Poster Session

HI JENA
Helmholtz Institute Jena

X-ray Emission Study Performed for H-like Lead at the Electron Cooler of CRYRING@ESR

Binghui Zhu

Helmholtz institute Jena

IOQ, Friedrich-Schiller-Universität Jena

10th International Conference on New Frontiers in Physics (ICNFP 2021)

August 23 –September 7, 2021

B. Zhu
G. Weber
T. Over
Z. Andelkovic
R. Chen
D. Dmytriiev
O. Forstner
A. Gumberidze
C. Hahn
M. O. Herdrich
P. M. Hillenbrand
A. Kalinin
Th. Köhler
F. M. Kröger
M. Lestinsky
Y. A. Litvinov
E. B. Menz
T. Morgenroth
N. Petridis
F. Herfurth
Ph. Pfäfflein
M. S. Sanjari
R. S. Sidhu
U. Spillmann
S. Trotsenko
L. Varga
G. Vorobyev
Th. Stöhlker*

HI JENA
Helmholtz Institute Jena

IOQ JENA
Friedrich-Schiller-Universität

sparc

FAIR Phase 0 Research Program

GSI

IMP
中国科学院近代物理研究所

EMMI

APPA

China Scholarship Council

Lanzhou University 1909

SPONSORED BY THE
Federal Ministry
of Education
and Research

HI JENA
Helmholtz Institute Jena

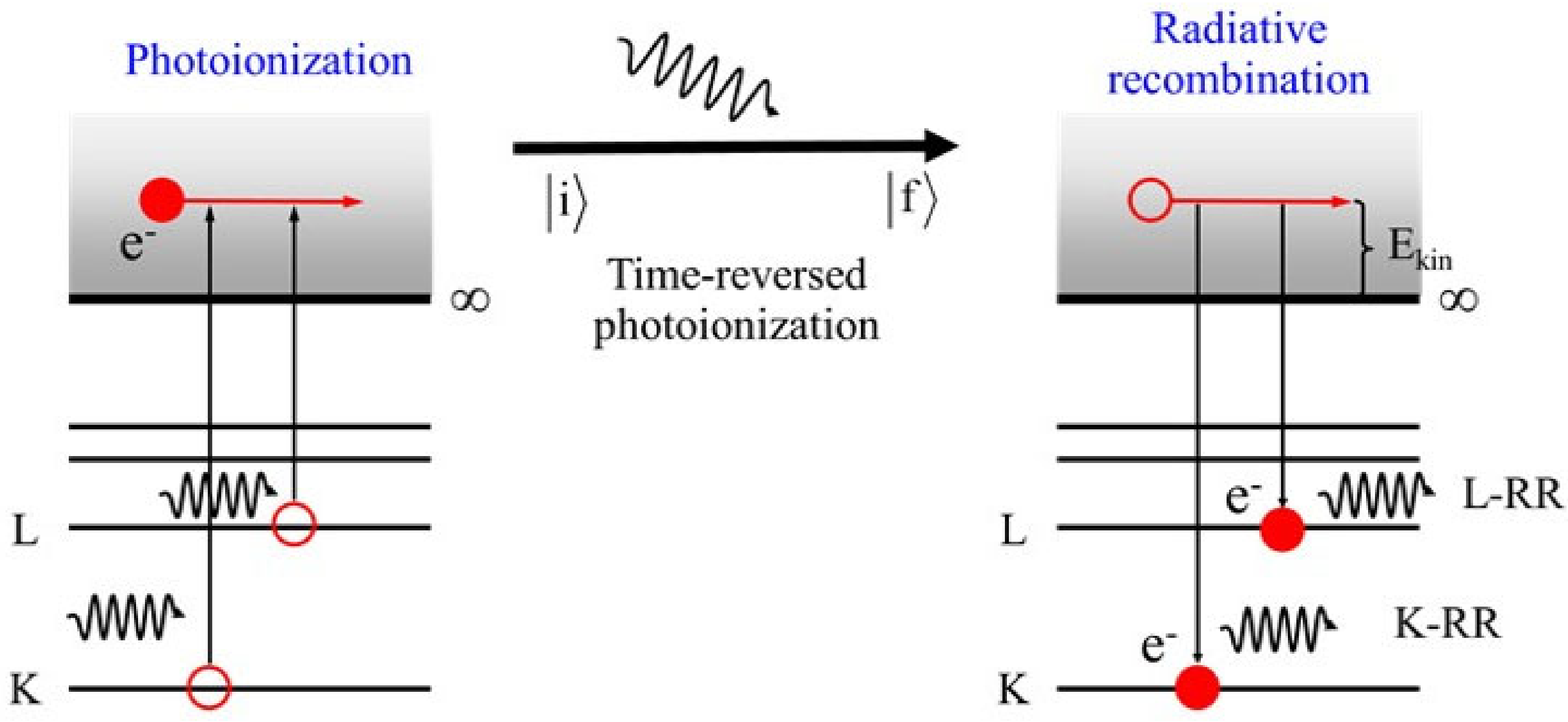
www.hi-jena.de

- Introduction
- Experimental Tools
- Radiative recombination Process for Pb^{82+}
  - RR rate coefficient
  - Angular distribution
  - Simulation of cascade feeding
  - Radiative decay dynamics: de-excitation cascade
- Summary / Conclusion

HI JENA
Helmholtz Institute Jena

www.hi-jena.de

Radiative recombination (RR)



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

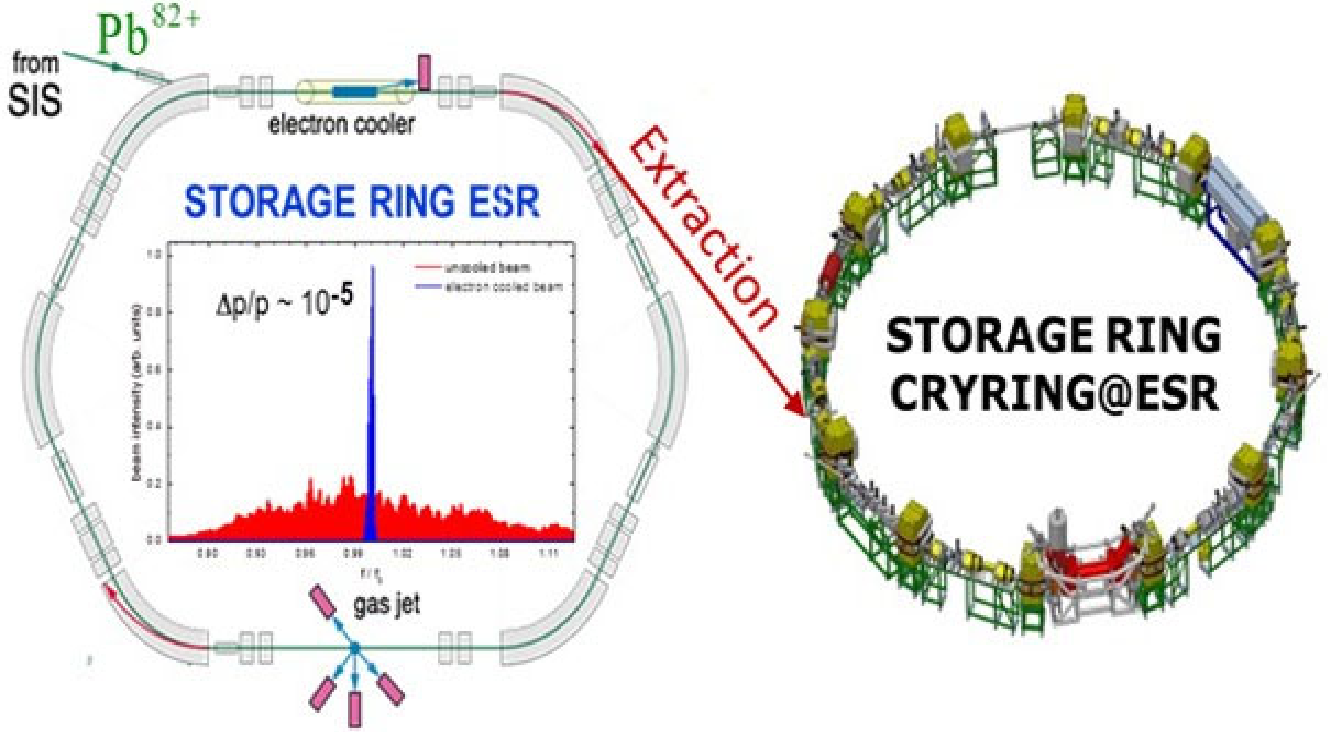
$$\hbar\omega = E_B + E_{KIN}$$

- Recombination process populates preferentially high *n,l* states at low relative electron-ion beam energies.

