Storage-Ring Merged Beams for Electron-Ion Collision Studies

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Vienna, 12-16 September 2016

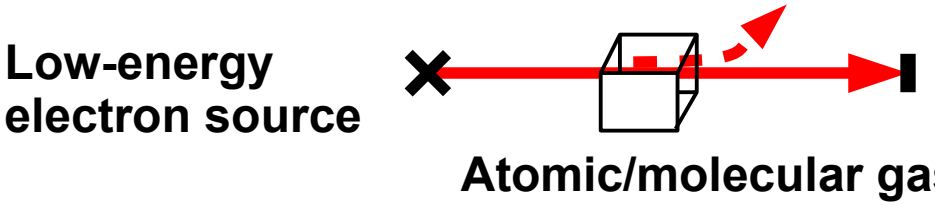
Method

Results: Open 4f-shell tungsten ions, HCl^+

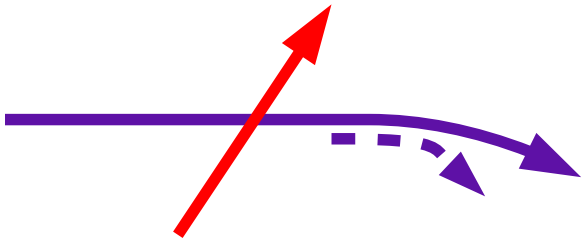
Developments: Cryogenic storage ring

Scattering and inelastic collisions with charged-particle beams

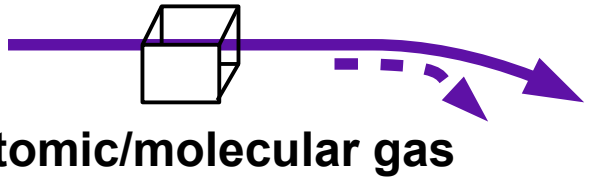
Low-energy electron scattering



Crossed-beams electron impact



Ion–molecule (atom) charge exchange



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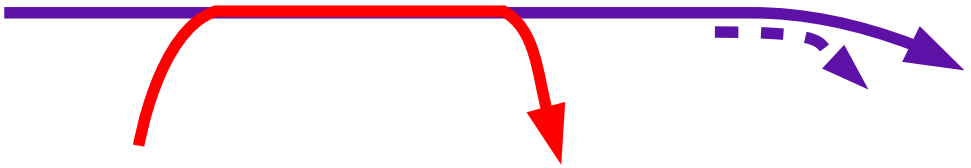

Scattering and inelastic collisions with charged-particle beams

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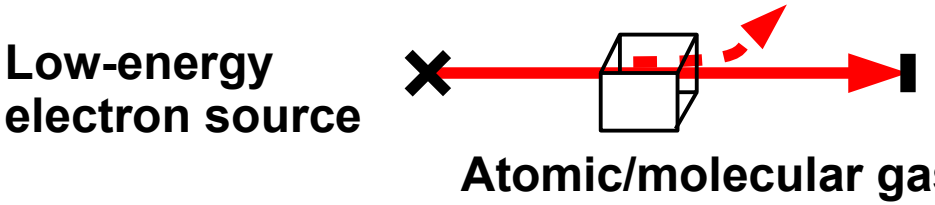

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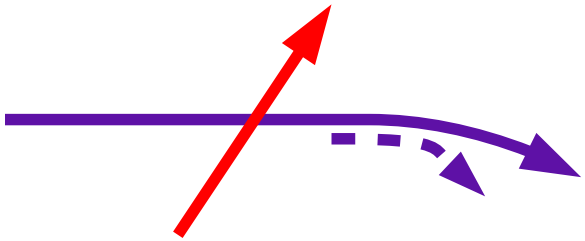

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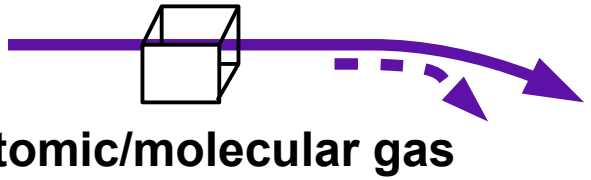

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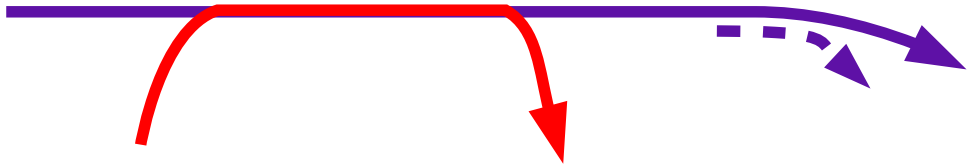


Down to zero collision energy

Narrow energy spread

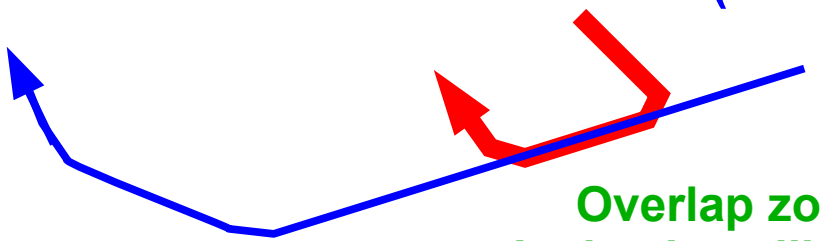
Extended overlap

Merged-beams electron ion collisions

***Velocity-matched* electron beam**

***Collision* energy:** $E_d = \frac{1}{2}\, m_e\, (v_e - v_i)^2$

Wide scan range: ~ 1 meV … keV



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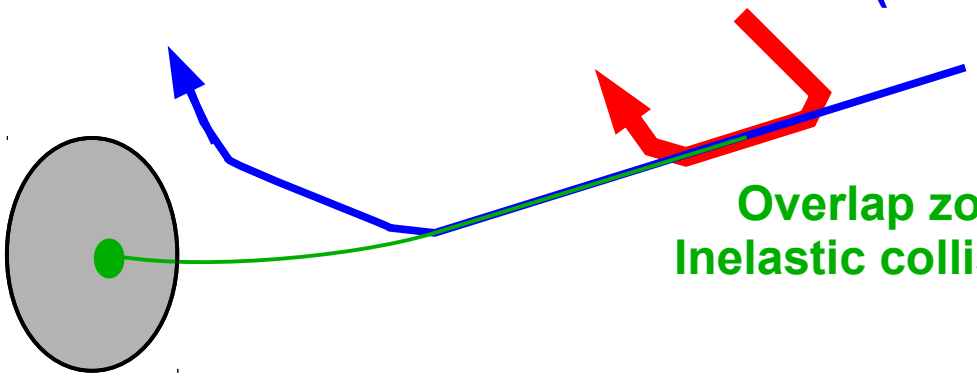
Products:

Charge changing reaction (photo-recombination)

$$X^{q+} + e^- \rightarrow X^{(q-1)+} + \gamma$$



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Fragmentation (dissociative recombination)

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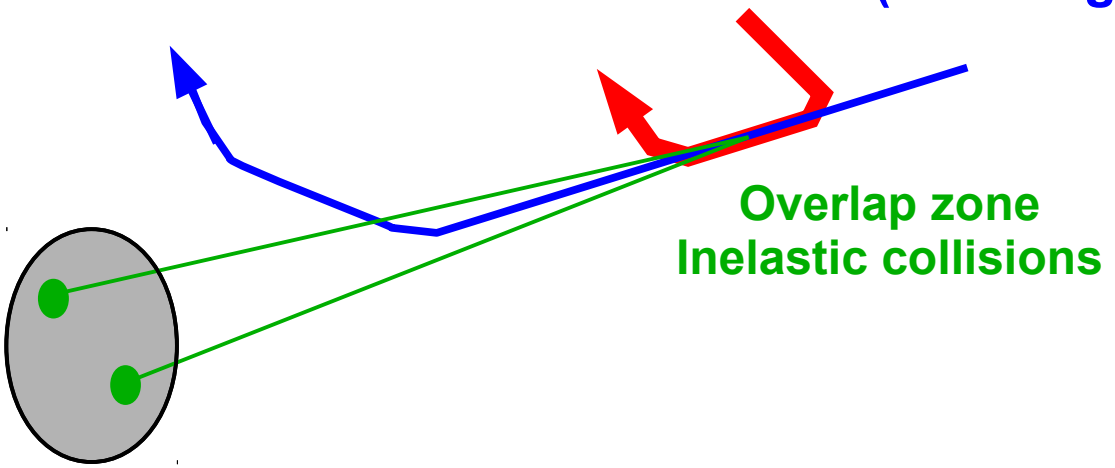


- Counting
- Momentum measurement
  (time + position)
- Coincidence measurements

Merged-beams electron ion collisions

Velocity-matched **electron beam**

Collision **energy:** $E_d = \frac{1}{2}\, m_e\, (v_e - v_i)^2$

Wide scan range: ~ 1 meV … keV

Ion beam (in storage ring)

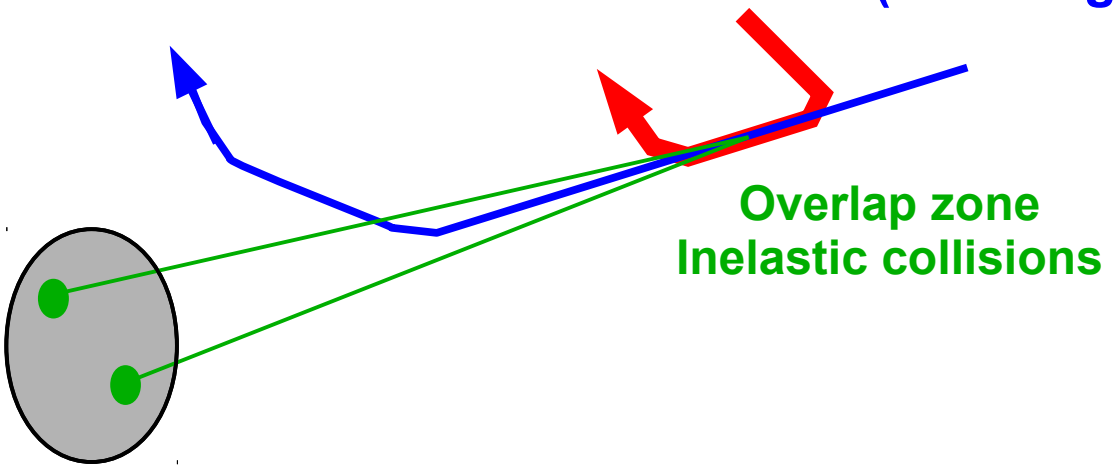
Products:

