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

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1. Introduction

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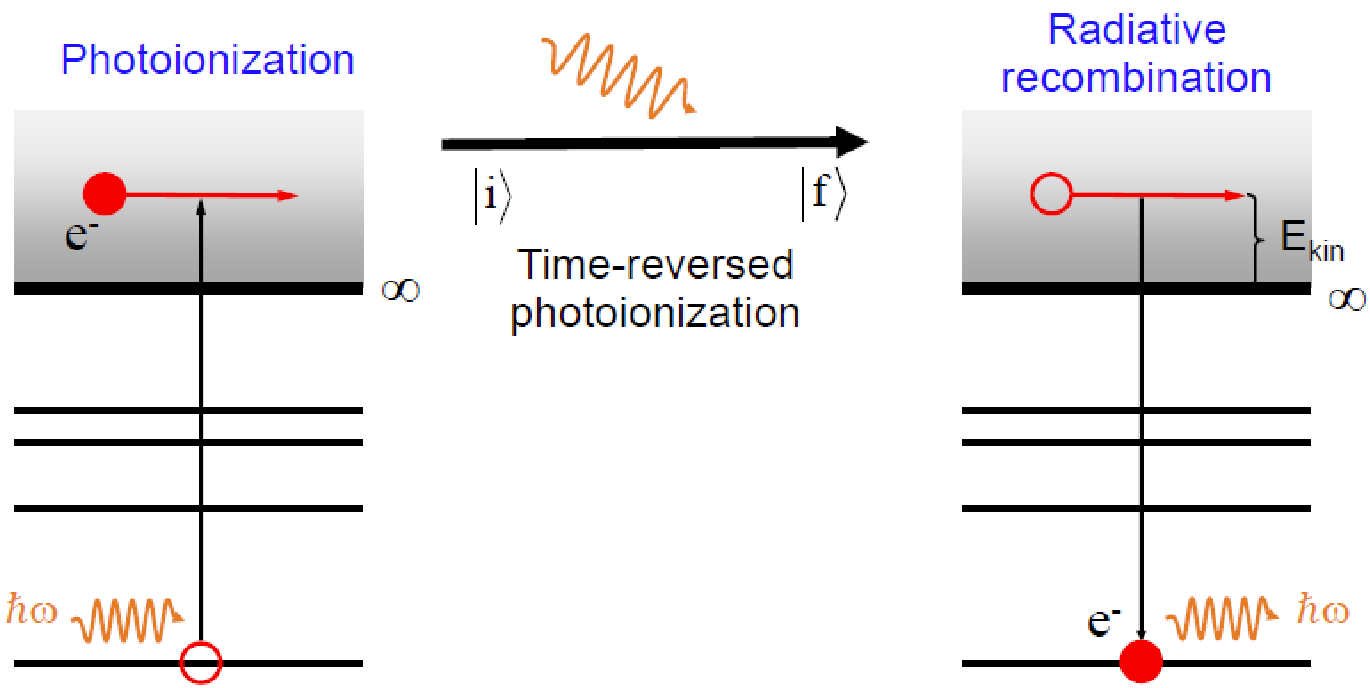
Radiative recombination (RR)



- 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.

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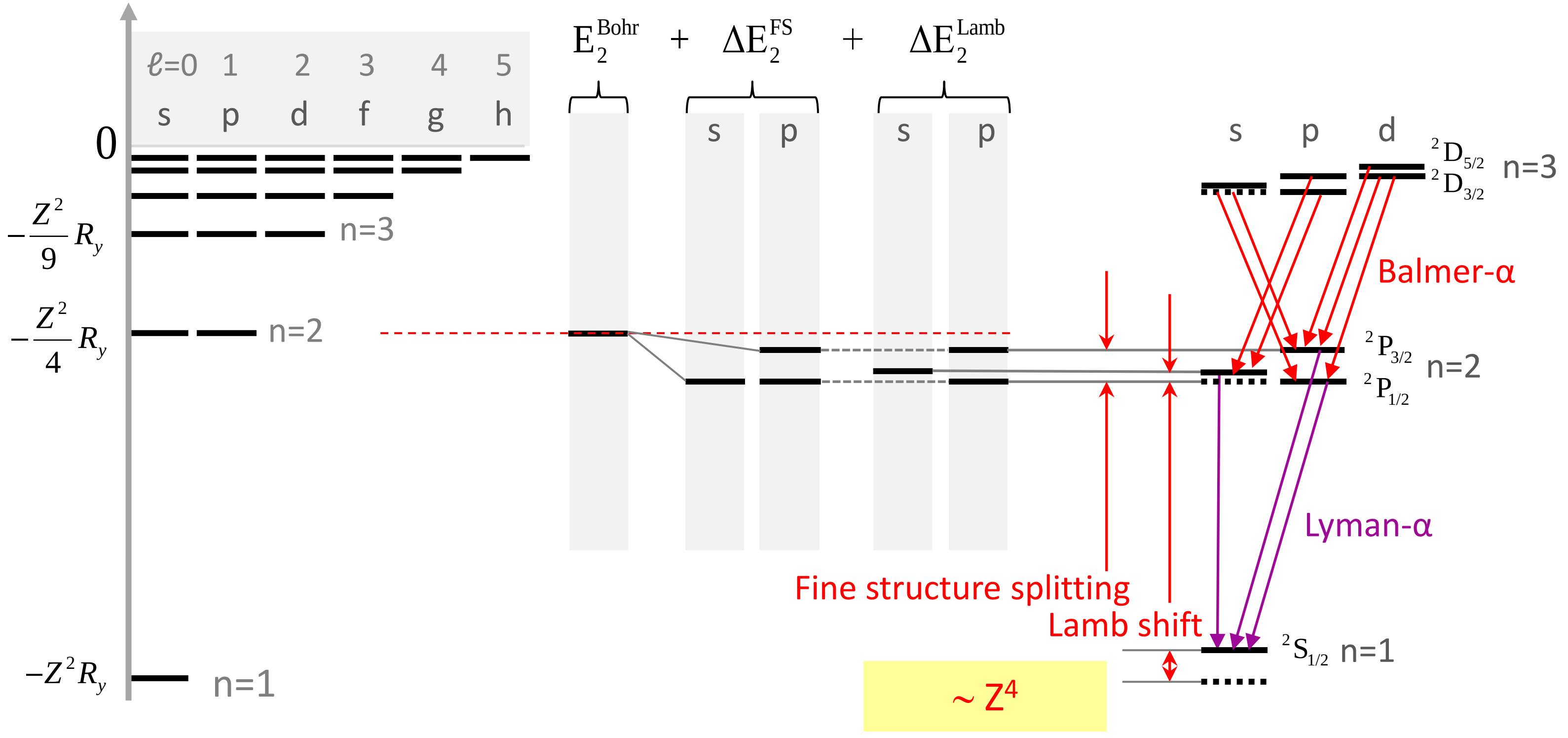
The structure of one-electron system: energy level



Fine structure shift: $\Delta E_{n,j} = -E_n \frac{Z^2\alpha^2}{n^2}\left(\frac{3}{4} - \frac{n}{j+1/2}\right)$

Lamb shift: $\Delta E = \frac{\alpha}{\pi}\frac{(Z\alpha)^4}{n^3}F(Z\alpha)m_e c^2$

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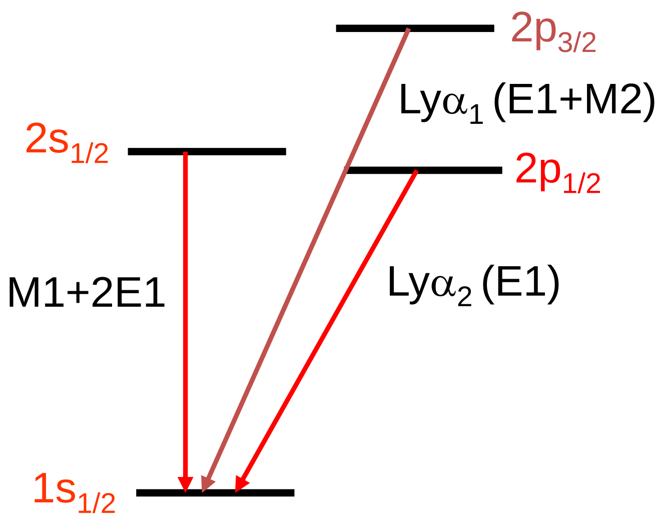
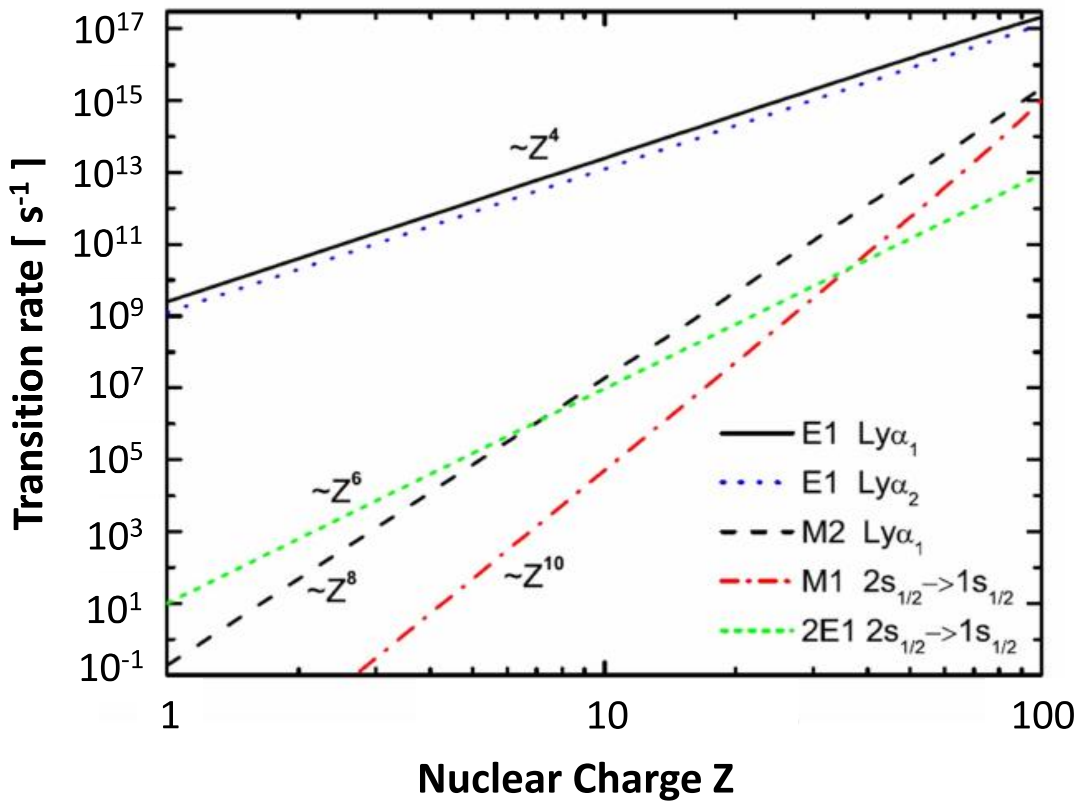
The structure of one-electron system: transition rate



Jitrik and Bunge., *Phys. Scr.* 69, 196 (2004)



- The transitions rates of Γ_{M1} and Γ_{2E1} for $2s_{1/2} \rightarrow 1s$ are enhanced by 2-6 orders of magnitude as compared to Γ_{E1} of $2p_{1/2} \rightarrow 1s$.
- $\Gamma_{M1}/\ \Gamma_{2E1}$ scales approximately as Z^2, and M1 represent the main contribution to the radiative decay of 2s state at high Z.