HI JENA
Helmholtz Institute Jena

www.hi-jena.de

Experimental environment



SIS18 400 Mev/u

↓

Pb^{82+} ESR — Stochastic cooling, Electron cooling

↓ Deceleration to 10 MeV/u

CRYRING@ESR — Electron cooling and storing

For the experiment, bare Pb ions were decelerated in the ESR to the energy of 10 MeV/u and injected into the CRYRING@ESR for radiative recombination study.

HI JENA
Helmholtz Institute Jena

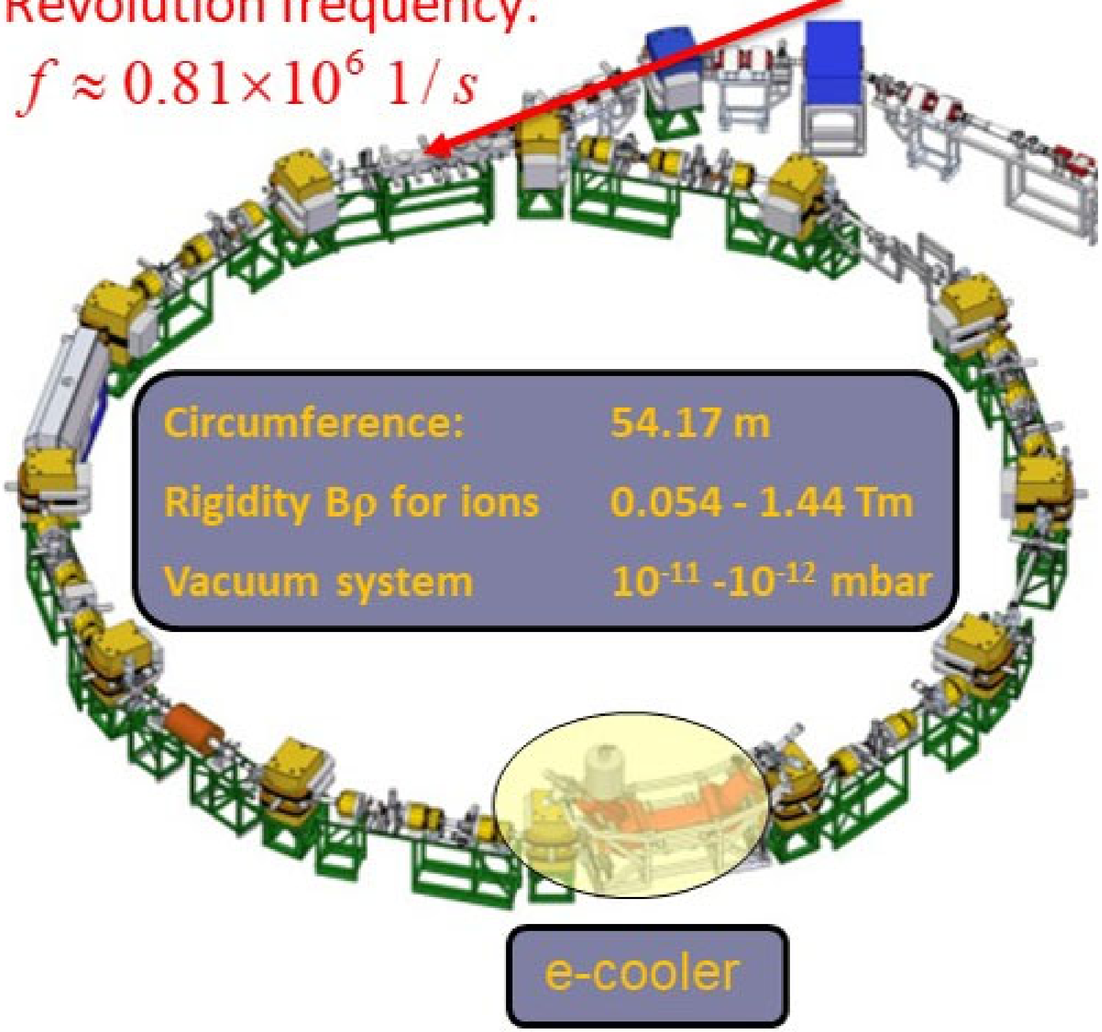
www.hi-jena.de

Radiative recombination study at CRYRING@ESR

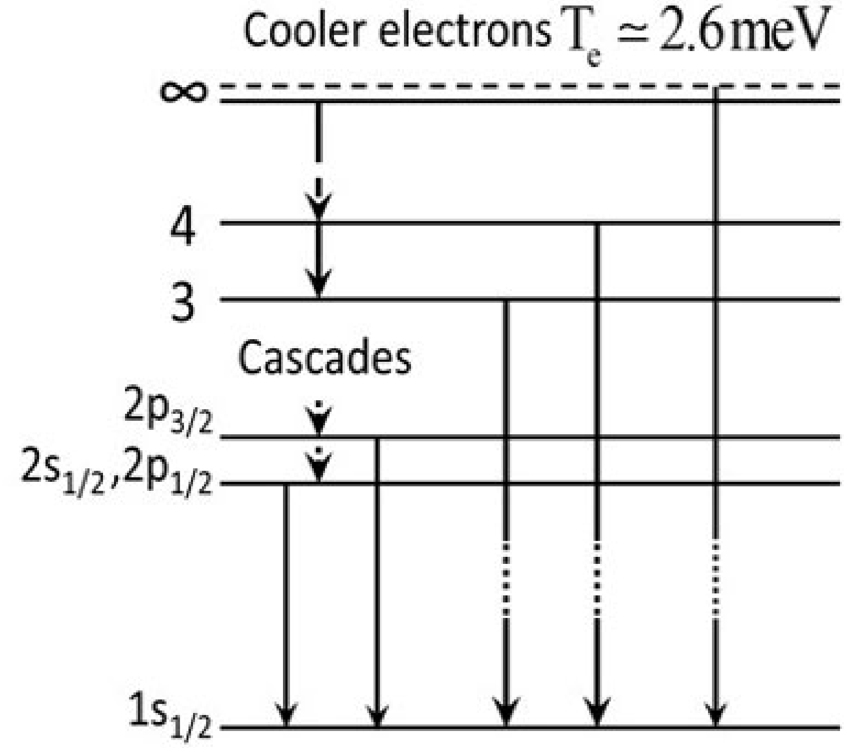
Revolution frequency:

