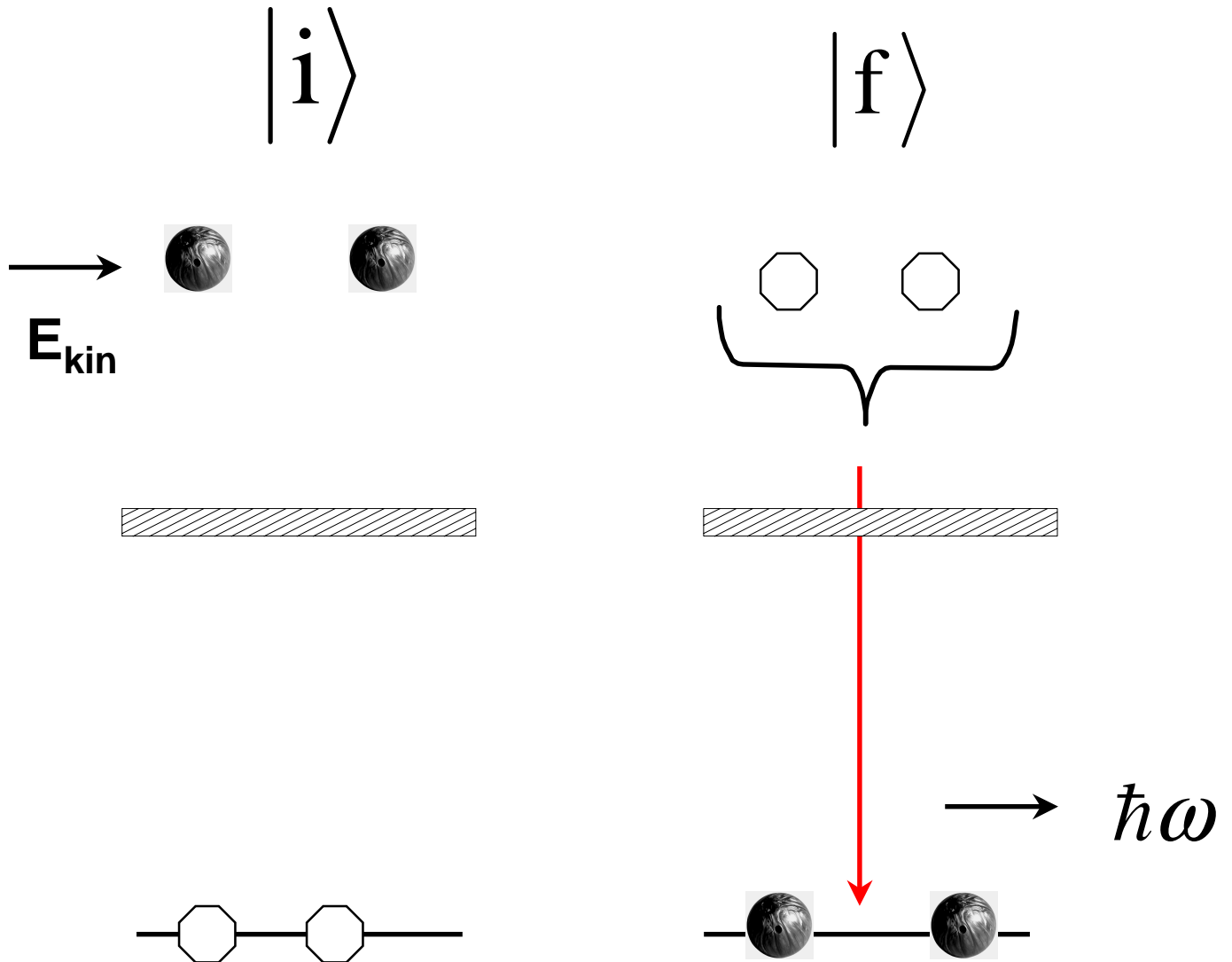
K-REC in 298 MeV/u $^{209}\text{Bi}^{83+} \longrightarrow \text{N}_2$