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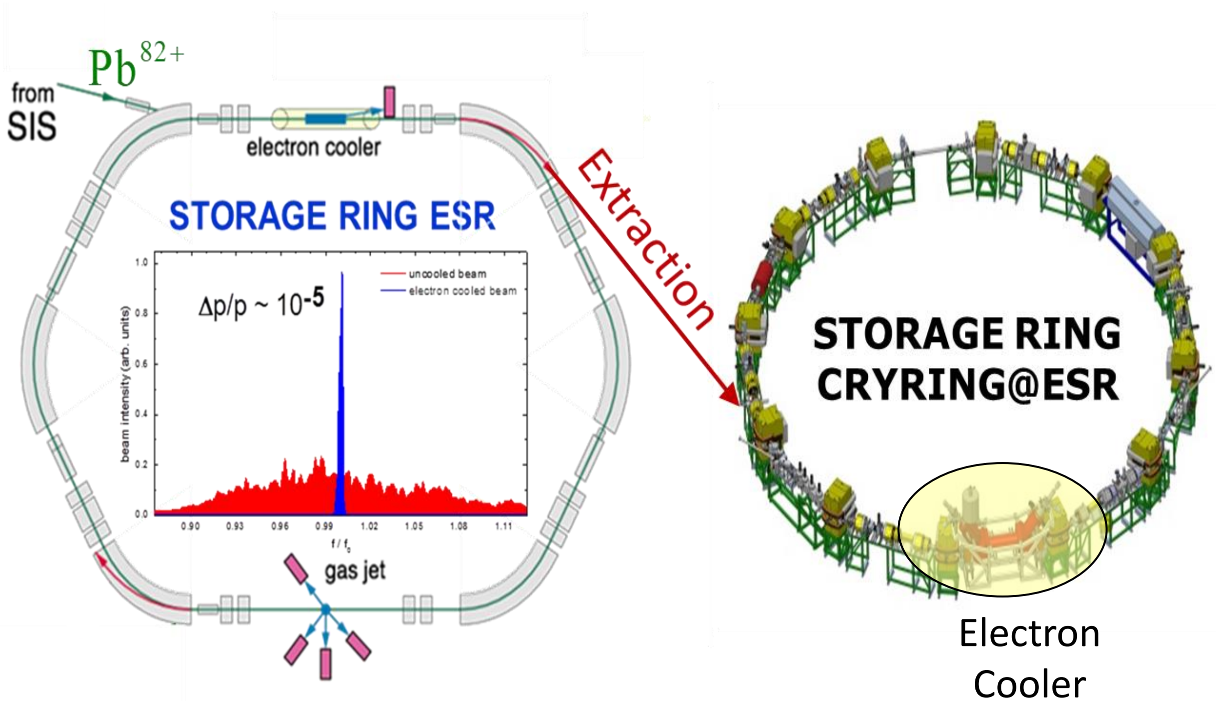
2. Experiment

Experimental environment at GSI



UNILAC
↓ 11 MeV/u Stripping
SIS18
↓ 400 MeV/u Stripping
ESR — Stochastic cooling, Electron cooling
↓ Deceleration to 10 MeV/u
CRYRING — Electron cooling and storing

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

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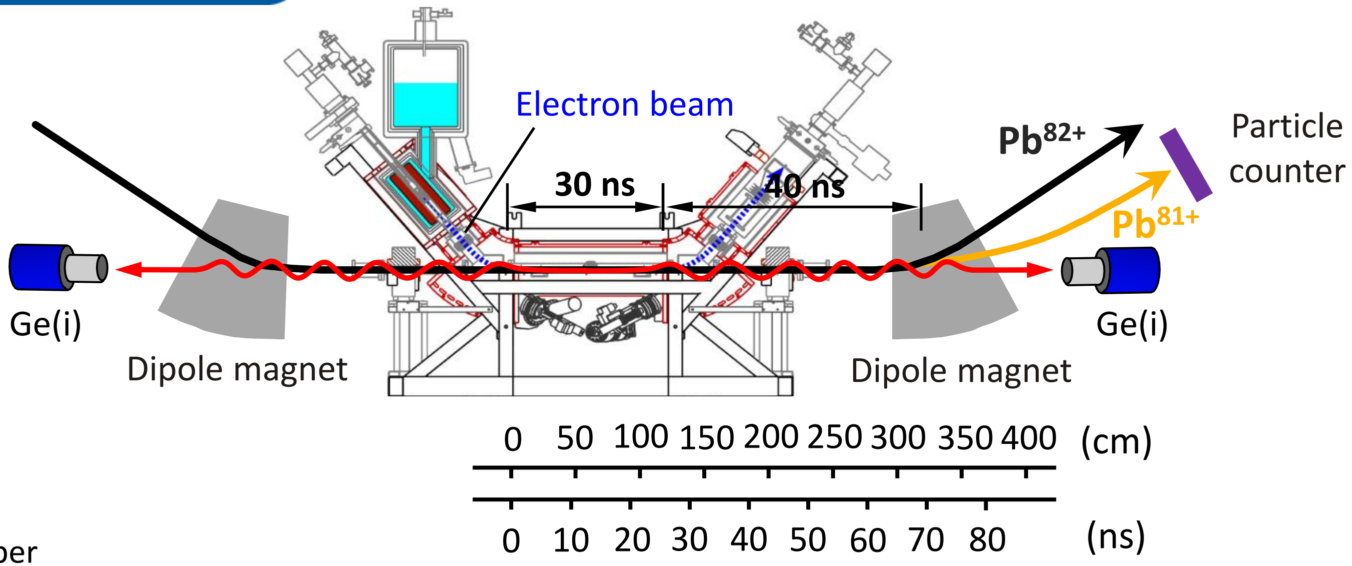
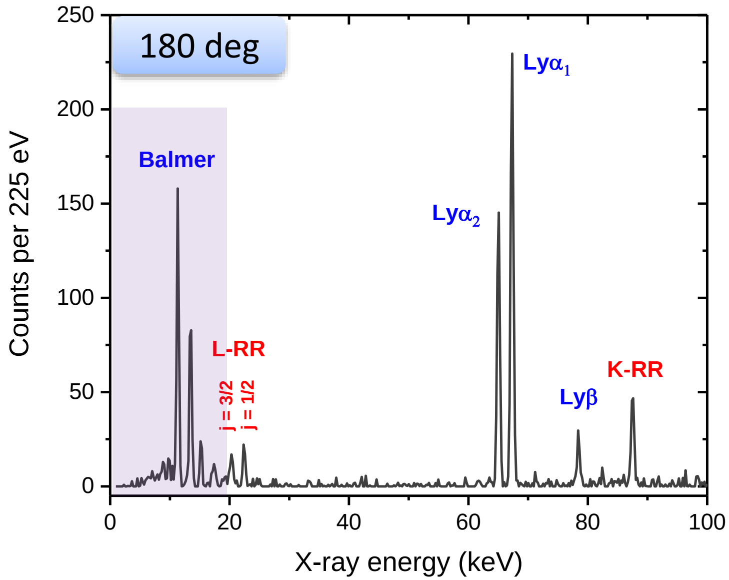
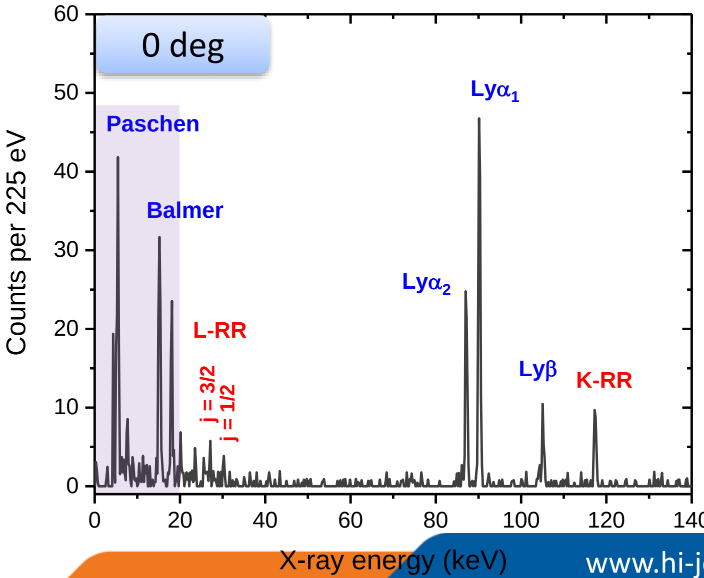
Experimental setup at the electron cooler