$f \approx 0.81 \times 10^{6}\ 1/s$

Pb^{82+} @10MeV/u



$$Pb^{82+} + e^{-} \rightarrow Pb^{81+} + \hbar\omega$$

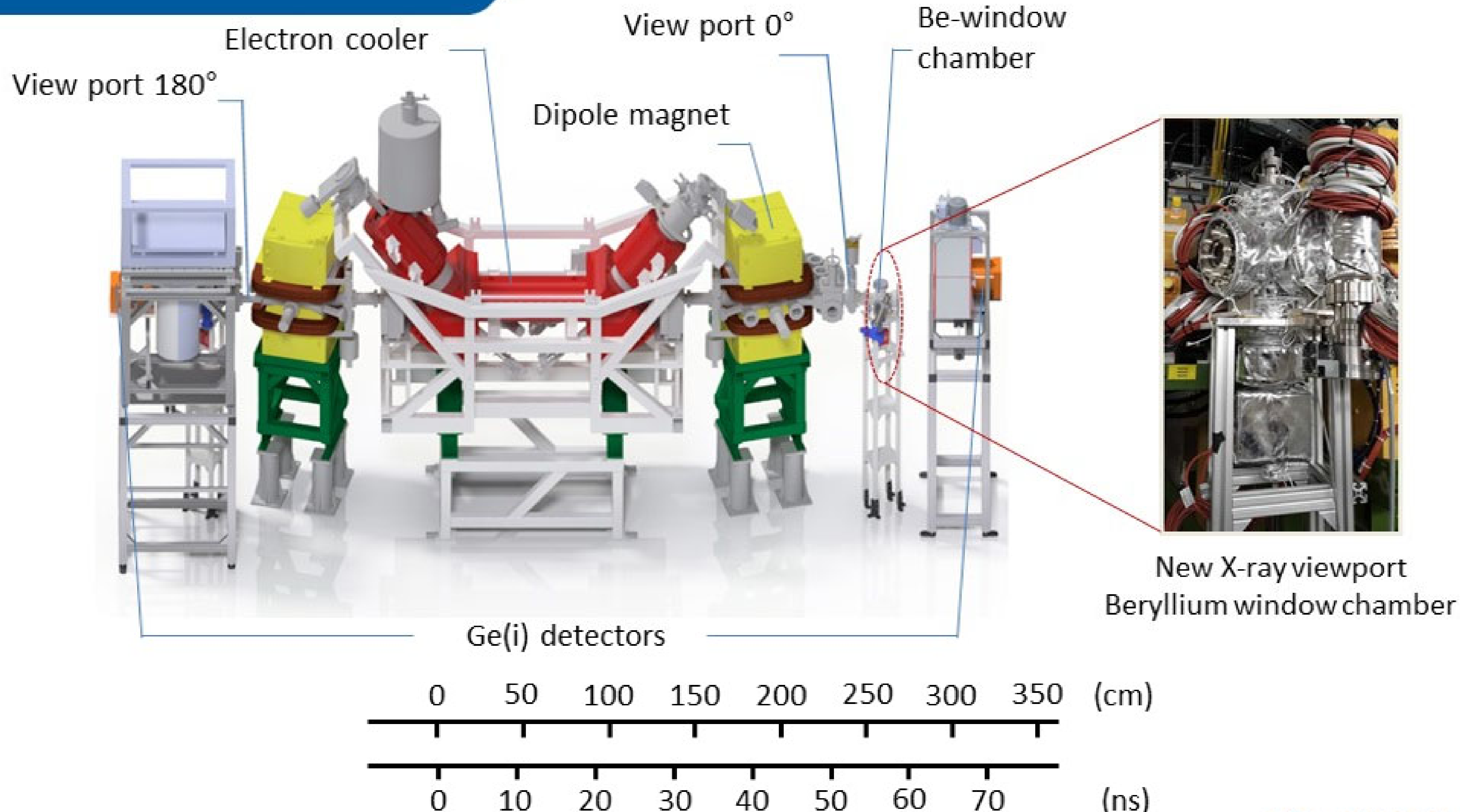


Prompt RR process followed by de-excitation cascades at electron cooler.

HI JENA
Helmholtz Institute Jena

www.hi-jena.de

Experiment at electron cooler



HI JENA
Helmholtz Institute Jena

www.hi-jena.de

Comparison with spectrum at ESR electron cooler

$$Pb^{82+} + e^- \rightarrow Pb^{81+} + \hbar\omega$$

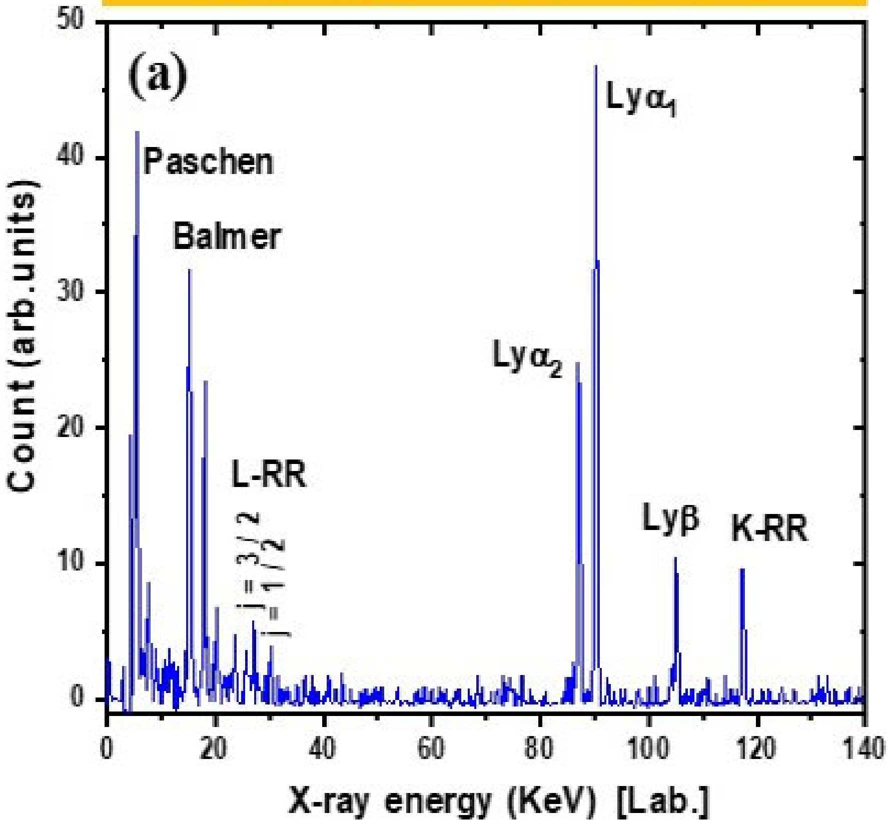


Fig. 1 X-ray spectrum registered in coincidence with Pb^{81+} at CRYRING electron cooler at exactly 0 deg observation angle.

$$U^{92+} + e^- \rightarrow U^{91+} + \hbar\omega$$

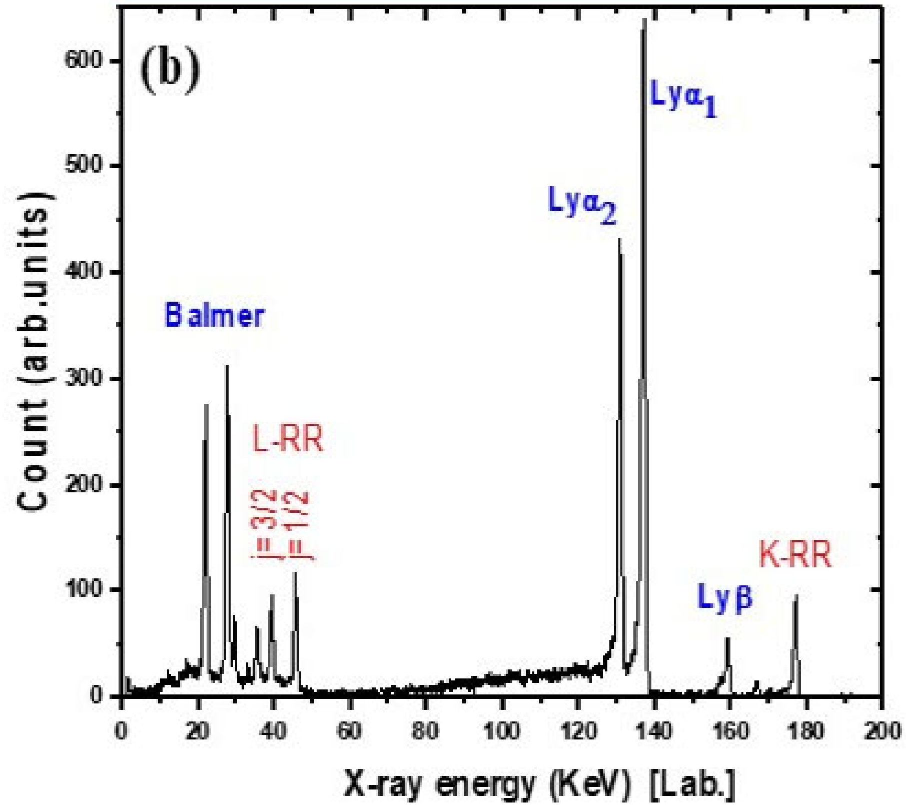


Fig. 2 X-ray spectrum registered in coincidence with U^{91+} at ESR electron cooler at an observation angle of 0.5 deg.

