Electron collision-spectroscopy of highly charged ions

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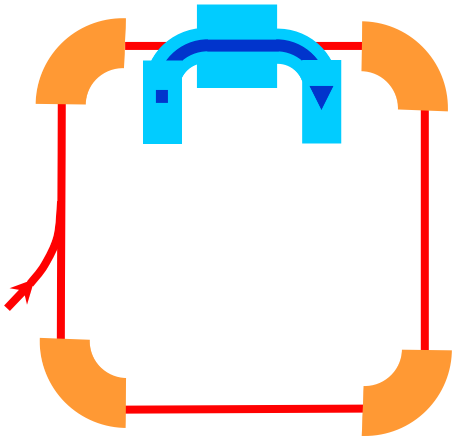
Outline

- **Experimental aspects**
  - Recombination experiments at heavy-ion storage rings
  - Determination of absolute rate coefficients
  - Experimental energy spread

- **Selected recent results**
  - Hyperfine splitting of DR resonances
  - Isotope shifts of DR resonances
  - KLL DR of hydrogenlike heavy ions
  - Hyperfine induced transitions in Be-like ions

Heavy-ion storage rings

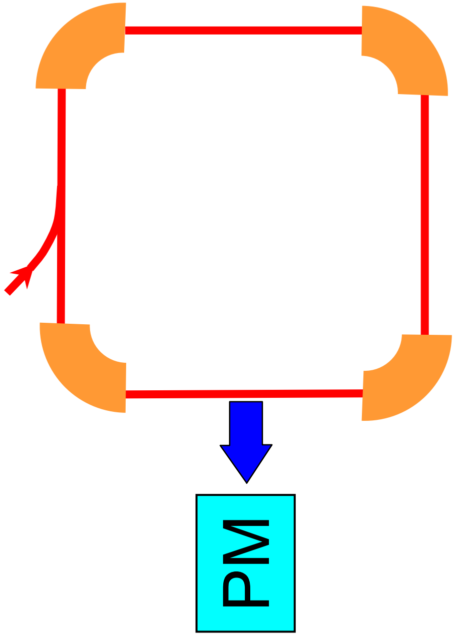


- electron cooling
- laser cooling
- stochastic cooling

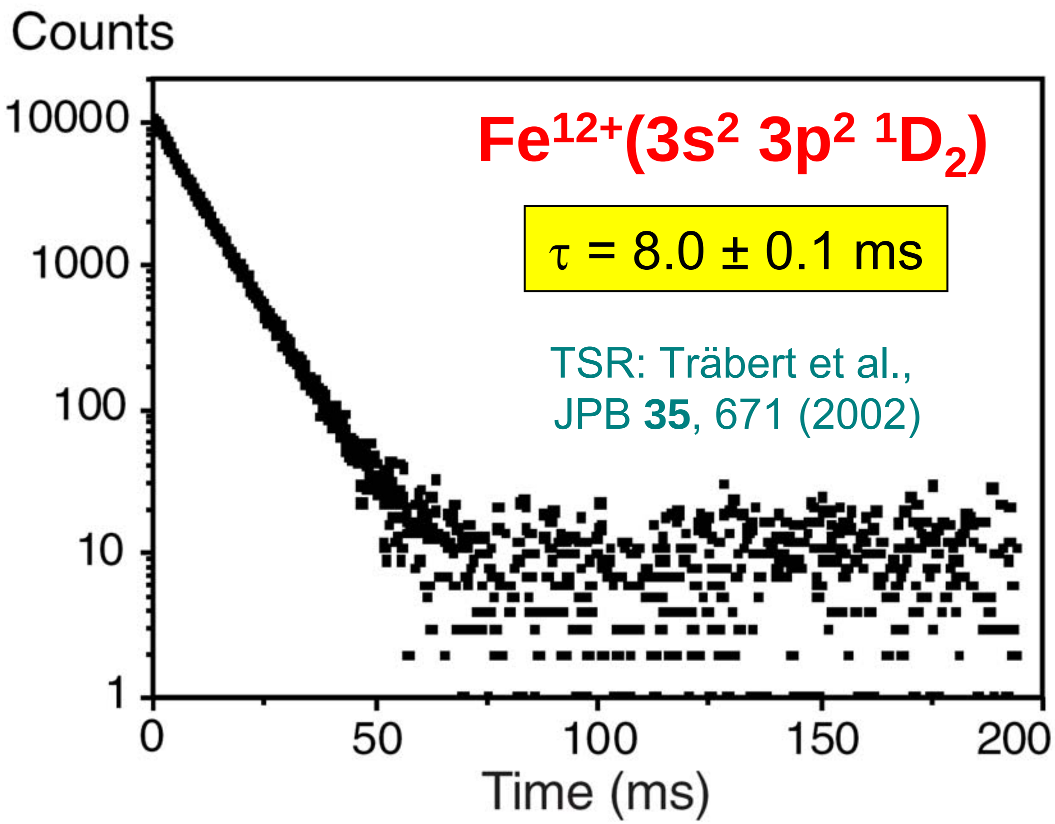
- **Storage of charged particles in** **well defined states**
  - mass
  - charge
  - velocity
- **Ion beam cooling**
  - velocity spread
  - internal energy

Control of external and internal degrees of freedom

Decay of excited states

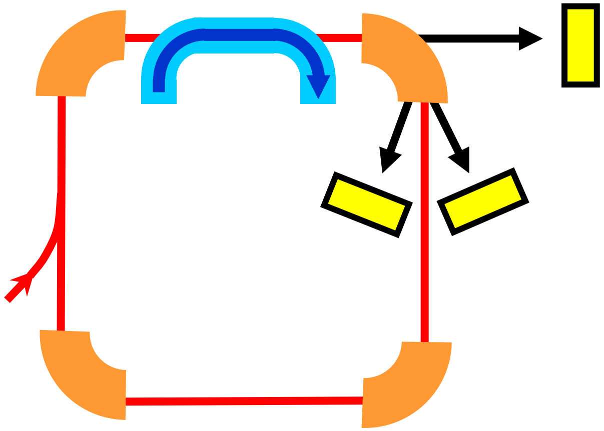


Injection of ions in metastable states



TSR: Träbert et al., JPB **35**, 671 (2002)

