Off-resonant dielectronic recombination in a collision of an electron with a heavy hydrogen-like ion

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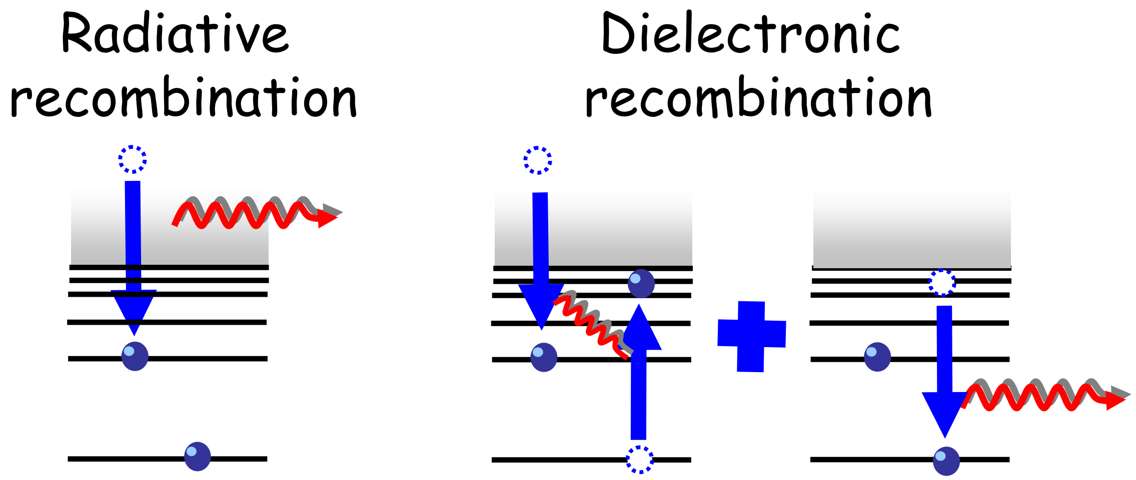
RR and DR: different recombination channels?



• To the zeroth order, radiative recombination (RR) and dielectronic recombination can be considered as two independent recombination channels.

• More accurate calculations take into account the quantum interference between RR and DR.

• If we are interested in the effect of the electron-electron interaction, RR and DR cannot be meaningfully separated. The standard DR mechanism is just a resonant part of the electron-electron correction to the RR.

Motivation

• The off-resonant DR can induce the contribution of the same order of magnitude as, e.g., the screening of the nuclear charge by the core electrons.

• This effect is not accounted if one just calculates RR with the correlated wave functions, as is often done (e.g., MCDF calculations).

• In a recent experiment on RR into an H-like uranium [R. Reuschl et al., Phys. Rev. A 77, 032701 (2008)], a deviation from the relativistic one-electron theory was observed on a level of 10%, whereas theoretical estimates for the electron-electron interaction effect yielded about 2%.