In the case of CRYRING electron cooler:

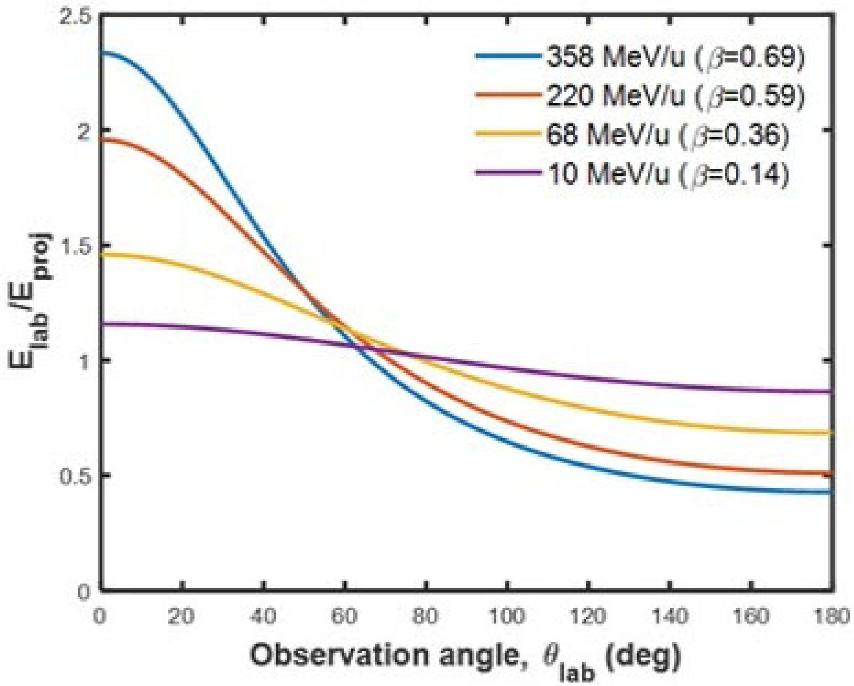
- High transmission of the low energy photons observed below 20 KeV.
- No distinctive tails of Lyman-α transition lines and eliminated Doppler broadening.

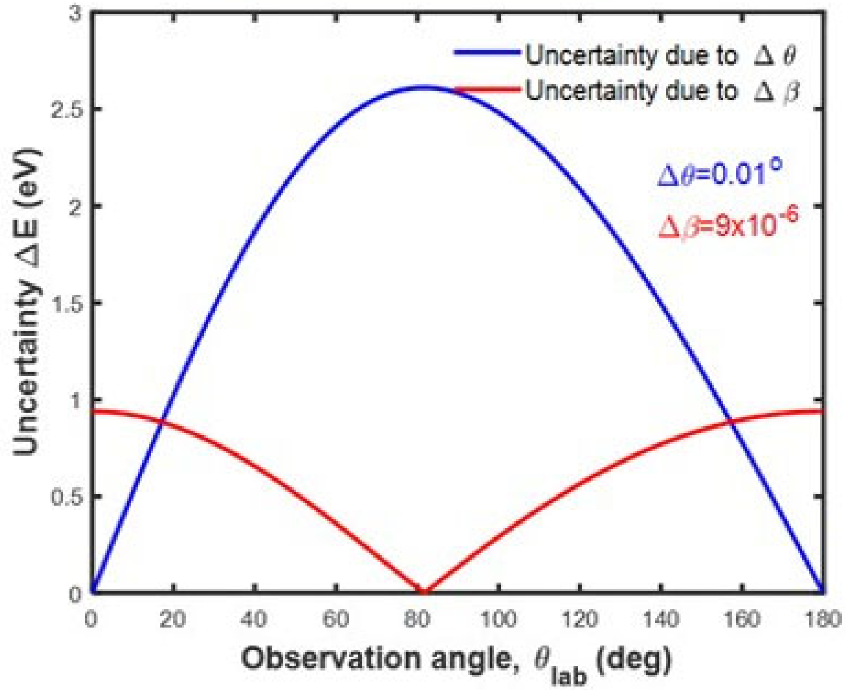
HI JENA
Helmholtz Institute Jena
www.hi-jena.de

Key features of experimental setup

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

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{\beta \sin\theta_{lab}}{1 - \beta\cos\theta_{lab}} \Delta\theta_{lab}\right)^2 + \left(\gamma^2 \frac{\cos\theta_{lab} - \beta}{1 - \beta\cos\theta_{lab}} \Delta\beta\right)^2 + \left(\frac{\Delta E_{lab}}{E_{lab}}\right)^2$$





- X-ray detectors placed at 0° and 180° observation angles at electron cooler of CRYRING@ESR

⇒ Insensitive to misalignment

- Small β value (deceleration mode)

⇒ Reduced Doppler uncertainty

HI JENA
Helmholtz Institute Jena

RR rate coefficients at electron cooler

RR rate coefficient:

$$\alpha_{n,l} = \langle v\sigma_{n,l}(v)\rangle = \int v\sigma_{n,l}(v) f(v) d^3v$$

Parameters setting:

- Projectile ions: Pb^{82+}
- Maximum main quantum number n=200.
- Free electron kinetic energy range for flattened velocity distribution integral: 1E-15 eV – 10 eV.
- Electron velocity distribution at an electron cooler:

$$f(\mathbf{v}) = \left(\frac{m_e}{2\pi}\right)^{3/2} \frac{1}{kT_\perp (kT_\parallel)^{1/2}} exp\left[-\left(\frac{m_e v_\perp^2}{2kT_\perp} + \frac{m_e v_\parallel^2}{2kT_\parallel}\right)\right]$$

- Transversal temperature: $kT_{||}$=2.59 meV
- Longitudinal temperature: $kT_\perp$=51.8 μeV

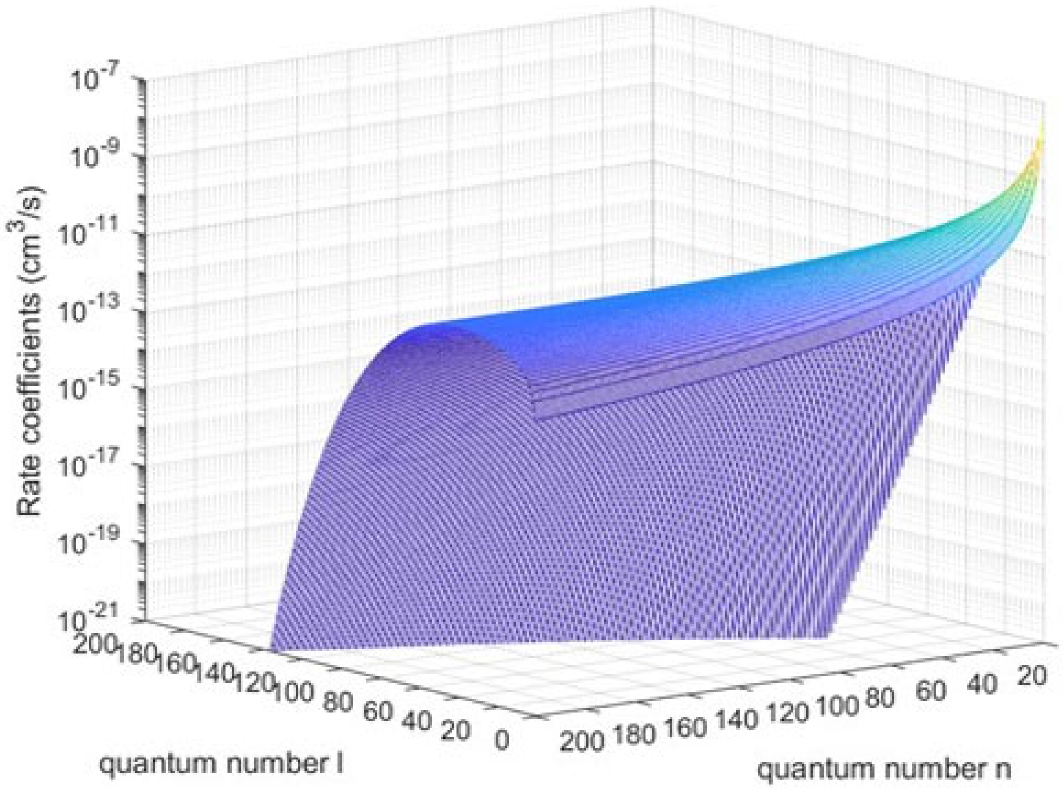
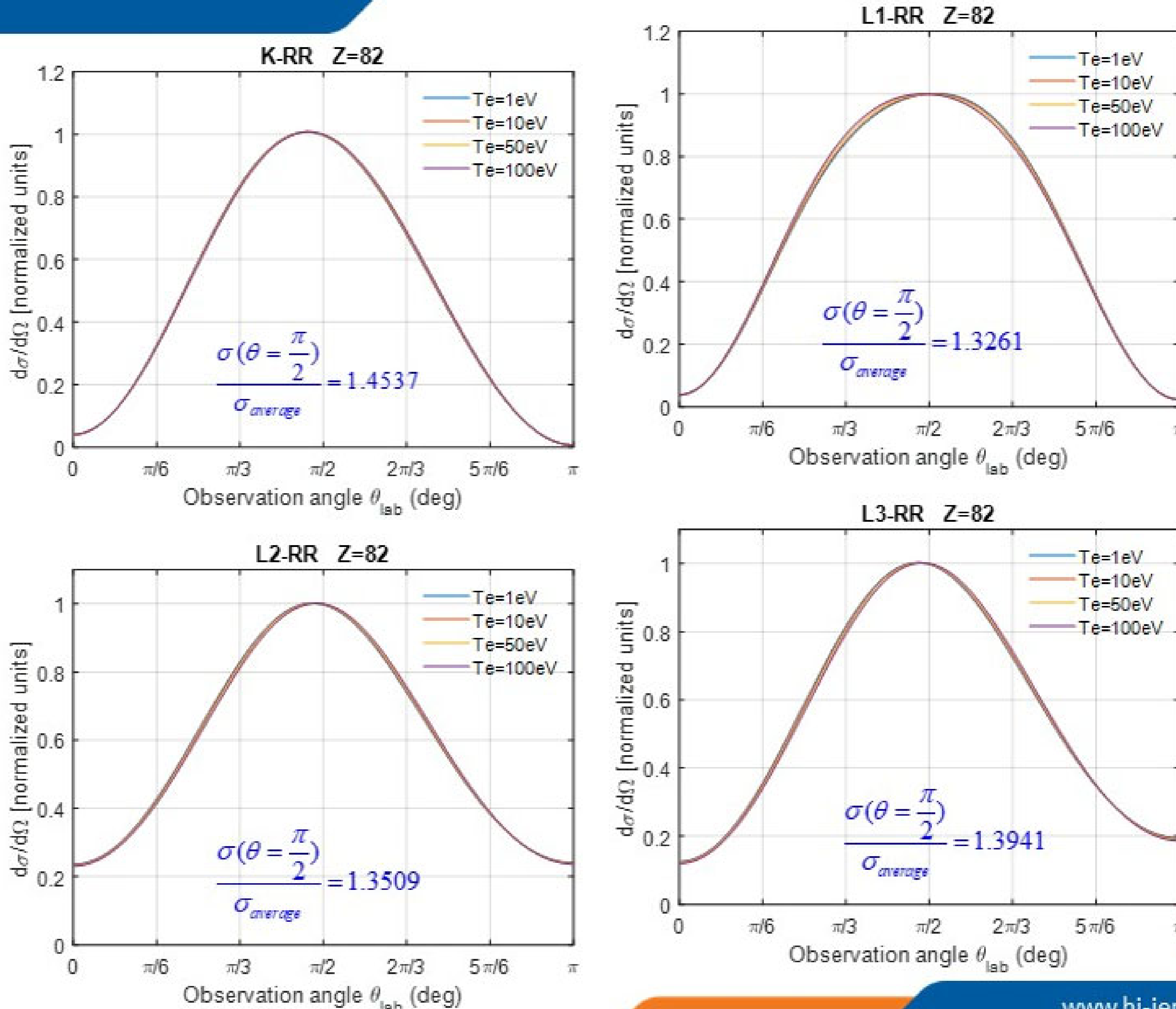