New x-ray viewport
Beryllium window chamber







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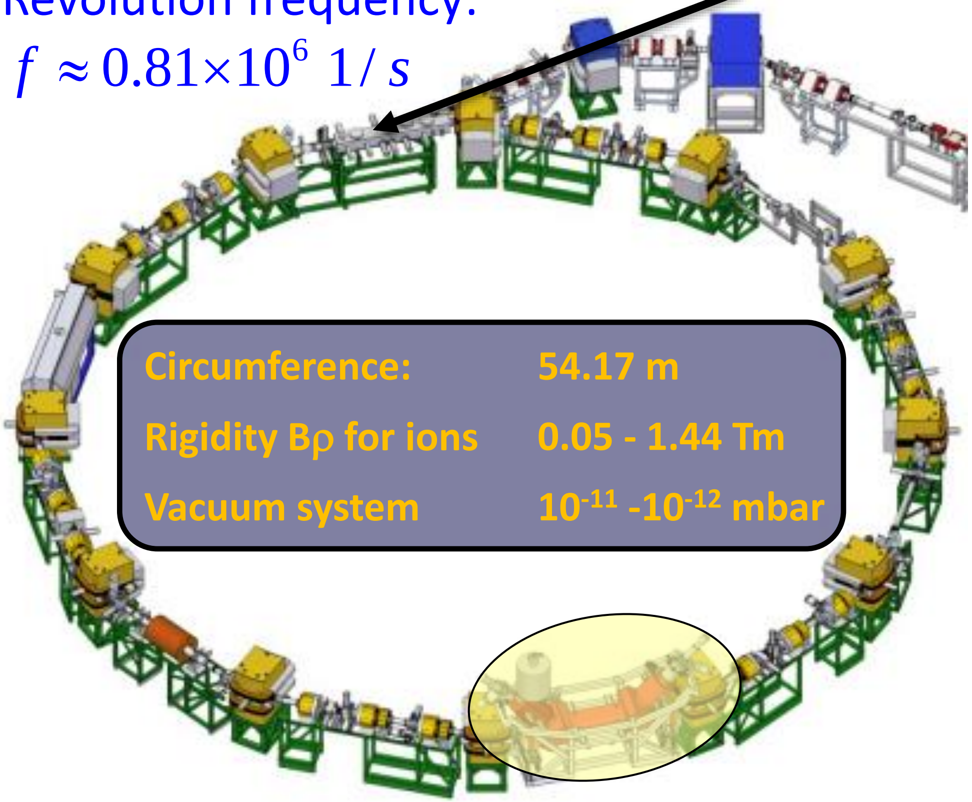
Field ionization effect in magnetic fields

Revolution frequency:
$f \approx 0.81\times10^{6}\ 1/s$

Pb^{82+} @10MeV/u



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

Charge state of Pb^{81+} : $q = 81$

Reduced velocity: $\beta = \frac{v}{c} = 0.14$

Dipole magnet radius: $\rho = 1.2\,\mathrm{m}$

Magnetic field: $B = \frac{m\cdot v}{q\cdot\rho} = 0.98\ \mathrm{T}$

Field ionization limit n_{dip} derived from the empirical formula:

$$n_{dip} = \left(6.2\times10^{10} q^{3} / v\cdot B\right)^{1/4}$$
$$\approx 165$$

Zong *et al., J. Phys. B.* 31, 3729 (1998)

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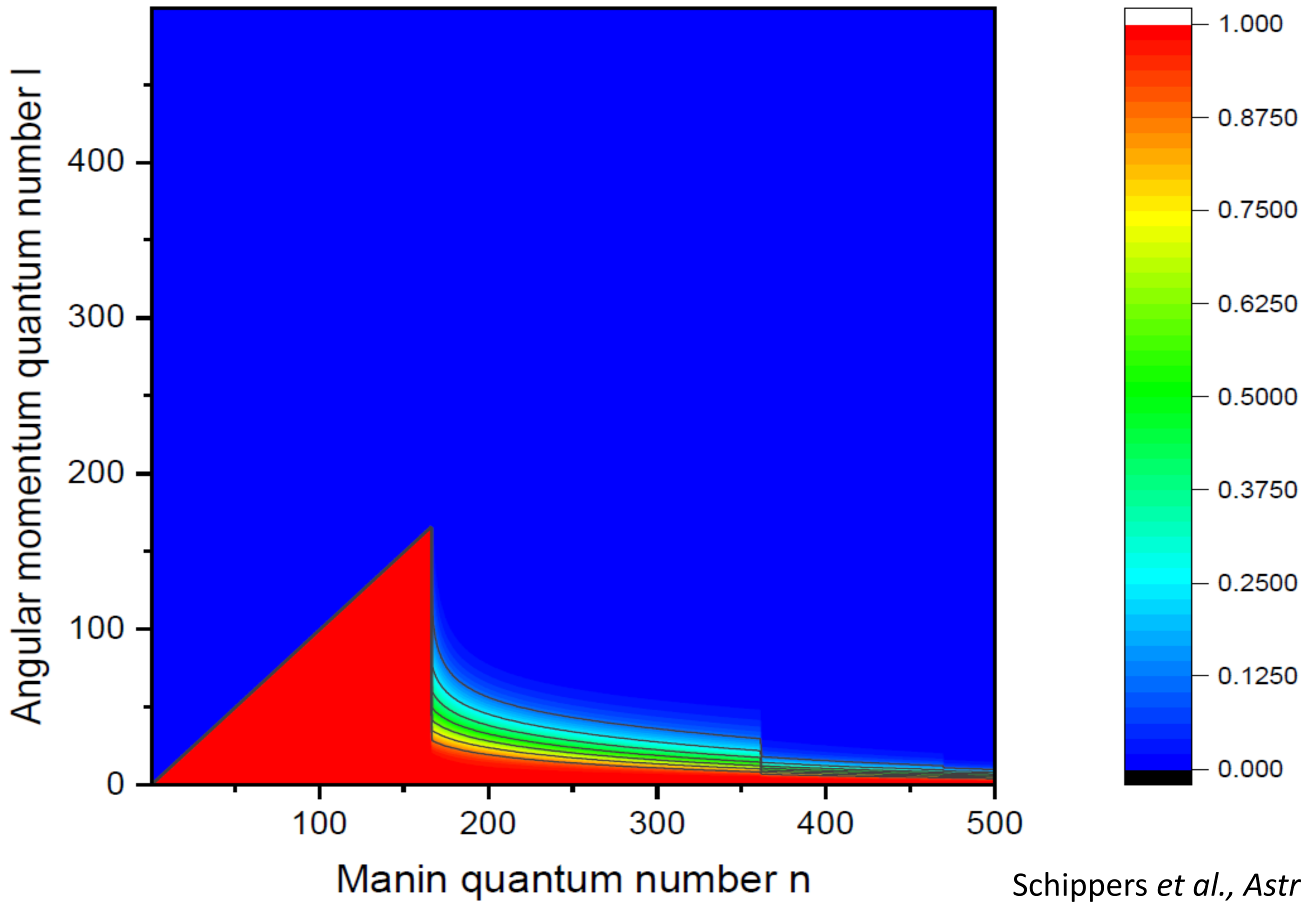
Field ionization effect in magnetic fields



Schippers *et al.*, *Astrophys. J.* 555, 1027 (2001)
Böhm et al., *Phys. Rev. A* 65, 052728 (2002)

Rydberg states with even higher n but low l are typically not field ionized in magnetic fields, and contribute via fast radiative cascades.

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3. Theory

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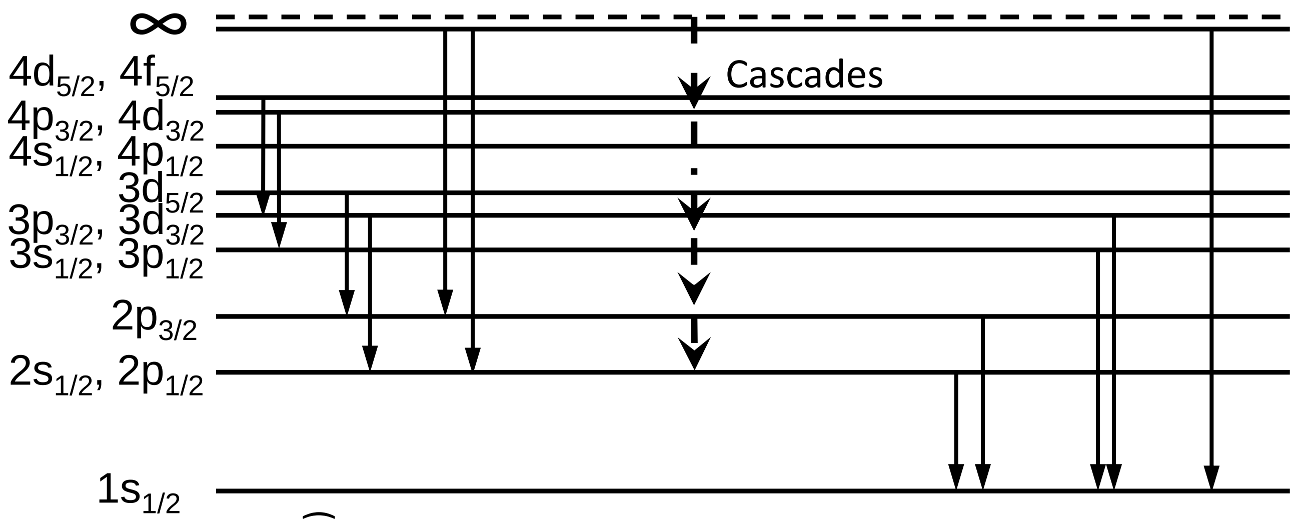
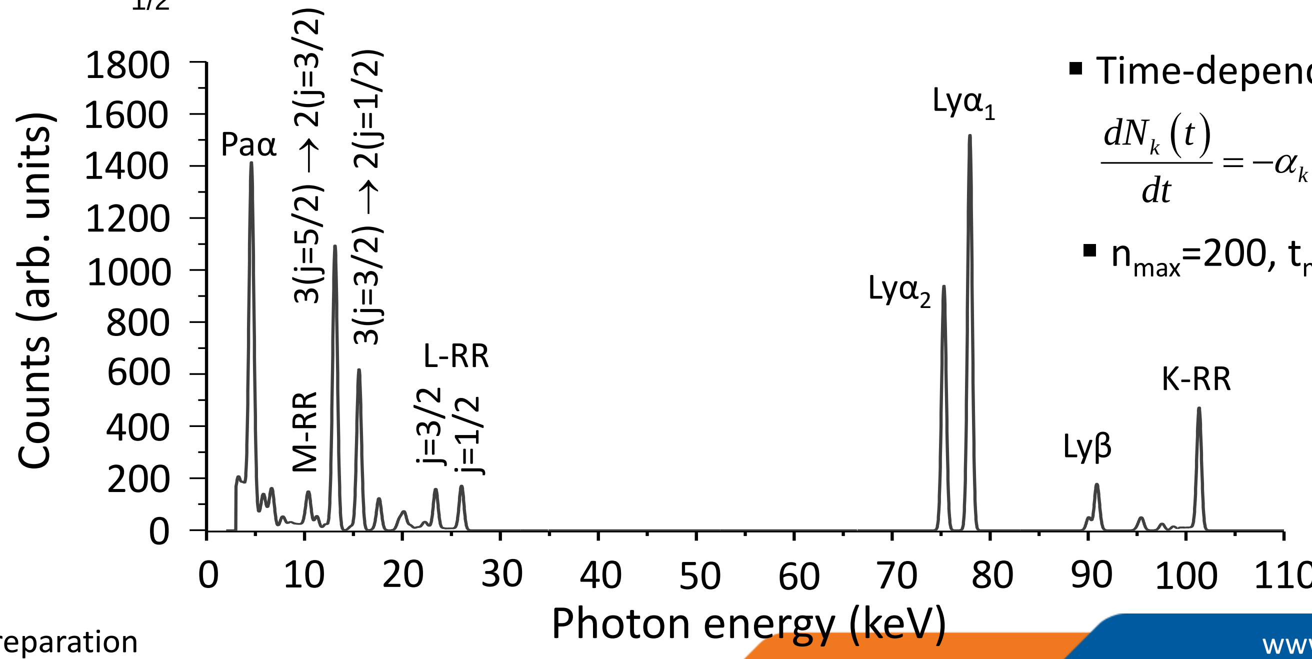
Simulation of radiative cascades