Reactions
e.g. charge changing electron collisions



Reaction products

- beams of high directionality
- high particle energies in lab frame

100% detection efficiency

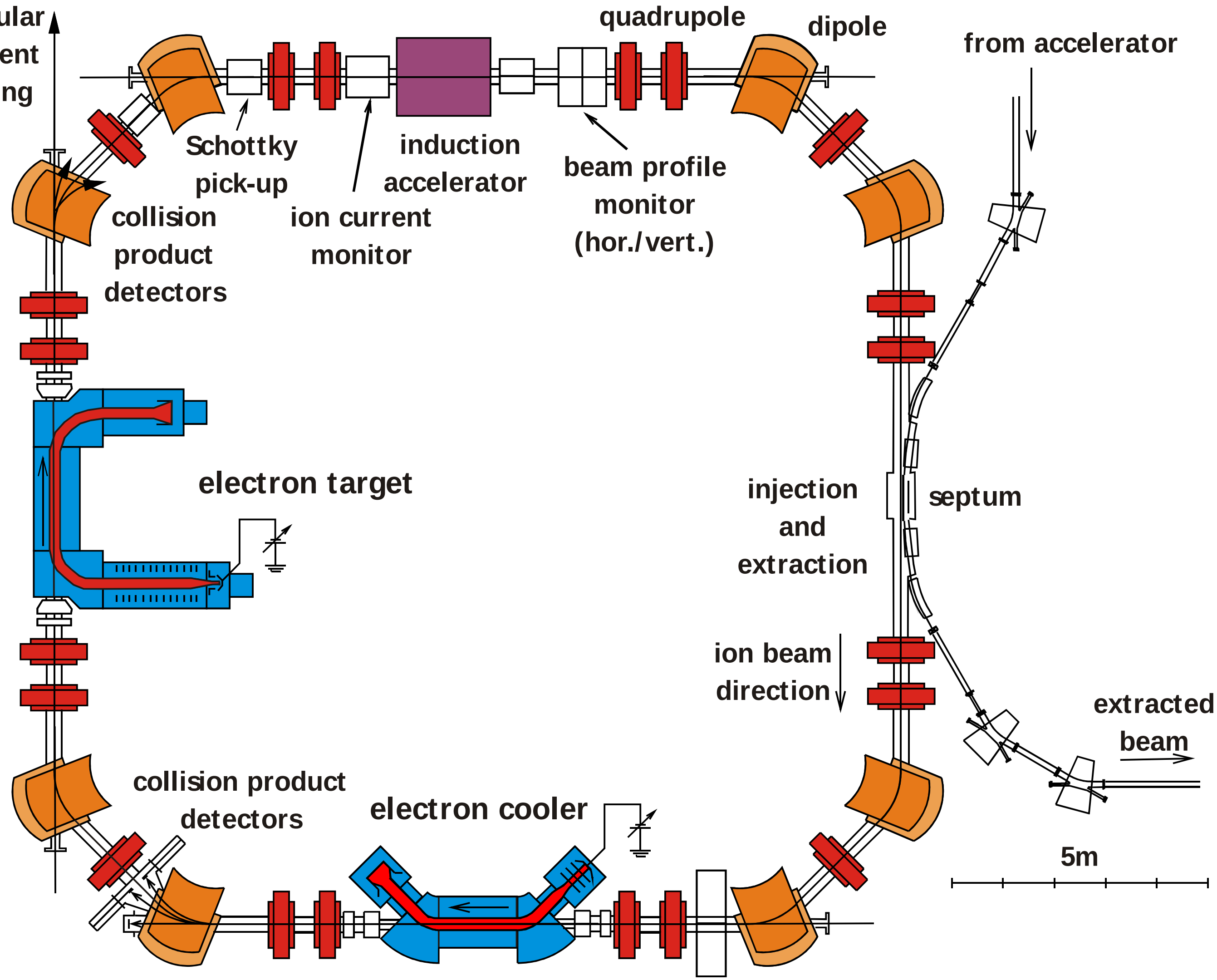
collision experiments with dilute ensembles of particles

tunable relative energy: sub **meV** to sub **MeV**

e.g. electron-ion recombination:

$$A^{q+} + e^{-} \rightarrow A^{(q-1)+} + \text{photons}$$

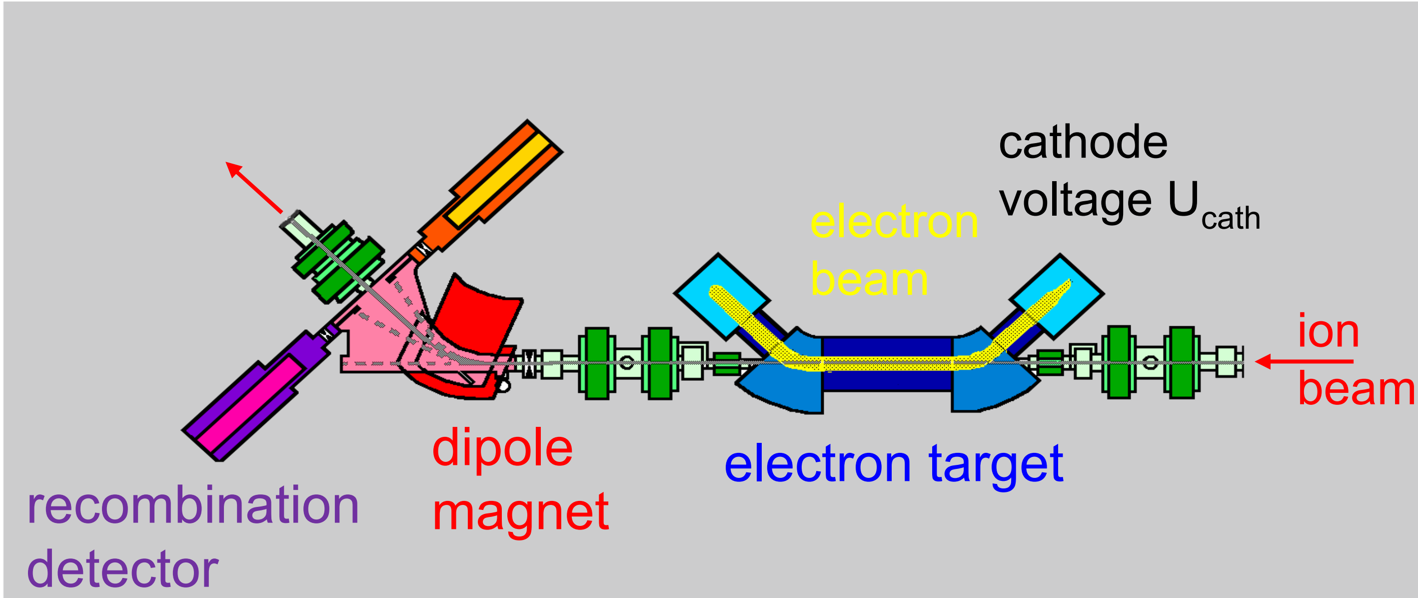
The Heidelberg storage ring TSR
- twin electron beams -