Charge changing reaction (photo-recombination)

$$X^{q+} + e^- \rightarrow X^{(q-1)+} + \gamma$$

Fragmentation (dissociative recombination)

$$AB^+ + e^- \rightarrow A + B + \varepsilon$$



- Counting
- Momentum measurement (time + position)
- Coincidence measurements

- Fragment mass identification

Fragments keep (approx.) the beam velocity v_i

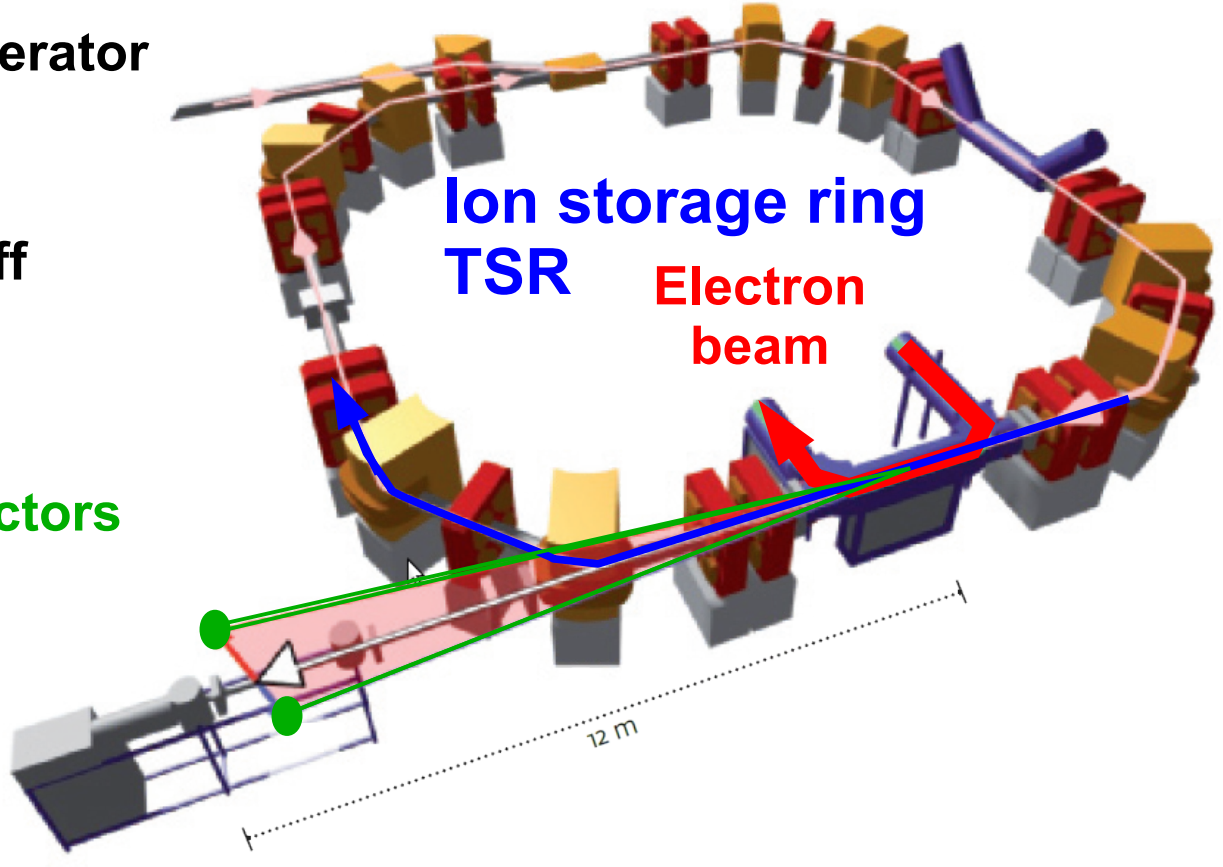
→ Laboratory kinetic energy of fragment *f:*

$$E_f = \frac{1}{2}\, M_f\, v_i^2$$

Storage ring merged beams experiments

Tandem accelerator
(~ 10 MeV·*q*)

Molecule
Van-de-Graaff
(~ 1...2 MeV)



Max-Planck-Institut
für Kernphysik
1988 to 2012

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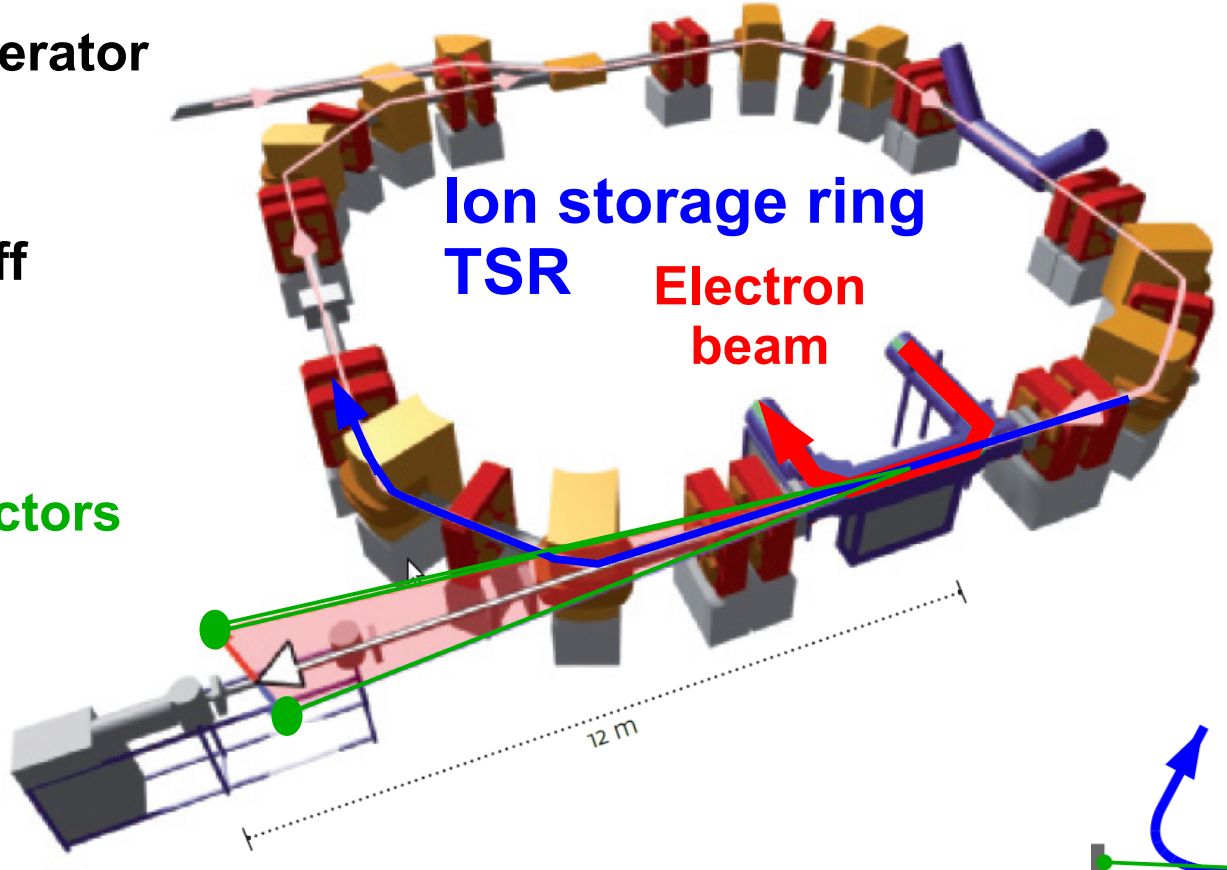

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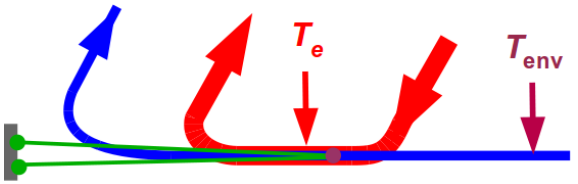


- **Store and phase-space cool molecular ion beam**
- **Reduce/control internal excitation of molecular ions (T_{env} = 300 K)**
- **Cold electrons (T_e ~ 10 K) – vary collision energy of electrons**
- **Neutral fragment detection: rates**
  product momenta
  product masses

Iron ion dielectronic recombination

$$Fe^{q+} + e \rightarrow (Fe^{(q-1)+})^{**} \rightarrow (Fe^{(q-1)+})^{*} + \gamma$$

F-like Fe^{17+}

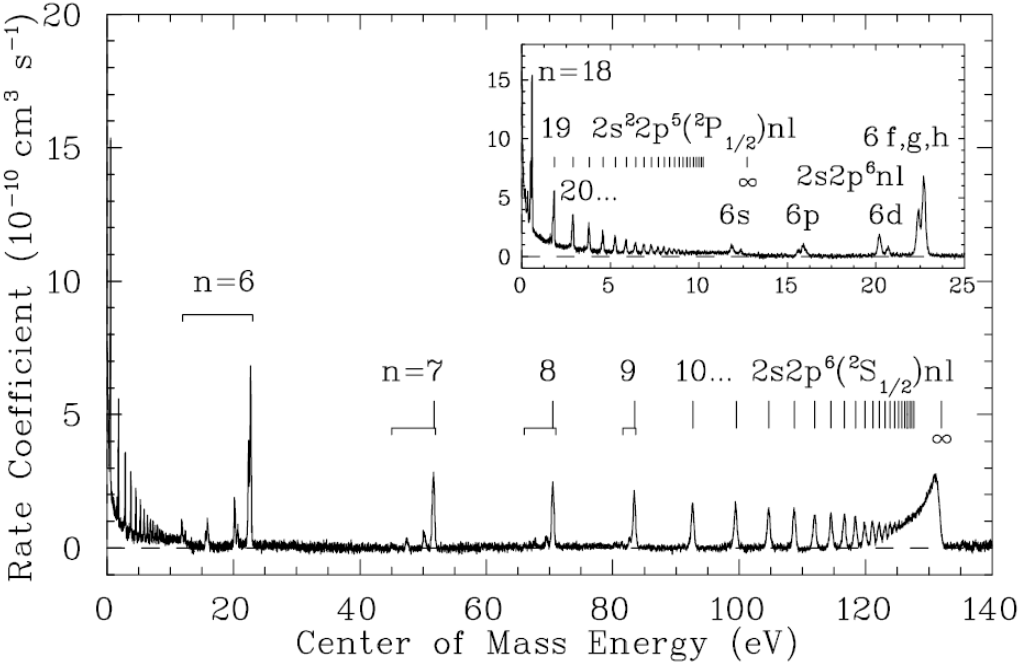
$2s^22p^5\ (^2P_{3/2}) \rightarrow 2s2p^6\ n\ell$

$\rightarrow 2s^22p^5\ (^2P_{1/2})\ n\ell$

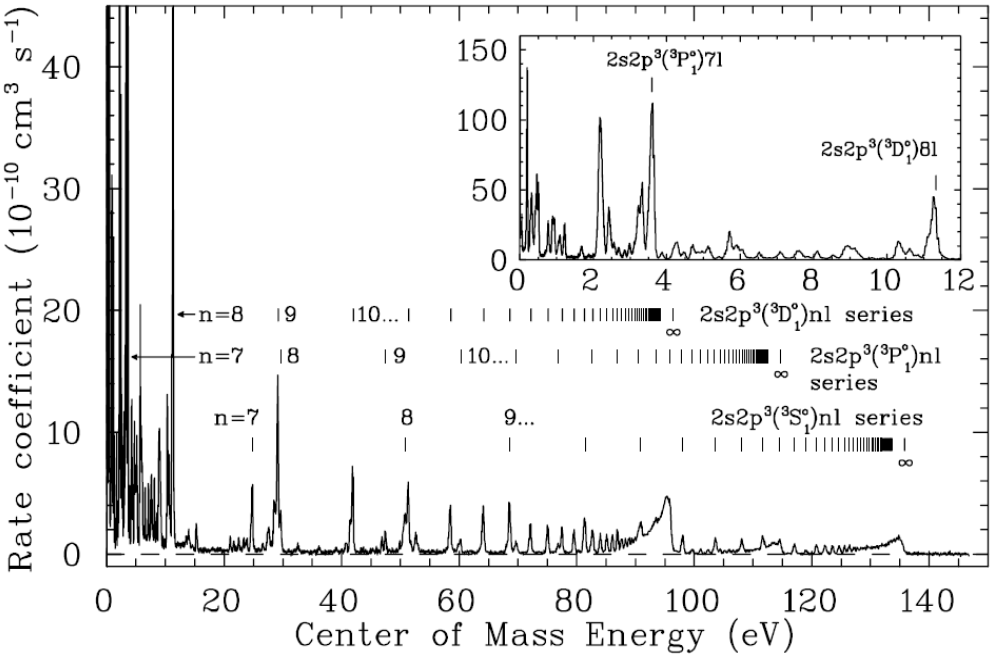
C-like Fe^{20+}

$2s^22p^2\ (^3P_0) \rightarrow 2s2p^3\ (^SL_J)\ n\ell$

$[\rightarrow 2s^22p^2\ (^SL_J)\ n\ell\ ]$



D. Savin et al., Astrophys. J. Lett. 489, L115 (1997)



D. Savin et al., Astrophys. J. Suppl. 147, 421 (2003)

Theory: T. Gorczyca et al., N. Badnell et al.

