KLL-Photorecombination into highly charged heavy ions

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1 Introduction

Problem: Calculation of cross sections for DR and RTE with the emission of one or two photons

Dielectronic recombination (DR):

1. Radiationless resonant capture of a free electron into an ion with simultaneous excitation of a bound electron
2. Stabilization by emission of photon(s)

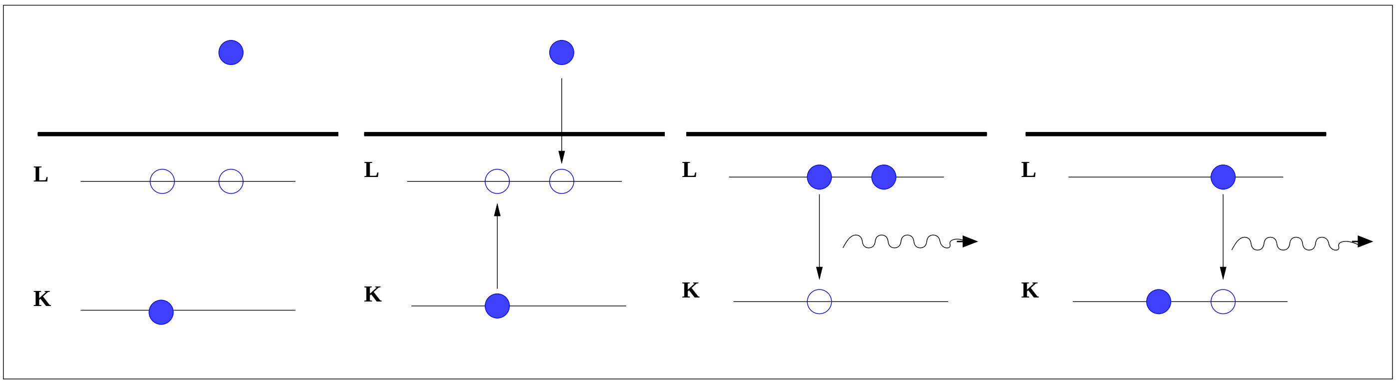


Figure 1: KLL-DR into a hydrogen-like ion

Resonant Transfer and Excitation (RTE):

Similar process: capture of a previously bound atomic electron

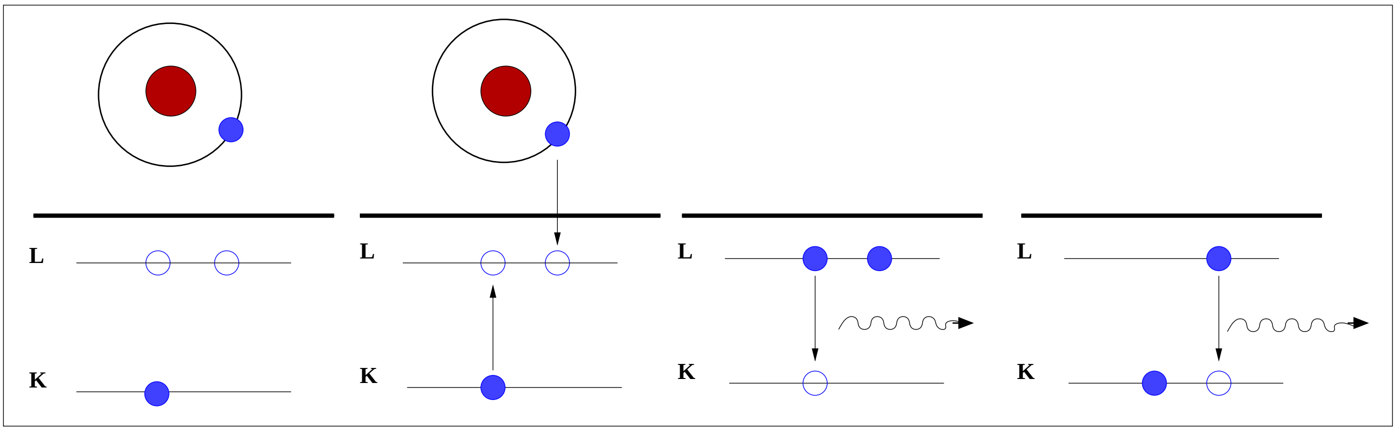


Figure 2: KLL-RTE into a hydrogen-like ion

Recent experiment at GSI:

X. Ma et al., GSI Scientific Report 2000:
KLL-RTE in collisions of U^{91+}-ions with atomic hydrogen

2 Theory for the one-photon process

2.1 The total cross section for DR

In the lowest order of perturbation theory, the total cross section for DR is

$$\sigma_{i\to f}^{DR} = \frac{2\pi}{p^2}\sum_d \frac{A_{d\to f}}{\Gamma_d} V_d L_d\left(E - E_d\right)$$

with

- p: momentum of the incoming electron,
- E_d: energy of the intermediate state d,
- Γ_d: total width of the state d and
- $L_d(E - E_d) = \frac{\Gamma_d/(2\pi)}{(E-E_d)^2+\Gamma_d^2/4}$: Lorentz resonance profile.