Objective

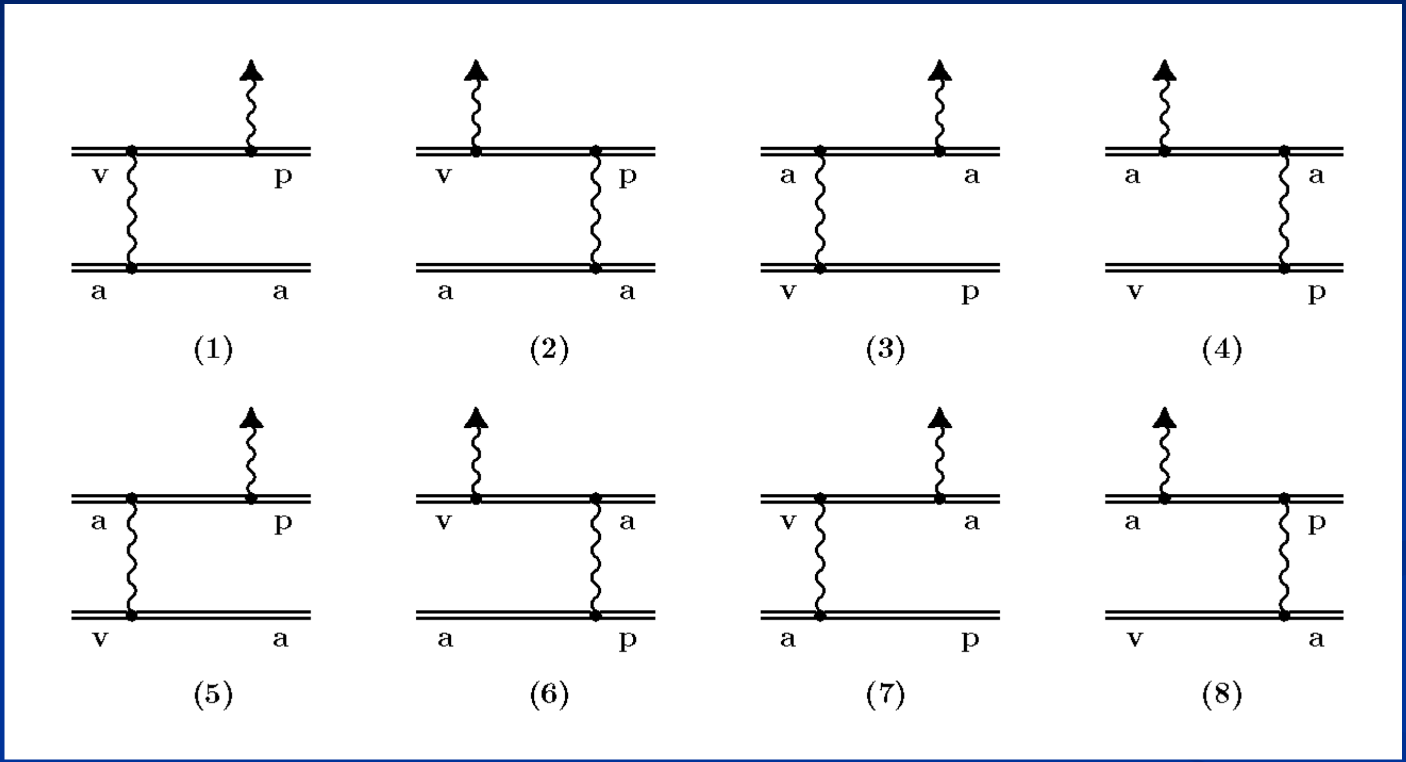
- Perform an *ab initio* calculation of the electron-electron interaction correction to RR of an electron with an (initially) H-like high-Z ion. To the first order in 1/Z, the effect is treated rigorously within QED, whereas higher orders in 1/Z are accounted for approximately within the screening-potential approximation.

- Try to explain the disagreement with the experiment.

- Identify the situations when the off-resonant DR mechanism needs to be taken into account and when it can be omitted.

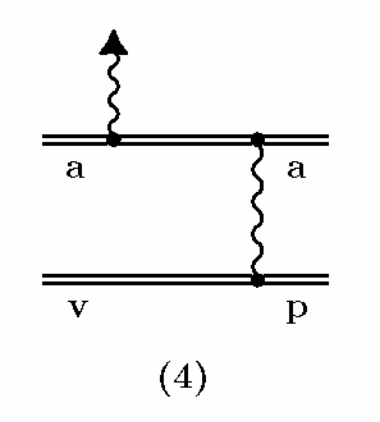
V.A. Yerokhin and A. Surzhykov, Phys. Rev. A 81, 062703 (2010)

Feynman diagrams



Notations: p denotes the incoming electron, a is the initially bound (core) electron, v is the captured (valence) electron, wavy line with an arrow denotes the emitted electron.

Let's take diagram (4) as an example



The contribution to the transition amplitude from this diagram is

$$\tau^{(1,4)} = \sum_n \frac{\langle a|\boldsymbol{\alpha}\cdot\hat{\boldsymbol{u}}^* e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}|n\rangle\langle vn|I(\varepsilon_p - \varepsilon_v)|pa\rangle}{\varepsilon_a - \varepsilon_v + \varepsilon_p - \varepsilon_n(1 - i0)},$$