Figure: State selective *n,l* rate coefficients calculated for radiative recombination into bare Lead ions, with flattened free electron velocity distribution convolution.

HI JENA
Helmholtz Institute Jena

Angular distributions for K-RR and L-RR



HI JENA
Helmholtz Institute Jena

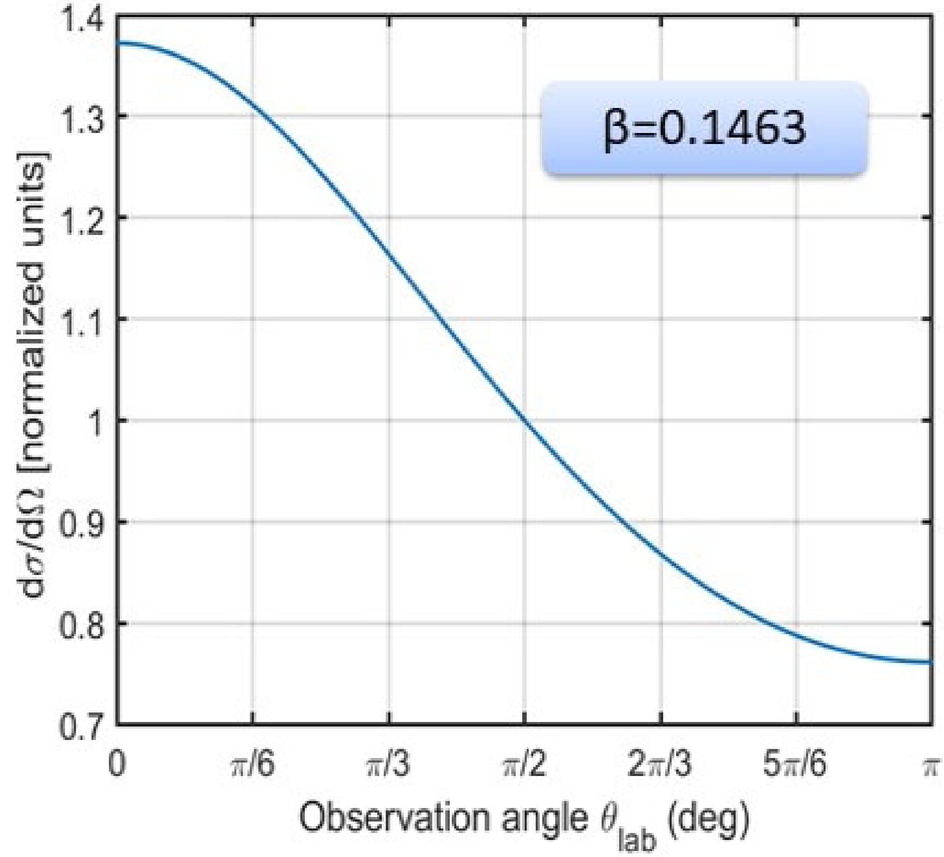
www.hi-jena.de

Angular distributions of Lyman Balmer at electron cooler

- Considering RR into highly excited Rydberg state, the effect of radiative cascade weakens the alignment of the low-lying intermediate states, e.g. $2P_{3/2}$.
- $\frac{d\sigma(\theta)}{d\Omega}$ is isotropic in the projectile frame.

Angular distribution transformed from the projectile to the laboratory system:

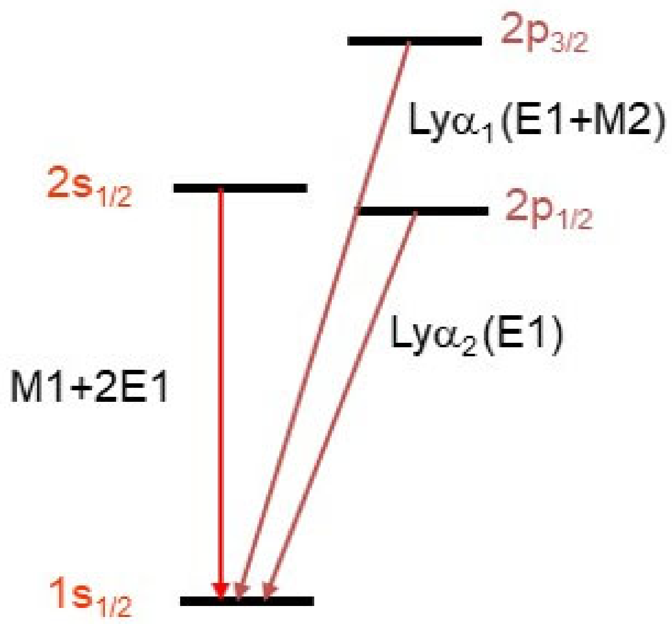
$$\frac{d\sigma(\theta_{lab})}{d\Omega_{lab}} = \frac{1}{\gamma^2(1-\beta\cos\theta_{lab})^2}\frac{d\sigma(\theta)}{d\Omega}$$