Iron ion dielectronic recombination

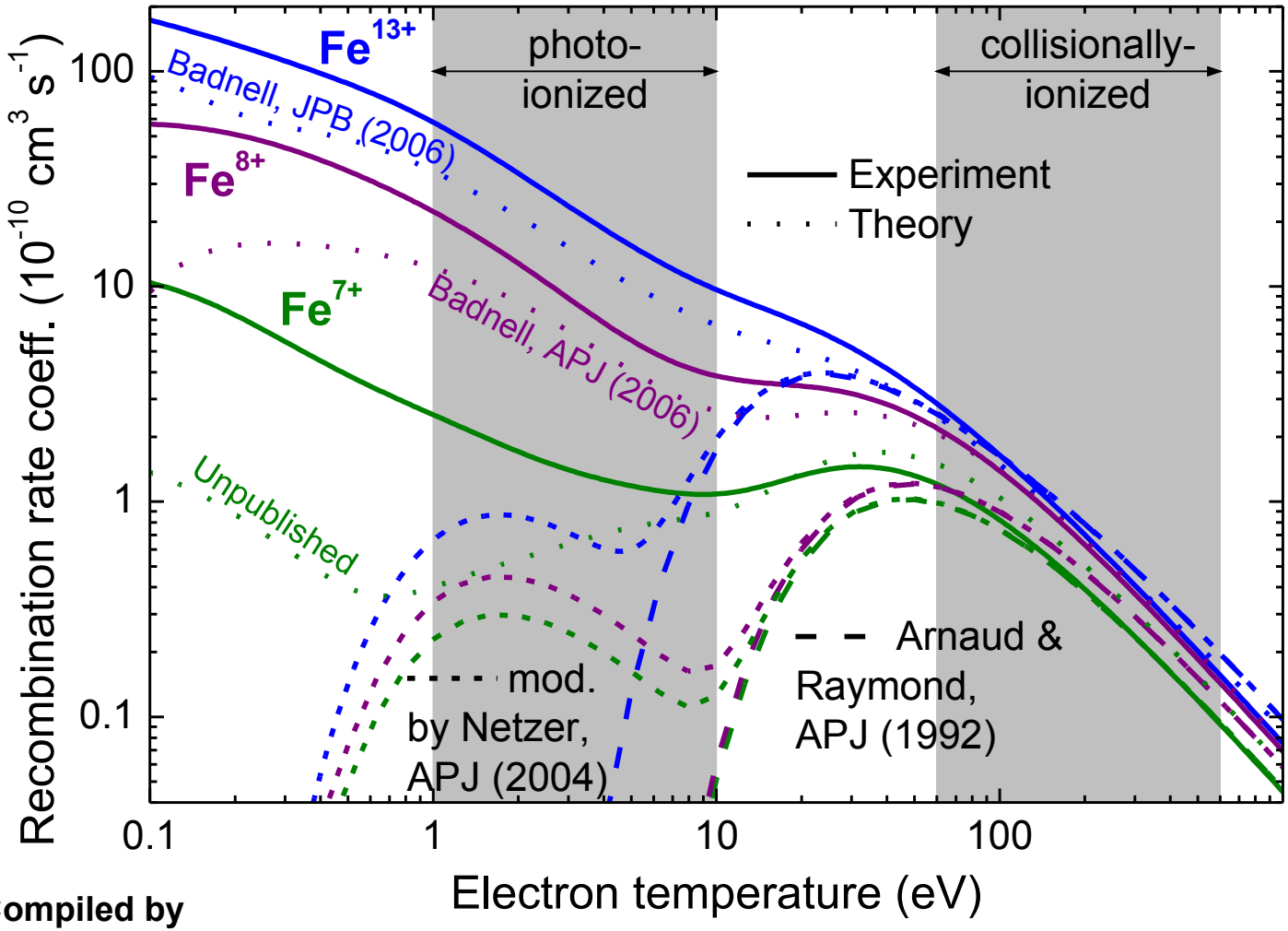
Derived thermal plasma rate coefficients

Al-like Fe^{13+}

$3s^2 3p\ (^2P_{1/2})$

→ **$3s3p^2\ n\ell$**

→ **$3s^2 2p\ (^2P_{3/2})\ n\ell$**



Compiled by S. Schippers

E. W. Schmidt et al., Astrophys. J. Lett. 641, L157 (2006)

Tungsten ions: merged beams rate coefficients

Xe-like W^{20+}

$4d^{10}\ 4f^8\ (^7F_6)$

→ $4d^9\ 4f^9\ n\ell$

→ $4d^{10}\ 4f^9\ 5d\ n\ell$

→ $4d^{10}\ 4f^9\ 5g\ n\ell$

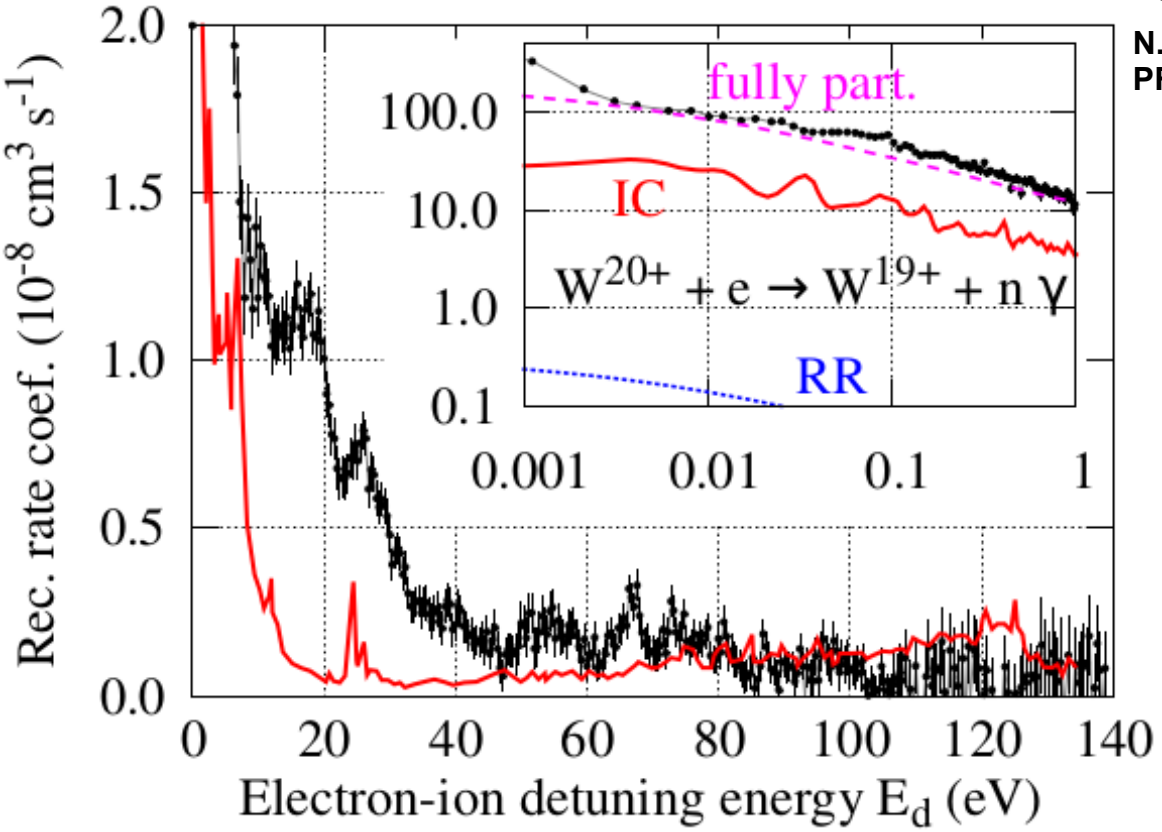
→ $4d^{10}\ 4f^8$ (f.s.) $n\ell$

(0 … 30 eV)

W^{20+} $[Kr]4d^{10}4f^8$

S. Schippers et al., PRA 83, 012711 (2011)

N. Badnell et al., PRA 85, 052716 (2012)



C. Krantz et al., J. Phys. B Topical Review (JPB accepted aper link 2016)

Fully partitioned (statistical) calculation

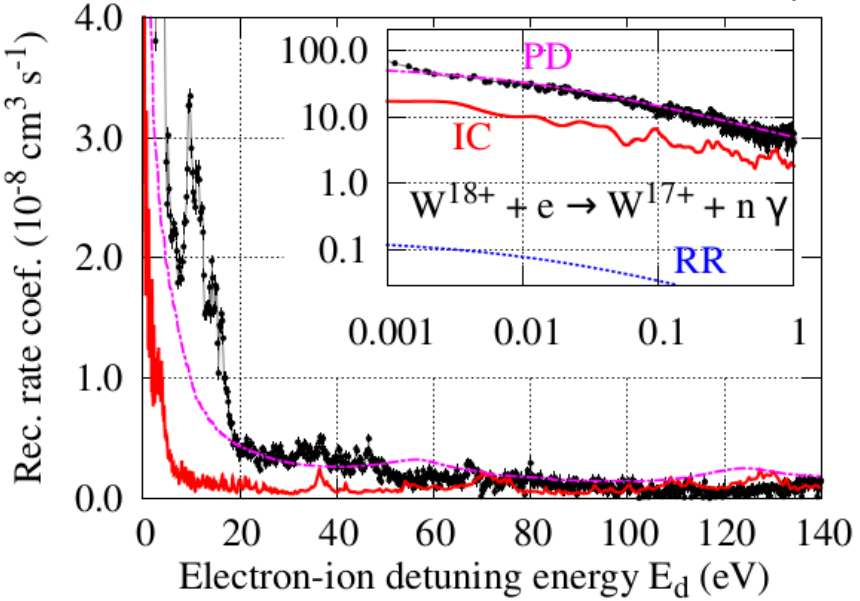
Intermediate coupling calculation

Radiative recombination

Tungsten ions: merged beams rate coefficients

W^{18+} $[Kr]4d^{10}4f^{10}$

K. Spruck et al., PRA 90, 032715 (2014)



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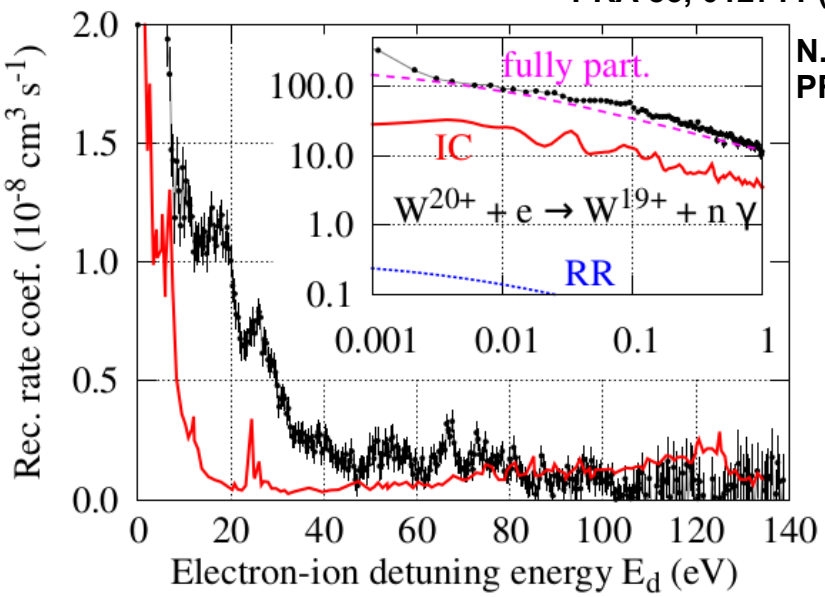
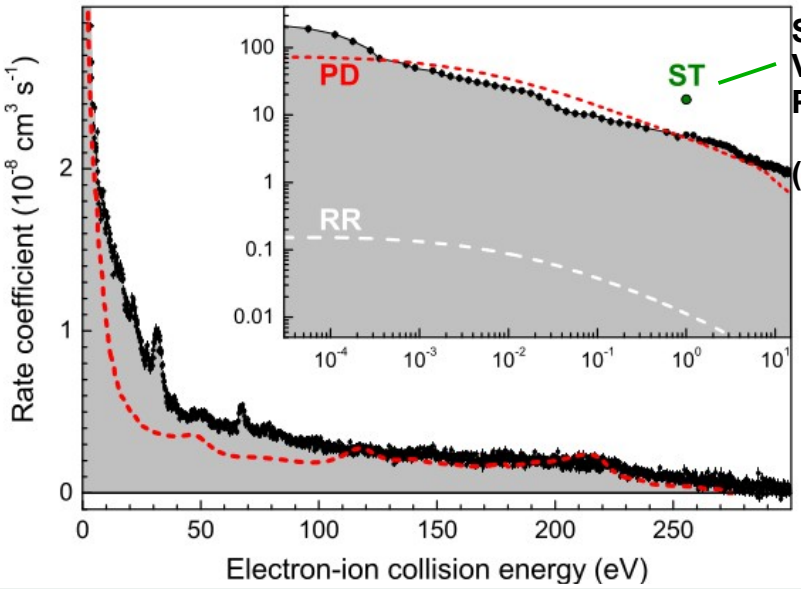