ultracold electron beam for high-resolution measurements

continuously cooled ion beam with well defined veolcity

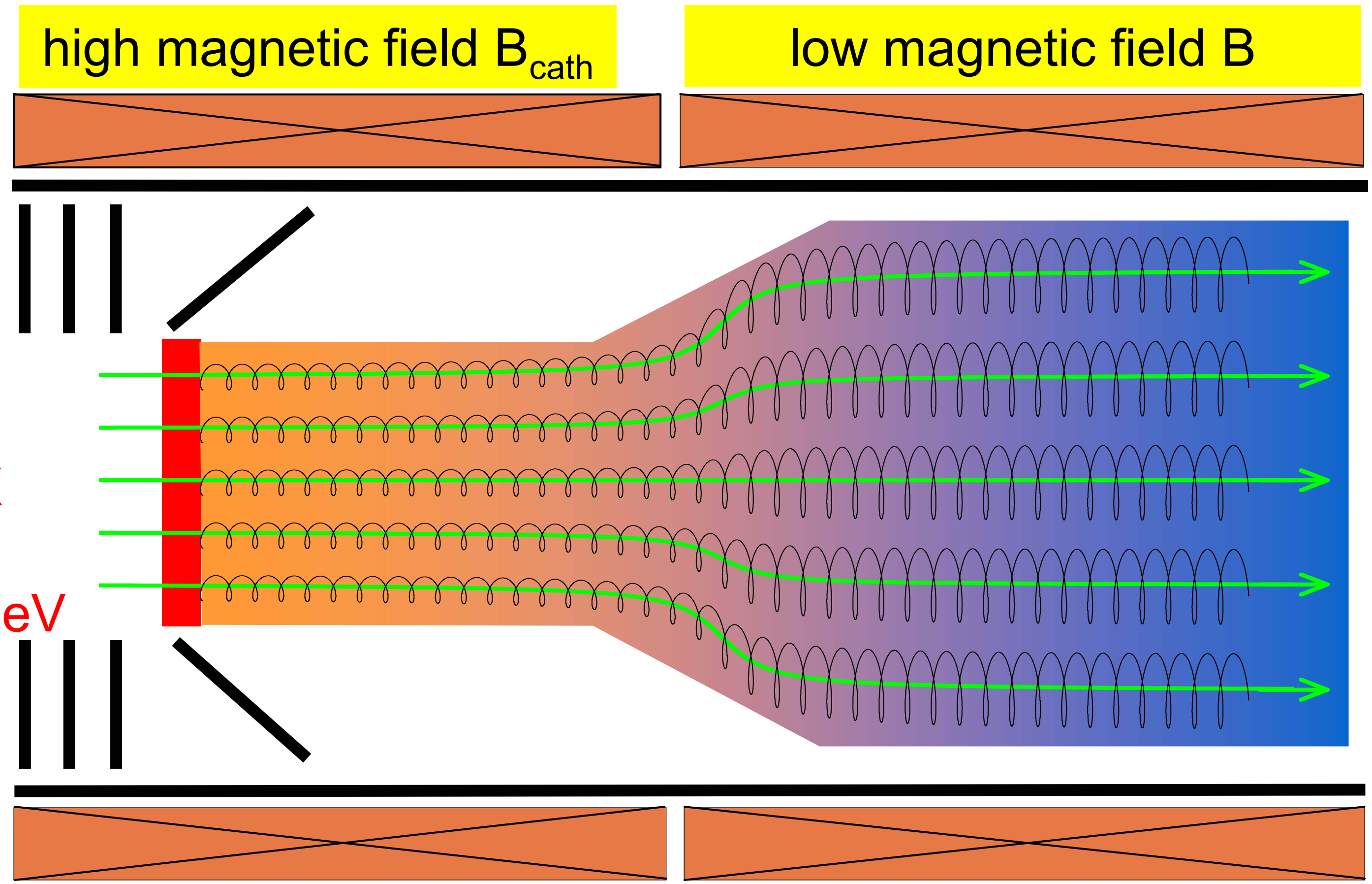
Scheme of recombination measurement



merged-beams rate coefficient: $\alpha = \langle \sigma v \rangle = \dfrac{R\,/(1-\beta_{ion}\beta_e)}{N_{ion}\; n_e\; L/C}$

