Electron–Ion Collision Experiments in Storage Rings: Cross Section Data and Fundamental Understanding

Andreas Wolf

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Experimentalists' Network on Atomic and Molecular Data
IAEA Vienna
Nov 19 – 21, 2018

Outline

Merged electron–ion beam experiments

Experimental facilities

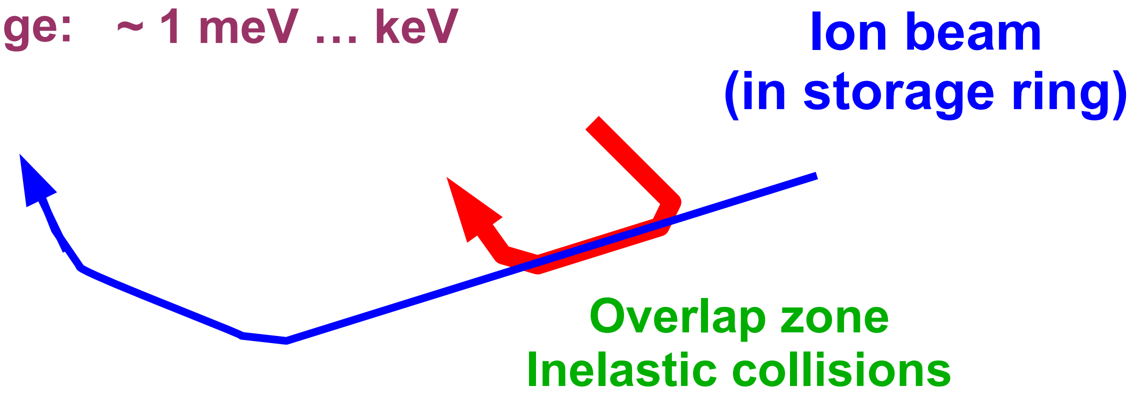
Plasma rate constants from high-resolution recombination measurements:
Atoms
Molecules
State-selected cold molecules

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



Merged-beams electron ion collisions

Velocity-matched electron beam

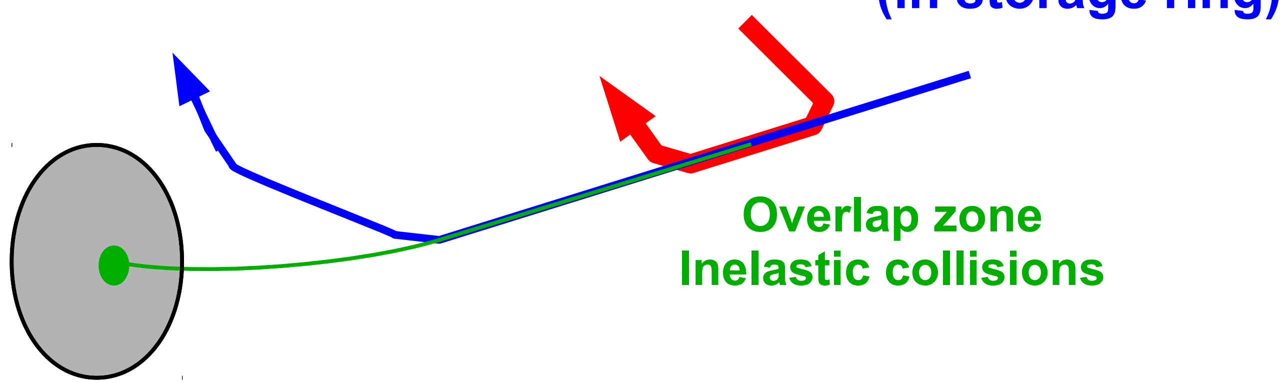
Collision energy: $E_d = \frac{1}{2} m_e (v_e - v_i)^2$

Wide scan range: ~ 1 meV … keV

Products:

Charge changing reaction (radiative, dielectronic recombination)

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



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

Products:

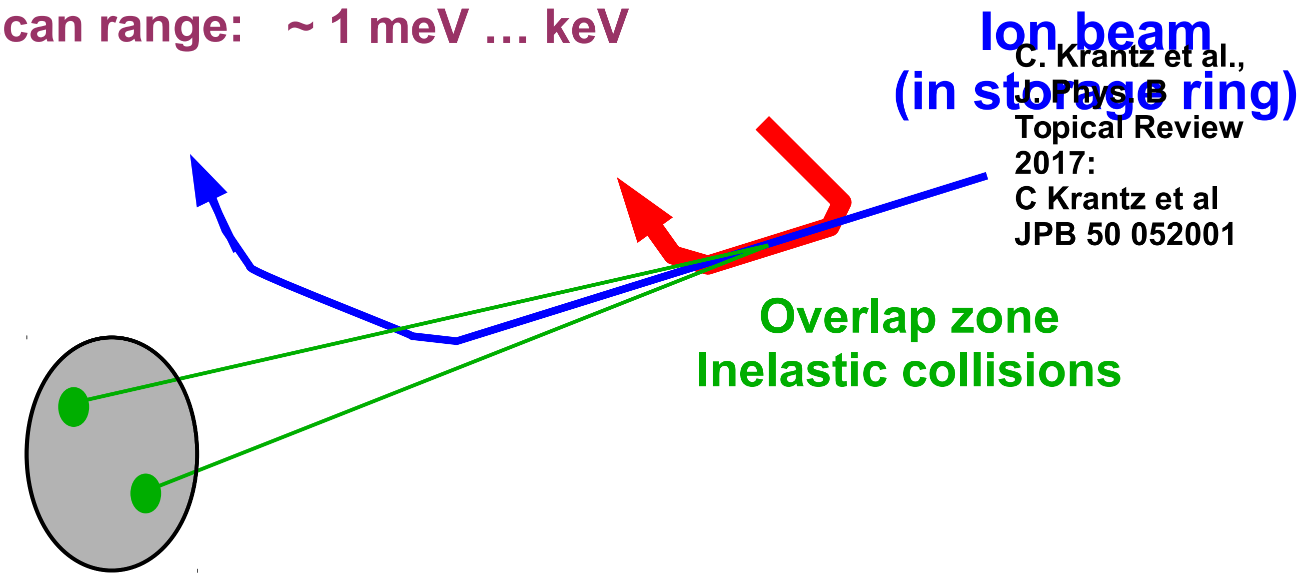
Charge changing reaction (radiative, dielectronic recombination)

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

Fragmentation (dissociative recombination)

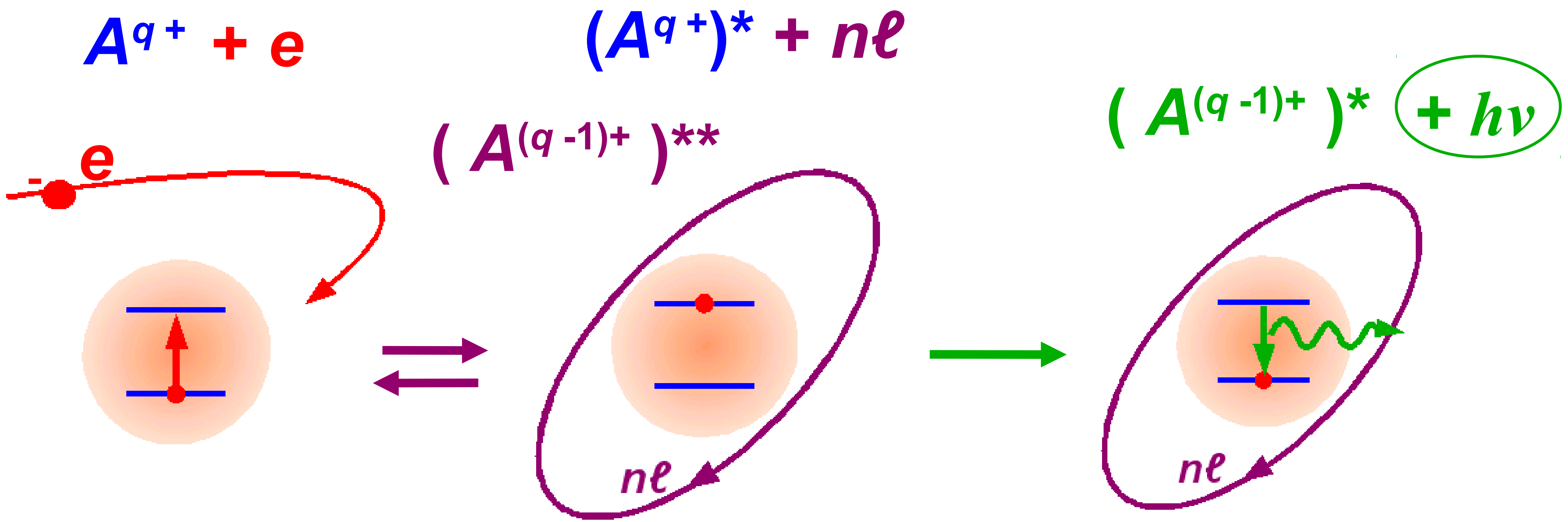
$$AB^+ + e^- \rightarrow A + B + \varepsilon$$

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



C. Krantz et al., J. Phys. B Topical Review 2017: C Krantz et al JPB 50 052001

Resonant (“dielectronic”) recombination



Doubly excited state

Feshbach resonance in the electronic continuum

Ion core excitations

Photoemission from doubly excited state

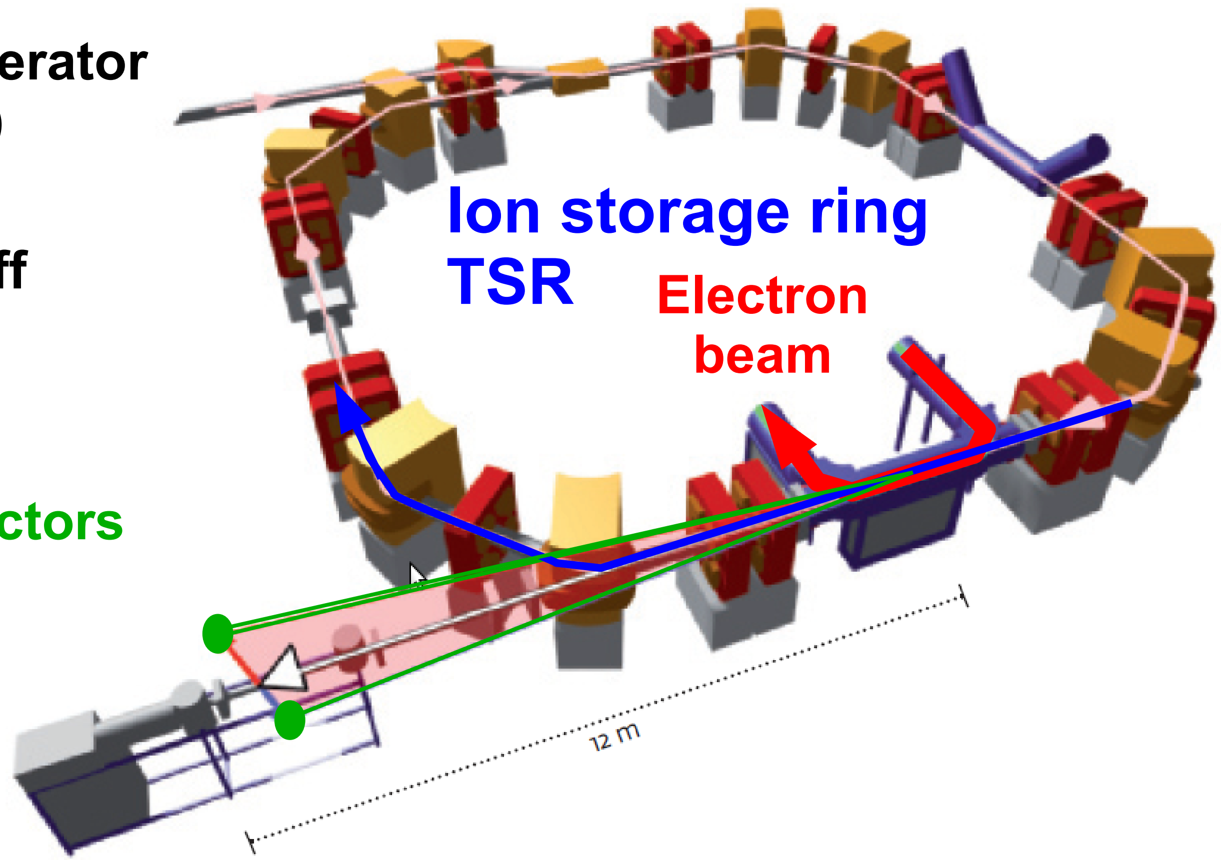
Storage ring merged beams experiments

Tandem accelerator
(~ 10 MeV·q)

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

Fragment detectors

Max-Planck-Institut
für Kernphysik
1988 to 2012

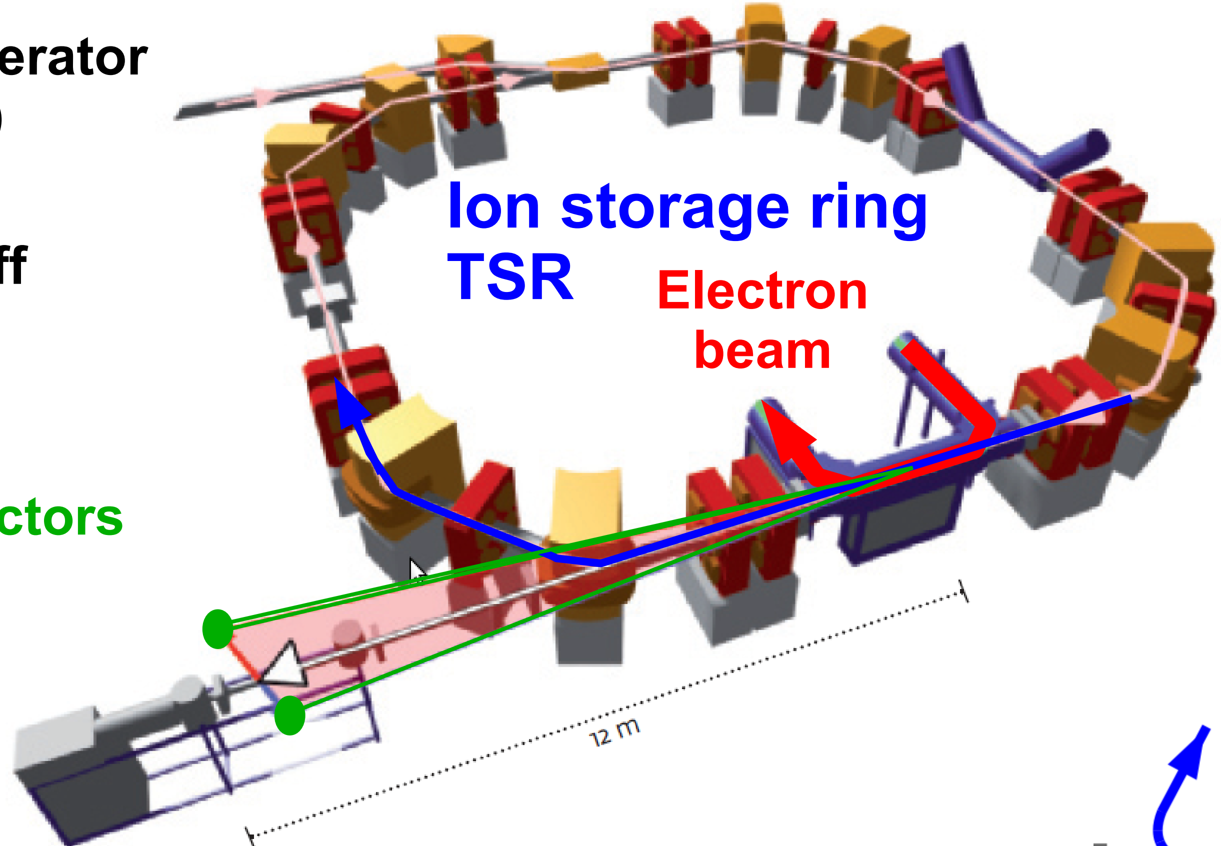


Storage ring merged beams experiments

Tandem accelerator
(~ 10 MeV·*q*)