W^{19+} $[Kr]4d^{10}4f^{9}$

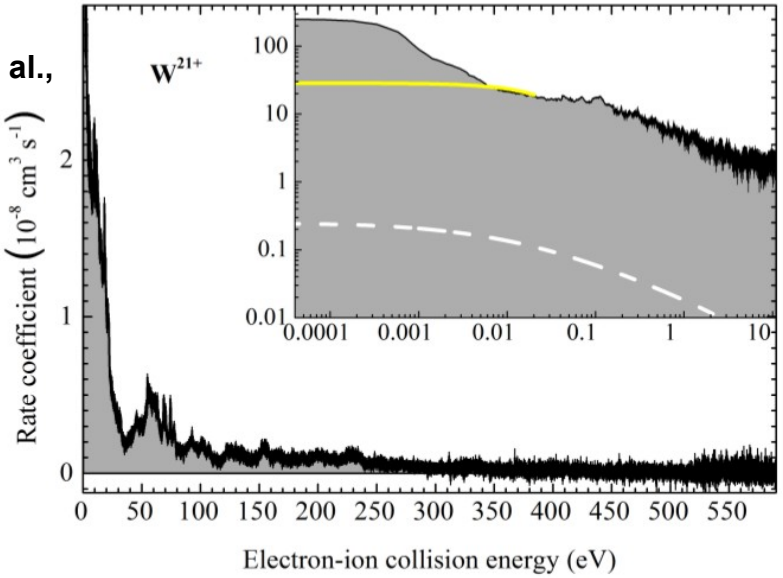
N. Badnell et al., PRA 93, 052703 (2016)

Stat. theor. V. A. Dzuba et al., PRA 86, 022714 (2012).



W^{21+} $[Kr]4d^{10}4f^{7}$

K. Spruck, Thesis, Univ. of Giessen, 2015

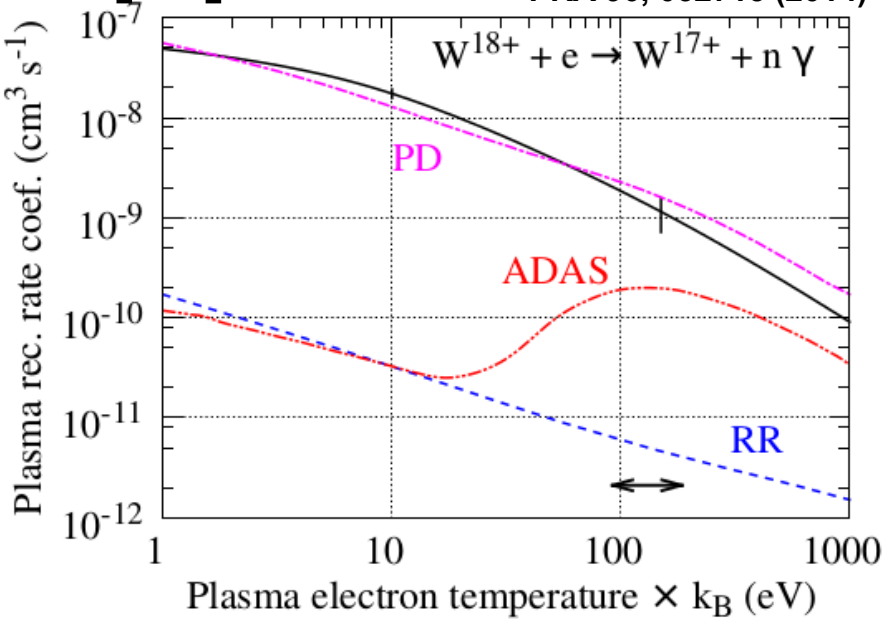


~37% accuracy (90% conf.) incl. non-detection of $n > 69$

Tungsten ions: plasma recombination rate constants

W^{18+} [Kr]$4d^{10}4f^{10}$

K. Spruck et al., PRA 90, 032715 (2014)



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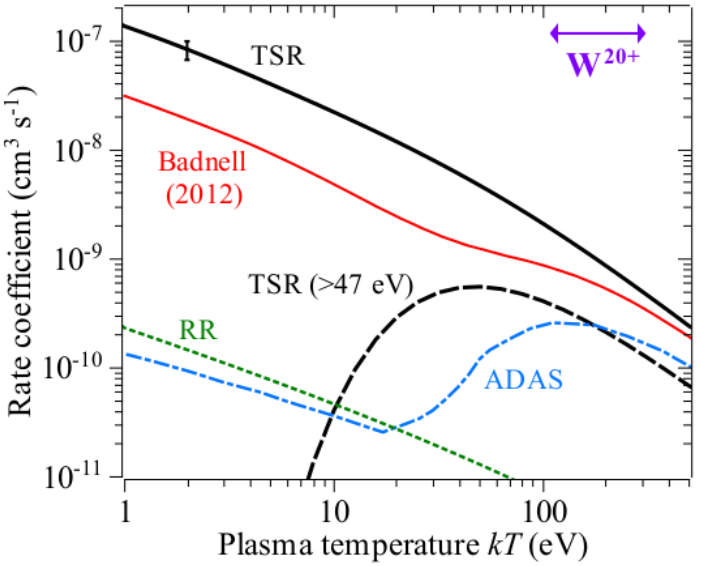

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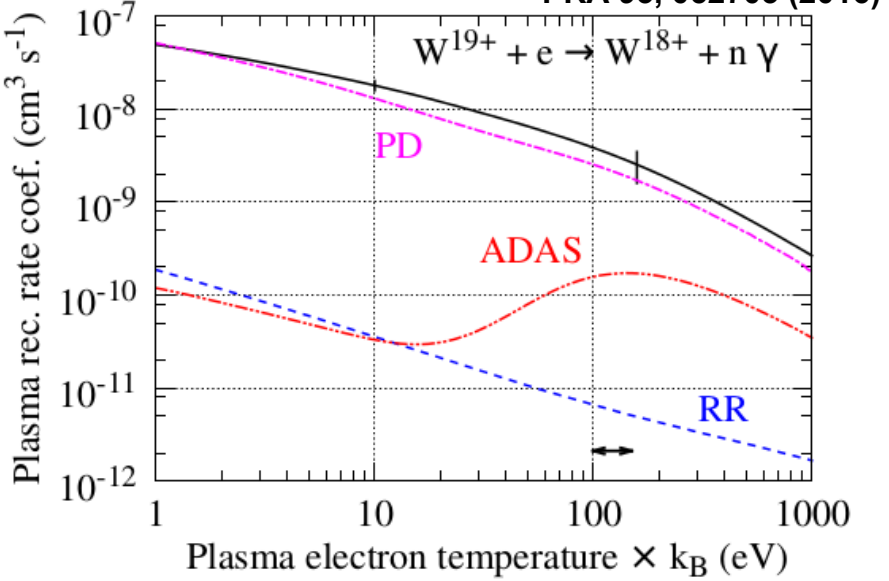

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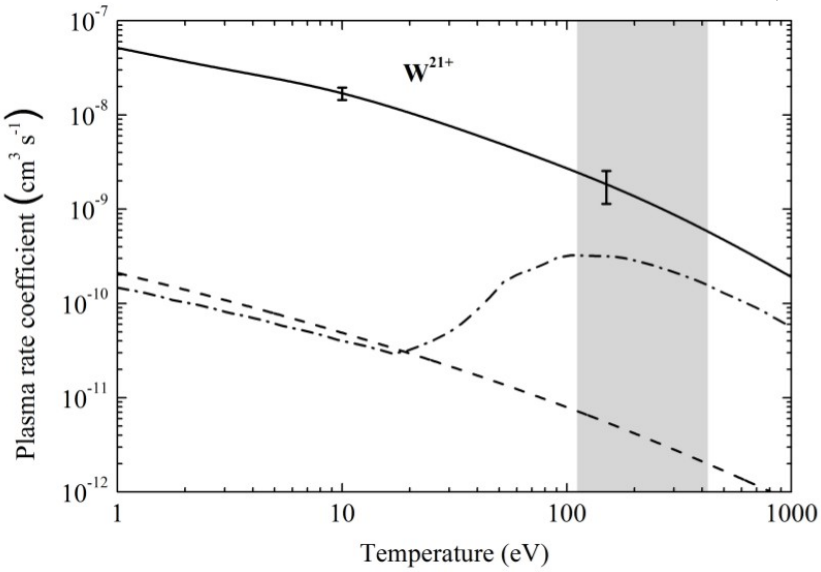
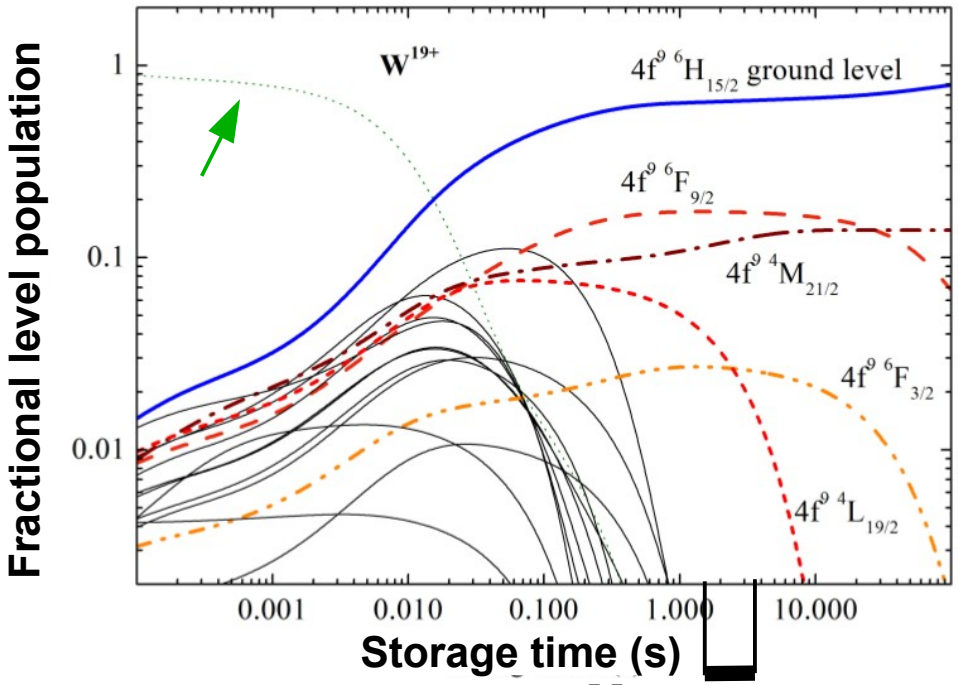