- Time-dependent rate equation:

$$\frac{dN_k(t)}{dt} = -\alpha_k N_k(t) + \sum_{m(>k)} \Gamma_{m \to k} N_m(t)$$

- n_{max}=200, t_{max}=70 ns

Zhu *et al.*, in preparation

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Atomic structure calculations: FAC code

M. F. Gu, *Can. J. Phys.* 86**,** 675 (2008)

- The atomic structure calculations are based on the relativistic configuration interaction with independent particle basis wavefunctions.
- The basis wavefunctions are derived from a local central potential, which is self-consistently determined to represent electronic screening of the nuclear potential.
- Relativistic effects are fully taken into account using the Dirac Coulomb Hamiltonian.
- Higher order QED effects are included: self-energy, finite nuclear size and vacuum polarization effects.
- Fast and reasonable accurate.

For hydrogen-like lead:

- $\sim 10^{-4}$ in level energies as compared to the results from Yerokhin and Shabaev [1].
- The transition rates are accurate to 99% when compared with tabulated data from Pal'chikov [2].

[1] Yerokhin and Shabaev, *J. Phys. Chem. Ref. Data* 44**,** 033103 (2015)
[2] Pal'chikov, *Phys. Scr*. 57, 581 (1998)

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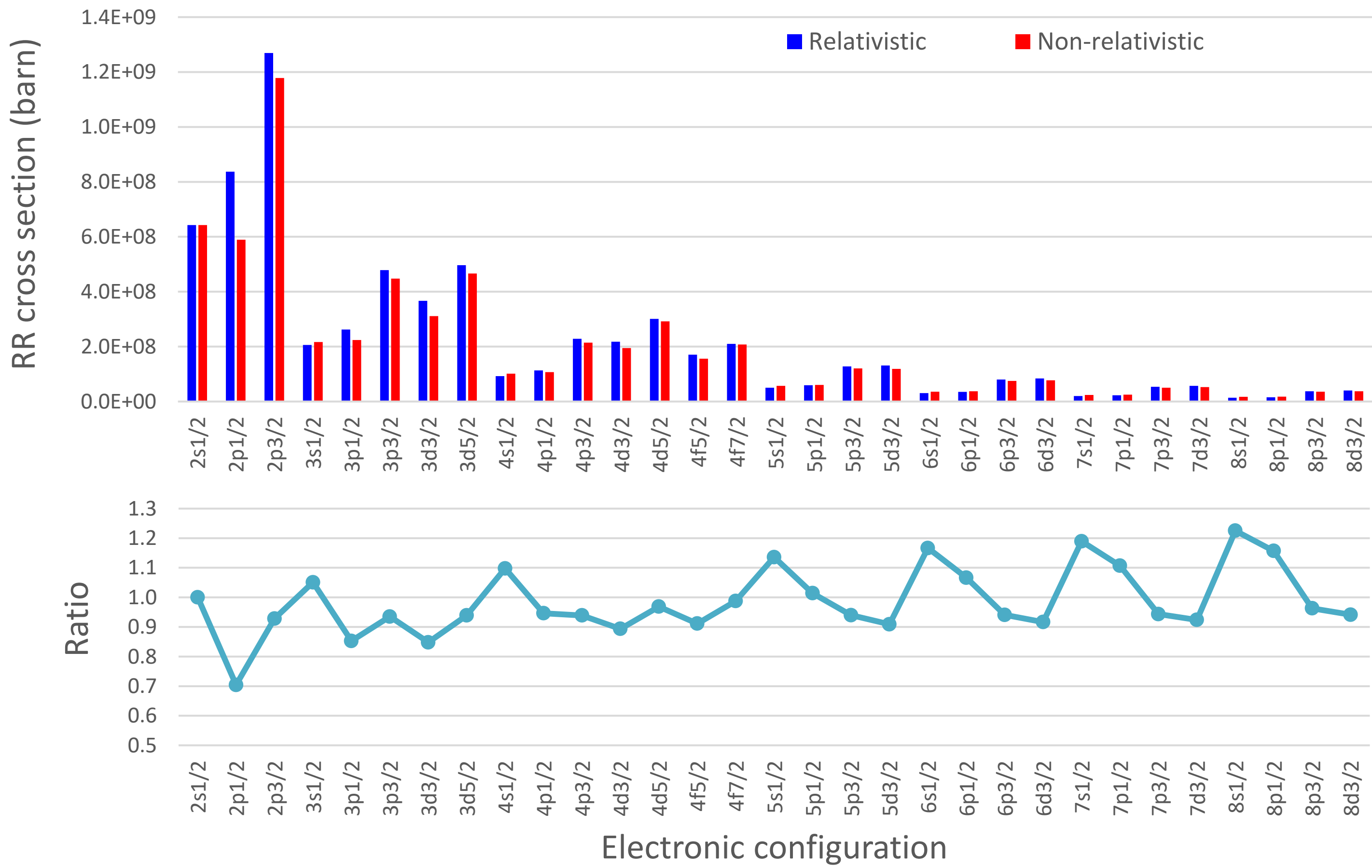
RR cross sections: nonrelativistic versus relativistic theory

Parameters setting:

- Nuclear charge Z: 82
- Electron-ion collision energy: 2.6 meV



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Burgess, *Mem. R. Astron. Soc.* 69, 1 (1965)
Ichihara and Eichler, *At. Data Nucl. Data Tables* 74, 1 (2000)

RR rate coefficients at the electron cooler

Parameters setting:

- Projectile ions: Pb^{82+}
- Maximum main quantum number n=200.
- Electron velocity distribution at an electron cooler:

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

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

RR rate coefficient:

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

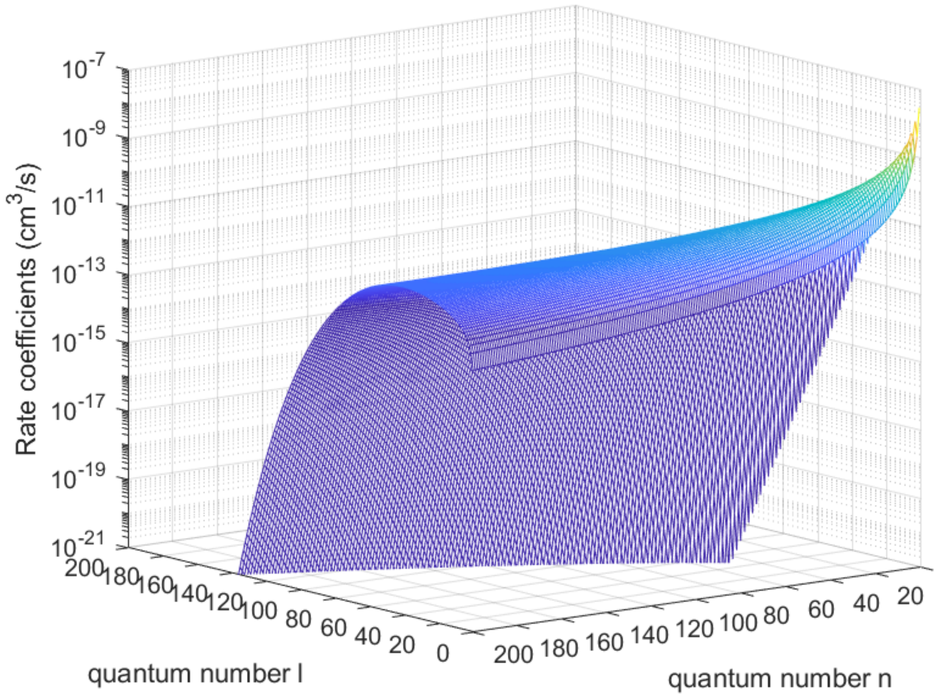

Figure: State-selective (n,l) rate coefficients calculated for radiative recombination into bare lead ions, with flattened free electron velocity distribution convolution.