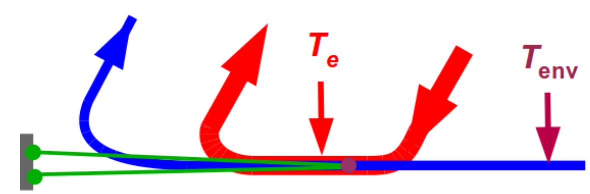
Molecule
Van-de-Graaff
(~ 1...2 MeV)

Max-Planck-Institut für Kernphysik
1988 to 2012



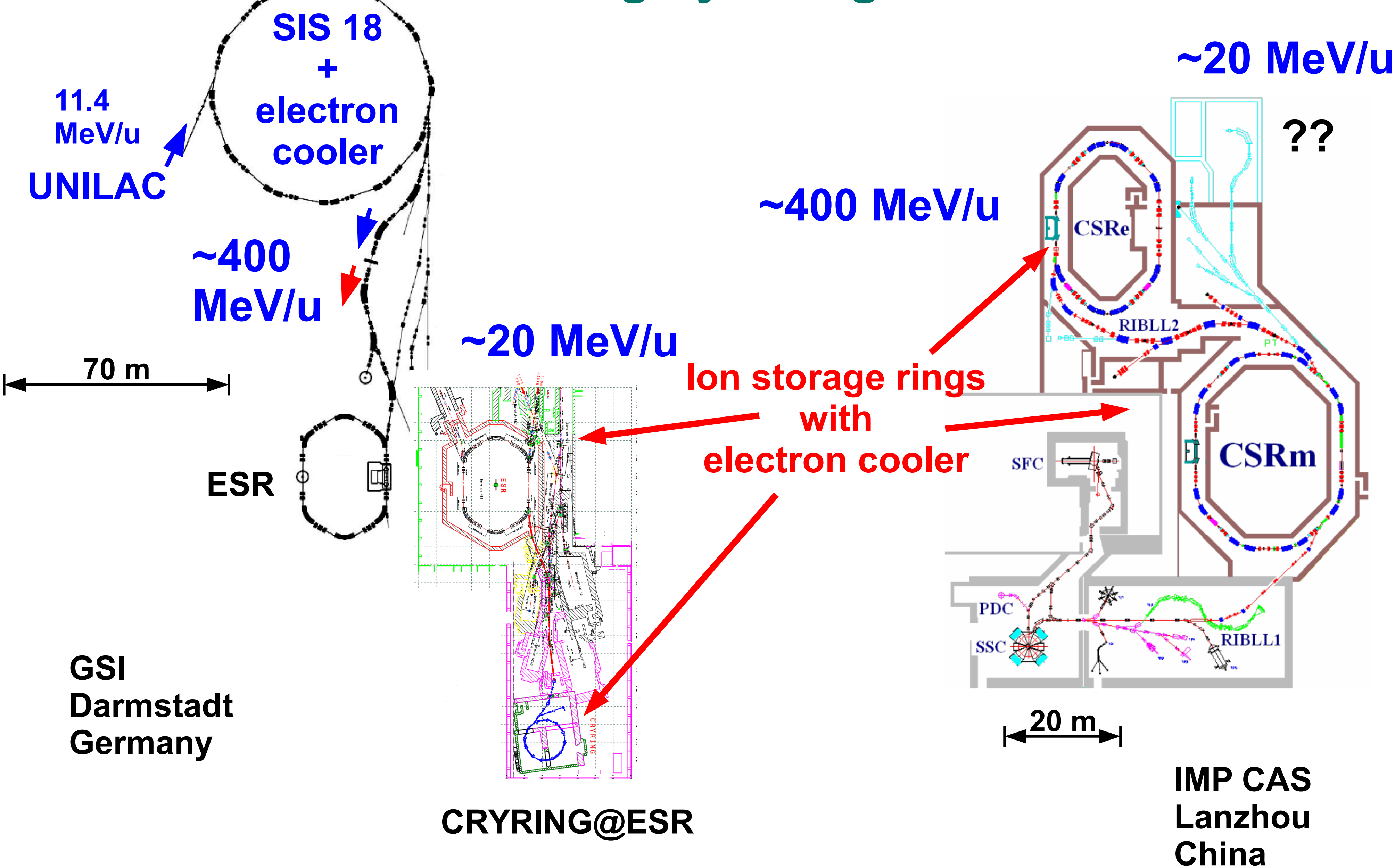
Molecular ion beam

Fragment detectors



- 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

Present merged electron beam experimental facilities for highly charged ions



Iron ion dielectronic recombination

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

X-ray view of Galaxy M 106
with supermassive black hole

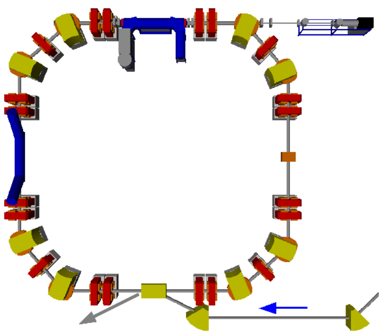
NASA/CXC/Univ. Maryland/A.S. Wilson et al./
Palomar Observatory DSS/JPL-Caltech/NRAO/AUI/NSF

X-ray ionized plasma

High ion charge states
by photoionization

Low electron
temperature

→ Charge states dependent on
$\Delta N = 0$ dielectronic recombination



NASA-funded storage ring studies at TSR

D. W. Savin, Columbia Astrophysics Laboratory, NY

S. Schippers, A. Müller et al., Univ. Gießen, Germany

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

Iron ion dielectronic recombination

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

F-like Fe^{17+}

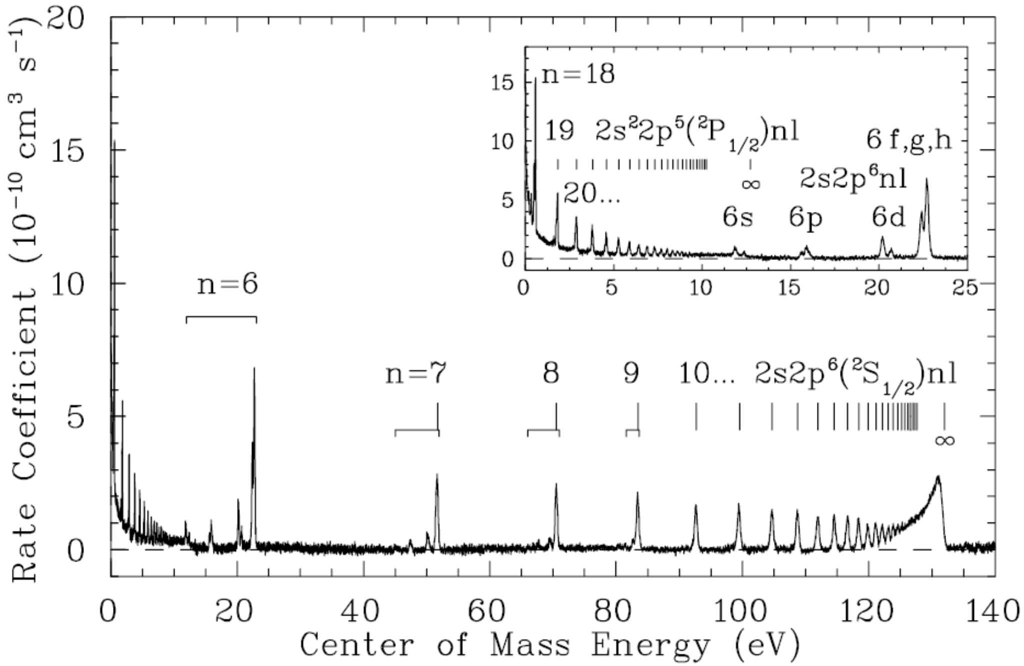
$2s^22p^5\ (^2P_{3/2}) \rightarrow 2s2p^6\ n\ell$

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

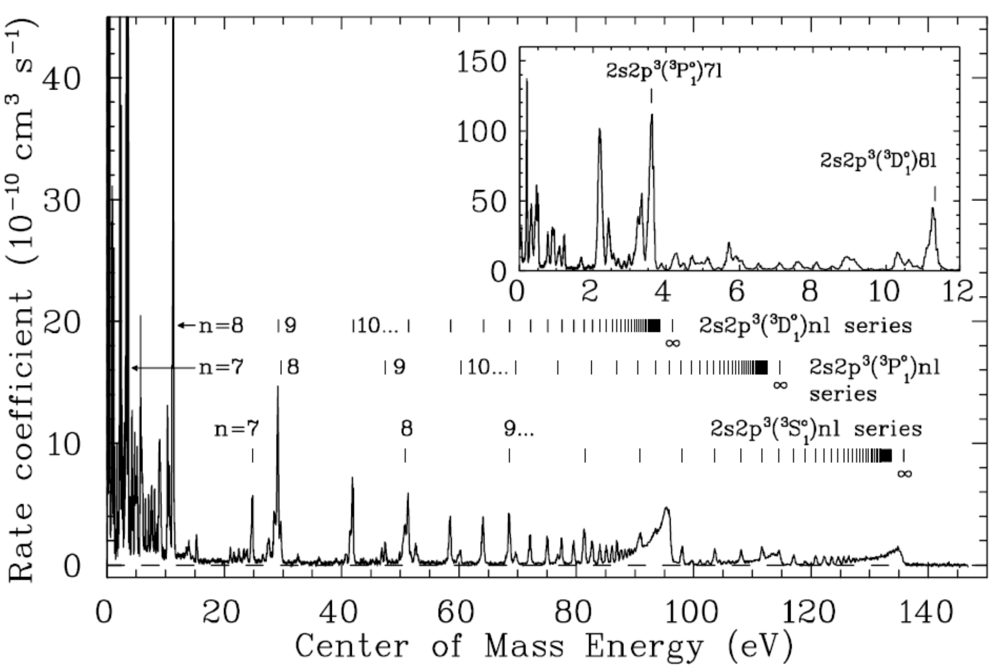
C-like Fe^{20+}

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

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



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

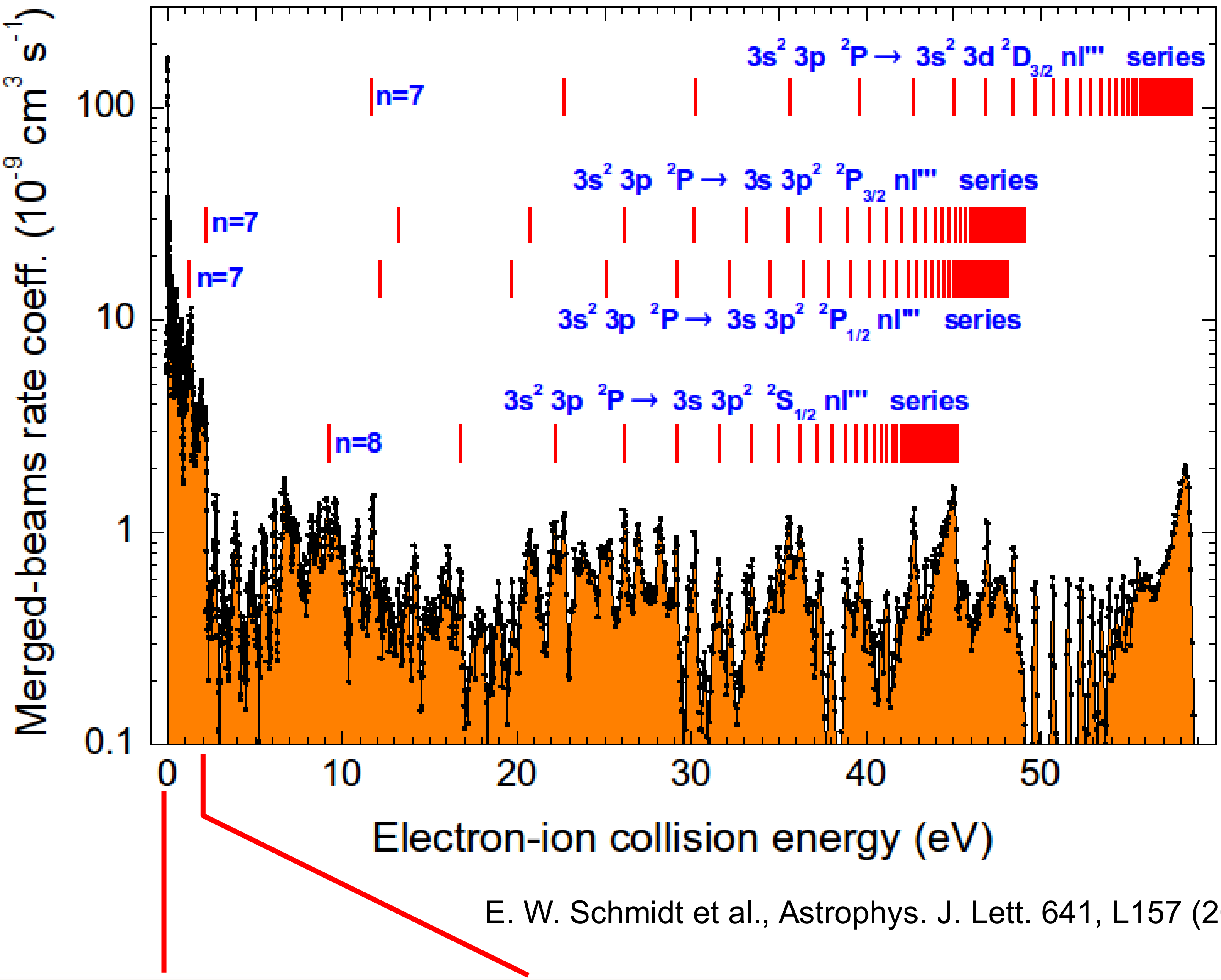
$Fe^{13+} + e \rightarrow (Fe^{12+})^{**} \rightarrow (Fe^{12+})^{*} + h\nu$