~37% accuracy (90% conf.) @150 eV

Tungsten ions: excited ionic states

W^{19+} [Kr]$4d^{10}4f^9$



$k_B T$ = 560 eV

(for ion velocity in stripping target ~10 MeV W carbide anions)

Metastable levels

W^{19+} [Kr]$4d^{10}4f^9$ and $4d^{10}4f^8$ 5s

E_{ex} (eV)	level	lifetime (s)
0	$4f^9\ {}^6H_{15/2}$	∞
2.114	$4f^9\ {}^5H_{11/2}$	1.54×10^{-1}
2.523	$4f^9\ {}^5F_{9/2}$	$8.88\times10^{+1}$
2.588	$4f^9\ {}^5F_{11/2}$	4.17×10^{-2}
2.979	$4f^9\ {}^5H_{9/2}$	3.53×10^{-2}
3.422	$4f^9\ {}^3H_{7/2}$	4.90×10^{-2}
3.602	$4f^9\ {}^5F_{7/2}$	4.57×10^{-2}
3.839	$4f^9\ {}^5H_{5/2}$	2.83×10^{-1}
4.178	$4f^9\ {}^5F_{3/2}$	$3.48\times10^{+1}$
4.524	$4f^9\ {}^5F_{1/2}$	3.41×10^{-1}
6.025	$4f^9\ {}^3M_{21/2}$	∞
6.065	$4f^9\ {}^5K_{17/2}$	4.23×10^{-2}
6.343	$4f^9\ {}^3L_{19/2}$	$2.31\times10^{+0}$
12.117	$4f^9\ {}^3O_{23/2}$	4.78×10^{-2}
28.278	$4f^8\ 5s\ {}^3H_{25/2}$	6.39×10^{-2}

+ 2468 other levels τ < 10 ms

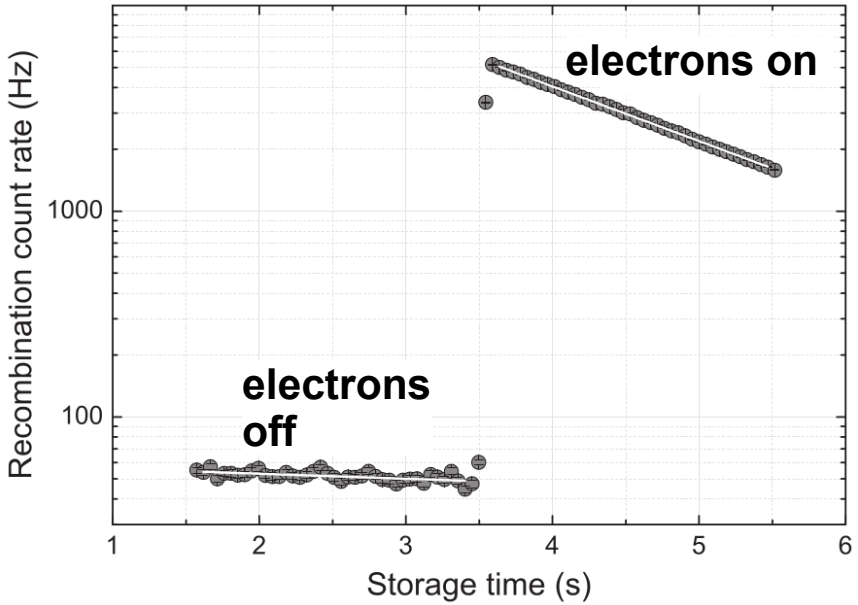
K. Spruck, Thesis,
Univ. of Giessen, 2015

Absolute normalization: the lifetime method

H. B. Pedersen, Phys. Rev. A 72, 012712 (2005)
O. Novotný, Astrophys. J. 777, 54 (2013)

W^{18+}

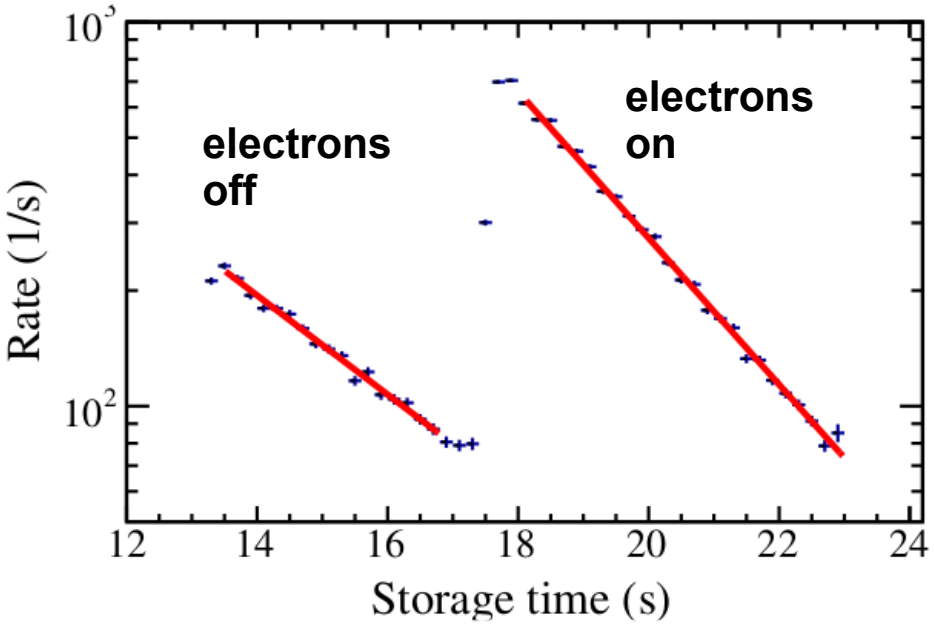
$n_e \sim 1 \times 10^7$ cm^{-3}



K. Spruck et al.,
PRA 90, 032715 (2014)

SH^+

$n_e \sim 3 \times 10^6$ cm^{-3}



A. Becker, Thesis,
Univ. of Heidelberg, 2016

Electron induced loss rate r
Overlap fraction L_e/C
Electron density n_e

} Reaction rate constant
$\alpha = r/(n_e \cdot \text{overlap fraction})$

Detuning energy $E_d = 0$

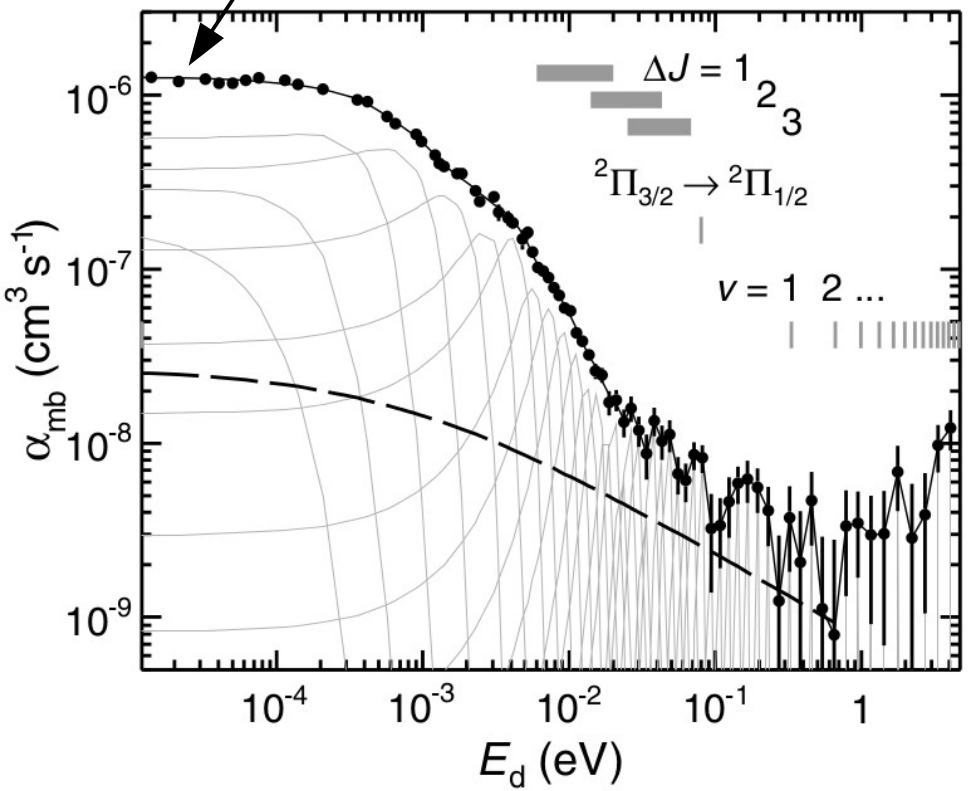
Molecular recombination measurements: Analysis

$HCl^+ + e \rightarrow H + Cl + \varepsilon_{kin}$

O. Novotný, Astrophys. J. 777, 54 (2013)

Merged-beams rate coefficient signal

Calibration:
Lifetime method



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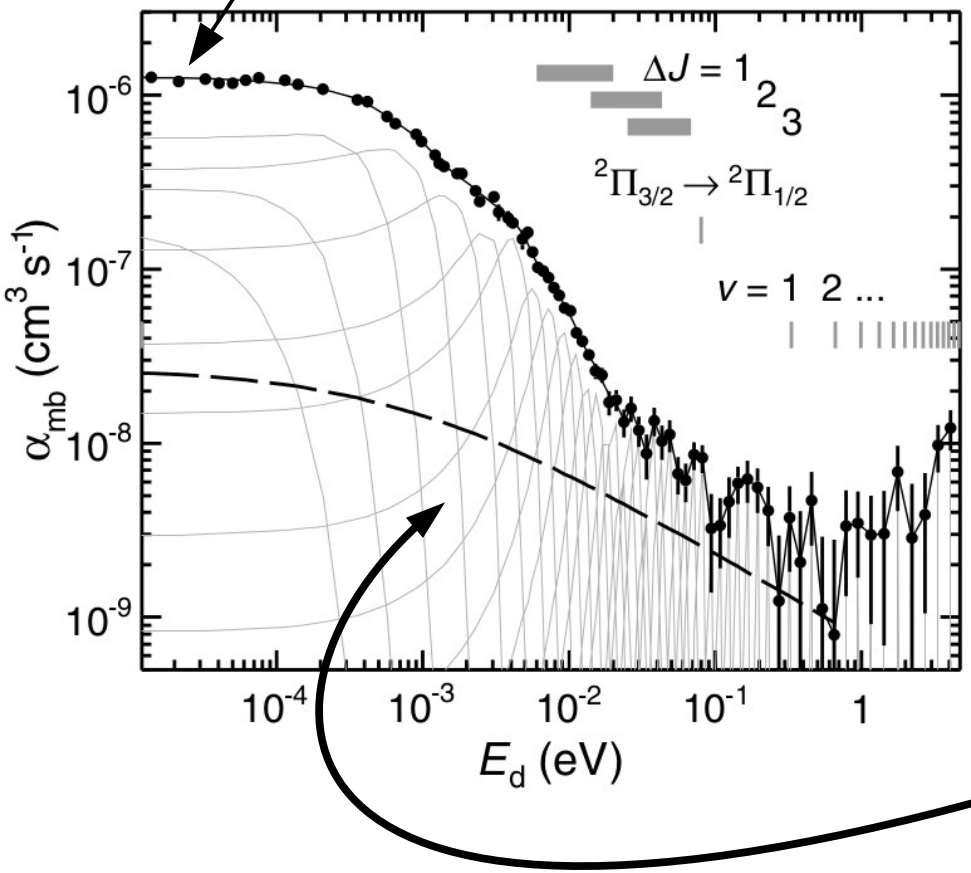
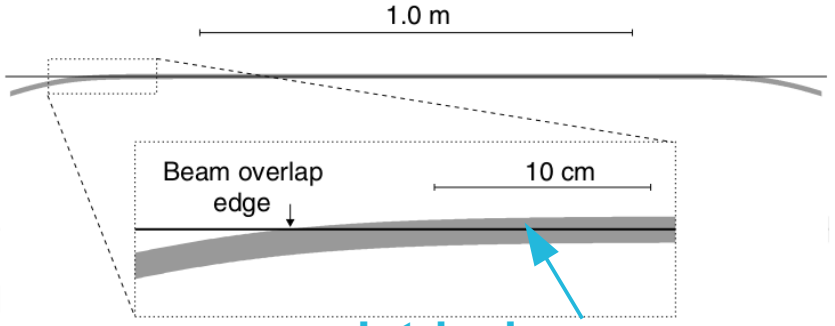
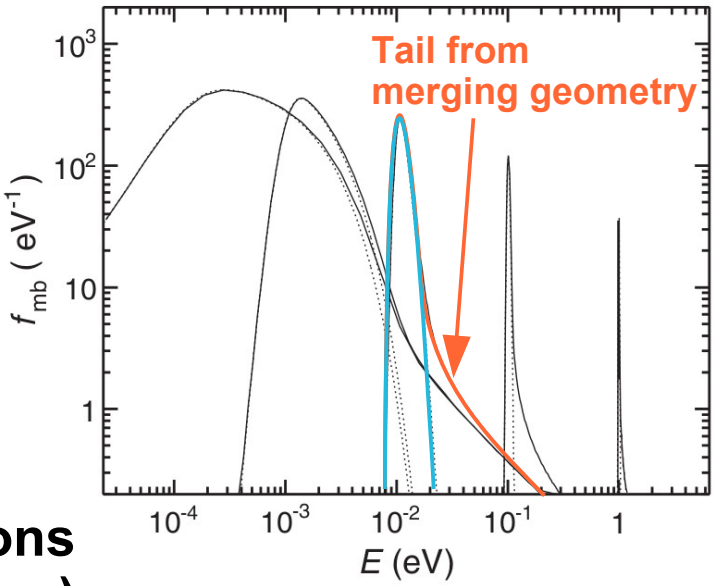