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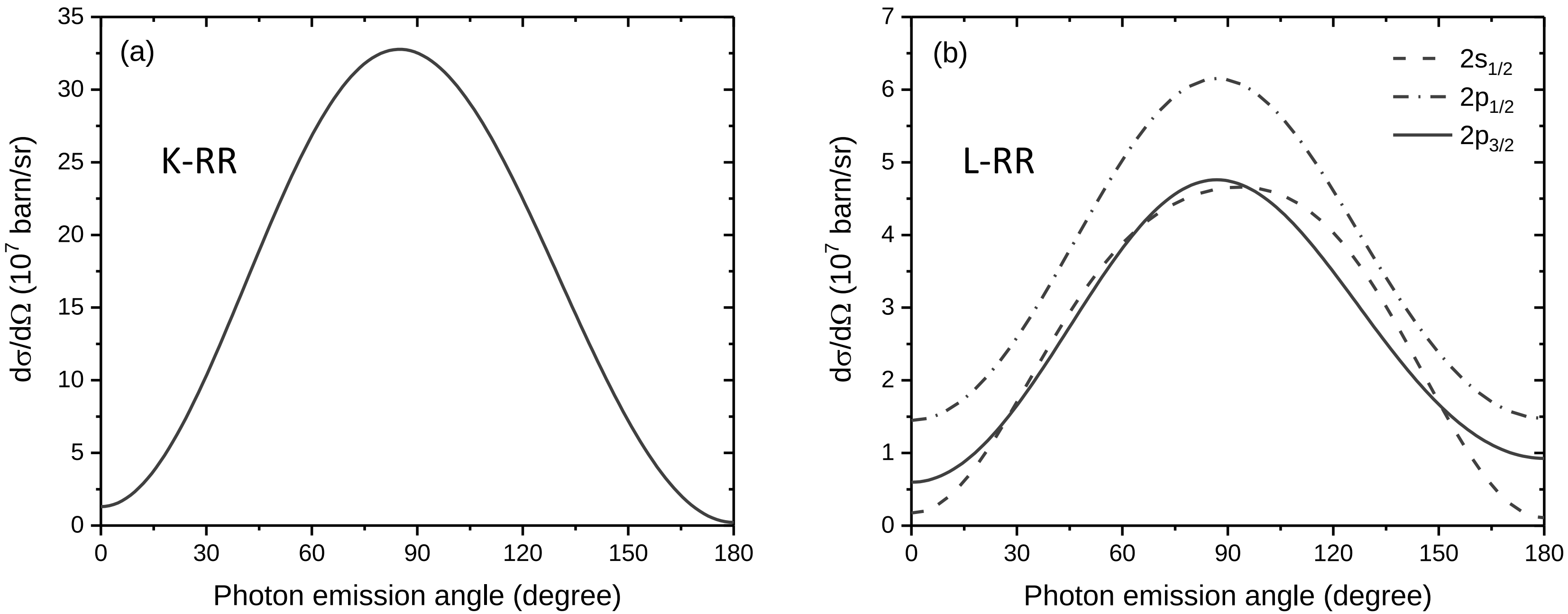
Angular Distributions

- K-RR and L-RR

Eichler and Stöhlker, *Phys. Rep.* 439, 1 (2007)



Hint: At electron cooler, we regard the direction of transverse electron beam as collisional axis ($kT_{\perp} >> kT_{||}$), thus the radiative recombination events registered by Ge(i) detectors at angle at 0 deg and 180 deg would correspond to $\theta_{lab} = 90^{\circ}$ in laboratory frame.

- Characteristic x-rays

Recombination into high Rydberg states and following radiative cascades will substantially attenuate any potential initial alignment of excited states produced via RR, as a consequence, an isotropic emission pattern in the projectile frame for subsequent characteristic projectile transitions is expected.

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

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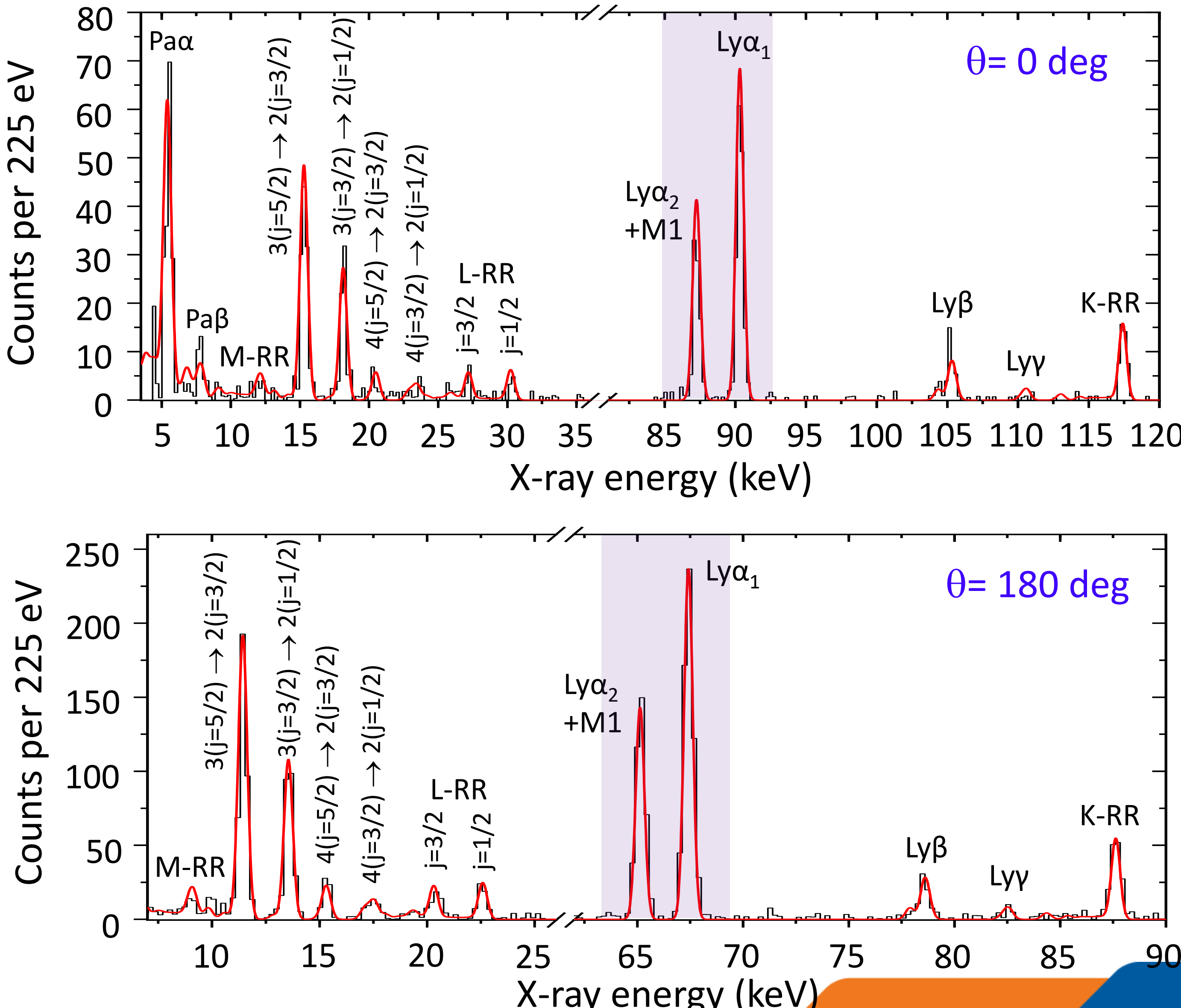
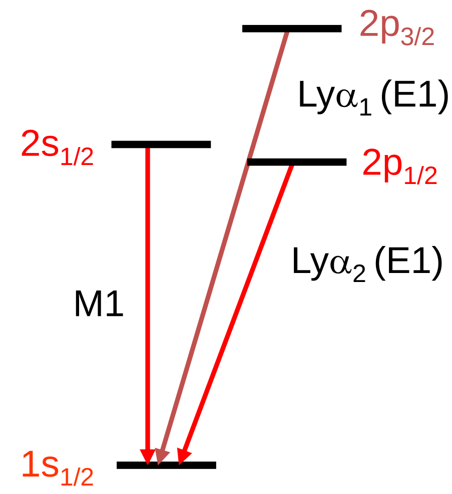
4. Results and discussions

Experimental results and comparison with theory

Zhu *et al.*, *Phys. Rev. A* 105, 052804 (2022)





- $2s_{1/2} \rightarrow 1s_{1/2}$:
  $\Gamma_{M1}= 5.32 \times 10^{13}\ s^{-1}$
- $2p_{1/2} \rightarrow 1s_{1/2}$:
  $\Gamma_{E1}= 2.93 \times 10^{16}\ s^{-1}$
- $2p_{3/2} \rightarrow 1s_{1/2}$:
  $\Gamma_{E1}= 2.57 \times 10^{16}\ s^{-1}$

Experimental results and comparison with theory

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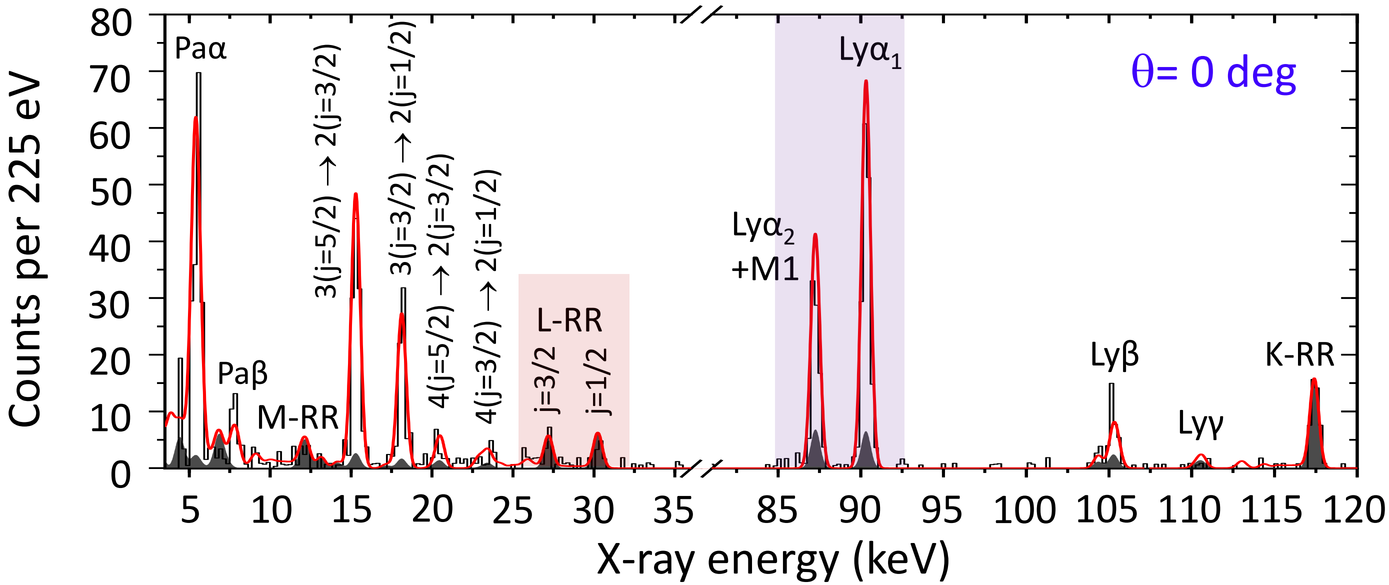