The electron beam

acceleration and transverse expansion



cathode temperature $T_{cath} \approx 1400$ K

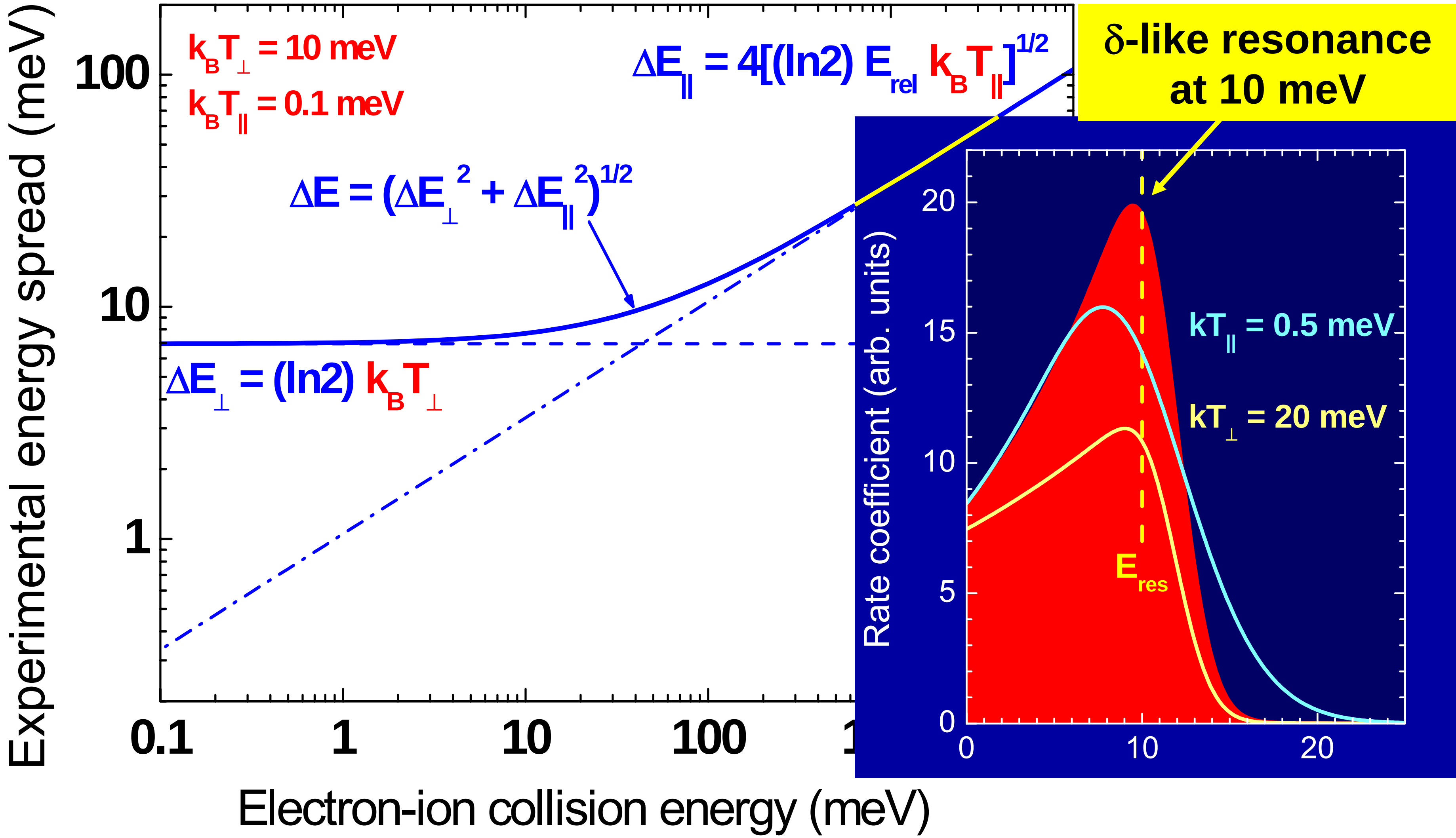
$k_B T_{cath} \approx 0.12$ eV

longitudinal temperature $T_{\parallel} = \frac{(k_B T_{cath})^2}{2eU_{acc}} + \underline{\textit{relaxation}}$