Overlap geometry



Intrinsic electron velocity distribution

Effective **energy distribution**



Binned signal contributions (fitted cross section values)

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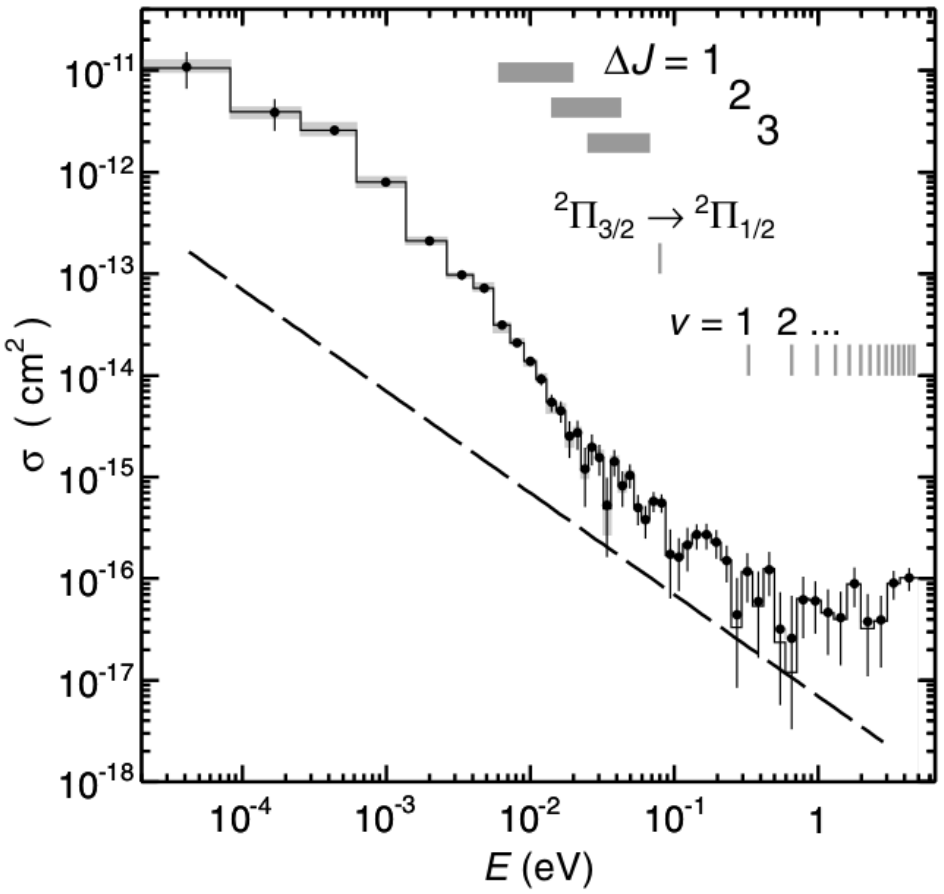
O. Novotný, Astrophys. J. 777, 54 (2013)

Binned cross section



Molecular recombination measurements: Analysis

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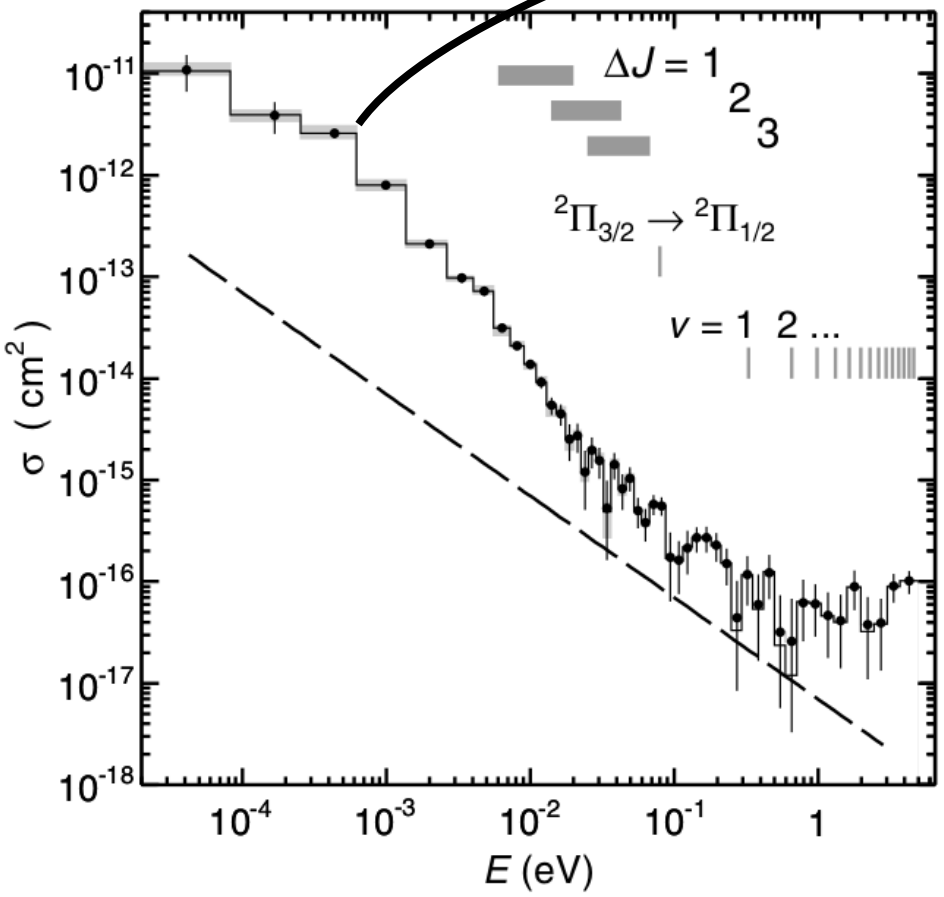
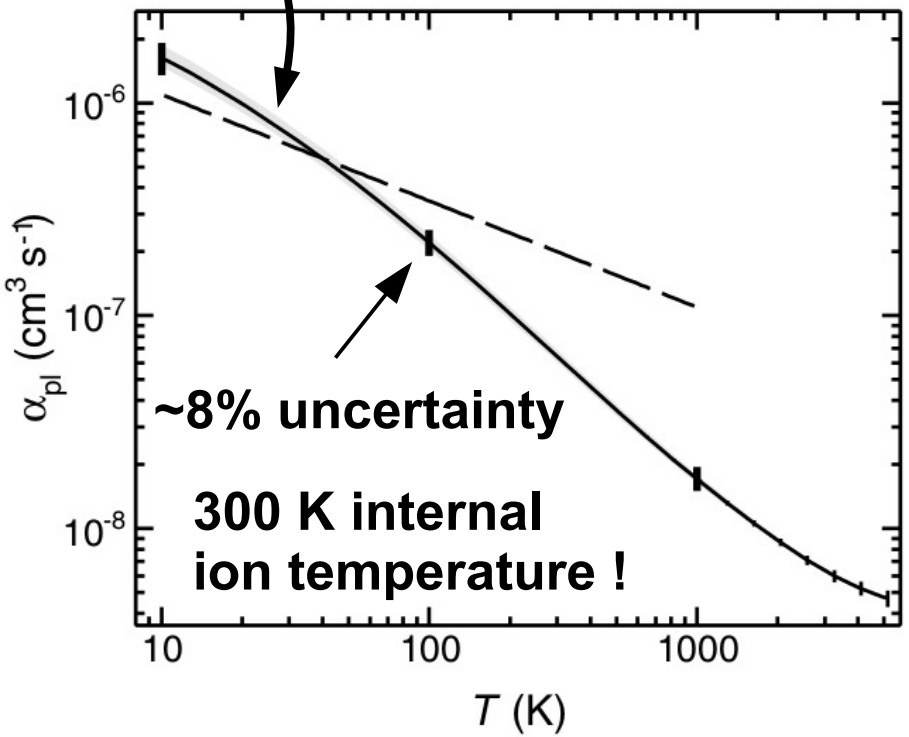
O. Novotný, Astrophys. J. 777, 54 (2013)