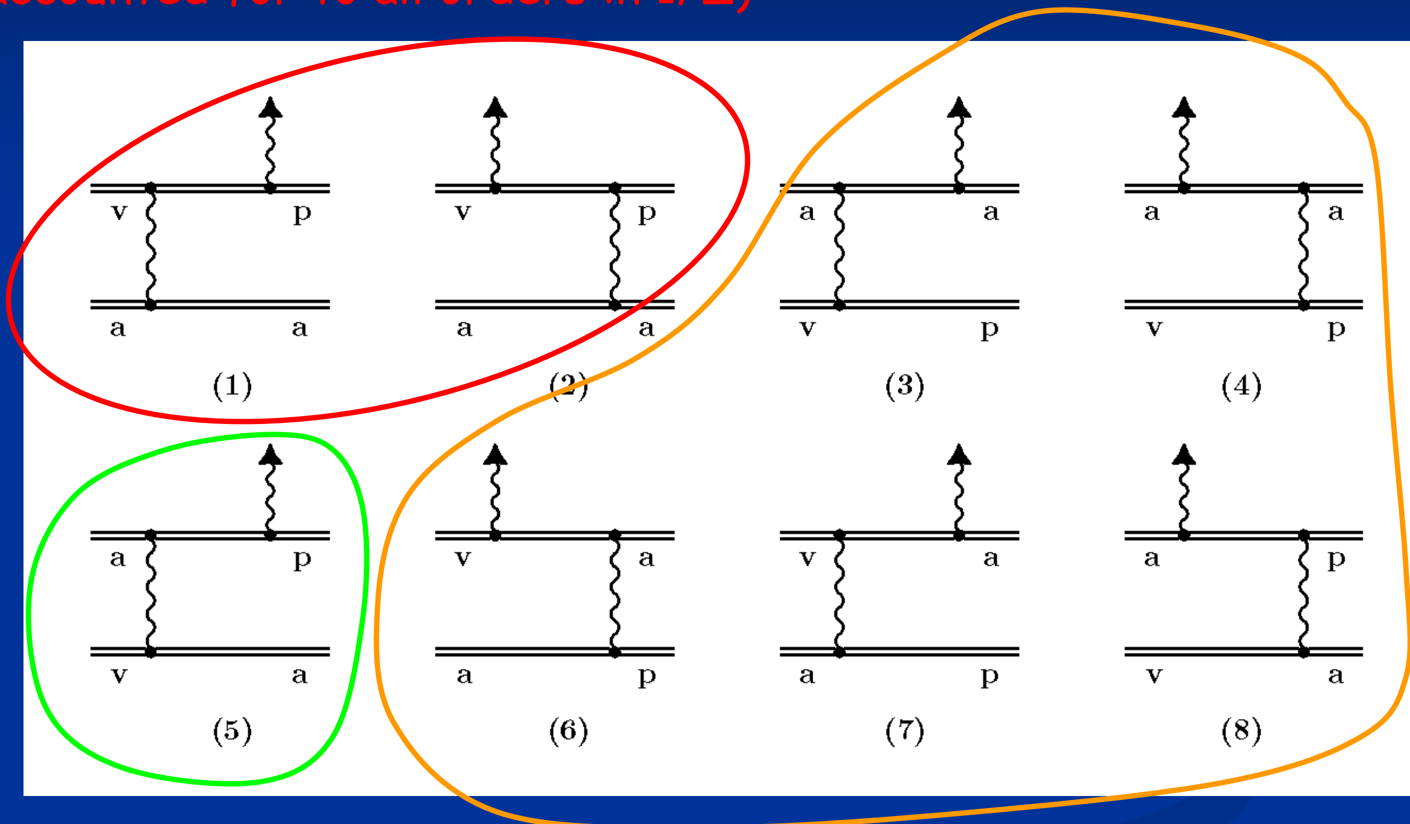
where I is the operator of the electron-electron interaction: $I(\omega) = e^2\alpha_\mu\alpha_\nu D^{\mu\nu}(\omega, x_{12})$ and $D^{\mu\nu}$ is the photon propagator. The sum over n runs over the whole spectrum of the Dirac equation.

The denominator vanishes when $\varepsilon_p = \varepsilon_v - \varepsilon_a + \varepsilon_n > mc^2$ (where ε_n are the Dirac bound-state energies), thus giving the resonances of the standard DR.

To represent the Dirac spectrum, one may use the finite basis set (e.g., B-splines) if the energy in the electron propagator E is $E<mc^2$. When $E>mc^2$, the exact representation of the Dirac Green function is required.

Interpretation

Screening of the nuclear charge by the core electron
(can be accounted for to all orders in 1/Z)



Correlation on the bound wave function

Off-resonant DR

Caution: separate pieces are not gauge-invariant.