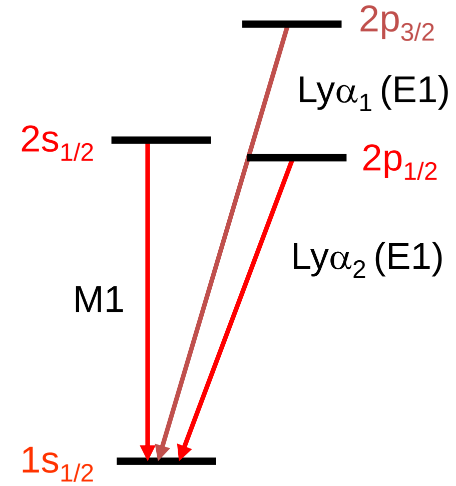

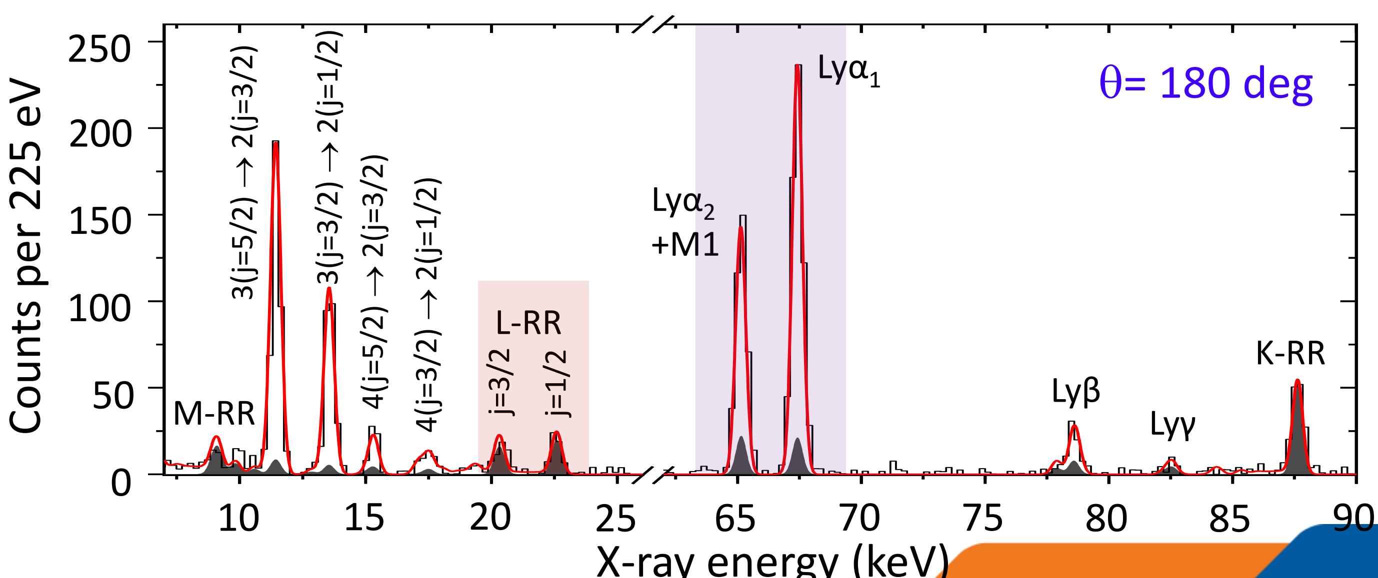

- $2s_{1/2} \to 1s_{1/2}$:
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Experimental results and comparison with theory

Table: Contribution from feeding cascades to the intensity of Lyman-α_1 and Lyman-α_2 lines. Uncertainties shown here are due to counting statistics whereas systematic uncertainties are neglected.

Characteristic x-rays	0 deg.	180 deg.	Theory
Lyα_1	$93.6\% \pm 12.0\%$	$94.0\% \pm 5.5\%$	93.9%
Lyα_2	$86.3\% \pm 15.6\%$	$87.4\% \pm 6.5\%$	86.8%

More than 90% from feeding cascades contribute to the intensities of Lyman-α radiation.

Zhu *et al.,* in preparation

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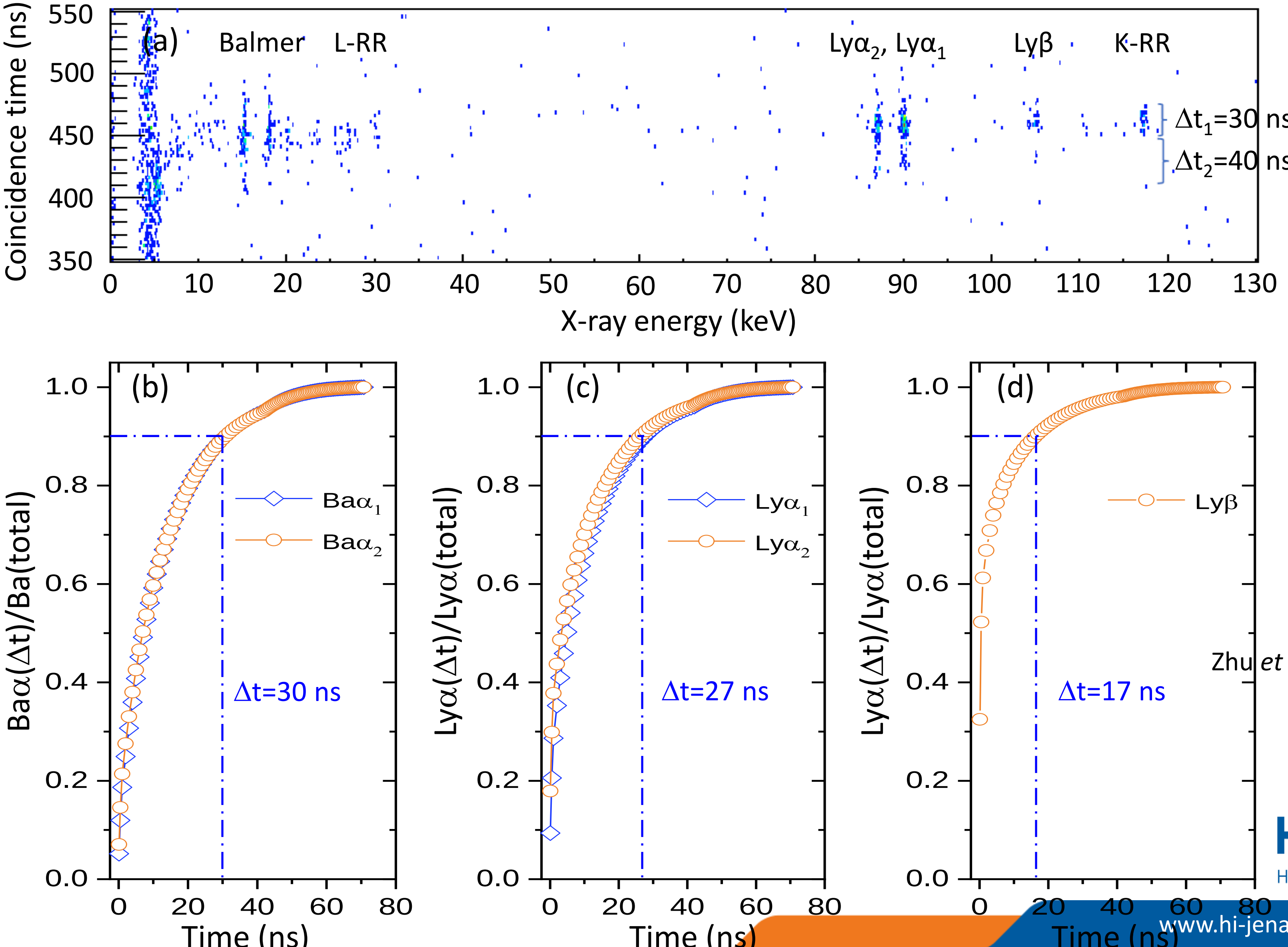
Time evolution of radiative cascades

Zhu *et al.*, *Phys. Rev. A* 105, 052804 (2022)



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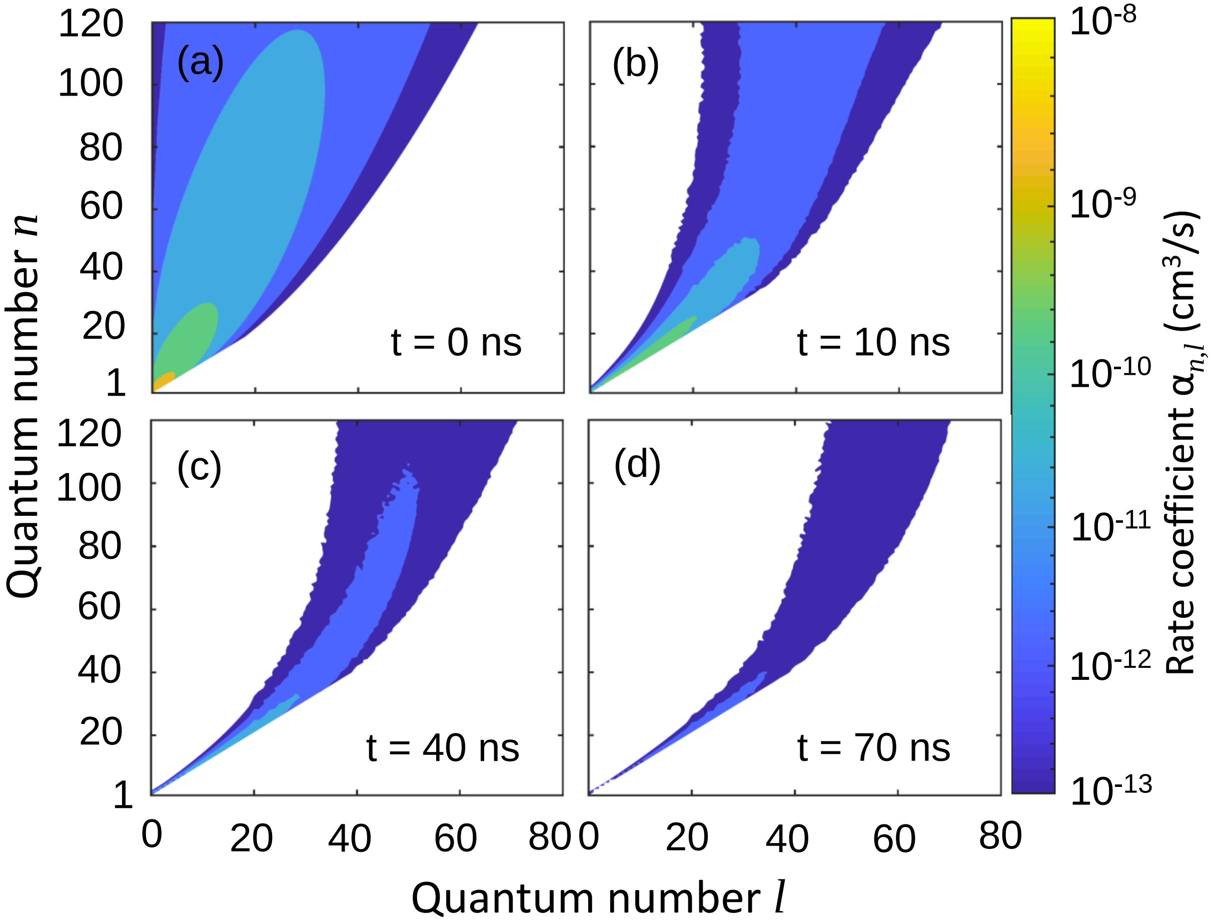
Calculated (n,l)-population rate coefficients versus time



- The (n, l) states having a high n but a low l will decay directly to the inner shells via fast E1 transitions.