Al-like Fe^{13+}

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

$\rightarrow 3s3p^2\ n\ell$

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



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

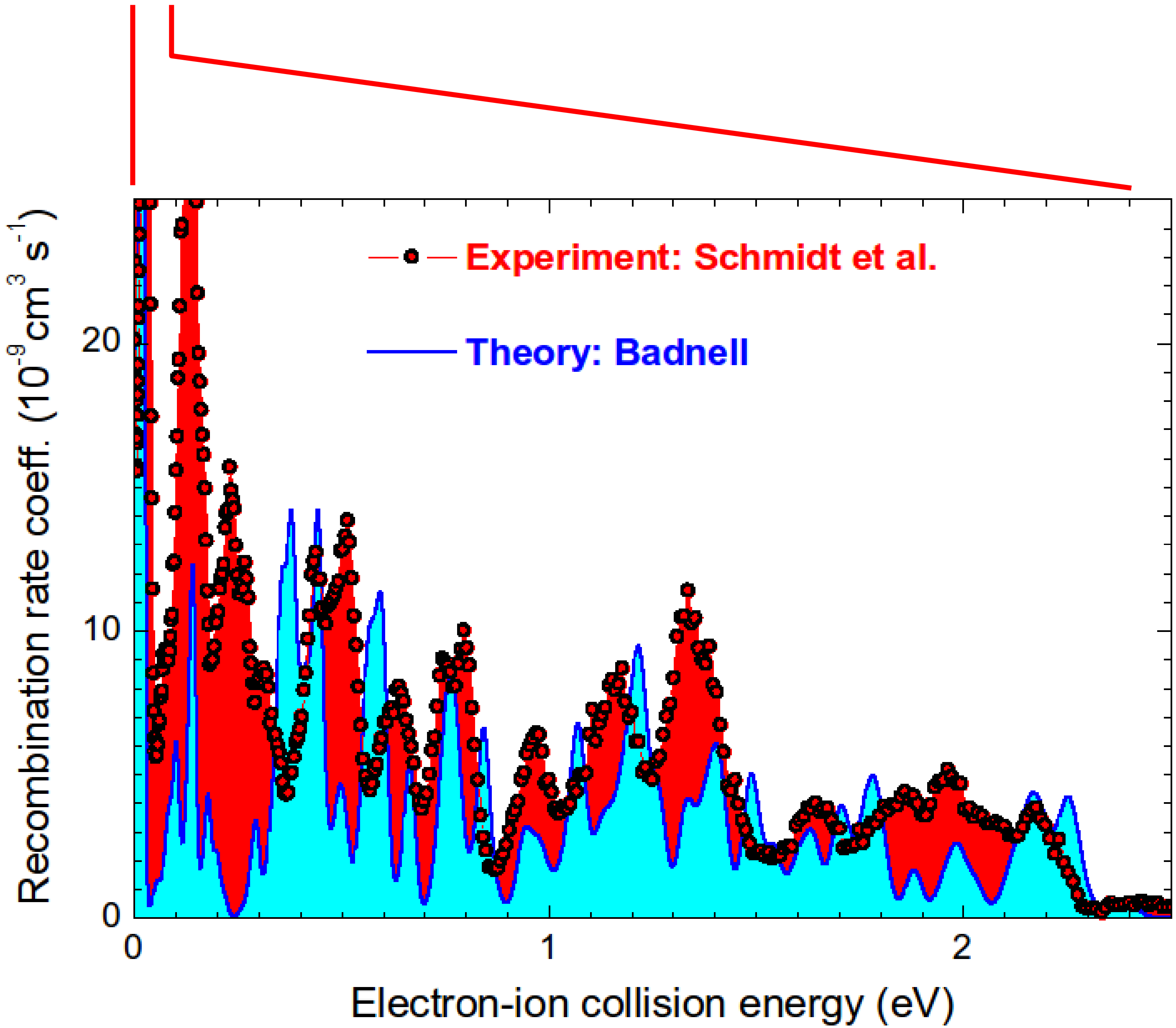
Iron ion dielectronic recombination

Al-like Fe^{13+}

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

$\rightarrow 3s3p^2\ n\ell$

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



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

Iron ion dielectronic recombination

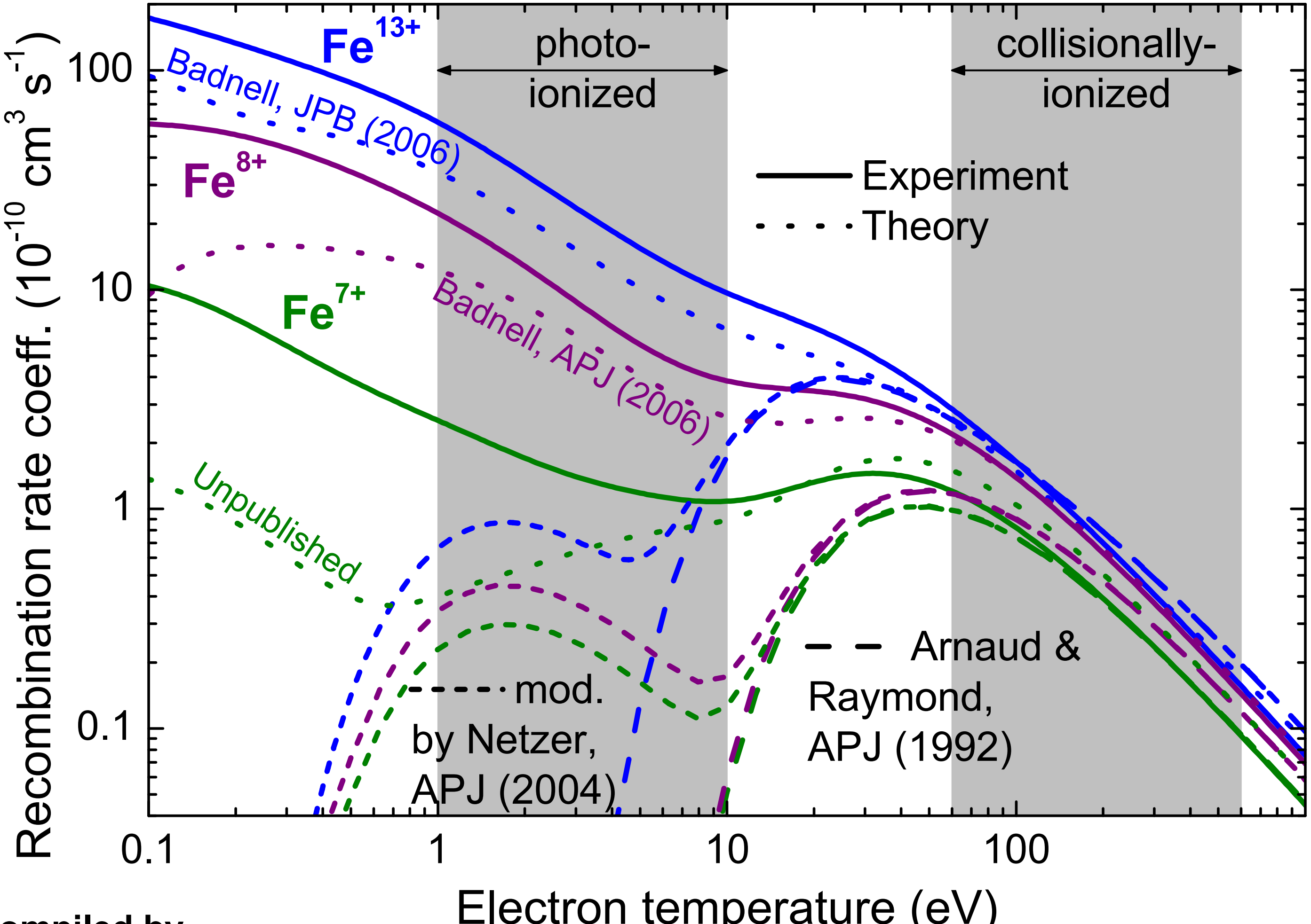
Derived thermal plasma rate coefficients

Al-like Fe^{13+}

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

$\rightarrow 3s3p^2\ n\ell$

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



Compiled by
S. Schippers

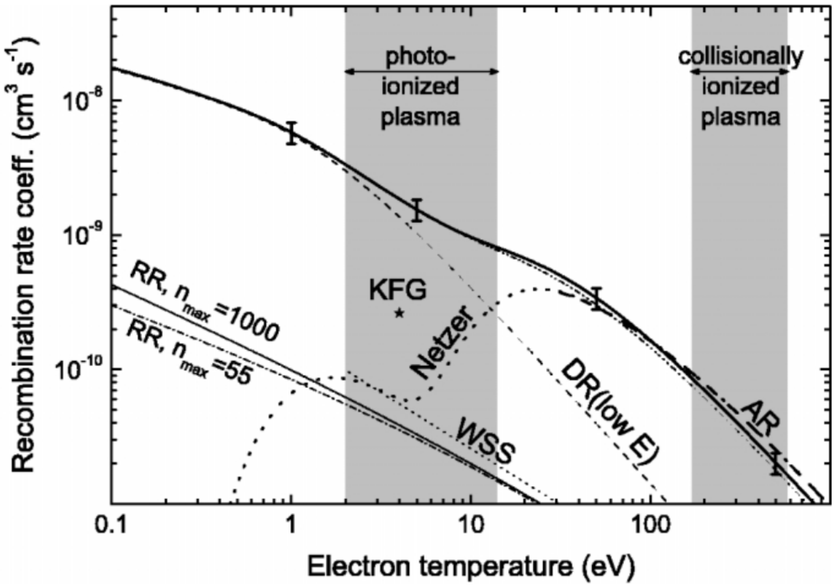
E. W. Schmidt et al., Astrophys. J. Lett. 641, L157 (2006)

Experimental rate constant data

$Fe^{13+} + e \rightarrow (Fe^{12+})^{**} \rightarrow (Fe^{12+})^{*} + h\nu$

$$\alpha_{\text{plasma}}(T_e) = T_e^{-3/2} \sum_{i=1}^{10} c_i \exp(-E_i/k_B T_e) \qquad (1)$$

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



Parameters for the Fit of Equation (1)

i	c_i (cm^3 s^{-1} K^{-1})	E_i (eV)
1	3.55×10^{-4}	2.19×10^{-2}
2	2.40×10^{-3}	1.79×10^{-1}
3	7.83×10^{-3}	7.53×10^{-1}
4	1.10×10^{-2}	2.21×10^{0}
5	3.30×10^{-2}	9.57×10^{0}
6	1.45×10^{-1}	3.09×10^{1}
7	8.50×10^{-2}	6.37×10^{1}
8	2.59×10^{-2}	2.19×10^{2}
9	8.93×10^{-3}	1.50×10^{3}
10	9.80×10^{-3}	7.86×10^{3}

Errors:

~15% ion current and electron density systematics
~8% estimate of non-DR recombination (=RR)

~18% overall

Experimental rate constant data

Ar^{14+} + e → $(Ar^{13+})^{**}$
→ $(Ar^{13+})^{*}$ + $h\nu$

(Be-like)

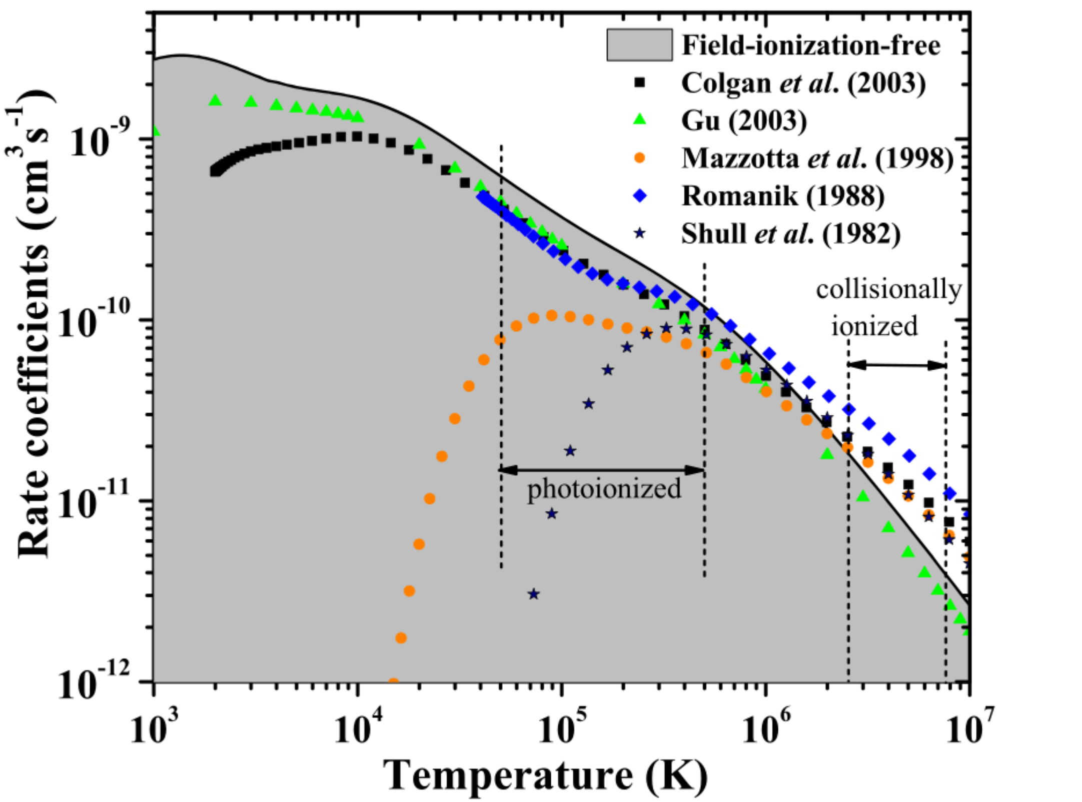
Z. K. Huang et al., Astrophys. J. Suppl. 235, 2 (2018)

CSRm, Lanzhou — Dielectronic / Trielectronic recombination

Fitted Coefficients for the RR-subtracted $\Delta N = 0$ DR+TR Rate Coefficients from Figure 3 for Two Different Values of $n_{\rm cutoff}$ and $n_{\rm max} = 1000$ (Field-ionization-free)

No.	$n_{\rm cutoff}$		$n_{\rm max} = 1000$	
i	c_i	E_i	c_i	E_i
1	0.254	0.12	0.244	0.115
2	0.580	0.28	0.590	0.278
3	3.74	3.47	3.77	3.45
4	5.17	1.43	5.14	1.43
5	14.3	12.42	14.38	12.45
6	23.39	31.84	23.13	31.95
7	38.84	56.39	40.30	57.03

Note. The units of c_i and E_i are 10^{-3} cm^3 s^{-1} $K^{3/2}$ and eV, respectively.



$$\alpha(T_e) = T_e^{-3/2} \sum_i c_i \times \exp\left(-\frac{E_i}{kT_e}\right)$$

Errors:

~30% overall

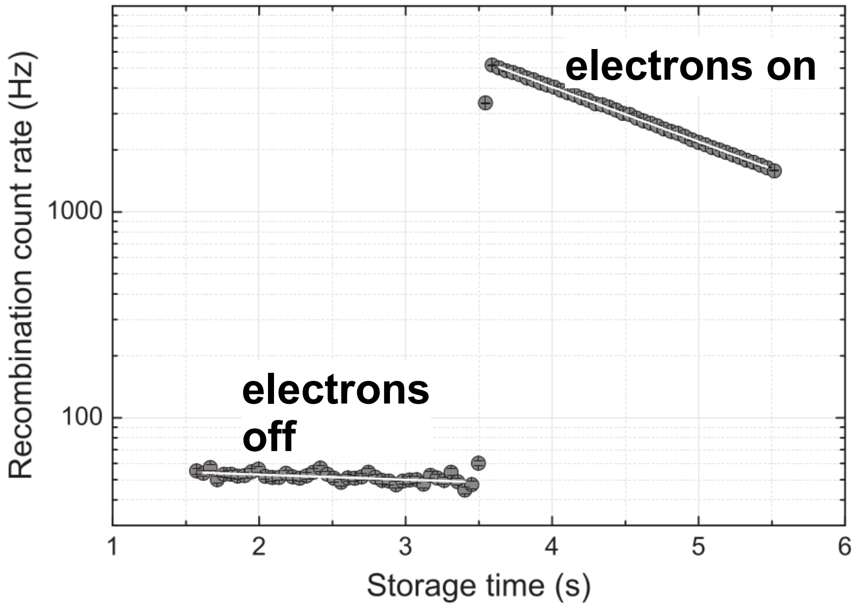
~15% ion and electron current, counting statistics
~5% remaining (too long-lived) metatstable content
~20% electron beam density profile and ion position

Absolute normalization: the lifetime method

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

W^{18+}

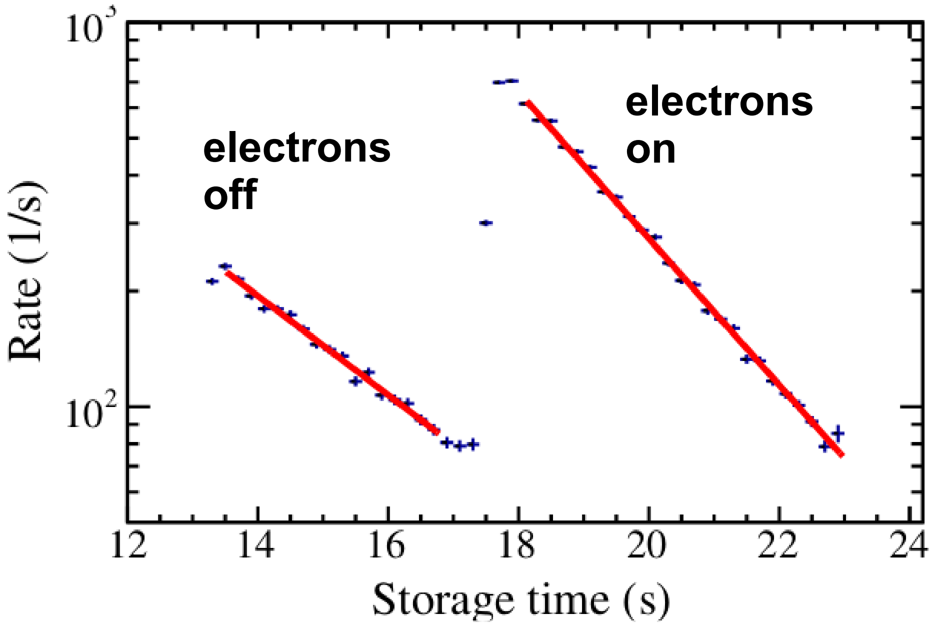
$n_e \sim 1 \times 10^7$ cm^{-3}



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 $E_d = 0$

Tungsten ions: merged beams rate coefficients

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 2017: C Krantz et al JPB 50 052001

Xe-like W^{20+}

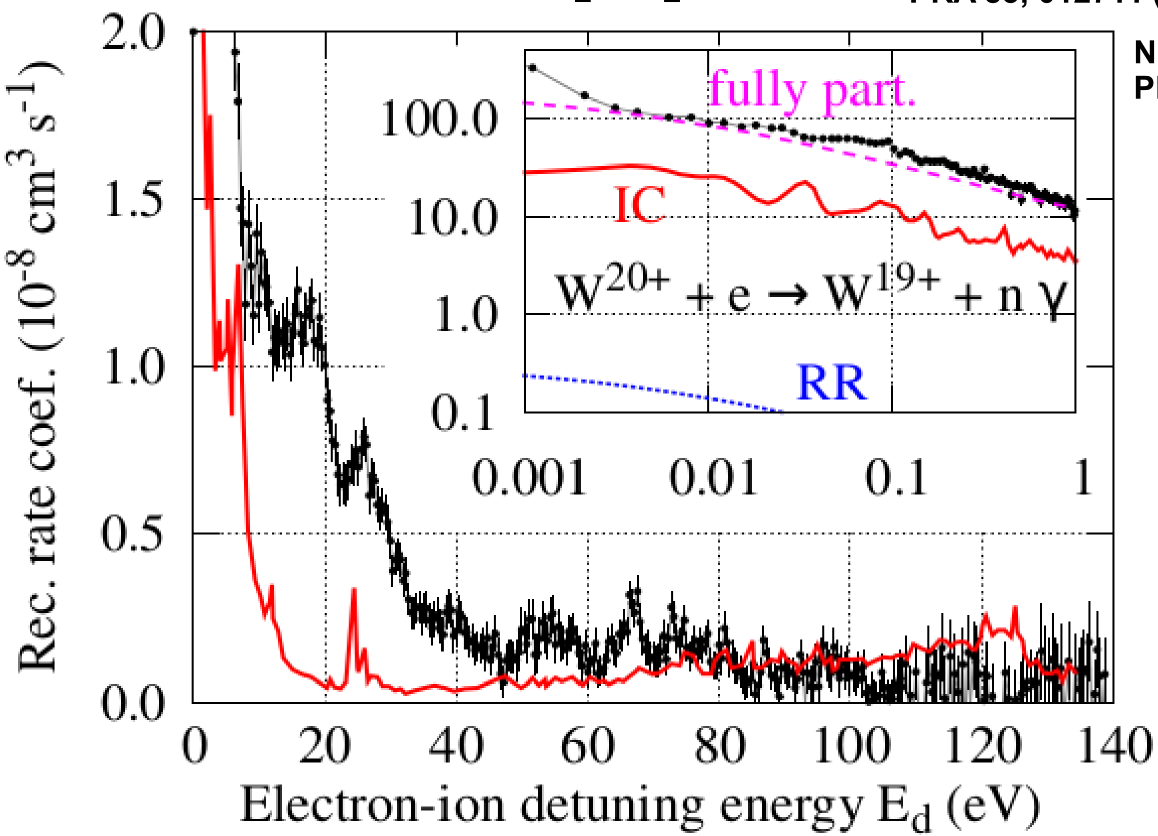
$4d^{10}\ 4f^{8}\ (^7F_6)$

→ $4d^9\ 4f^9\ n\ell$

→ $4d^{10}\ 4f^9\ 5d\ n\ell$

→ $4d^{10}\ 4f^9\ 5g\ n\ell$

→ $4d^{10}\ 4f^8$ (f.s.) $n\ell$
(0 … 30 eV)



Fully partitioned (statistical) calculation

Intermediate coupling calculation

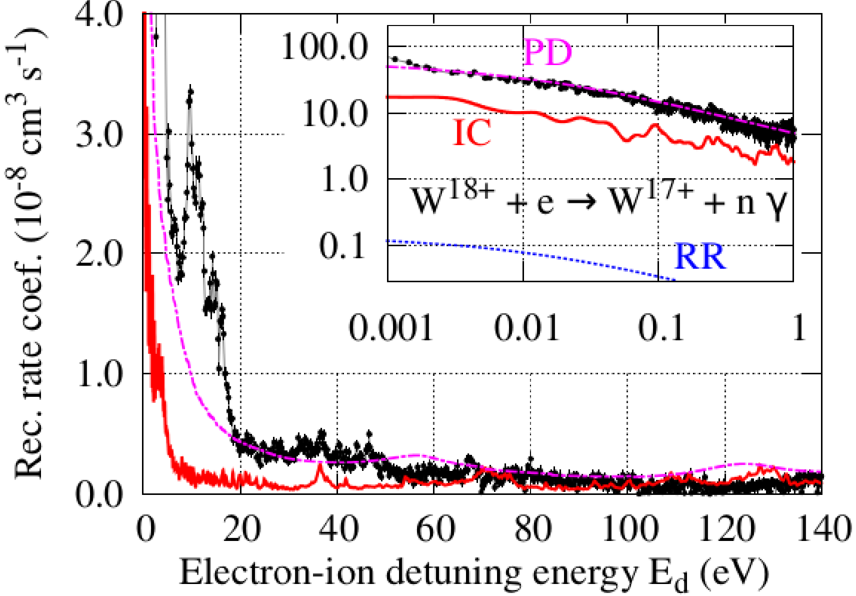
Radiative recombination

More at:
https://www-amdis.iaea.org/meetings/UQ2016/
Talk in session on Experimental Atomic Collision Data

Tungsten ions: merged beams rate coefficients

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

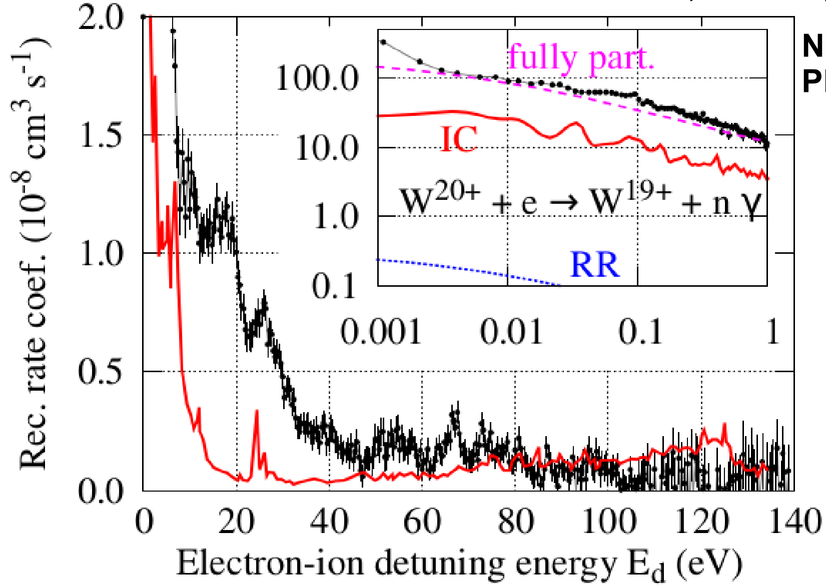
K. Spruck et al., PRA 90, 032715 (2014)



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

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

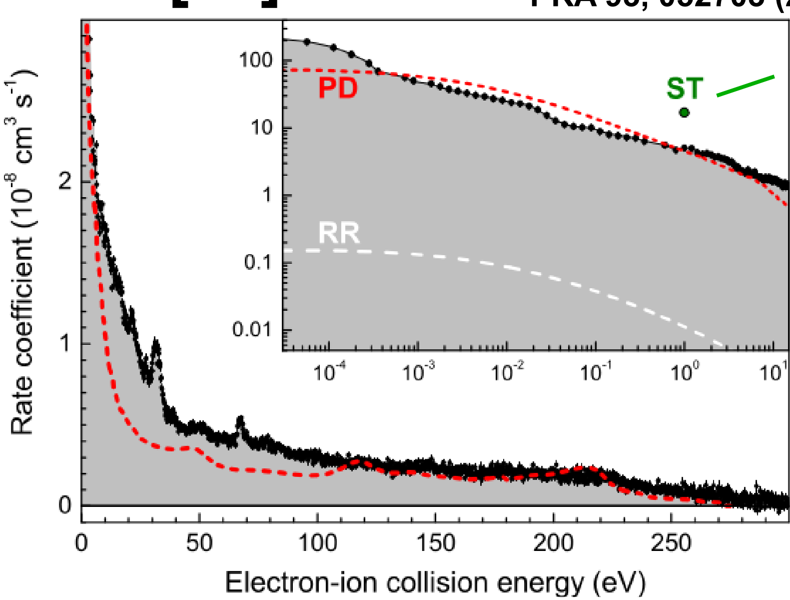
N. Badnell et al., PRA 85, 052716 (2012)



C. Krantz et al., J. Phys. B Topical Review 2017: C Krantz et al JPB 50 052001

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

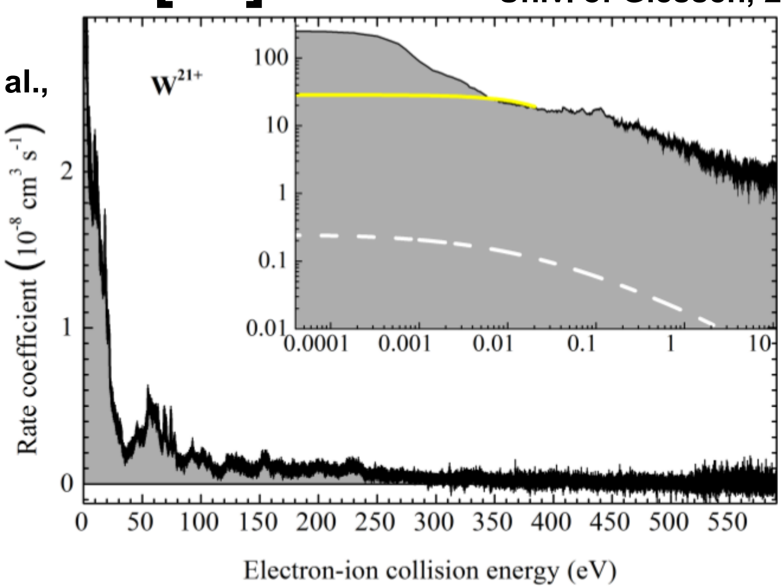
N. Badnell et al., PRA 93, 052703 (2016)