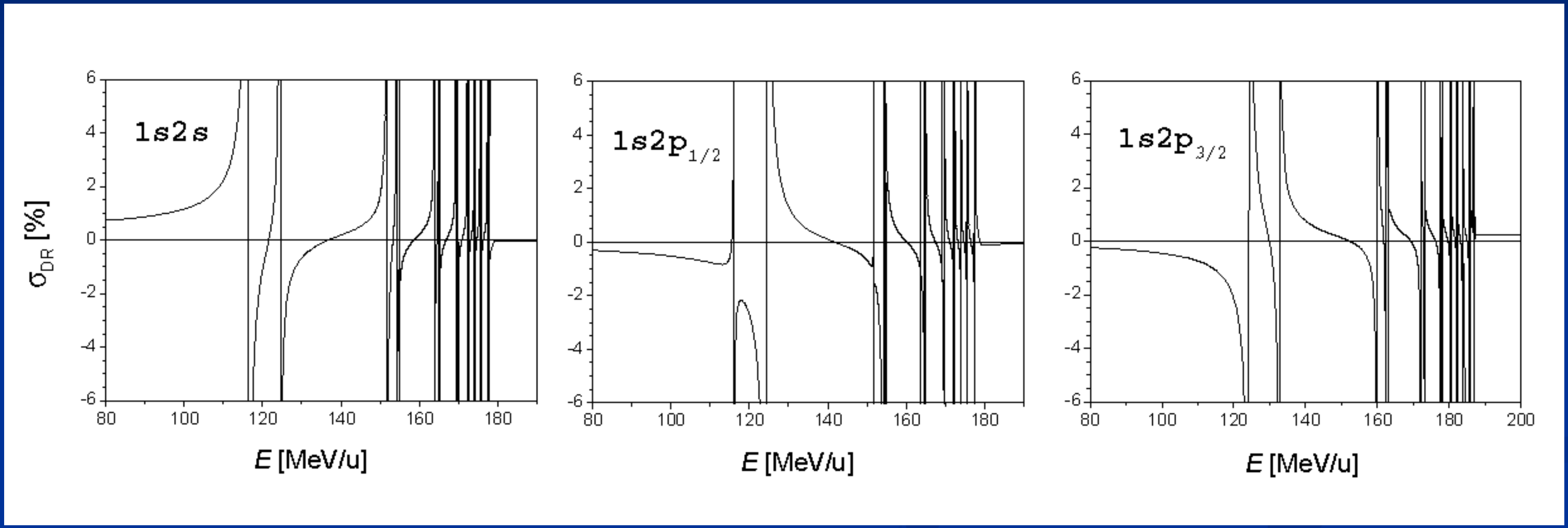
Contributions

The total recombination cross section is represented as

$$\sigma = \sigma^{(0)} + \sigma_{\text{scr}} + \sigma^{(1)}_{\text{corr}} + \sigma^{(1)}_{\text{DR}} .$$

- $\sigma^{(0)}$ is the zeroth-order cross section.
- σ_{scr} represents the *screening* effect. It corresponds to diagrams (1) and (2) and their iterations. This part is calculated to all orders in $1/Z$.
- $\sigma^{(1)}_{\text{corr}}$ corresponds to diagram (5) and is interpreted as the correlation effect on the bound-electron wave function.
- $\sigma^{(1)}_{\text{DR}}$ corresponds to diagrams (3), (4), (6), (7), and (8) and is referred to as the (off-resonant) DR correction.