The rates for capture and one-photon radiative decay are

$$V_d = \frac{2\pi}{2(2J_i+1)}\sum_{M_i m_s M_d}\int d\Omega_p \left|\langle \Phi_d J_d M_d \left|V_{capt}\right| \Phi_i J_i M_i, \vec{p} m_s\rangle\right|^2 \rho_i \quad \text{and}$$

$$A_{d\to f} = \frac{2\pi}{2J_d+1}\sum_{M_f \lambda M_d}\int d\Omega_k \left|\left\langle \Phi_f J_f M_f, \vec{k}\lambda \left|H_{er}\right| \Phi_d J_d M_d \right\rangle\right|^2 \rho_f,$$

where V_{capt} is the operator responsible for the capture:

$$V_{capt} = V_{Coulomb} + V_{Breit},$$

$$V_{Breit} = \sum_{i<j}\left\{-\alpha_i\alpha_j\frac{\cos(\omega r_{ij})}{r_{ij}} + (\alpha_i\nabla_i)(\alpha_j\nabla_j)\frac{\cos(\omega r_{ij})-1}{\omega^2 r_{ij}}\right\},$$

and the interaction of electrons with photons is:

$$H_{er} = \sum_{i=1}^{n_e}\sum_{\vec{k}\lambda}\sqrt{\frac{2\pi c^2}{V\omega_k}}\vec{\alpha}_i\left(\vec{\epsilon}_{\vec{k}\lambda}e^{i\vec{k}\cdot\vec{r}_i}a_{\vec{k}\lambda} + \vec{\epsilon}^{\,*}_{\vec{k}\lambda}e^{-i\vec{k}\cdot\vec{r}_i}a^+_{\vec{k}\lambda}\right).$$

2.2 Differential cross section for DR

The differential cross section has the following form:

$$\frac{d\sigma^{DR}}{d\Omega_k} = \sigma^{DR} W(\theta).$$

Considering only the dominant dipole radiation, one can write the angular distribution $W(\theta)$ as

$$W(\theta) = \frac{1}{4\pi} (1 + \beta P_2(\cos\theta))$$

with the parameter β measuring the anisotropy of the emission.

3 Two-photon emission in DR

Motivation: State after first photon emission is not stable $\Rightarrow$
Investigate effects of the second radiative transition on the cross section!

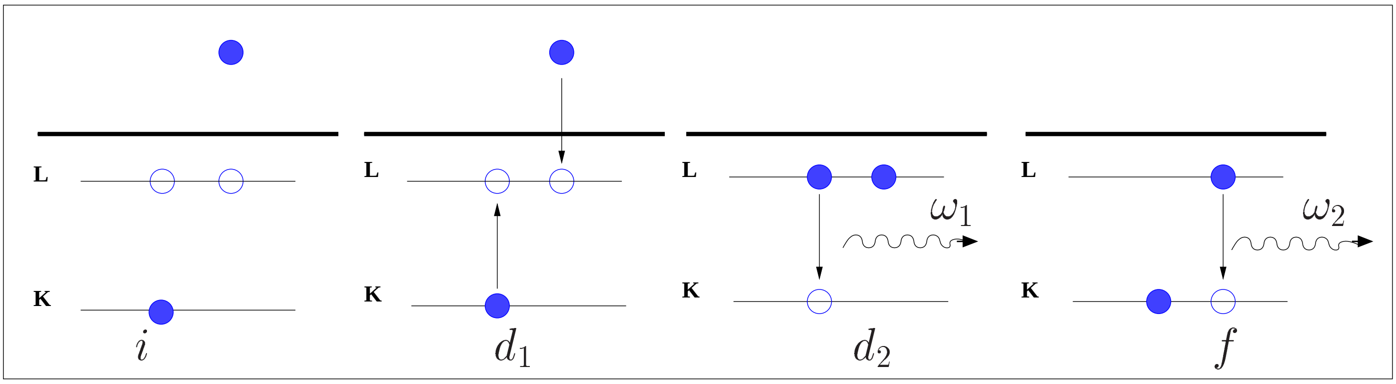


Figure 3: KLL-DR into a hydrogen-like ion

Changes compared to the one-photon case:

- Previous "final" state f becomes second intermediate state d_2.
- New final state f contains two photons.