Monte Carlo simulation

Experiment

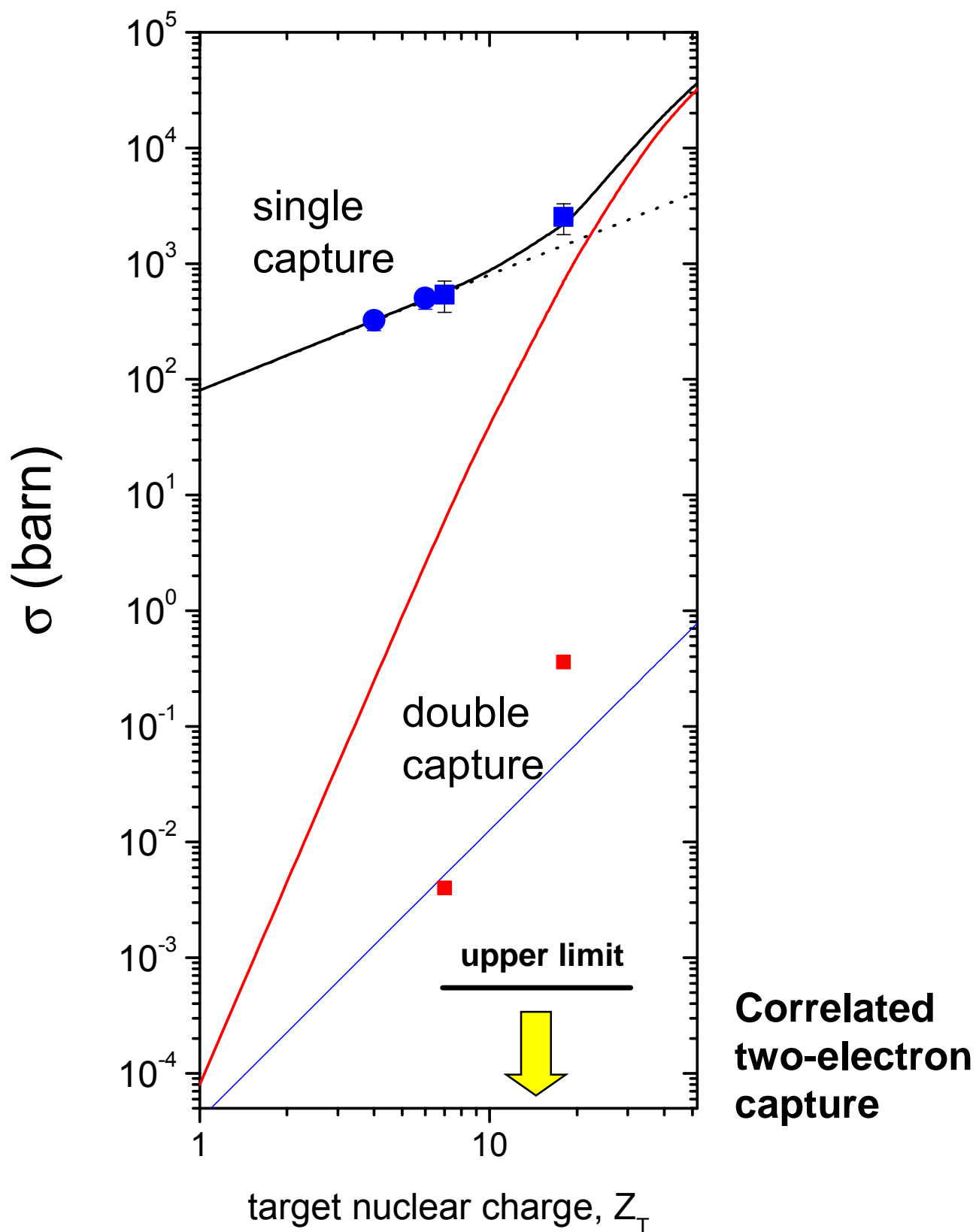


Search for Correlated Two-Electron Capture



Time reversed double photoionization

Due to relativistic corrections, strong cross-section enhancement expected



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)