Results: DR resonances



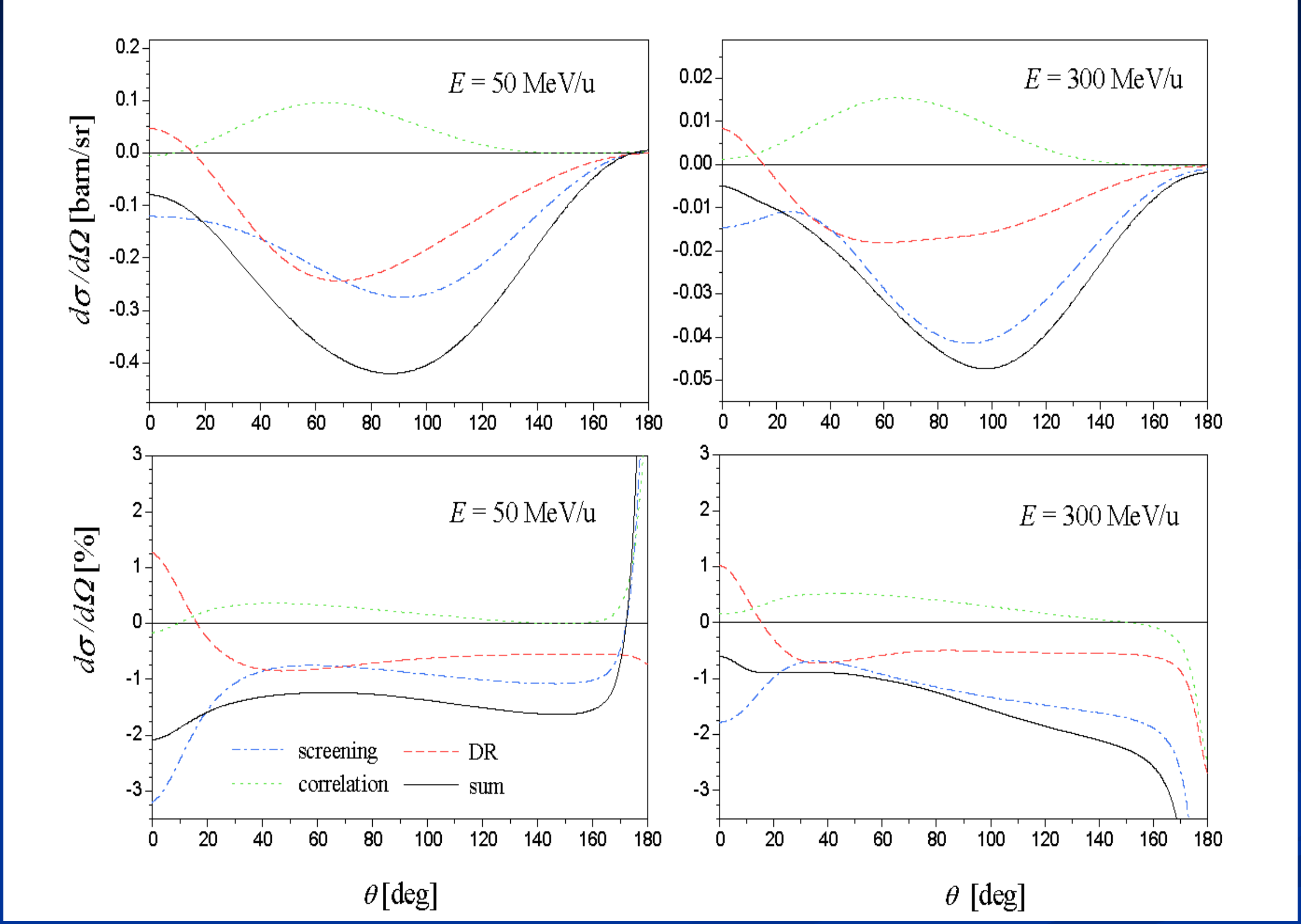
The dielectronic-recombination contribution for the capture into the 1s2s, $1s2p_{1/2}$, and $1s2p_{3/2}$ states of initially H-like uranium as a function of the energy of the incoming electron E, in percent of the zero-order cross section.

Results: total cross section

E [MeV/u]	$\sigma_{\rm scr}$ [%]	$\sigma^{(1)}_{\rm corr}$ [%]	$\sigma^{(1)}_{\rm DR}$ [%]	$\sigma_{\rm scr}$ [%]	$\sigma^{(1)}_{\rm corr}$ [%]	$\sigma^{(1)}_{\rm DR}$ [%]
	$(1s)^2$ state			$1s2s$ state		
1	−0.850	0.138	−0.703	−1.997	−0.232	0.387
5	−0.852	0.146	−0.702	−1.936	−0.217	0.396
10	−0.854	0.156	−0.701	−1.874	−0.201	0.408
50	−0.888	0.217	−0.683	−1.673	−0.124	0.524
75	−0.917	0.245	−0.668	−1.652	−0.101	0.669
100	−0.949	0.268	−0.650	−1.655	−0.086	1.141
125	−0.981	0.286	−0.634	−1.670	−0.076	−6.124
150	−1.013	0.302	−0.617	−1.690	−0.069	1.635
175	−1.043	0.314	−0.601	−1.712	−0.065	0.443
200	−1.072	0.325	−0.587	−1.735	−0.062	−0.044
300	−1.170	0.353	−0.542	−1.817	−0.060	−0.017
500	−1.292	0.378	−0.499	−1.926	−0.068	0.034
700	−1.350	0.387	−0.495	−1.980	−0.079	0.045

Individual two-electron contributions for the capture into the ground and the 1s2s states of initially H-like uranium as a function of the energy of the incoming electron E, in percent of the zero-order cross section.

Results: differential cross section



Individual two-electron contributions for the capture into the ground state of initially H-like uranium as a function of the energy of the incoming electron E.

Conclusions

• Off-resonant DR mechanism provides an important contribution to the total electron-electron interaction effect in the case of capture into the ground state of an initially H-like ion.

• For the capture into excited states, it might be of some significance in the region below the resonant DR threshold, even at relatively large distances from the resonant peaks.

• For the excited states and energies beyond the DR threshold, the effect is very small.

• For the conditions of the experiment [R. Reuschl et al., Phys. Rev. A 77, 032701 (2008)], the calculated two-electron effect is much smaller than the one observed.