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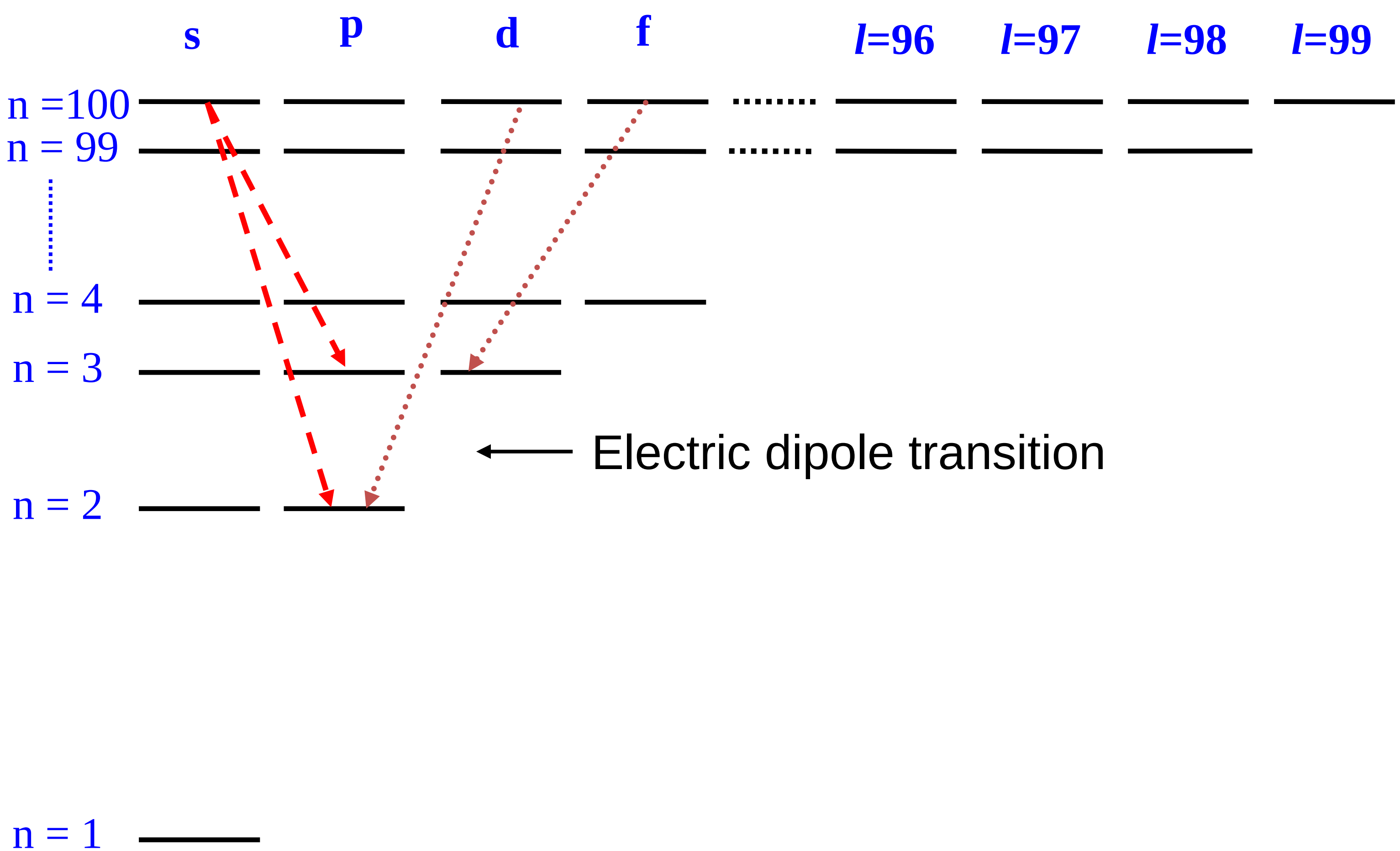
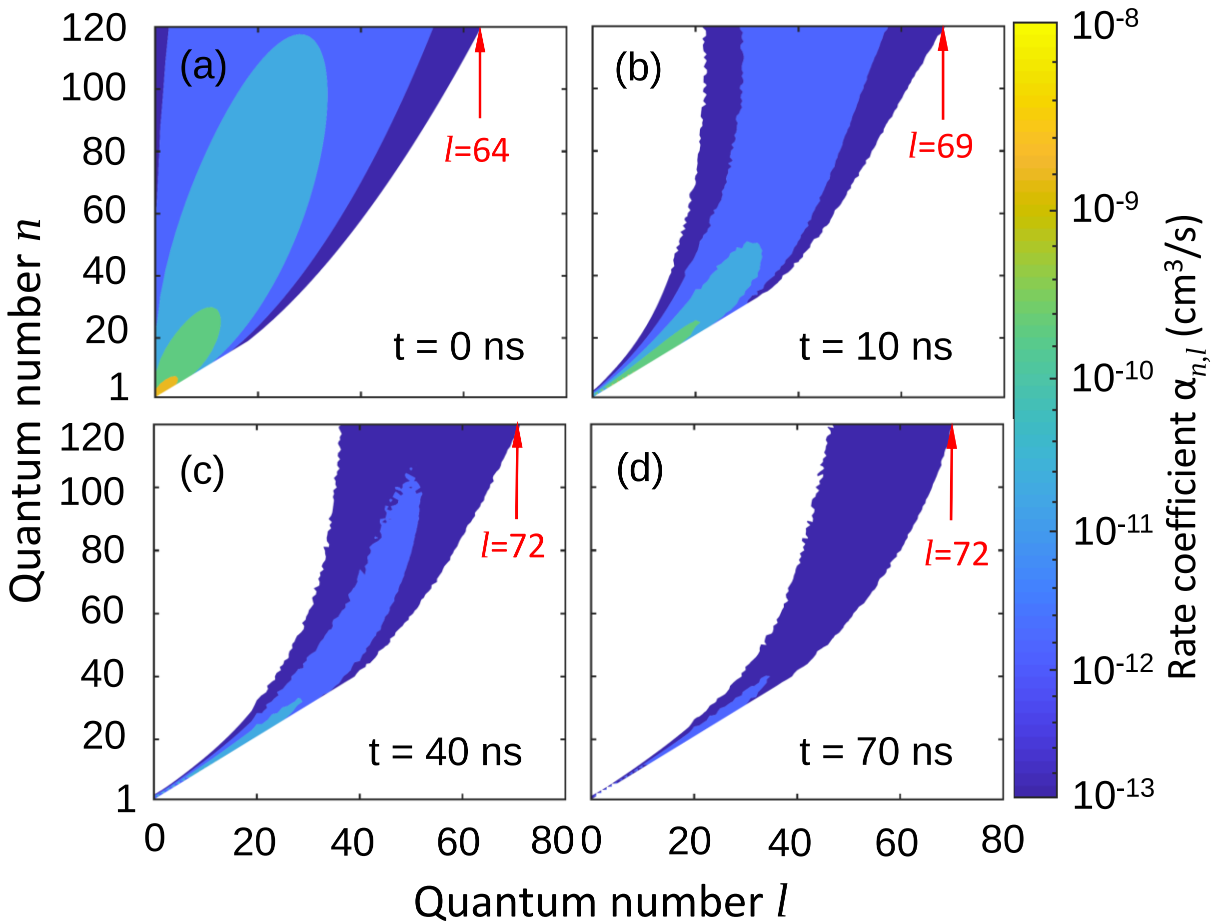
Level scheme of radiative cascades



Calculated (n,l)-population rate coefficients versus time



- The (n, l) states having a high n but a low l will decay directly to the inner shells via fast E1 transitions.
- The (n, l) states having a high n and a high l will decay step by step ($l \rightarrow l \pm 1$) to lower lying levels.

Zhu *et al.*, in preparation

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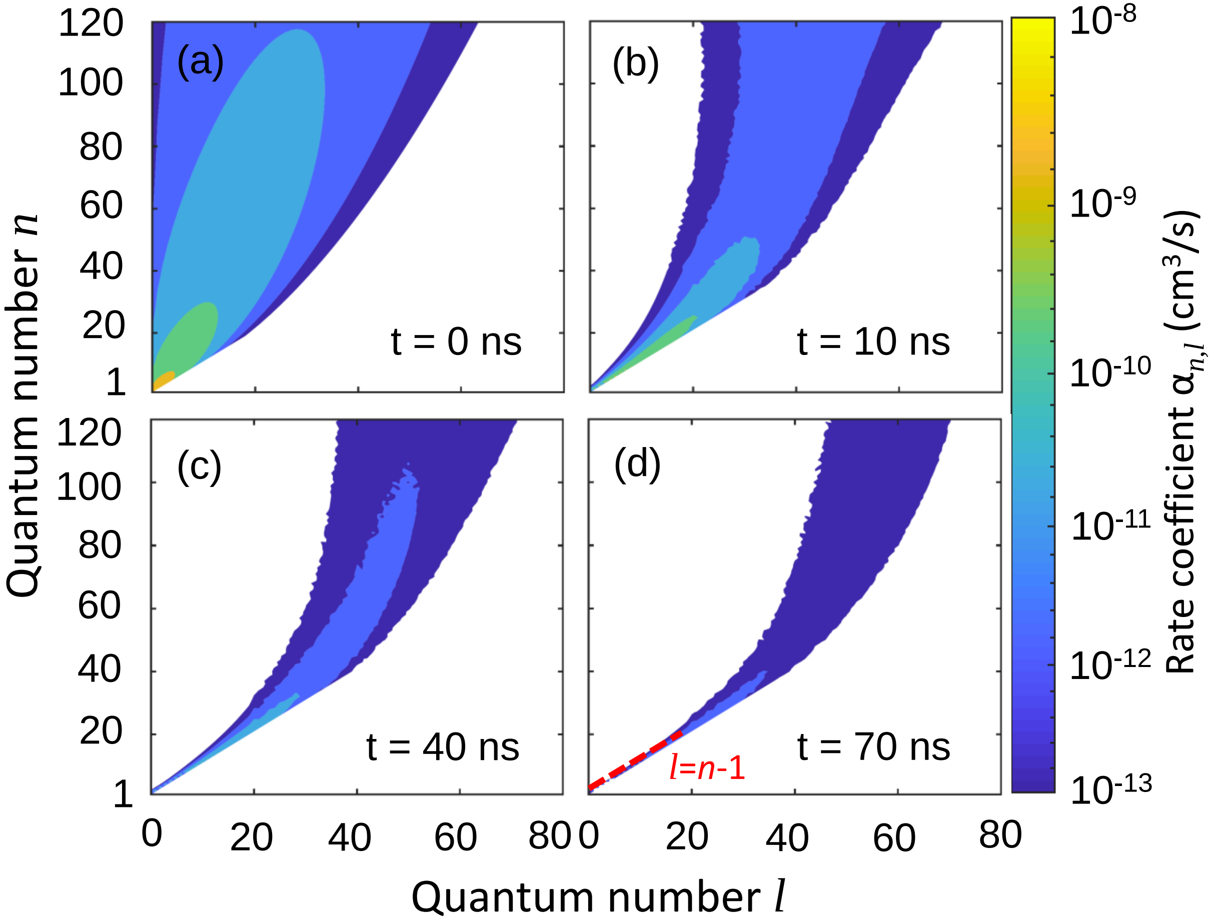