3.1 Total cross section for DR

Total cross section for DR with the emission of two photons:

$$\sigma_{DR}^{2\gamma} = \frac{2\pi^2}{p^2} \sum_{d_1,d_2} \frac{A_{d_1\to d_2}}{\Gamma_{d_1}} V_{d_1} L_{d_1}(E - E_{d_1}) g_{d_2}(E)$$

with

$$g_{d_2}(E) \;=\; \frac{A_{d_2\to f}}{\Gamma_{d_2}} \int_0^{E-E_f} d\omega \, L_{d_2}(E - E_{d_2} - \omega).$$

Compare with one-photon result:

$$\sigma_{DR}^{1\gamma} = \frac{2\pi^2}{p^2} \sum_{d,f} \frac{A_{d\to f}}{\Gamma_d} V_d L_d(E - E_d).$$

In the limit $A_{d_2\to f} = \Gamma_{d_2} \to 0$ (stable second intermediate states):

$$\sigma_{DR}^{2\gamma} \longrightarrow \frac{2\pi^2}{p^2} \sum_{d_1,d_2} \frac{A_{d_1\to d_2}}{\Gamma_{d_1}} V_{d_1} L_{d_1}(E - E_{d_1}) = \sigma_{DR}^{1\gamma}.$$

3.2 Numerical results for the total cross section for DR into U^{91+}

Total cross section calculated for the energy ranges of KLL-DR into U^{91+}

Relative change caused by consideration of the second radiative transition

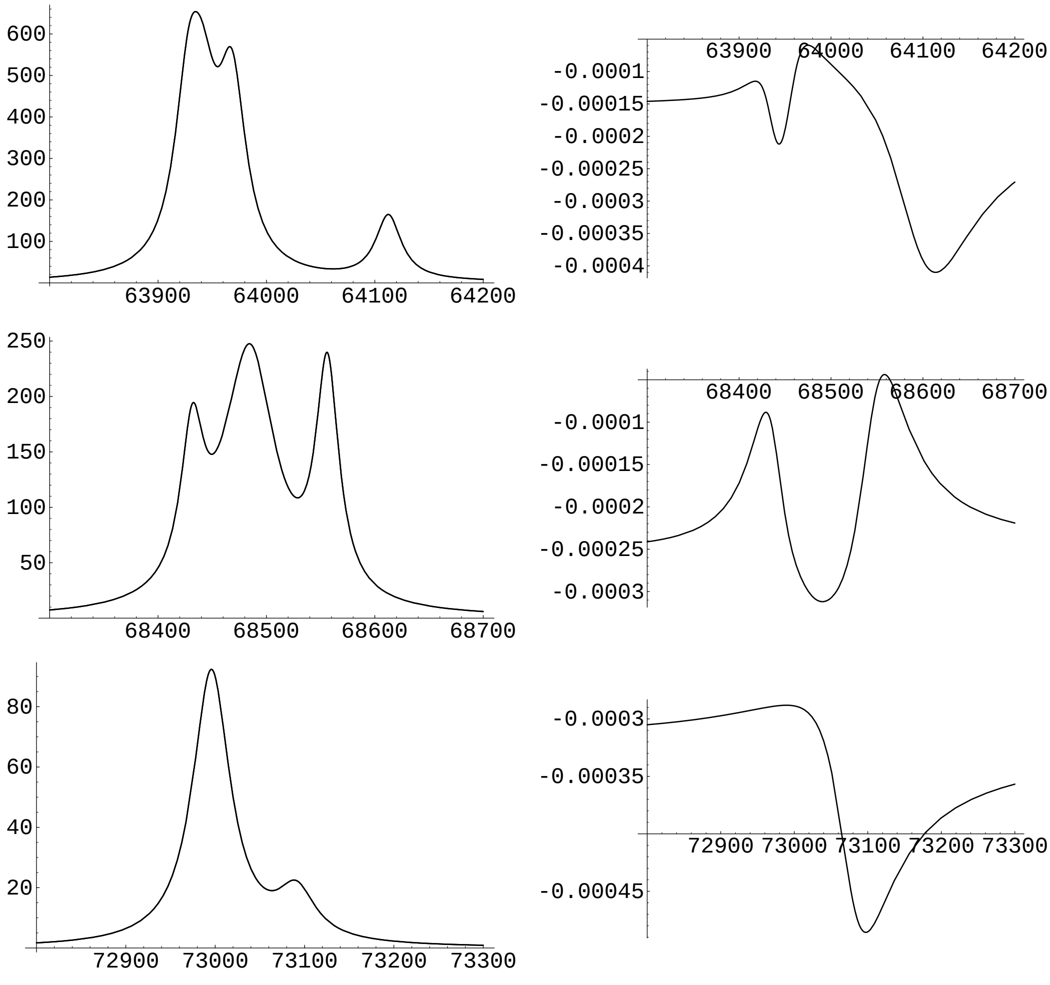
$\sigma^{2\gamma}$ [barn]