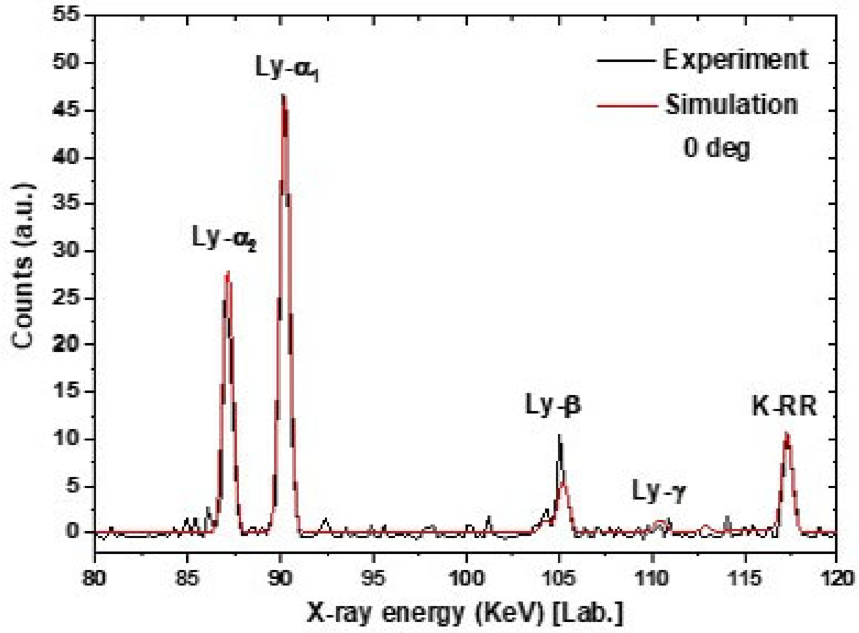


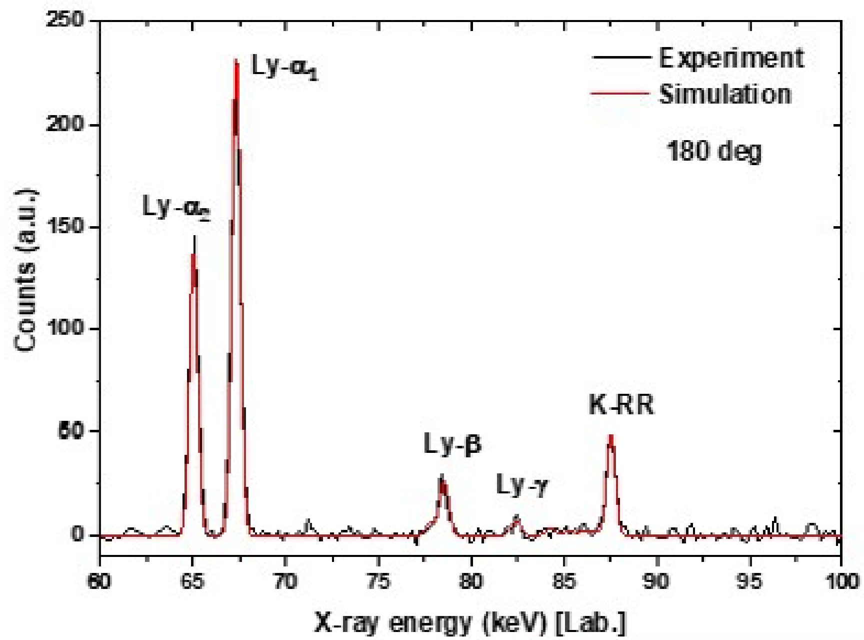
Hint: At electron cooler, we regard the direction of transversal electron beam as collisional axis, thus the radiative recombination events registered by Ge(i) detectors at angle at 0 deg and 180 deg would correspond to $\theta_{lab} = 90^o$ in laboratory frame, distinguished from the de-excitation processes.

HI JENA
Helmholtz Institute Jena

Lyman transitions in H-like lead at 10 MeV/u





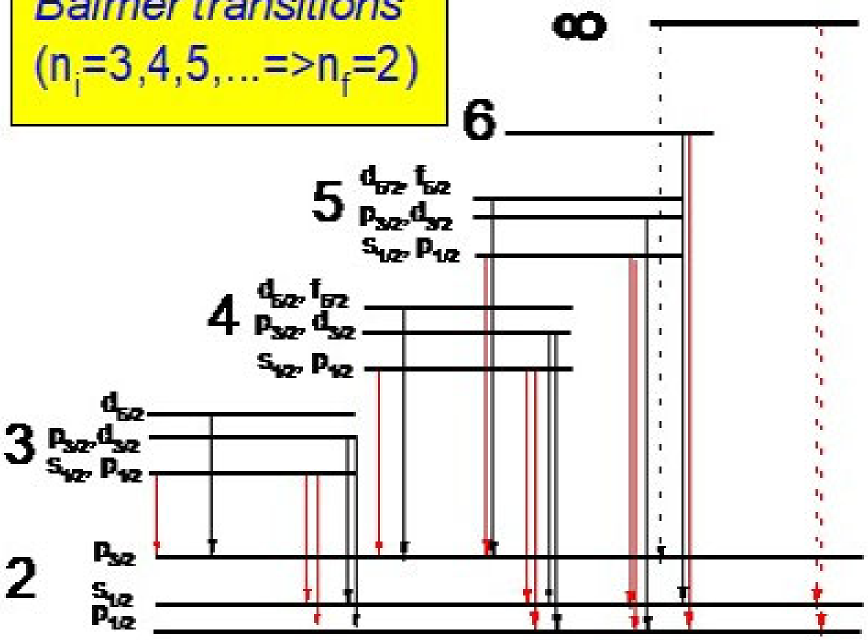


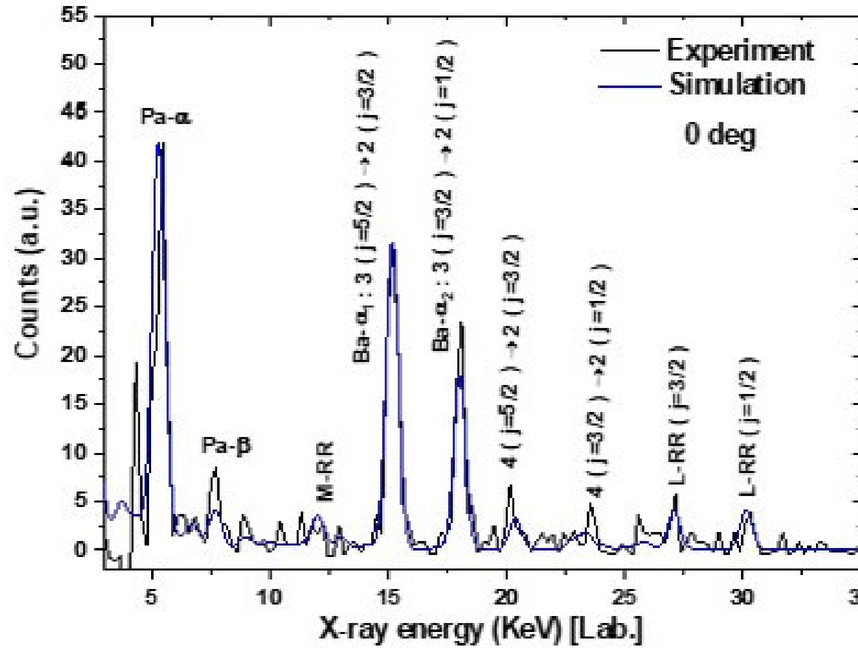
- Alignment effects are assumed to be absent for Lyman series.
- Angular distribution for K-RR is adjusted.

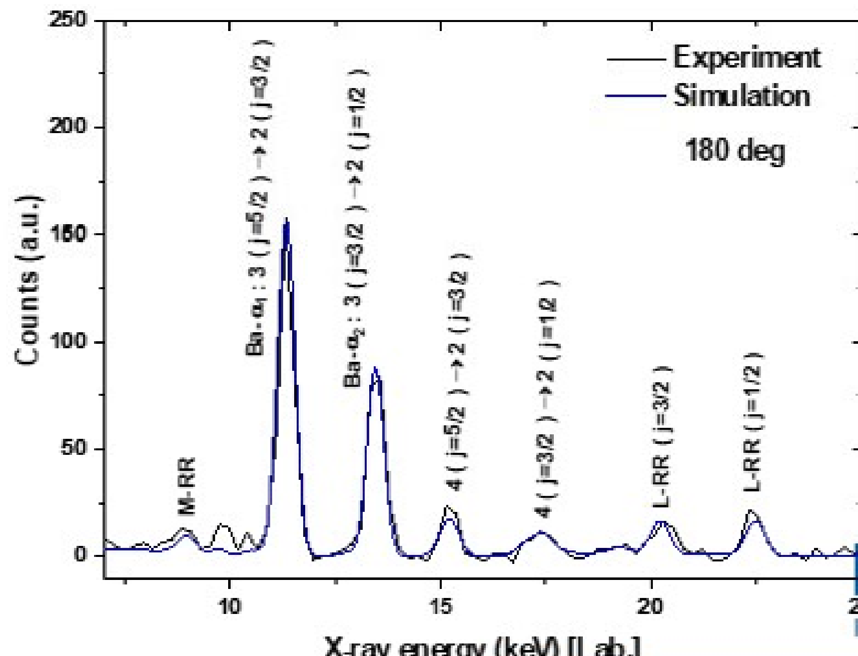
HI JENA
Helmholtz Institute Jena

Balmer and Paschen radiation in H-like lead at 10Mev/u: selective study

Balmer transitions
(n_i=3,4,5,...=>n_f=2)