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

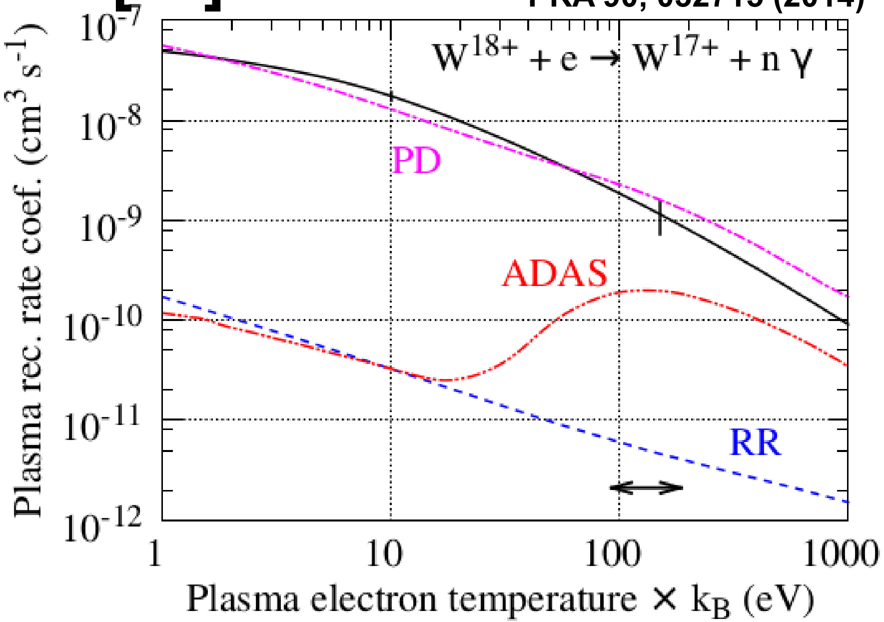


~37% accuracy (90% conf.) incl. non-detection of *n* > 69

Tungsten ions: plasma recombination rate constants

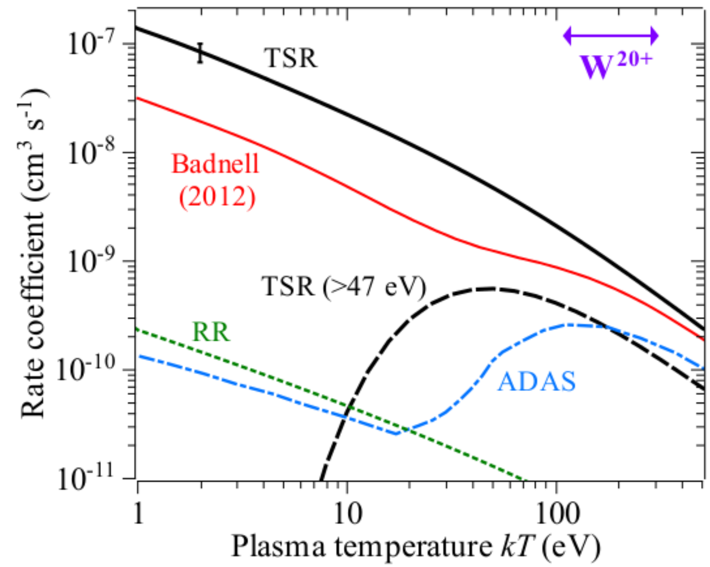
W^{18+} [Kr]$4d^{10}4f^{10}$

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



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

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

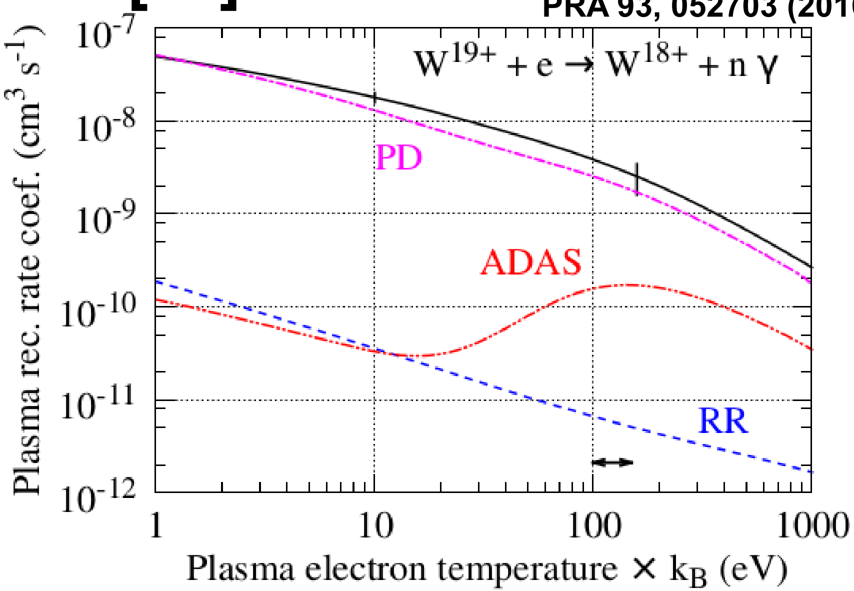


N. Badnell et al.,
PRA 85, 052716 (2012)

C. Krantz et al.,
J. Phys. B
Topical Review
2017:
C Krantz et al
JPB 50 052001

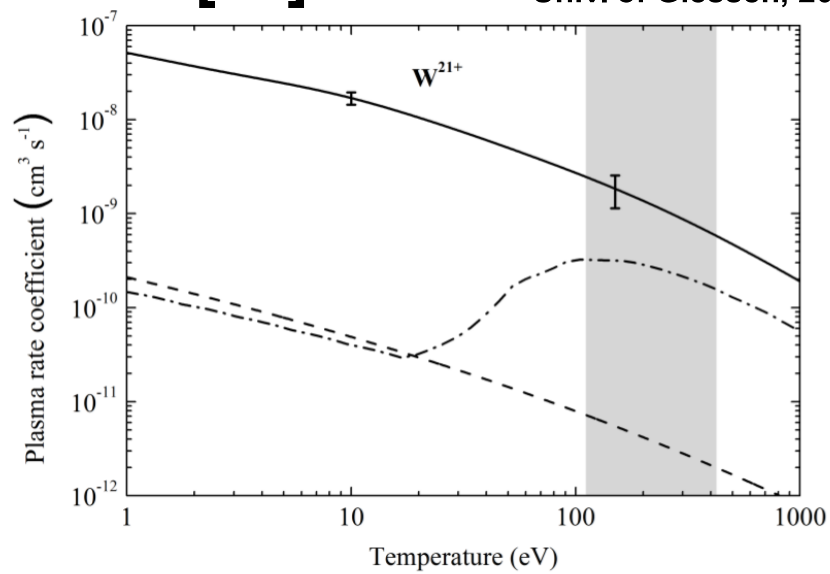
W^{19+} [Kr]$4d^{10}4f^{9}$

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



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

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



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

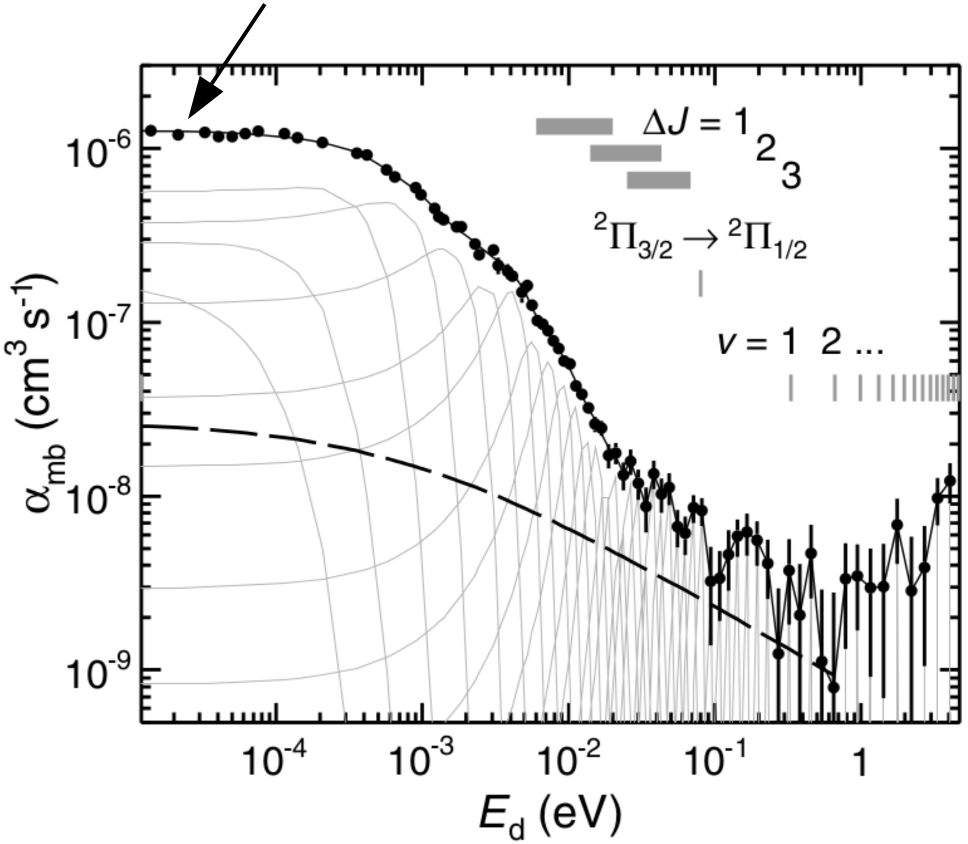
Molecular recombination measurements: Analysis

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

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

Merged-beams high-resolution rate constant

Calibration:
Lifetime method



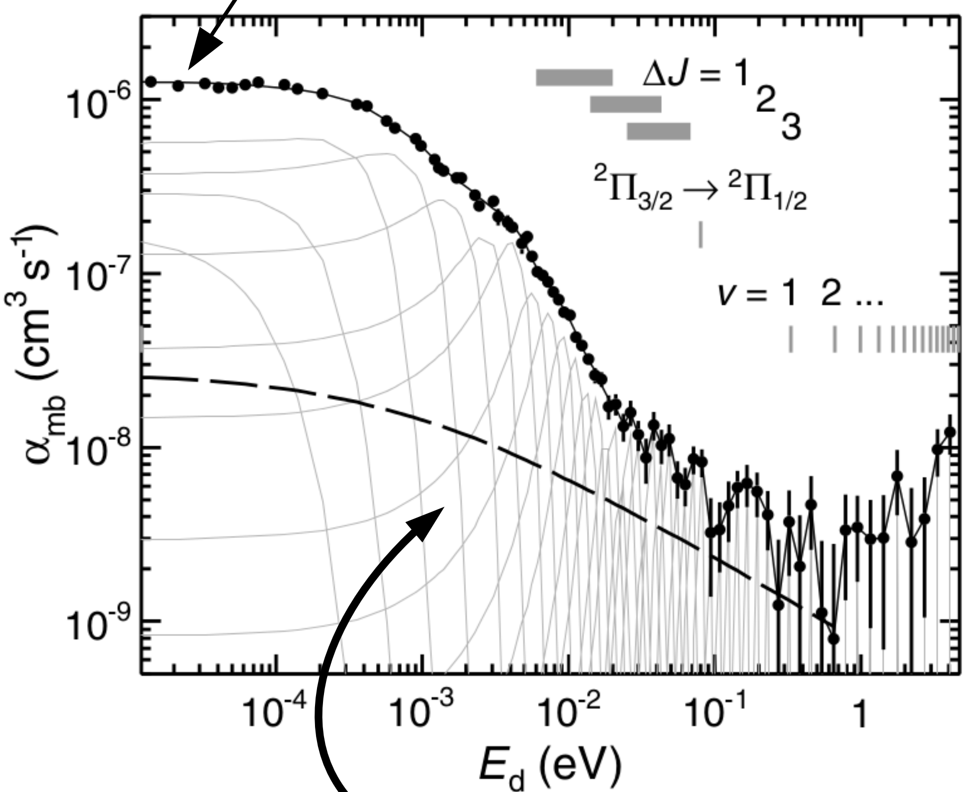
Molecular recombination measurements: Analysis

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

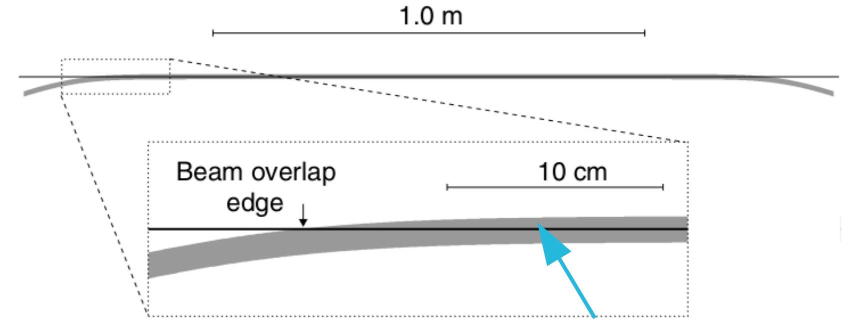
O. Novotný, Astrophys. J. 777, 54 (2013)

Merged-beams high-resolution rate constant

Calibration:
Lifetime method

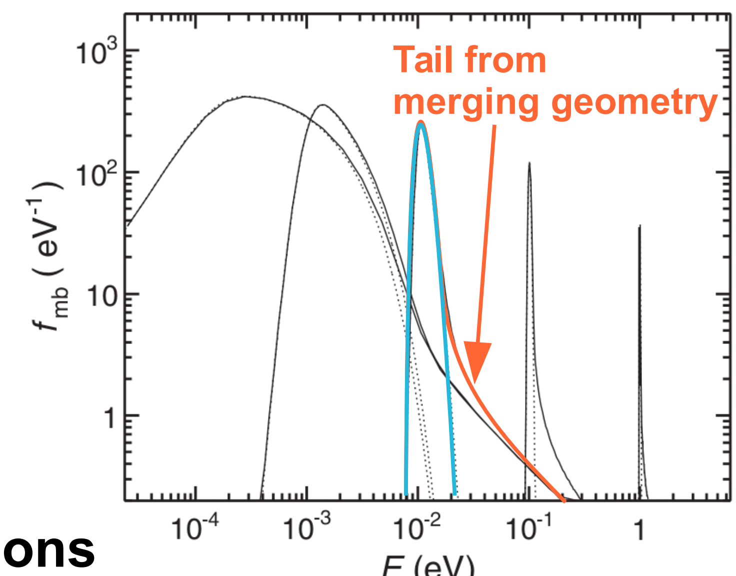


Overlap geometry



Intrinsic electron velocity distribution

***Effective* energy distribution**



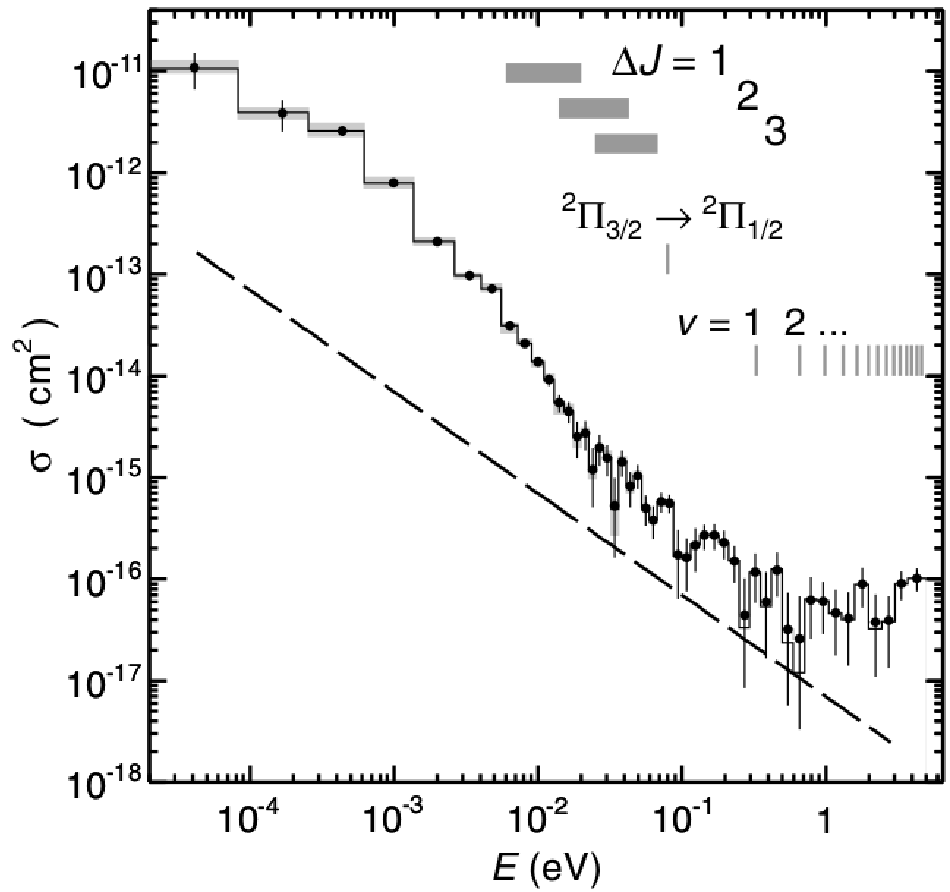
Binned signal contributions (fitted cross section values)