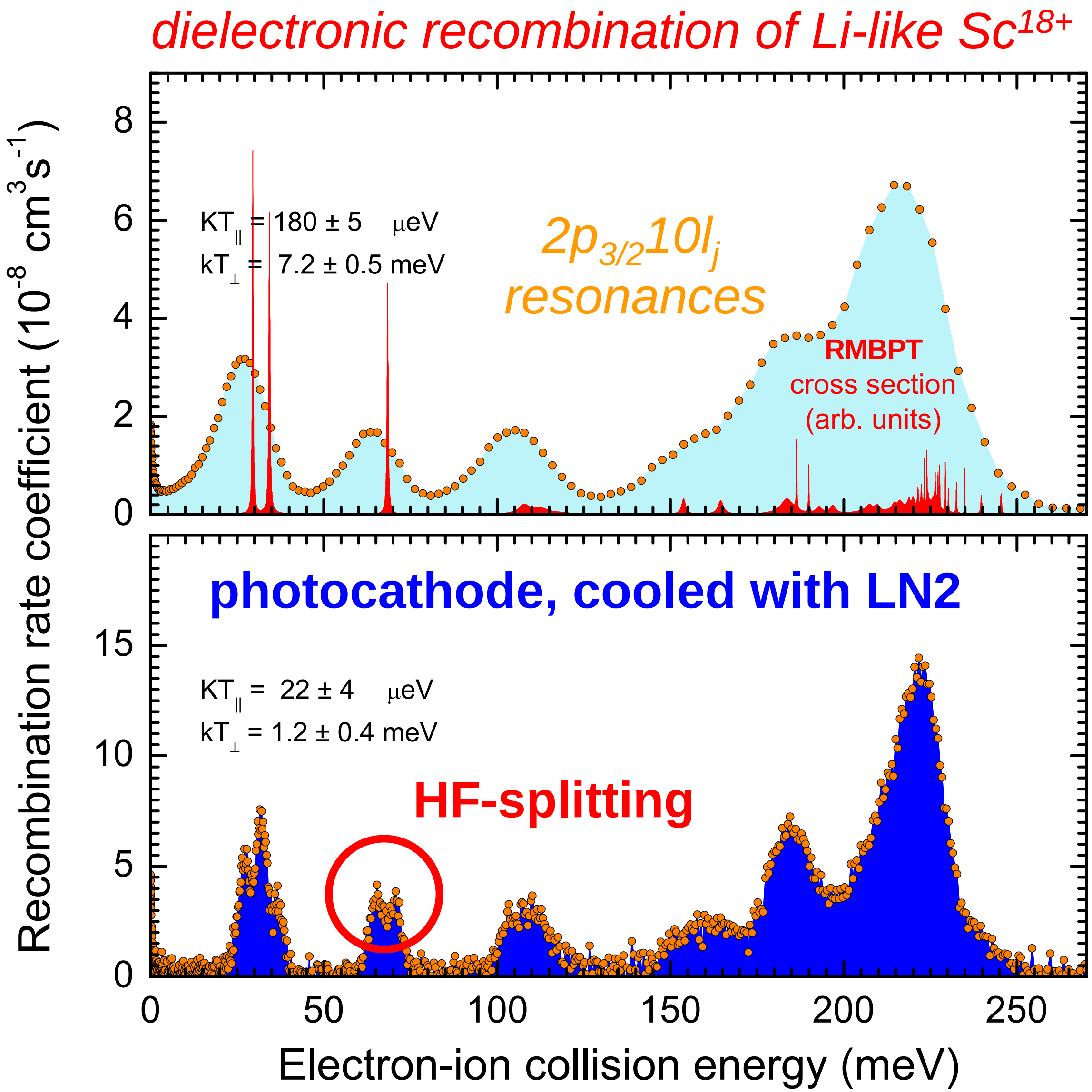
<<

transverse temperature $T_{\perp} = \frac{B}{B_{cath}} T_{cath}$

Merged-beams kinematics
- experimental electron energy spread -



Thermionic cathode vs. photocathode



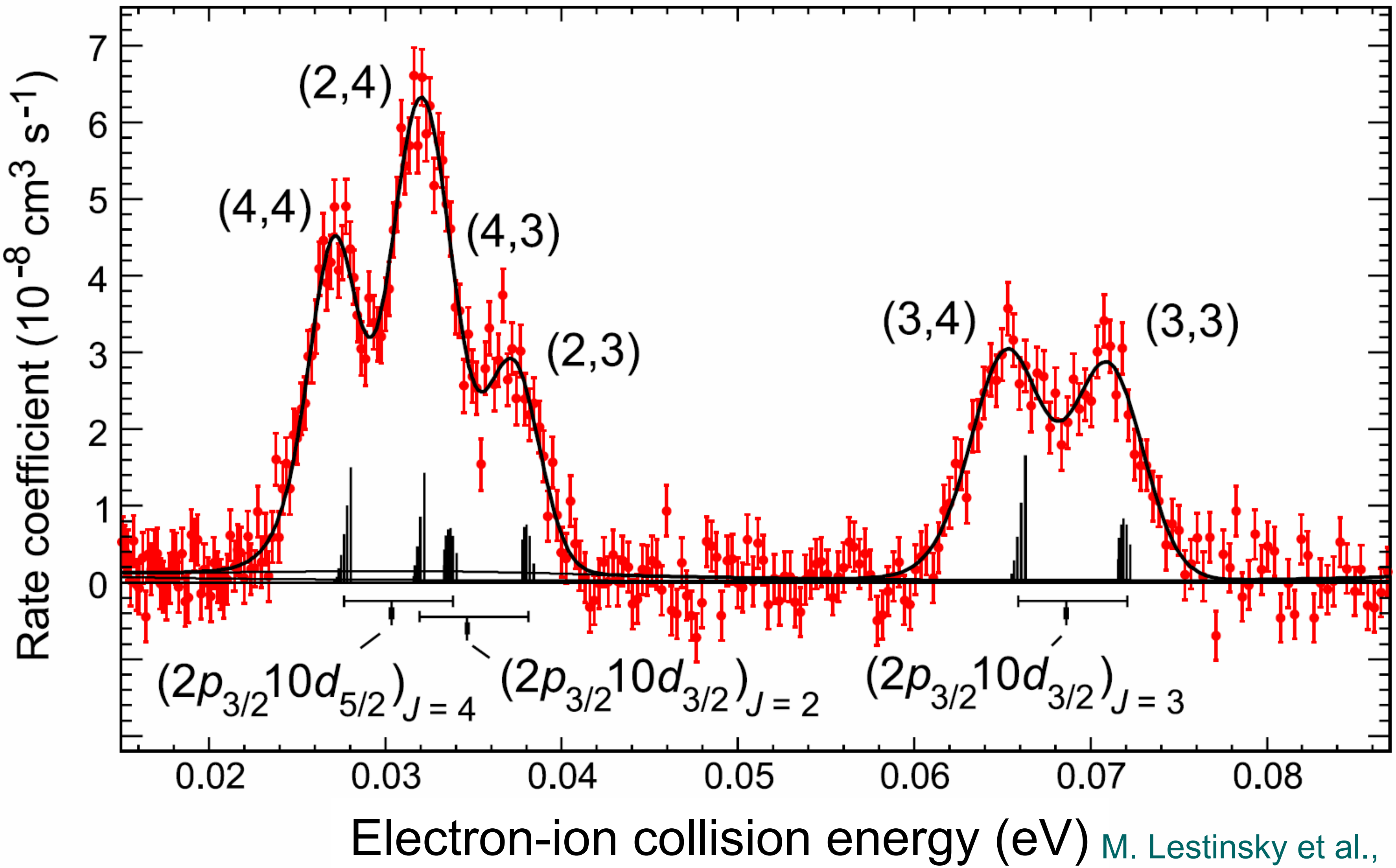
TSR electron cooler

S. Kieslich et al., PRA **70** (2004) 042714

TSR electron target

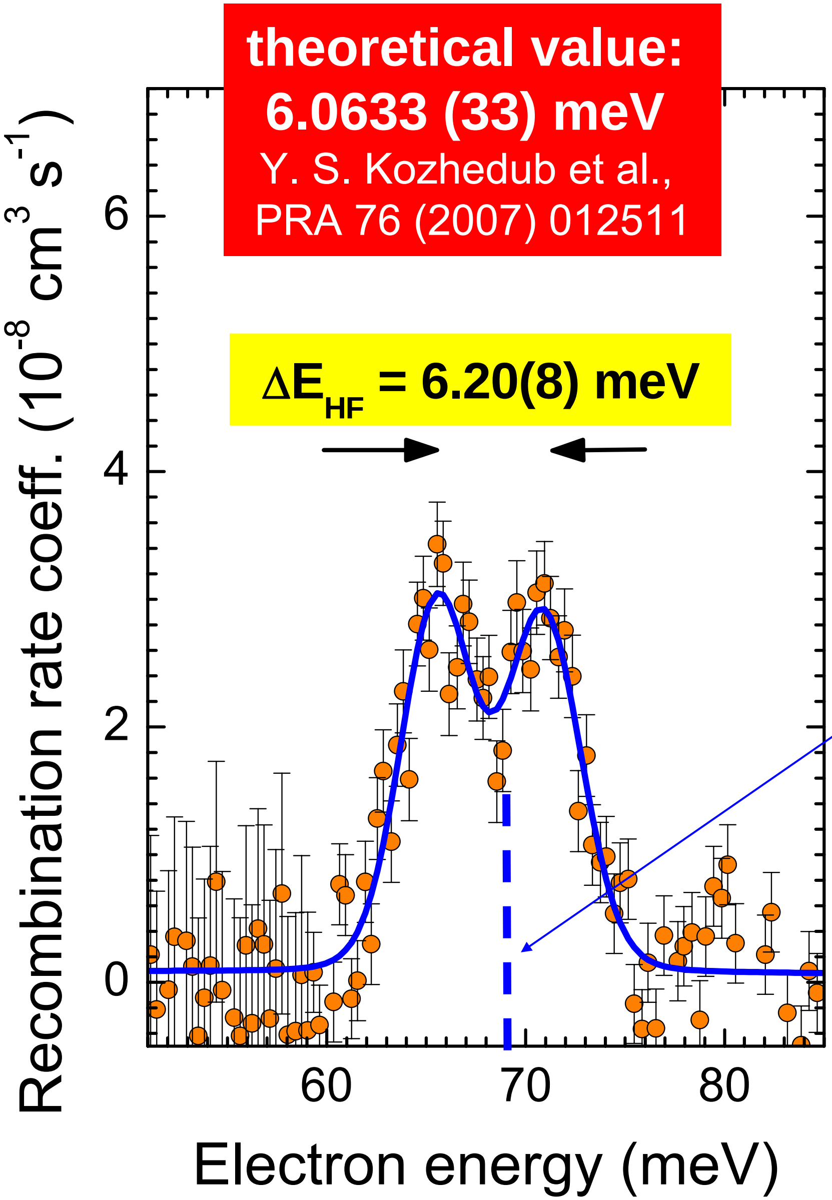
M. Lestinsky et al., PRL **100** (2008) 033001