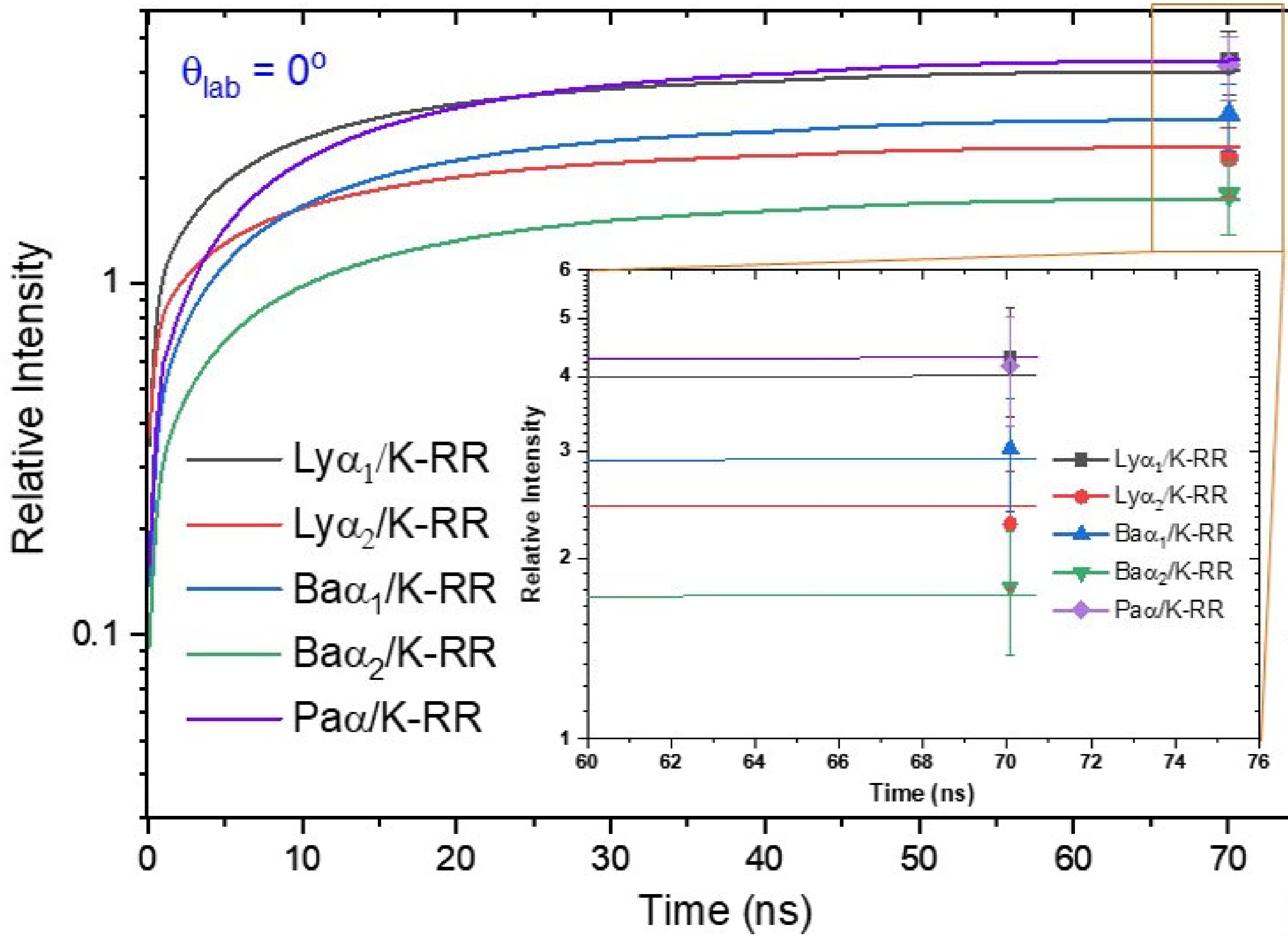


- Alignment effects are assumed to be absent for Balmer and Paschen series.
- Angular distribution for L-RR and M-RR are adjusted.

HI JENA
Helmholtz Institute Jena

www.hi-jena.de

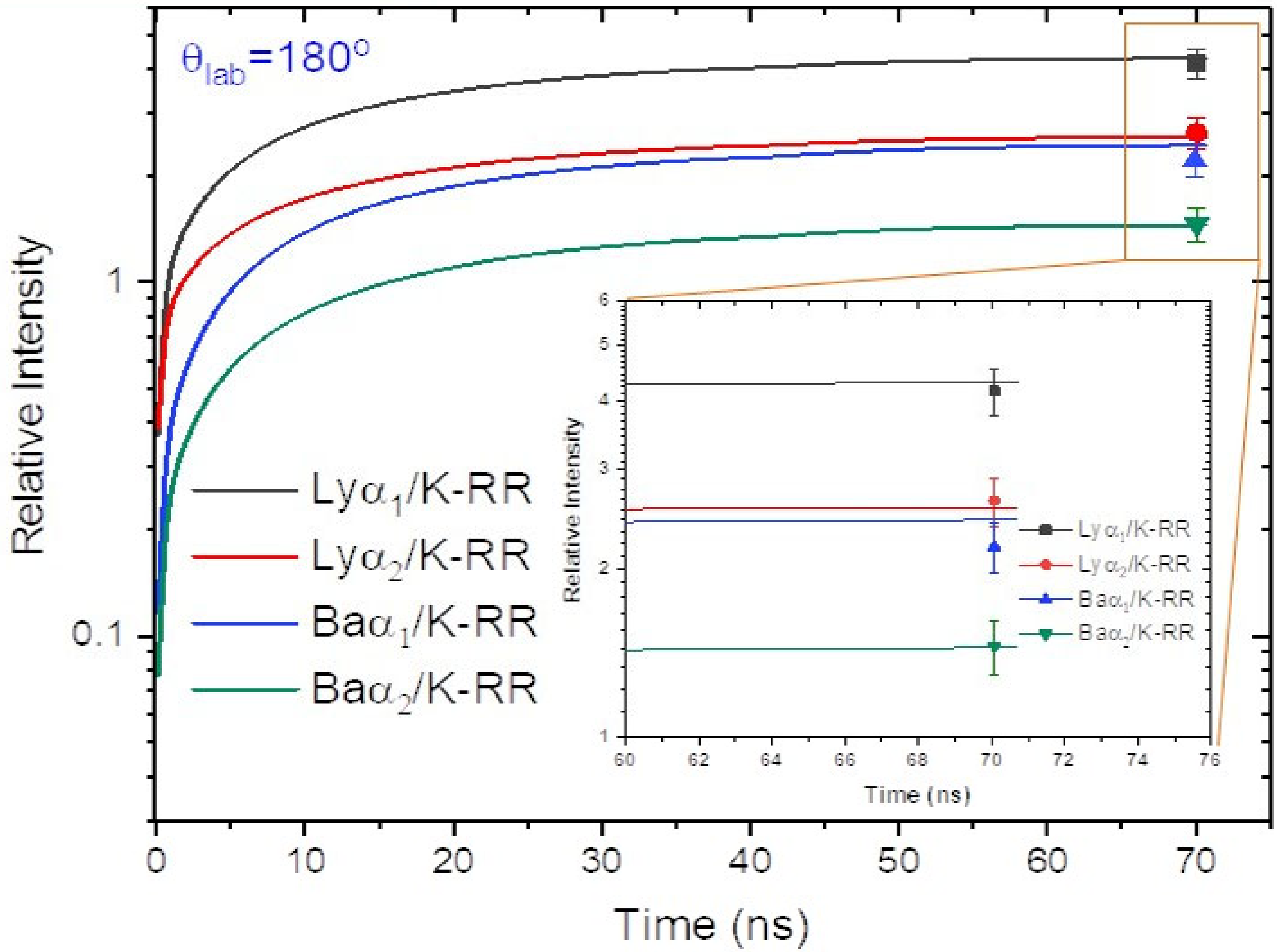
Intensity ratio as a function of time at 0 deg



Line intensities are normalized to K-RR population.