Molecular recombination measurements: Analysis

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

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

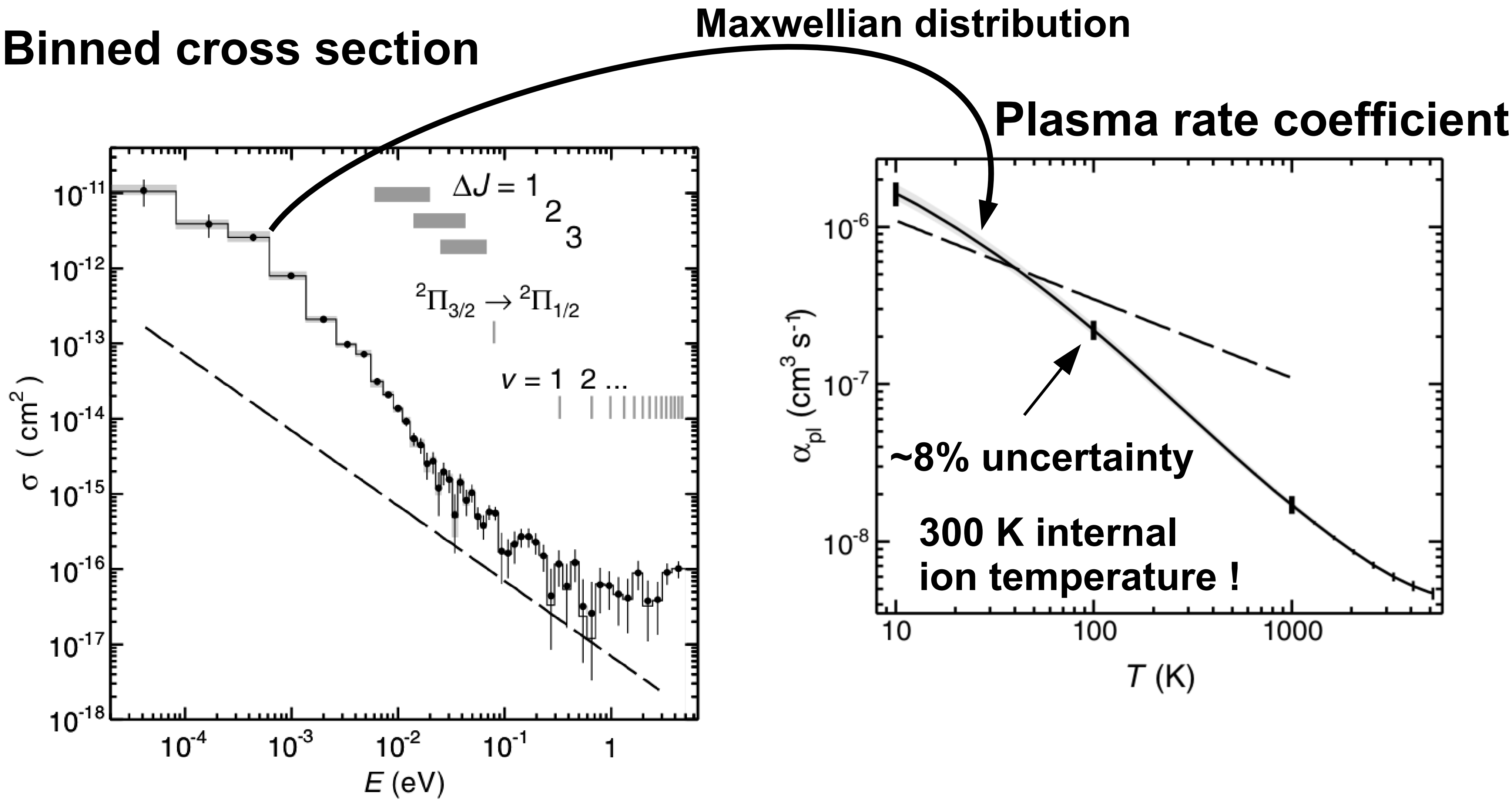
Binned cross section



Molecular recombination measurements: Analysis

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

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

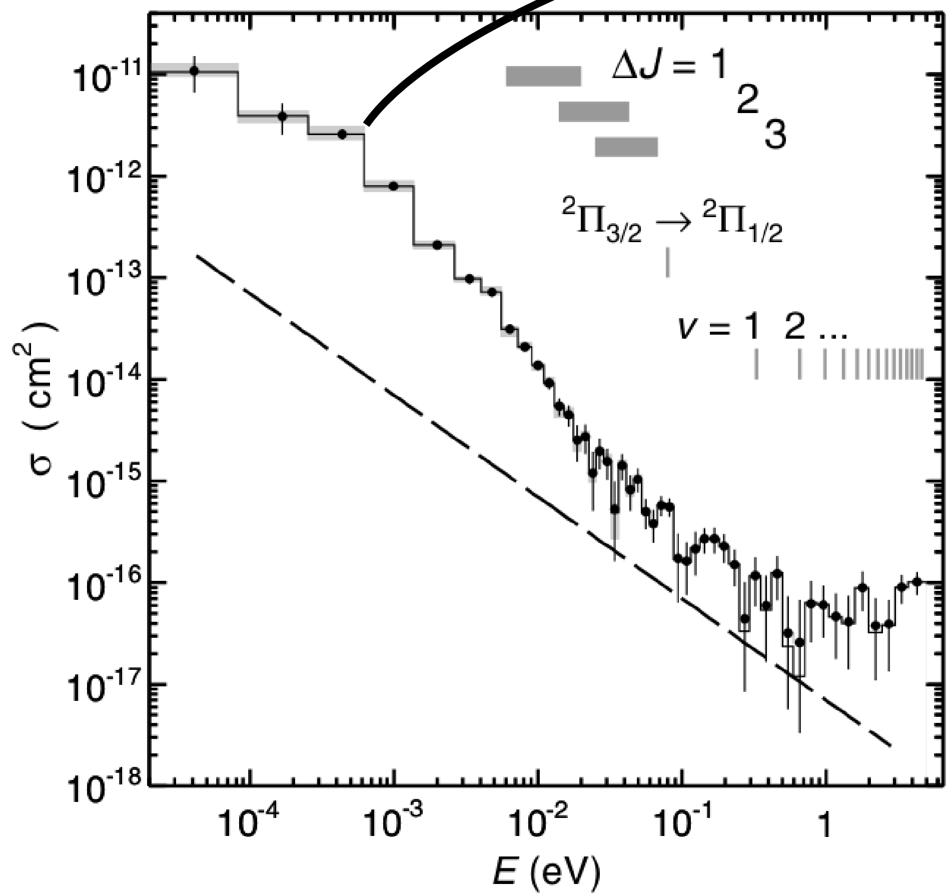


Molecular recombination measurements: Analysis

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

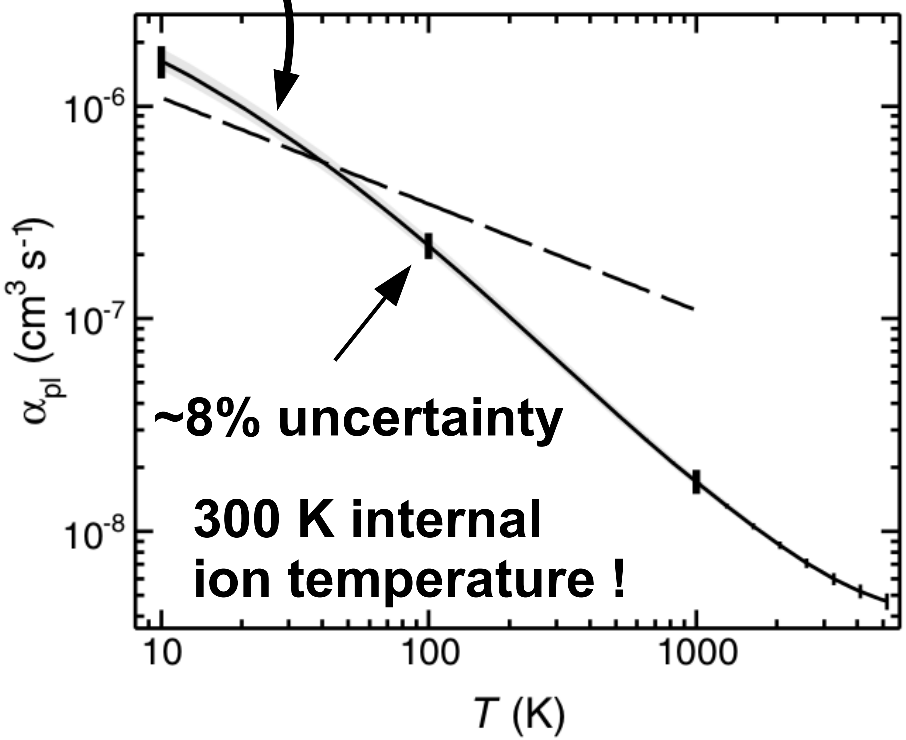
O. Novotný, Astrophys. J. 777, 54 (2013)

Binned cross section



Maxwellian distribution

Plasma rate coefficient



Fit model for temperature curve of rate coefficient

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

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

Cryogenic electrostatic storage rings

Storage rings equipped with cryogenic cooling (~4...15 K) of the vacuum chamber walls and the ion optical elements

- **Reduce residual gas density**
  small cryogenic Penning traps: $\sim 10^{-16}$ mbar estimated

- **Reduce background black-body radiation field**
  to avoid excitation of rotations or vibrations
  $kT \sim 0.026 \text{ eV} \cdot (T / 300 \text{ K})$

Cryogenic electrostatic storage rings

Storage rings equipped with cryogenic cooling (~4...15 K) of the vacuum chamber walls and the ion optical elements

- **Reduce residual gas density**
  small cryogenic Penning traps: ~10^{-16} mbar estimated

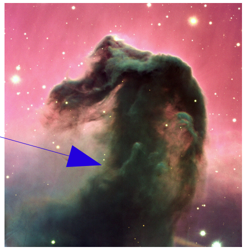
- **Reduce background black-body radiation field**
  to avoid excitation of rotations or vibrations
  $kT \sim 0.026\ \text{eV} \cdot (T\ /\ 300\ \text{K})$

Example: CH^+
(~ other diatomic hydrides)

$E(J{=}1) - E(J{=}0) = 2B$
$= 0.0035\ \text{eV}$

Thermal equilibrium populations of rotational levels

J \ T_{rot}	300 K	10 K
0	0.065	0.949
1	0.171	0.051
2	0.219	0.0
3	0.205	0.0
4	0.155	0.0



Cryogenic electrostatic storage rings

Storage rings equipped with cryogenic cooling (~4...15 K) of the vacuum chamber walls and the ion optical elements

- Reduce residual gas density
  small cryogenic Penning traps: ~10^{-16} mbar estimated

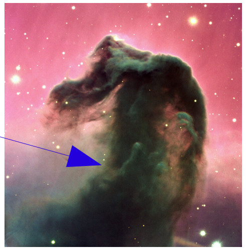
- Reduce background black-body radiation field
  to avoid excitation of rotations or vibrations
  $kT \sim 0.026$ eV · (T / 300 K)

Example: CH^+
(~ other diatomic hydrides)

$E(J=1) - E(J=0) = 2B$
$= 0.0035$ eV

Thermal equilibrium populations of rotational levels

J \ T_{rot}	300 K	10 K
0	0.065	0.949
1	0.171	0.051
2	0.219	0.0
3	0.205	0.0
4	0.155	0.0

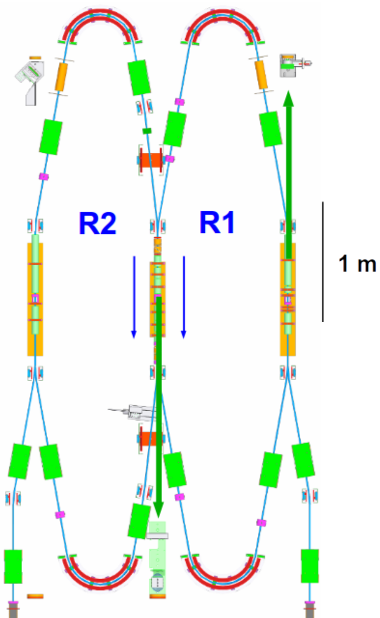


- Enable beam lifetimes long enough for phase space cooling / stacking

Cryogenic electrostatic storage rings

DESIREE
Stockholm

R. Thomas et al.,
Rev. Sci. Instrum. 82, 065112 (2011)
H. T. Schmidt et al.,
Rev. Sci. Instrum. 84, 055115 (2013)



Anion + cation beams

Interactions of polyatomic ions in cryogenic, extremely dilute environment

- Ion storage by electrostatic fields
- Light and heavy molecules, clusters
- All components cooled to ~10 K
- Extreme vacuum, ~min … h storage times