Hyperfine split DR resonances

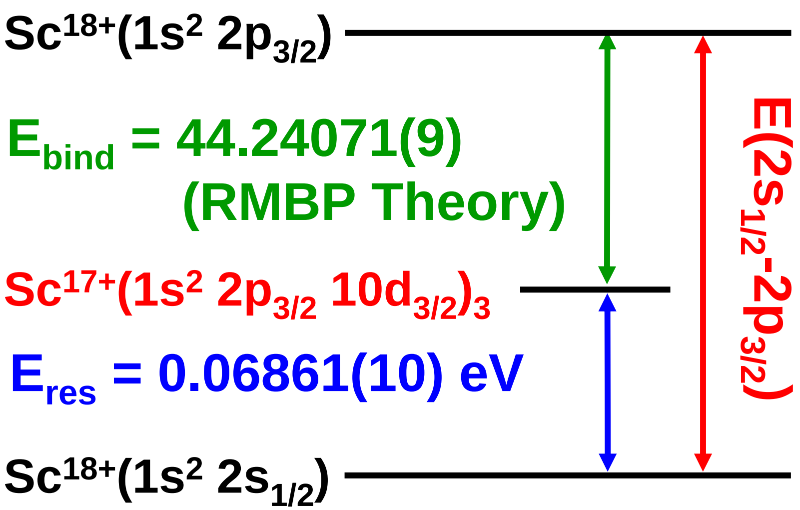


M. Lestinsky et al.,
PRL **100** (2008) 033001

Derivation of the $2s_{1/2}$-$2p_{3/2}$ splitting



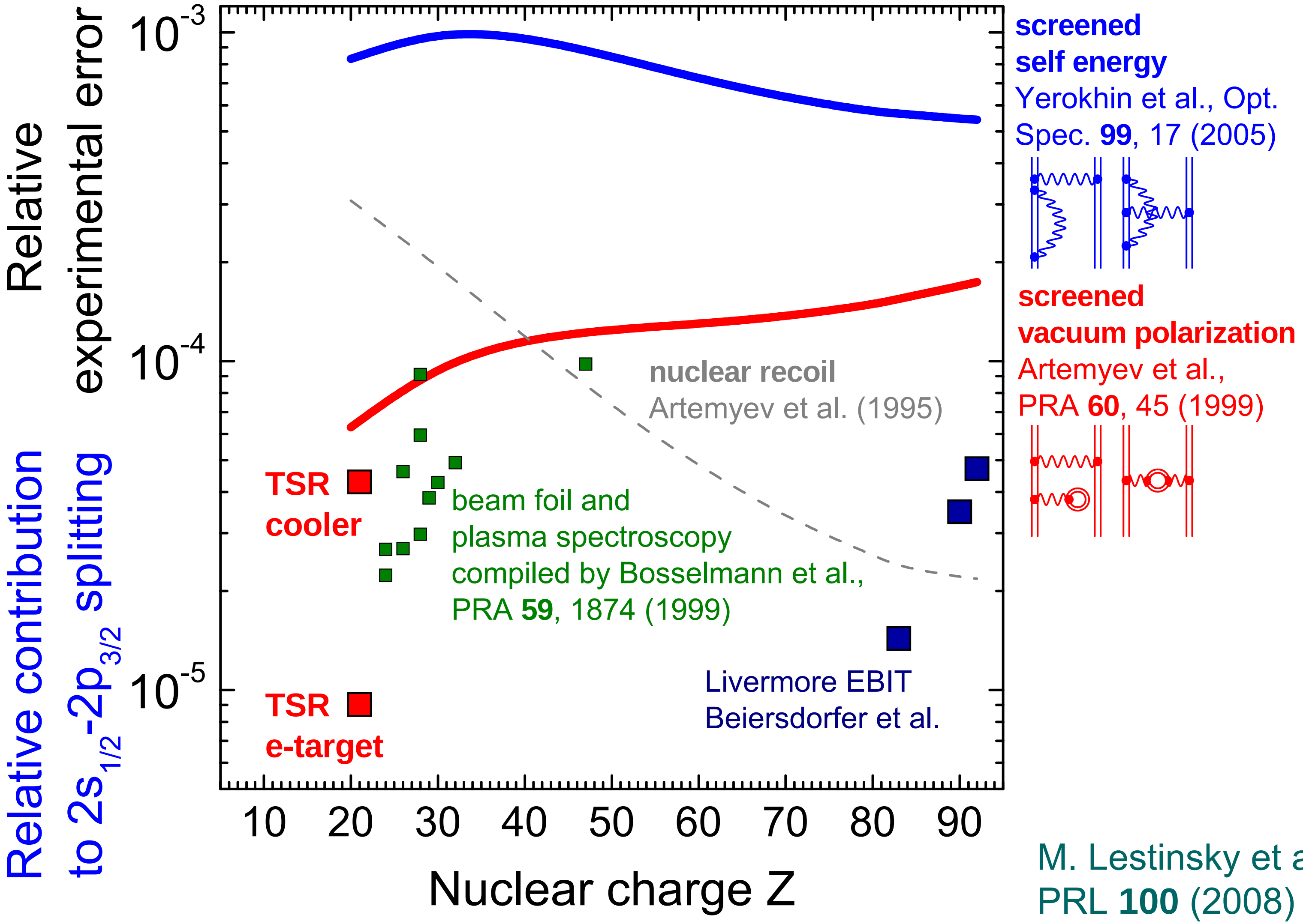
accurate determination of the $2s_{1/2} - 2p_{3/2}$ splitting:



$E(2s_{1/2}$-$2p_{3/2}) = E_{res} + E_{bind}$
$= 44.30932(15)$ eV

rel. accuracy: <5 ppm

Sensititivity to higher-order QED effects

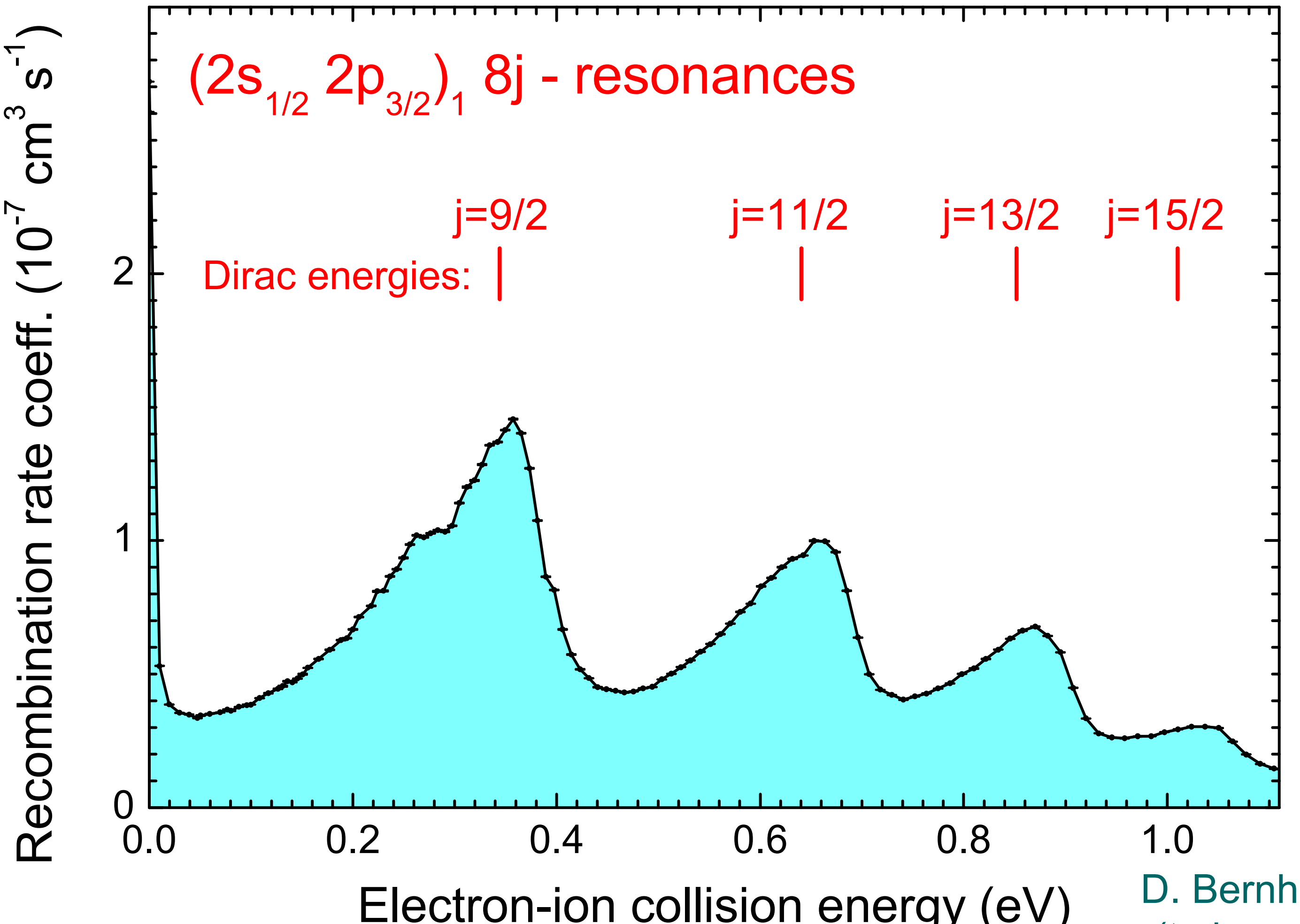


M. Lestinsky et al., PRL **100** (2008) 033001

Low-energy DR of Be-like Xe^{50+} @ ESR

$2s^2 \rightarrow (2s_{1/2}\,2p_{3/2})_1$ excitation energy: **532.759 eV**

RMBPT, Safronova et al., PRA **53**, 4036 (1996)