HI JENA
Helmholtz Institute Jena

Intensity ratio as a function of time at 180 deg



Prompt RR populations were estimated to contribute no more than 10% to the observed characteristic line intensities.

HI JENA
Helmholtz Institute Jena

Summary/Conclusion

- Storing and cooling of highly charged ions delivers brilliant beams for experiments.
- Efficient production of characteristic X-rays is achieved by deceleration of the ions.
- Good agreement between measured line intensities and cascade simulation on the basis of rigorous relativistic calculations.
- Cascade decay dynamics was revealed by the characteristic line intensities as a function of time.

HI JENA
Helmholtz Institute Jena

X-ray Emission of H-like Lead Observed at the Electron Cooler of CRYRING@ESR

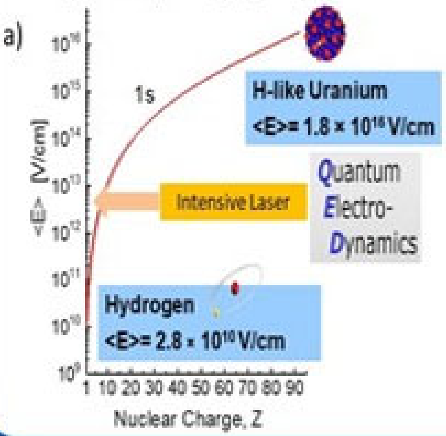
B. Zhu[1,2,4], G. Weber[2,3], T. Over[1], Z. Andelkovic[3], R. Chen[3], D. Dmytriiev[3], O. Forstner[1,2,3], A. Gumberidze[3], C. Hahn[1,2,3], M. O. Herdrich[1,2,3], P. M. Hillenbrand[3], A. Kalinin[2], Th. Köhler[1], F. M. Kröger[1,2], M. Lestinsky[3], Y. A. Litvinov[3], E. Menz[1,2,3], T. Morgenroth[3], N. Petridis[3], F. Herfurth[3], Ph. Pfäfflein[1,2,3], M. S. Sanjari[3], R. S. Sidhu[3], U. Spillmann[3], S. Trotsenko[2,3], L. Varga[3], G. Vorobyev[3], and Th. Stöhlker[1,2,3]

[1]Institut für Optik und Quantenelektronik, University of Jena, Jena, Germany
[2]Helmholtz-Institut Jena, Jena, Germany
[3]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[4]School of nuclear science and technology, Lanzhou University, Lanzhou, China

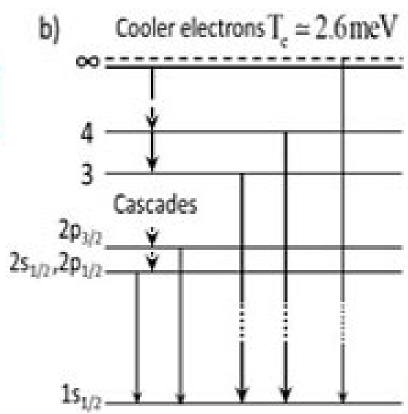
Introduction

- For H-like systems at high-Z, recombination of a free electron with a bare ion, provides a unique opportunity to probe bound-state QED in extreme Coulomb fields [1].
- The radiative recombination (RR) process [2] at "cold" temperature condition occurs at the electron cooler, leading to the population of excited ionic states. The observation of the subsequent X-ray emission enables the investigation of prevailing cascade decay dynamics up to high Rydberg states.

a)

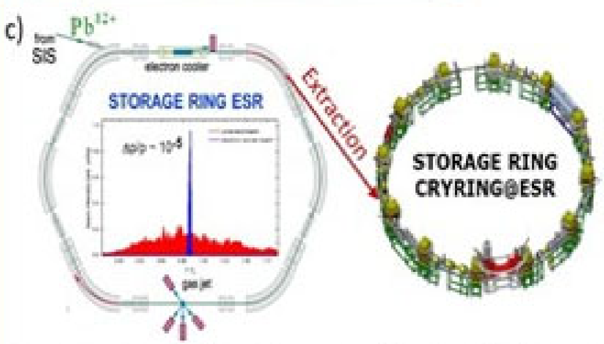


b)



Experimental environment

c)



SIS18 400 Mev/u

Pb^{82+} ESR — Stochastic cooling, Electron cooling

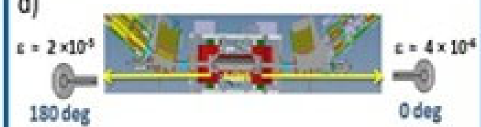
Deceleration to 10 MeV/u

CRYRING@ESR — Electron cooling and storing

For the experiment, bare Pb ions were decelerated in the ESR to the energy of 10 MeV/u and injected into the CRYRING@ESR.

Experimental setup

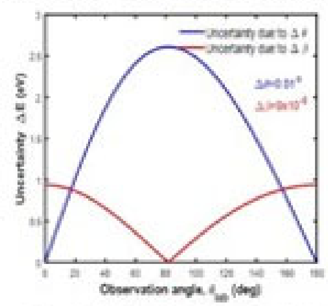
d)



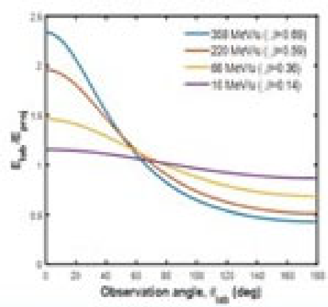
Be windows installed at two viewports ensure high transmission of the low energy photons first ever recorded at an electron cooler.

- X-ray detectors placed at 0° and 180° observation angles at electron cooler of CRYRING@ESR
  ⇒ Insensitive to misalignment (compare fig. e and f)
- Small β value (deceleration mode)
  ⇒ Reduced Doppler uncertainty (fig. f)

e)

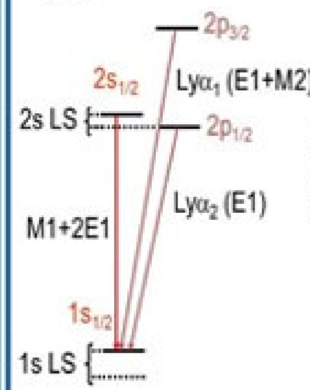


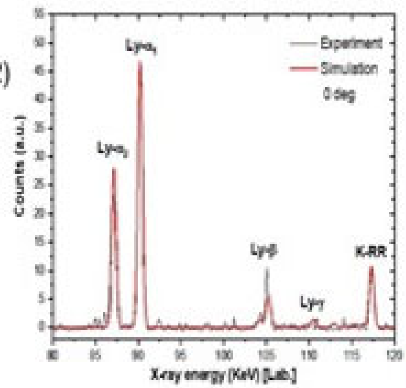
f)



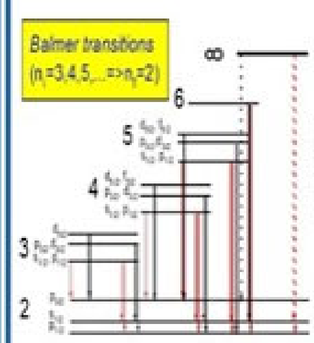
Preliminary results

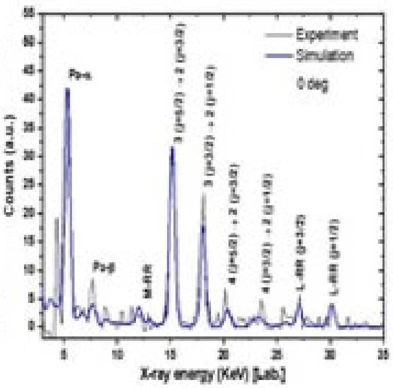
g) Lyman transitions in H-like lead at 10 MeV/u





h) Balmer and Paschen radiation: state selective study





The preliminary X-ray spectrum associated with RR, consisting of de-excitation radiation are compared with simulated spectral line profiles, considering recombination into excited projectile states up to n=165.

Reference:

[1] Th. Stöhlker *et al.*, "Test of strong field QED". In: *The physics of multiply and highly charged ions*. Springer, 2003, pp. 351-386.
[2] J. Eichler and Th. Stöhlker, *Phys. Rep.* **439**, 1 (2007)

Sponsored by the Federal Ministry of Education and Research

HI JENA
Helmholtz Institute Jena