Lasers

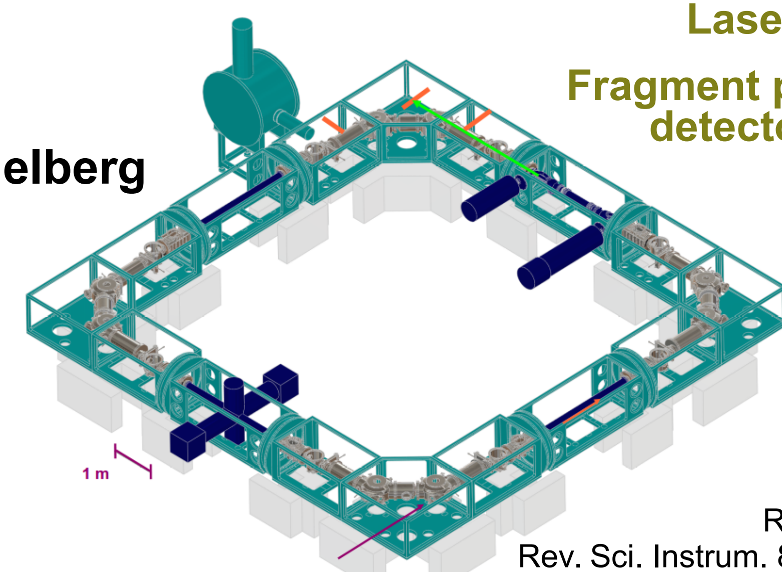
Fragment particle detectors

Merged electron beam

Neutral atom beam

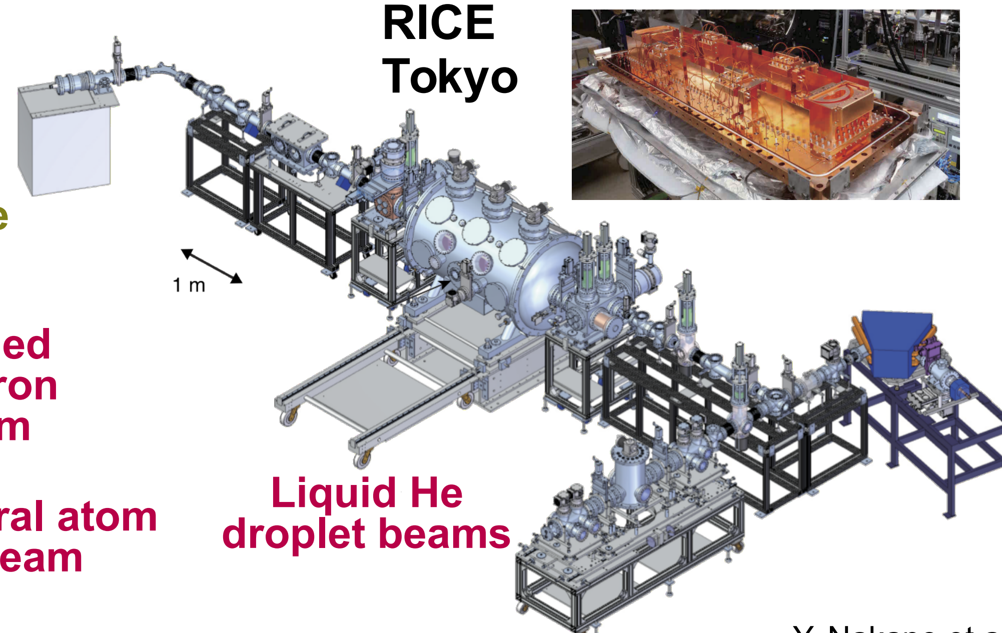
Liquid He droplet beams

CSR
Heidelberg



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

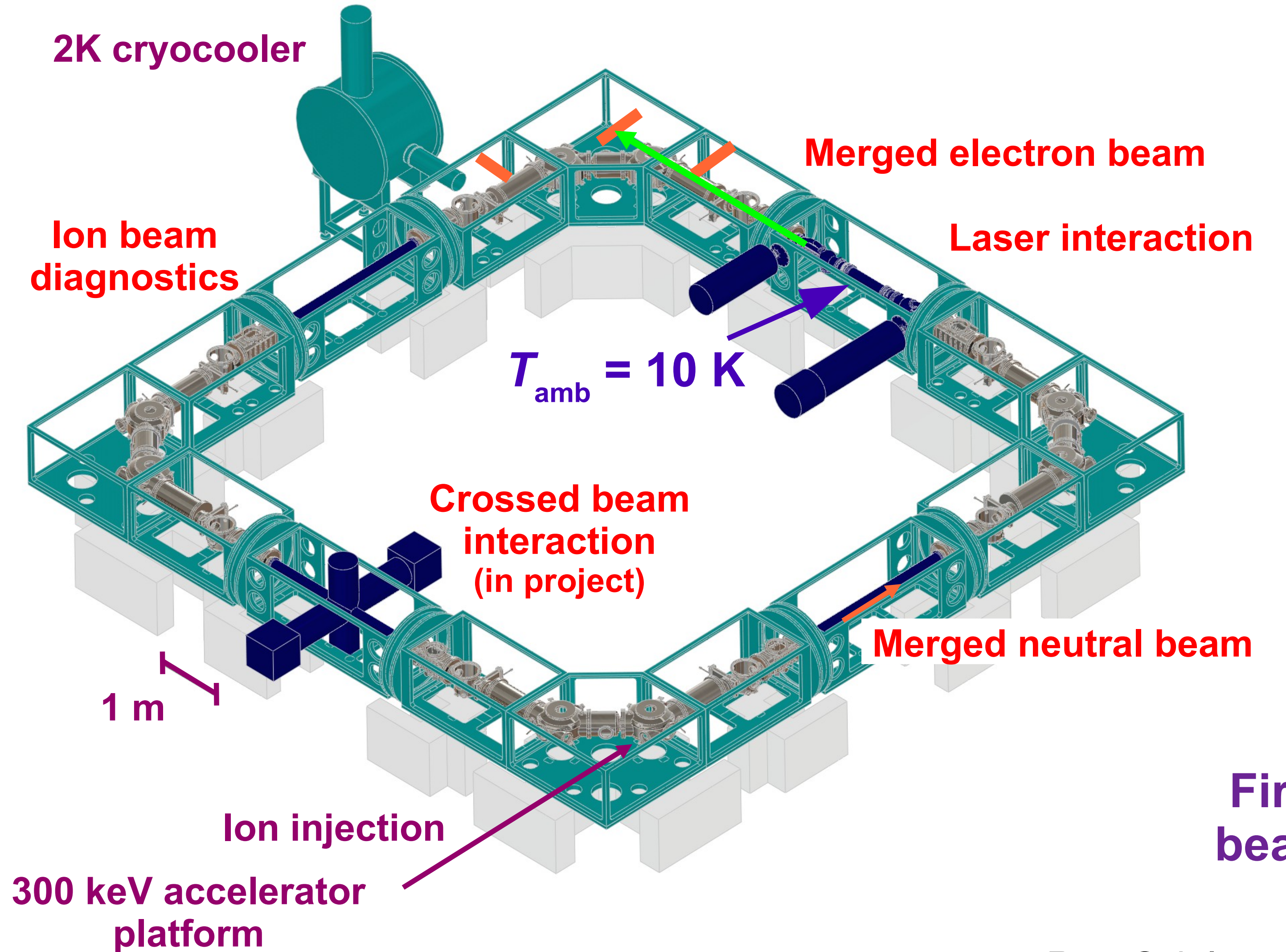
RICE
Tokyo



Y. Nakano et al.
Rev. Sci. Instrum. 88, 033110 (2017)

The cryogenic storage ring CSR

Electrostatic cryogenic storage ring for atomic, molecular and cluster ions



First cryogenic beam time: 2015

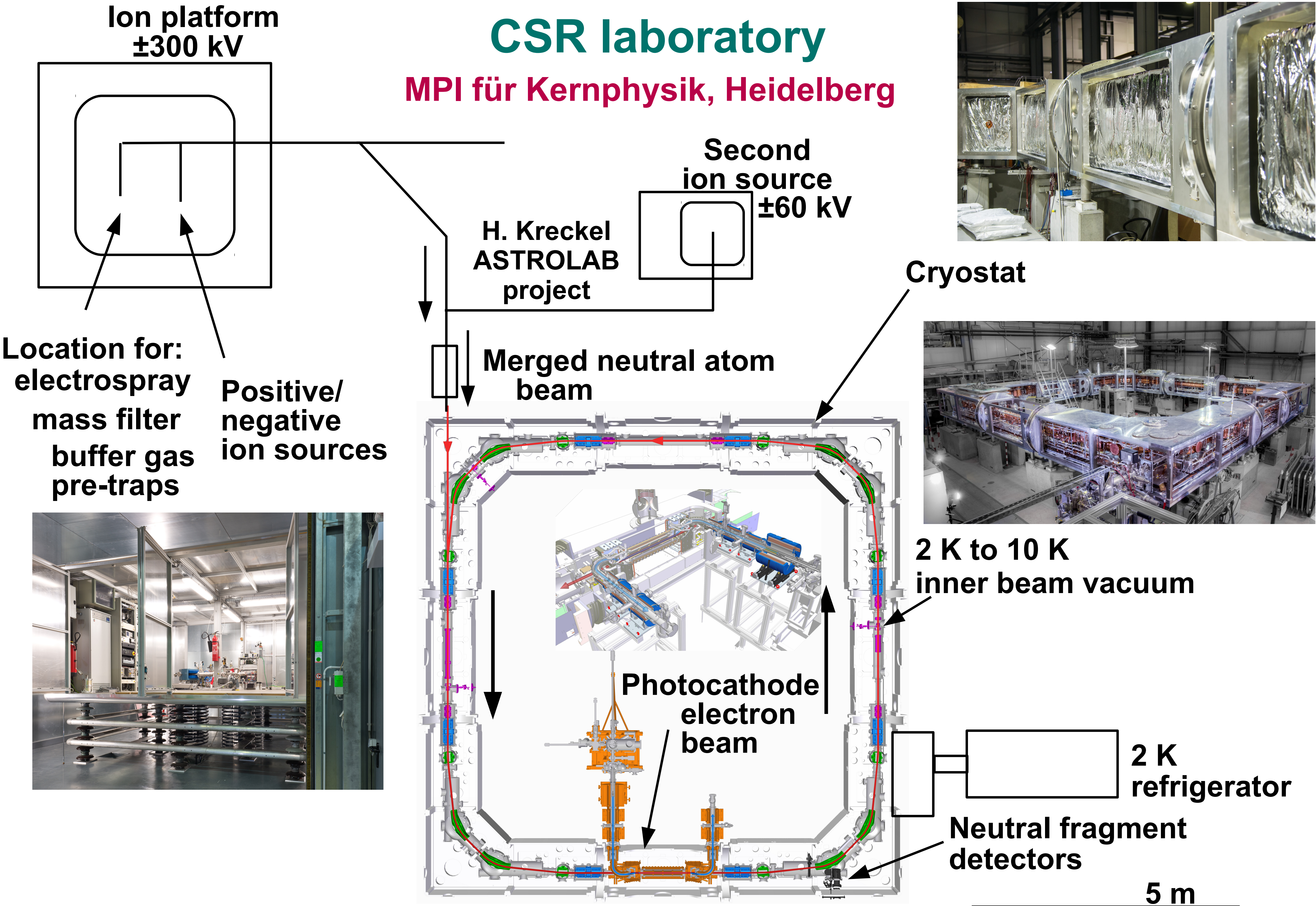
R. von Hahn et al.,
Rev. Sci. Instrum. 87, 063115 (2016)

Cryogenic storage ring CSR

View of CSR before first complete cool-down, spring 2015

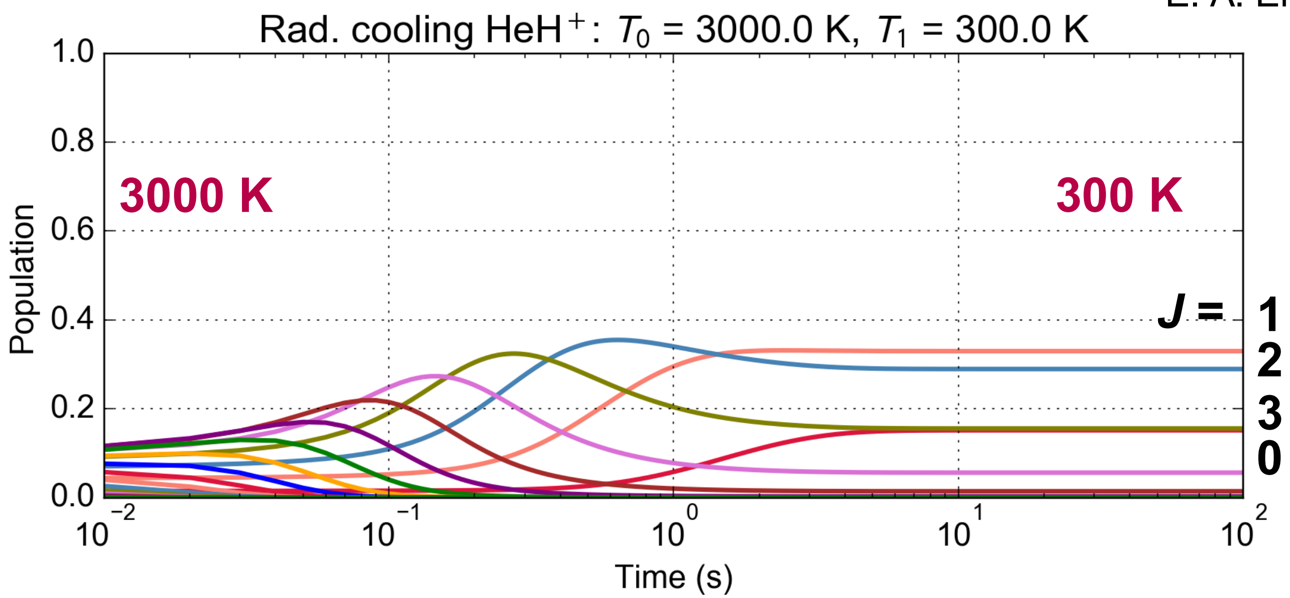
CSR laboratory

MPI für Kernphysik, Heidelberg



HeH⁺ rotational levels – radiative relaxation

Radiative cooling model



Theoretical HeH⁺ line list:

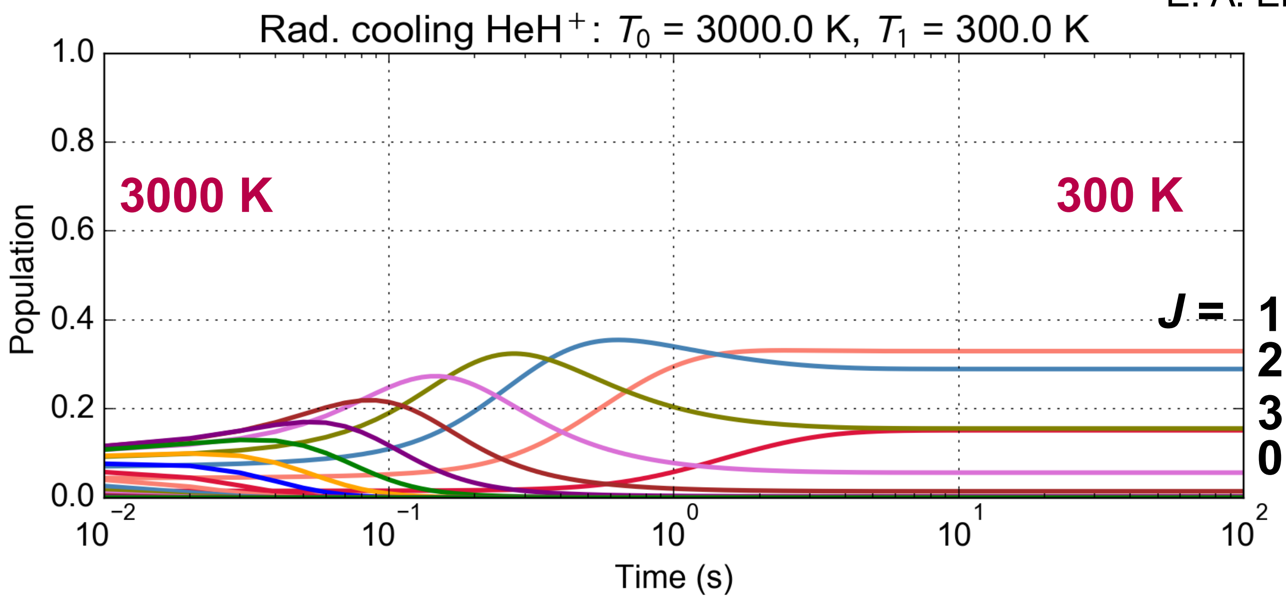
E. A. Engel, N. Doss, G. J. Harris, and J. Tennyson, Mon. Not. R. Astron. Soc. 357, 471 (2005)