$\frac{\sigma^{2\gamma}}{\sigma^{1\gamma}} - 1$

$KL_{1/2}L_{1/2}$ resonance group

$KL_{1/2}L_{3/2}$ resonance group

$KL_{3/2}L_{3/2}$ resonance group



electron energy [eV]

electron energy [eV]

Conclusion:
In this case, the cross sections remain practically unchanged

4 KLL-RTE for H-like U-ions

4.1 Cross section for RTE in the impulse approximation

The electron bound in a light atom can be regarded as quasi-free $\Rightarrow$
The impulse approximation can be applied to obtain the cross section for RTE:

$$\frac{d^2\sigma_{RTE}}{d\Omega\, d\omega} = \int d^3q' \frac{d\sigma_{DR}(\vec{q})}{d\Omega} \left|\tilde{\phi}_i(\vec{q}\,')\right|^2 \delta(\omega + E_f - e_i - E_i).$$

$\tilde{\phi}_i(\vec{q}\,')$: wavefunction of the bound electron in momentum space
$\vec{q}$: electron momentum transformed to the projectile rest frame
e_i: electron energy

4.2 Numerical results

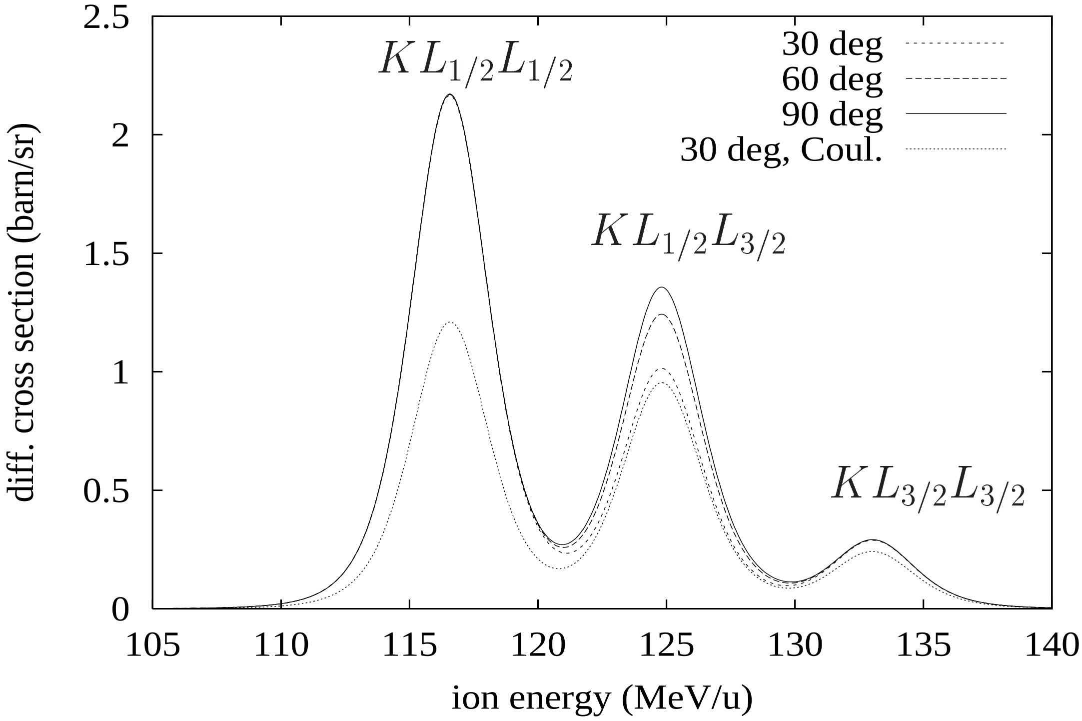


Figure 4: Differential cross sections for KLL-RTE in U^{91+} in the projectile frame at the angles $\theta = 30°$, $60°$ and $90°$.

5 Summary and outlook

What has been done:

- Total and differential cross sections for DR and RTE have been calculated in the case of KLL-DR into hydrogen-like U-ions.
- Effects of the second stabilizing radiation have been incorporated into the expression for the total cross section.

What will be done:

- Consideration of higher-order corrections to the Breit interaction
- Calculation of
  - the angular distribution of the second photon and
  - angular correlations between the two photons