Binned cross section

Maxwellian distribution

Plasma rate coefficient





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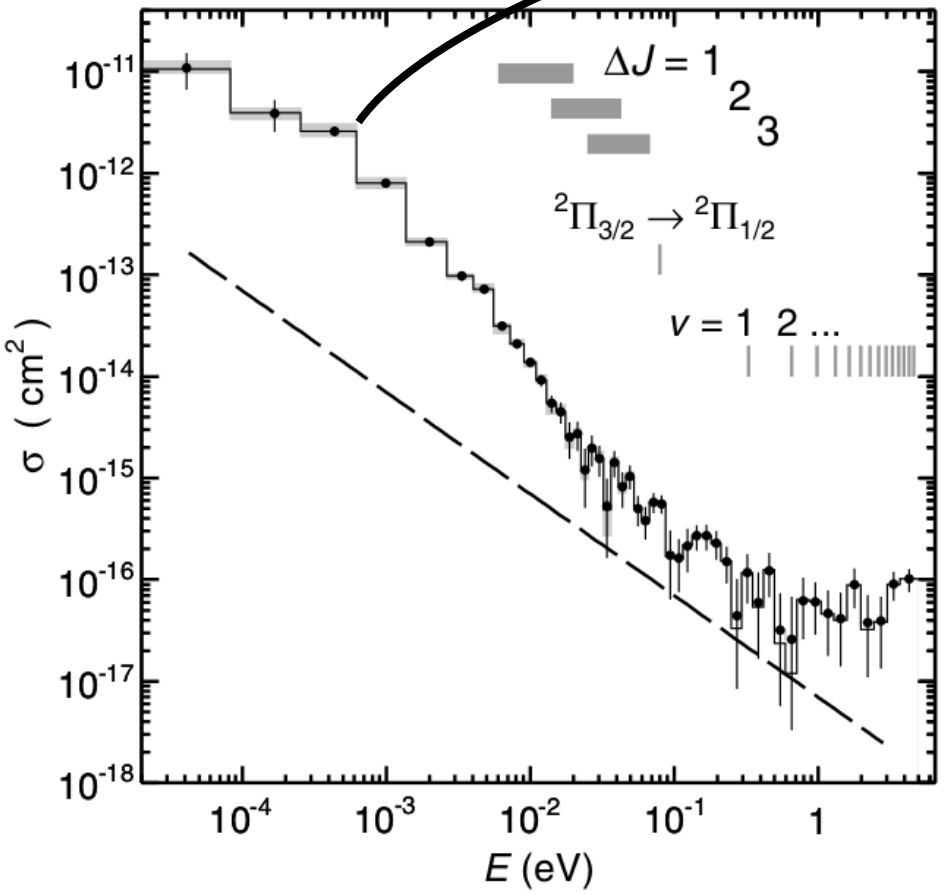
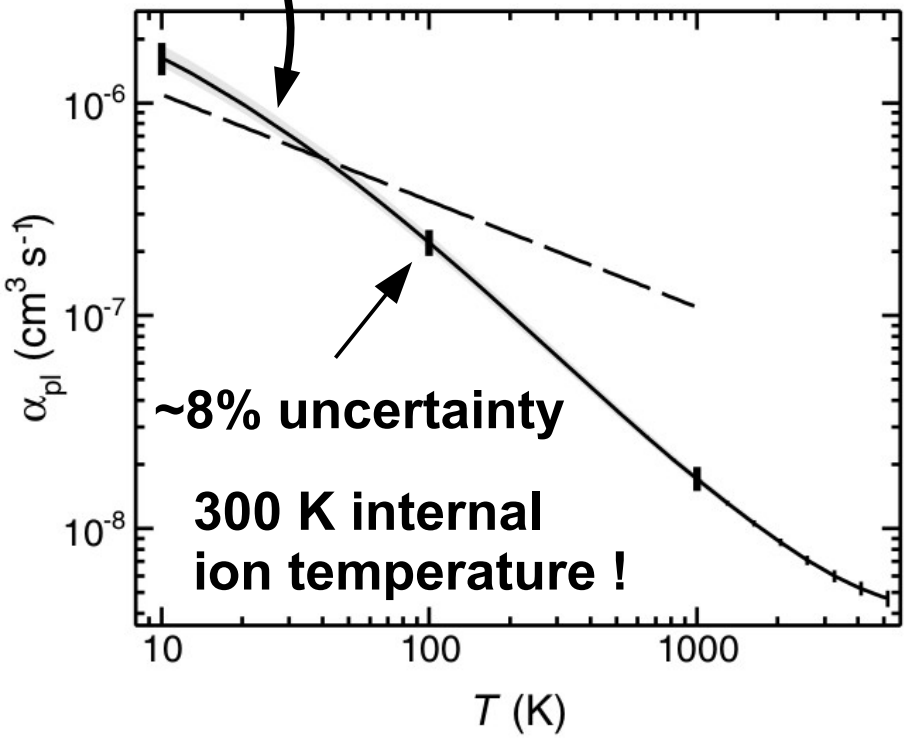
Plasma rate coefficient





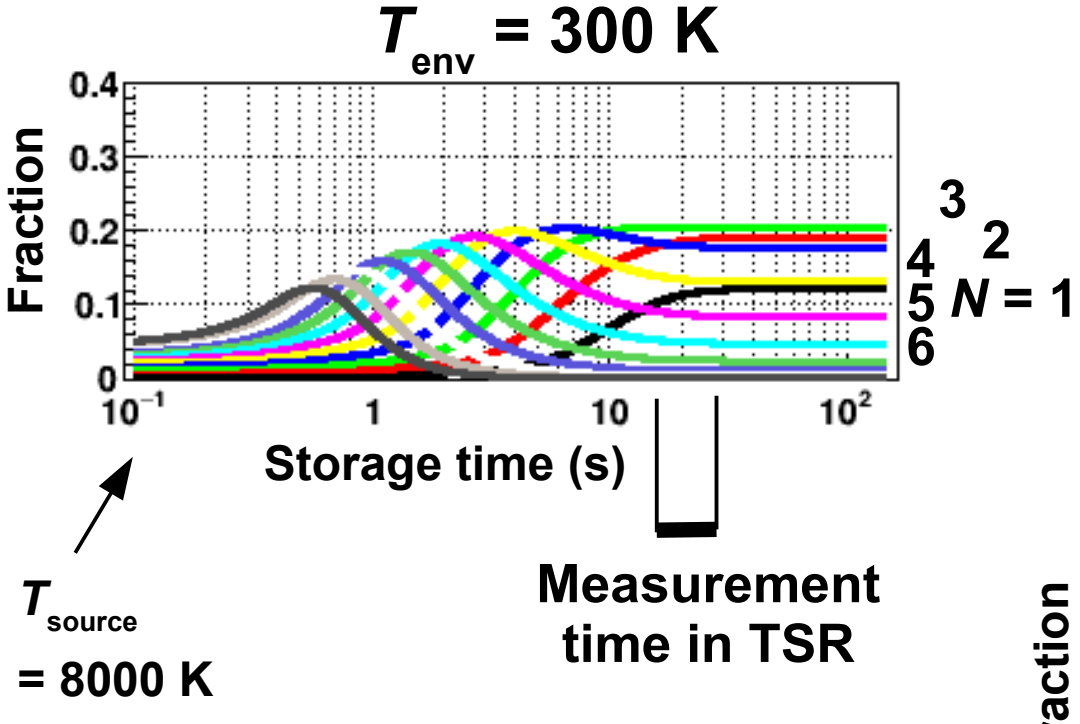
Fit model for temperature curve of rate coefficient

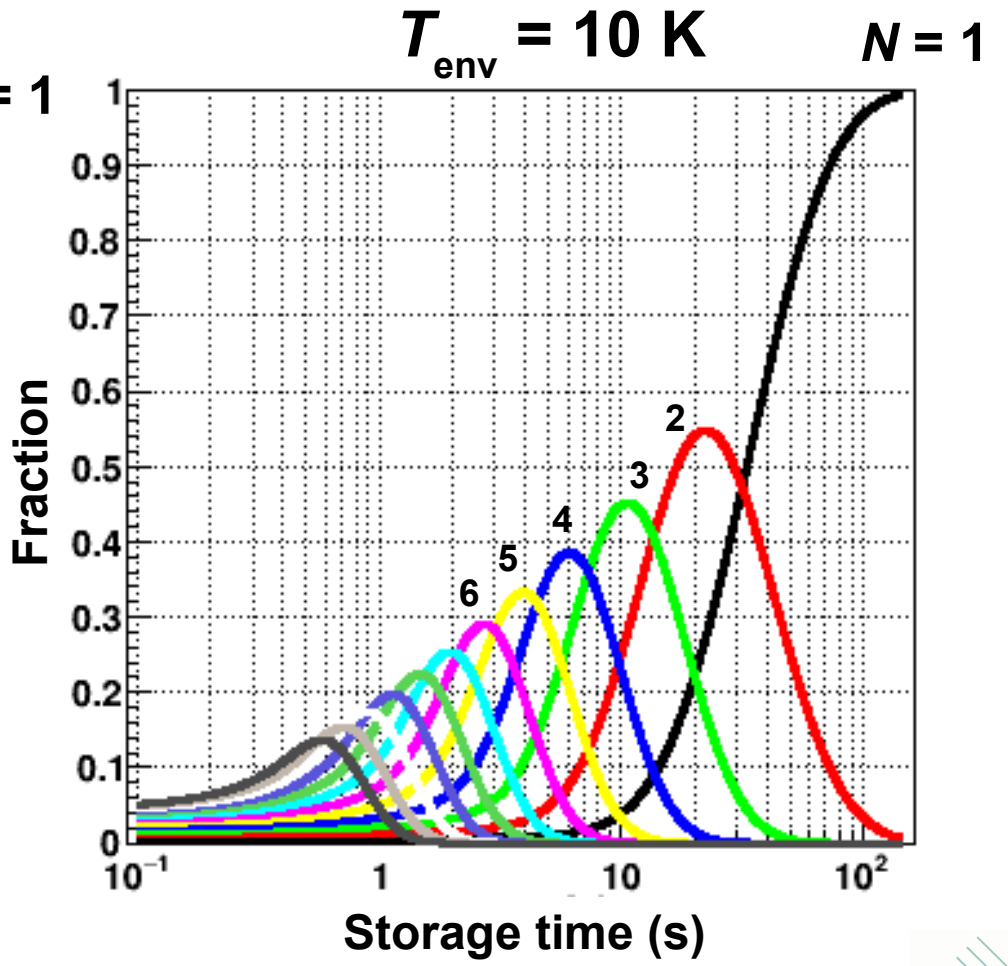
$$\alpha_{\mathrm{pl}}^{\mathrm{fit}}(T) = A\left(\frac{300}{T}\right)^{n} + B$$

$$B = T^{-3/2}\sum_{i=1}^{4} c_i \exp(-T_i/T)$$

Internal rotational excitation

Rotational populations in $\Pi_{3/2}$ ground state of HCl^+ ions stored in vacuum



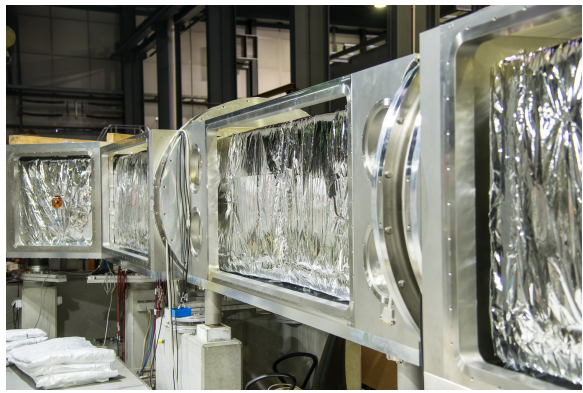


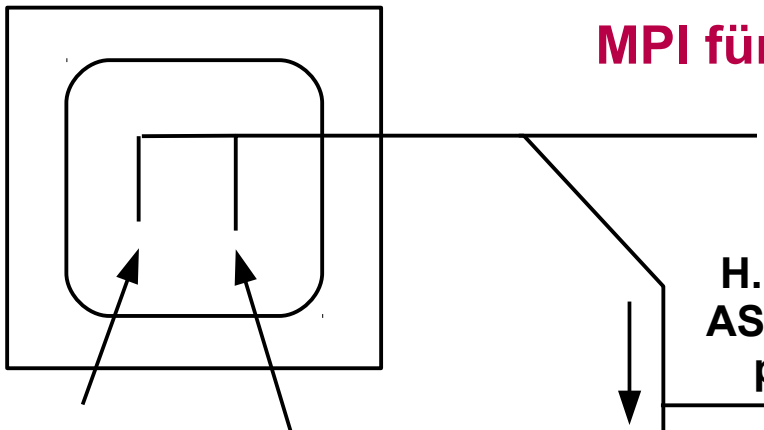
Radiative relaxation only

(electron collisional effects not included)