- The (n, l) states having a high n but a low l will decay directly to the inner shells via fast E1 transitions.
- The (n, l) states having a high n and a high l will decay step by step ($l \rightarrow l \pm 1$) to lower lying levels.
- The Yrast-cascades chain in inner shells forms the dominant features of characteristic projectile x-rays.

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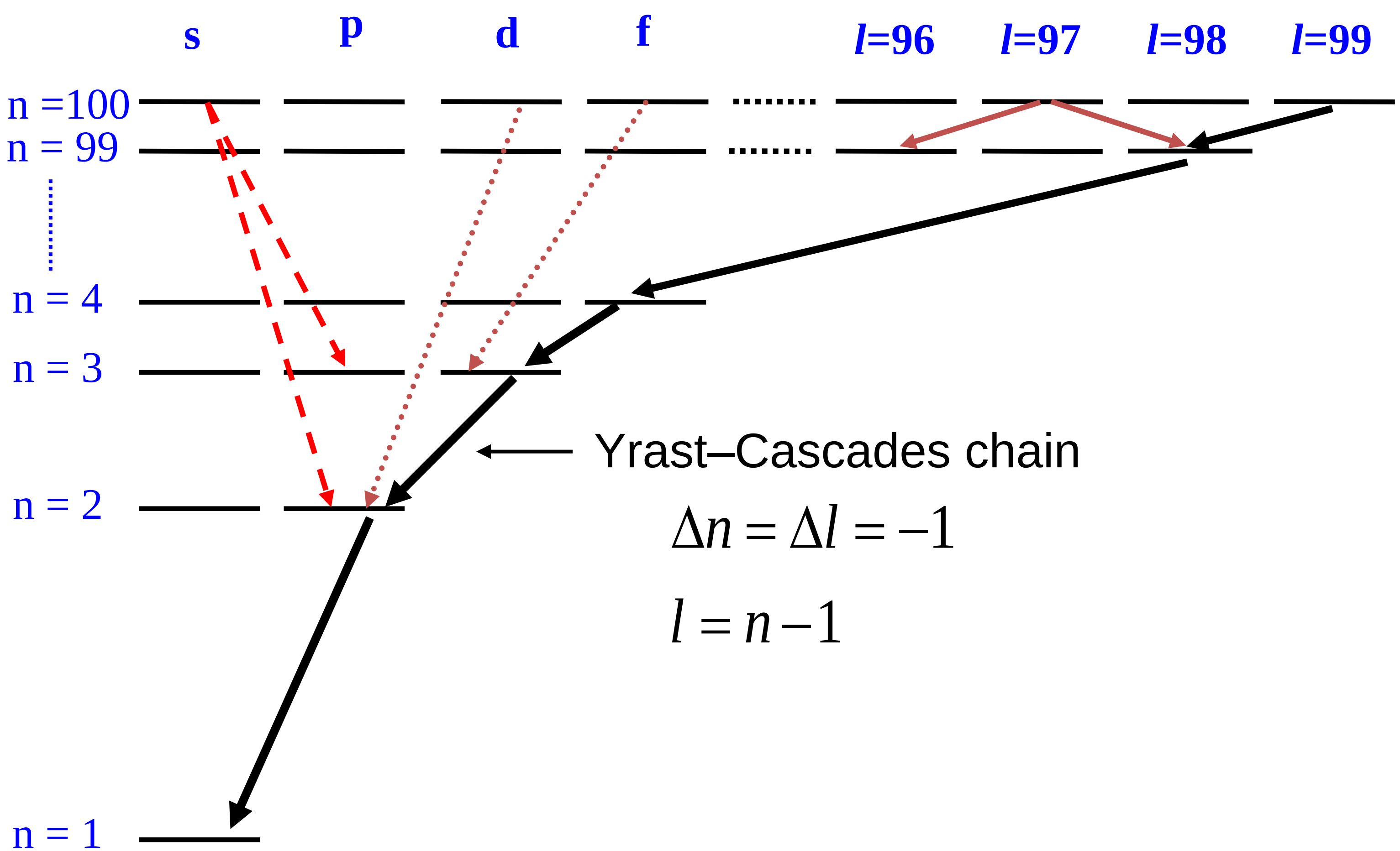
Level scheme of radiative cascades



$$\Delta n = \Delta l = -1$$

$$l = n - 1$$

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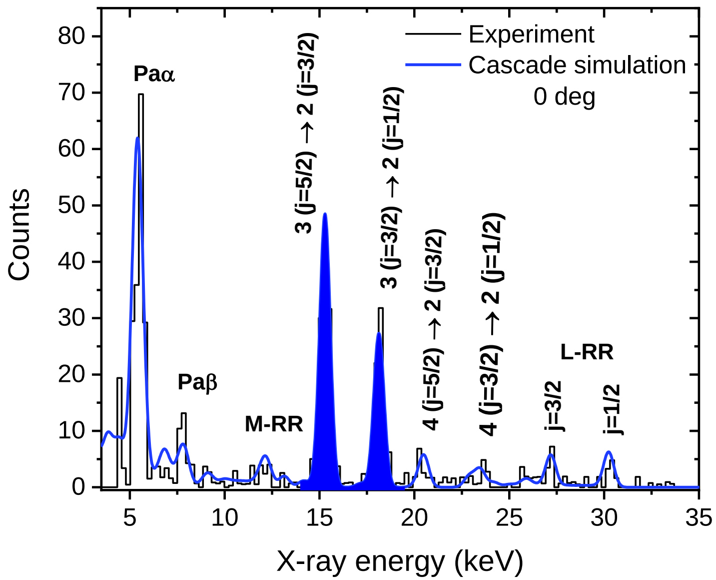
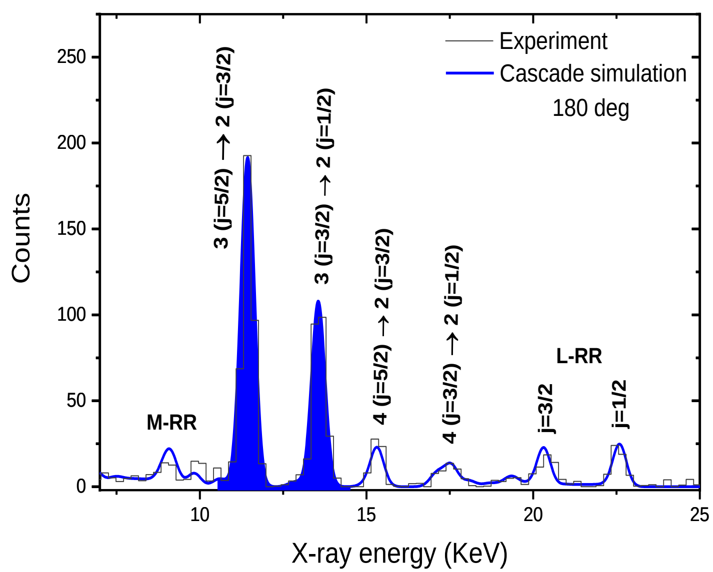
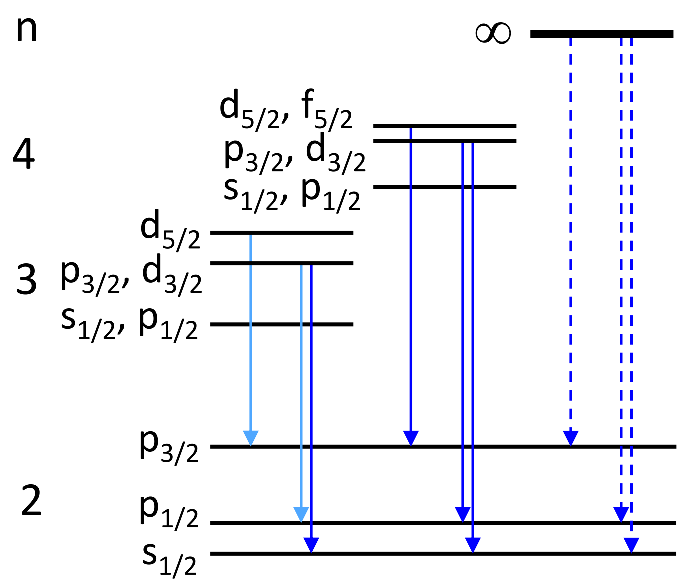
Balmer spectra: state selective study







Zhu *et al.*, *Phys. Rev. A* 105, 052804 (2022)

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Summary/Conclusion

- Capability of RR experiment for highly charged heavy ions has been fully commissioned at the CRYRING@ESR, and allows for the first physics production runs.
- Fine structure resolved level populations are studied in comparison with rigorous relativistic theory.
- Population pattern of characteristic x-ray emission is well revealved by our elaborate theoretical model calculating time-dependent cascade feeding processes.

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