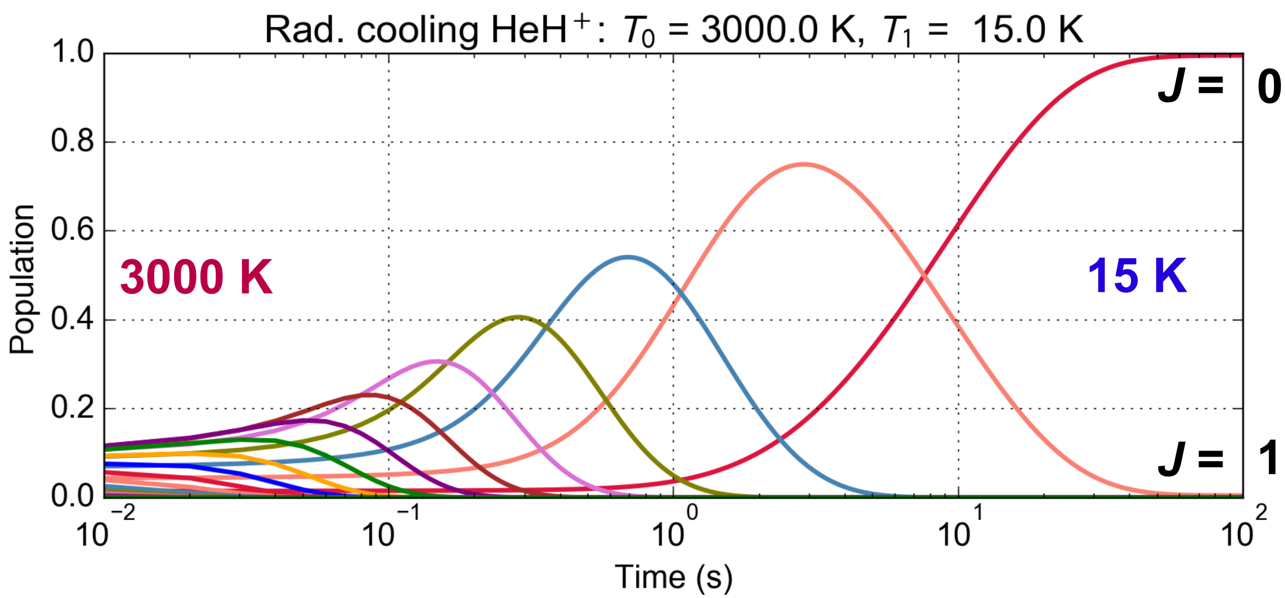
Room-temperature ion storage rings

J \ T_{rot}	300 K
0	0.151
1	0.330
2	0.284
3	0.156
4	0.056

HeH^+ rotational levels – radiative relaxation

Radiative cooling model





Theoretical HeH^+ line list:

E. A. Engel, N. Doss, G. J. Harris, and J. Tennyson, Mon. Not. R. Astron. Soc. 357, 471 (2005)

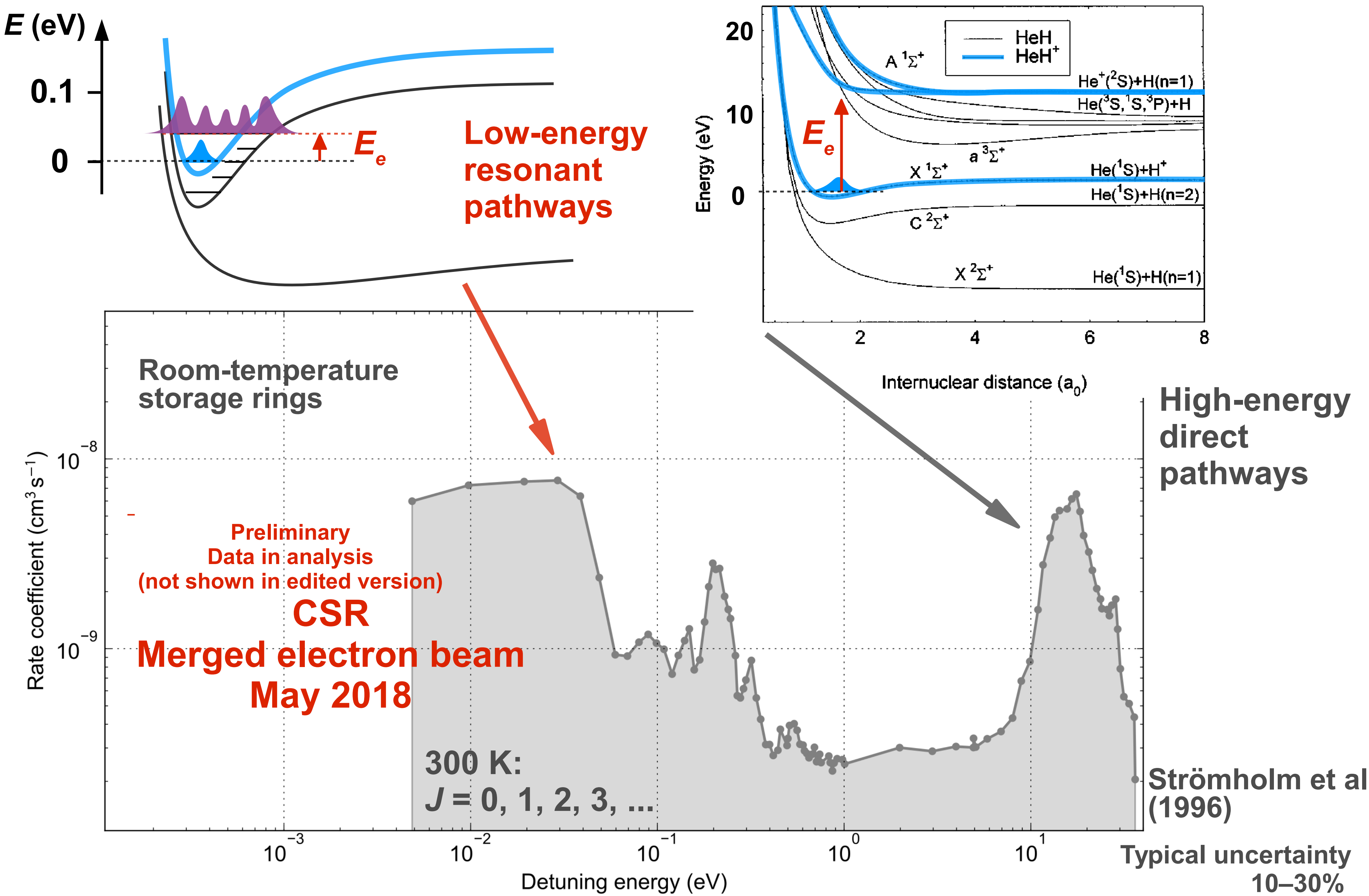
Room-temperature ion storage rings

J \ T_{rot}	300 K	15 K
0	0.151	0.995
1	0.330	0.005
2	0.284	0.0
3	0.156	0.0
4	0.056	0.0

Cryogenic storage ring

HeH^+ measurement at CSR May 2018

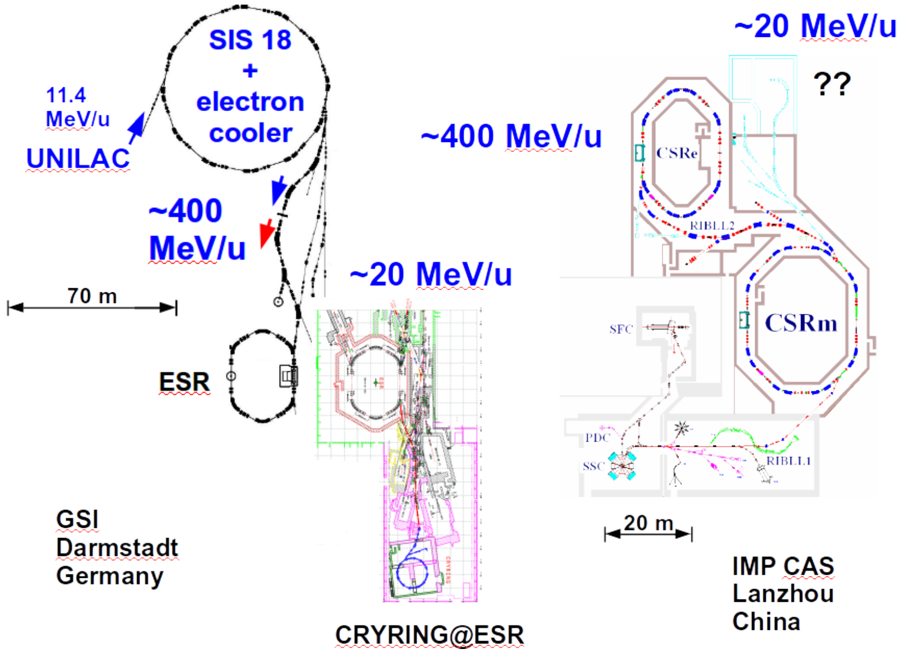
HeH⁺ dissociative recombination – energy-resolved



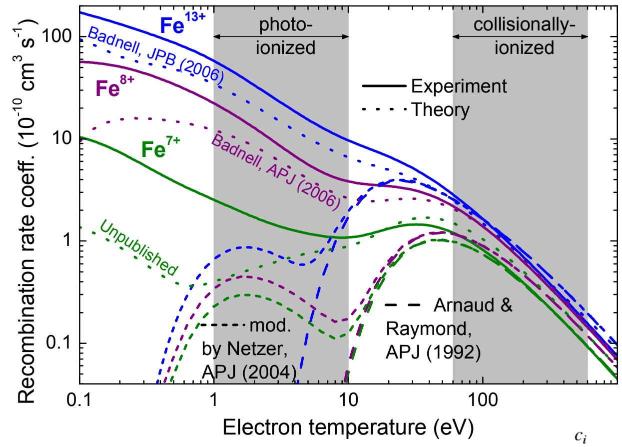
Summary

Electron–ion merged beams facilities

Experimental areas at large heavy-ion accelerators



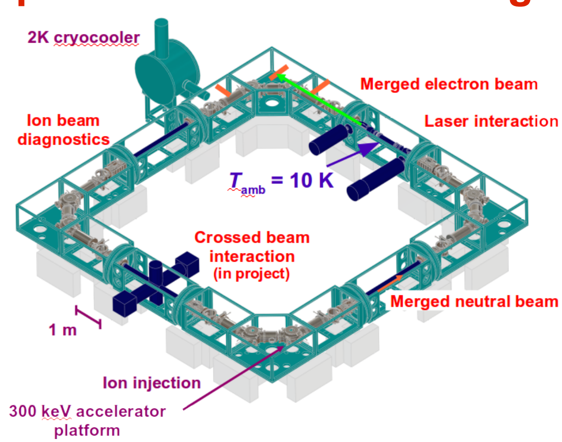
Dielectronic recombination: relaxed metastable states, complex open-shell ions



$$\alpha(T_e) = T_e^{-3/2} \sum_i c_i \times \exp\left(-\frac{E_i}{kT_e}\right)$$

c_i	E_i
0.254	0.12
0.580	0.28
3.74	3.47
5.17	1.43
14.3	12.42

Low-energy cryogenic storage ring CSR (up to ~1 h ion-beam storage lifetime)



Dissociative recombination: rotationally cold molecular ions

Preliminary
Data in analysis
(not shown in edited version)

Acknowledgments – TSR

Stefan Schippers

Nigel Badnell

Oldřich Novotný

Kaija Spruck

Claude Krantz

Alfred Müller

Manfred Grieser

Daniel Savin

CSR electron collisions beamtime team

Oldřich Novotný

Daniel Paul

Manfred Grieser

Patrick Wilhelm

Claude Krantz

Now at Marburger Ionenstrahl-Therapiezentrum

Sunny Saurabh

Ábel Kálosi

Visitor from
Group of Plasma Physics
Dept. of Surface and Plasma Science
Faculty of Mathematics and Physics
Charles University of Prague

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Acknowledgments

CSR detectors, electron cooler, laser experiments

O. Novotný
P. Wilhelm
D. Paul
S. Saurabh
A. Kálosi (visitor Prague)

C. Krantz
K. Spruck (Univ. Gießen)
S. Vogel
A. Becker
M. Rimmler
S. Lohmann
S. Spaniol

S. George
C. Breitenfeldt (Univ. Greifswald)
C. Meyer
J. Göck
P. Mishra
V. Schmidt

S. Schippers (Univ. Gießen)
D. Schwalm (MPIK/WIS Rehovot)

Microcalorimeter collaborators from Kirchhoff Inst. of Physics, Univ. Heidelberg:
S. Allgeier, C. Enss, A. Fleischmann, L. Gamer, D. Hengstler, S. Kempf, A. Pabiger, C. Pies

MPIK
C. D. Schröter
R. Moshammer
T. Pfeifer

Astrolab@CSR
H. Kreckel
F. Grussie
A. O'Connor
J. Hörl
E. Guerin
S. Kumar

Funding
MPG
Weizmann Institute
DFG Priority Program "Physics of the Interstellar Medium"
NASA and NSF (Columbia Univ.)
ERC/MPG

CSR team

R. von Hahn
M. Grieser
F. Fellenberger
S. George
M. Lange
R. Repnow
P. Herwig

C. Krantz
S. Vogel
K. Spruck (Univ. Gießen)
A. Becker
H. Kreckel (Astrolab)
F. Grussie (Astrolab)
A. O'Connor (Astrolab)

K. Blaum

and the MPIK workshops and labs

Collaborations CSR and experiments
WIS Rehovot (O. Heber, D. Zajfman)
Univ. Greifswald (L. Schweikhard)
Bar-Ilan Univ. (Y. Toker)
Univ. Gießen (S. Schippers)
Columbia Univ. (D. W. Savin)
Univ. Louvain-la-Neuve (X. Urbain)
Univ. Kaiserslautern (G. Niedner-Schatteburg)
Acad. Sci. Novosibirsk (A. S. Terekhov)

Theory
Univ. Le Havre (I. Schneider)
Purdue Univ. (C. Greene)
UC London (J. Tennyson)