CSR laboratory

MPI für Kernphysik, Heidelberg



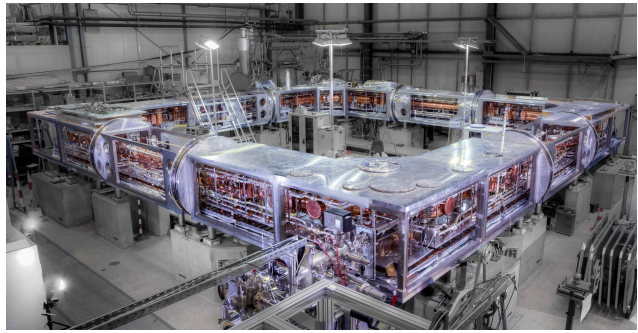


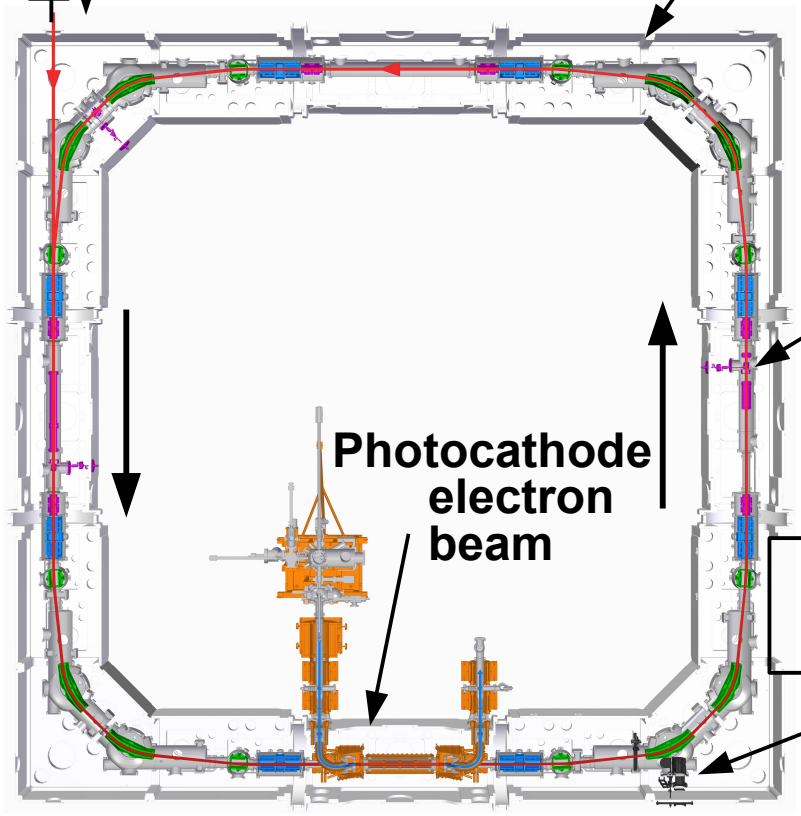
Second
ion source
±60 kV

H. Kreckel
ASTROLAB
project

Cryostat

Merged neutral atom
beam





2 K to 10 K
inner beam vacuum

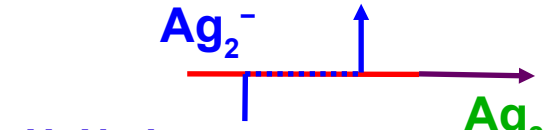
2 K
refrigerator

Neutral fragment
detectors

5 m

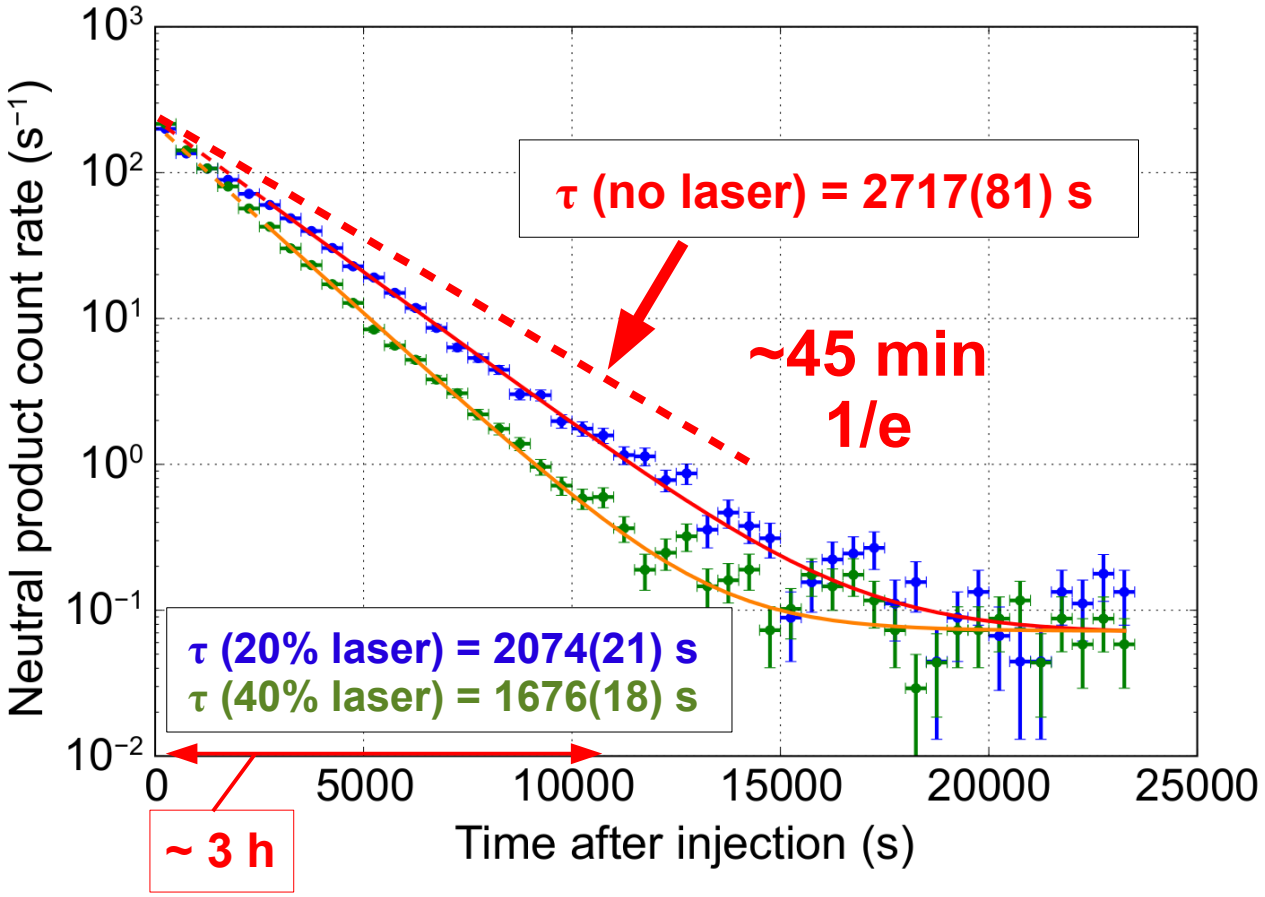
CSR: Beam lifetime measurement by photodetachment

60 keV Ag_2^- + *hν* (1.9 eV) → Ag_2 + e^- (*A* = 216)



HeNe laser chopped (20% 40%)

Ag_2^- EA: 1.02 eV



C. Meyer
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O. Novotný
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Vacuum

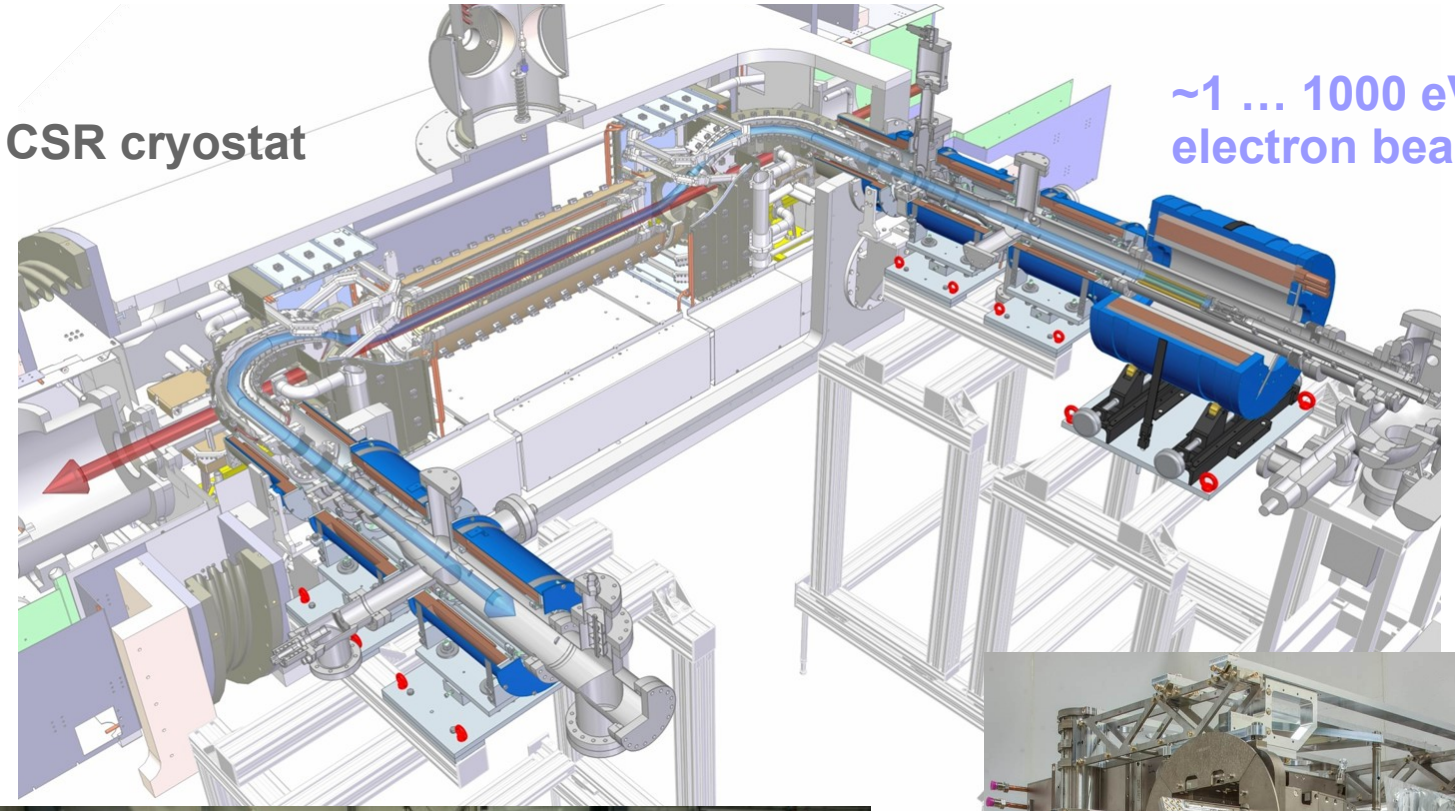
$n < 140\ cm^{-3}$
$P_{RTE} < 5.8 \times 10^{-15}$ mbar

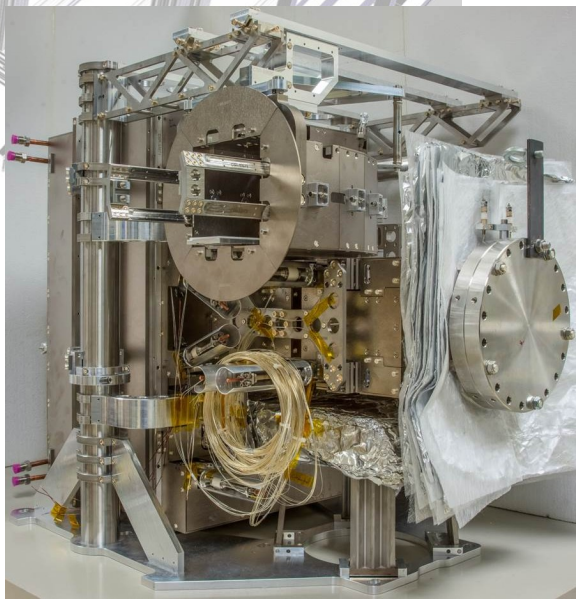
R. von Hahn et al., Rev. Sci. Instrum. 87, 063115 (2016)

CH^+ resonant photodissociation

A. O'Connor et al., Phys. Rev. Lett. 116, 113002 (2016)

Installation of the CSR merged electron beam





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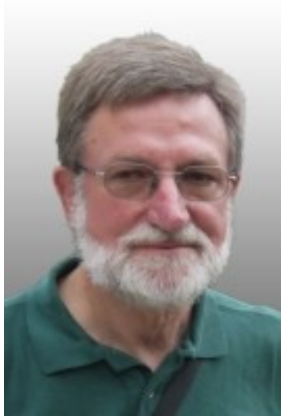

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Acknowledgments – CSR

CSR detectors,
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