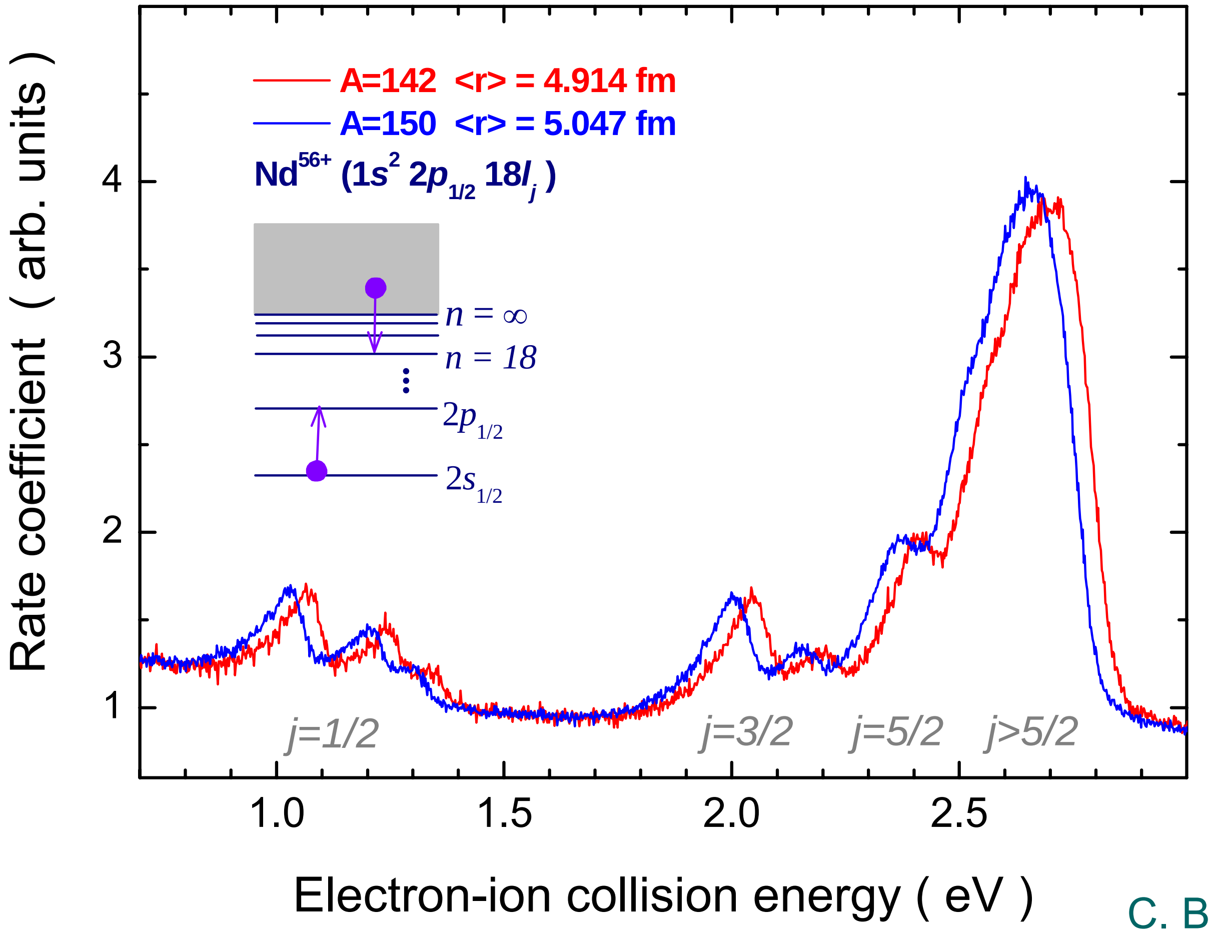


D. Bernhardt et al.
(to be published)

Isotope shift of DR resonances

Extraction of δ⟨ r^2 ⟩(142-150) = 1.36 (1)(3) fm^2

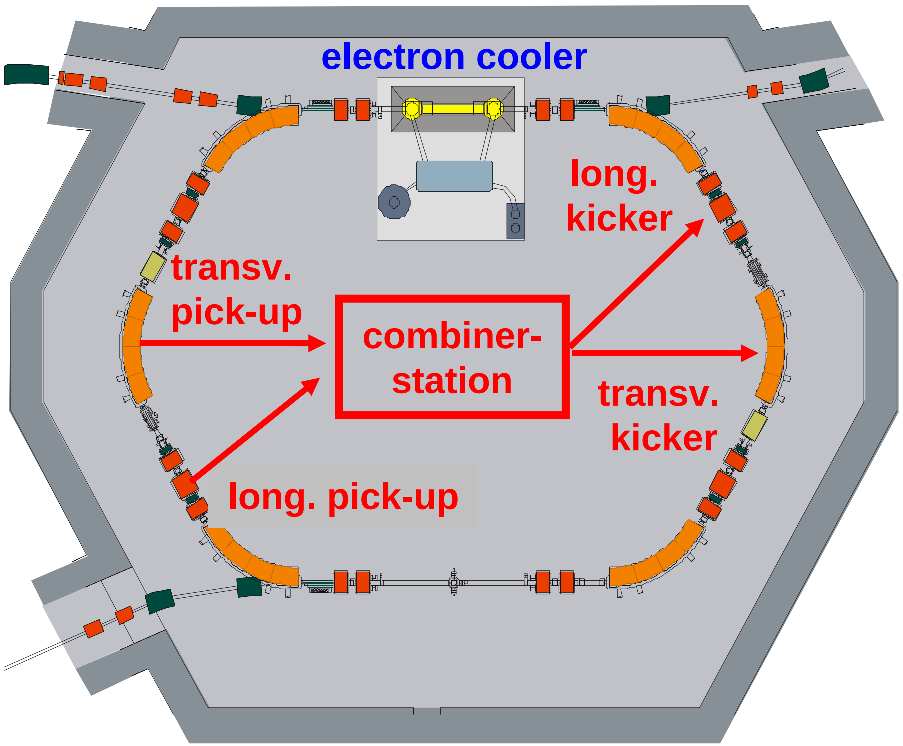
ESR storage ring at GSI: DR of Li-like Nd^{57+}



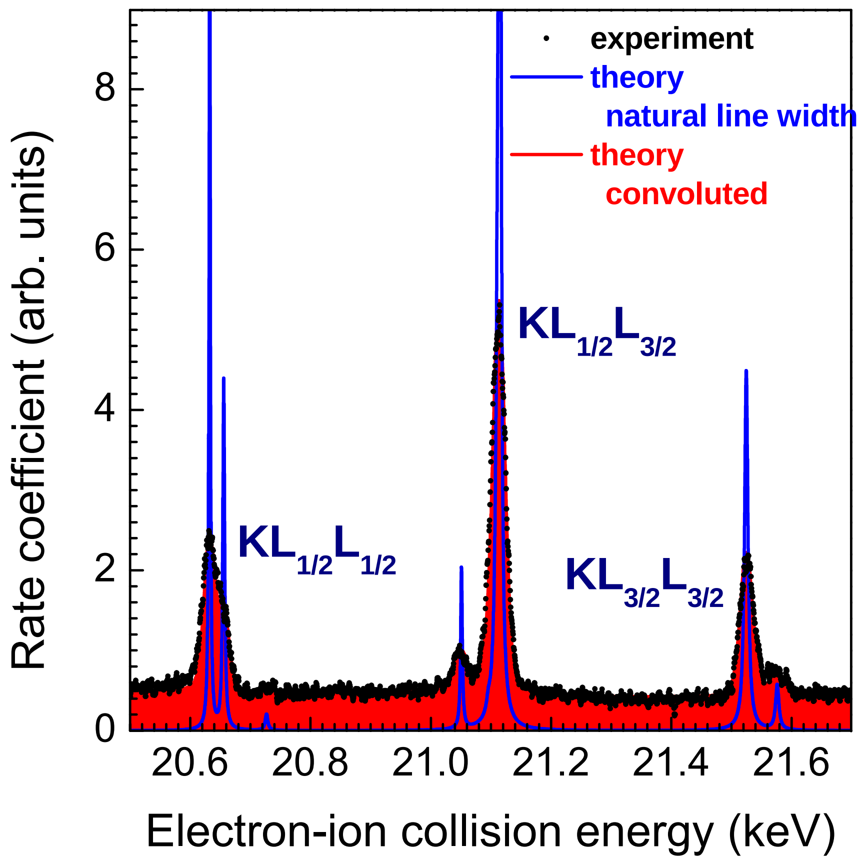
C. Brandau, et al.,
PRL **100** (2008) 073201

Dielectronic recombination of stochastically cooled ions

ESR storage ring, GSI Darmstadt



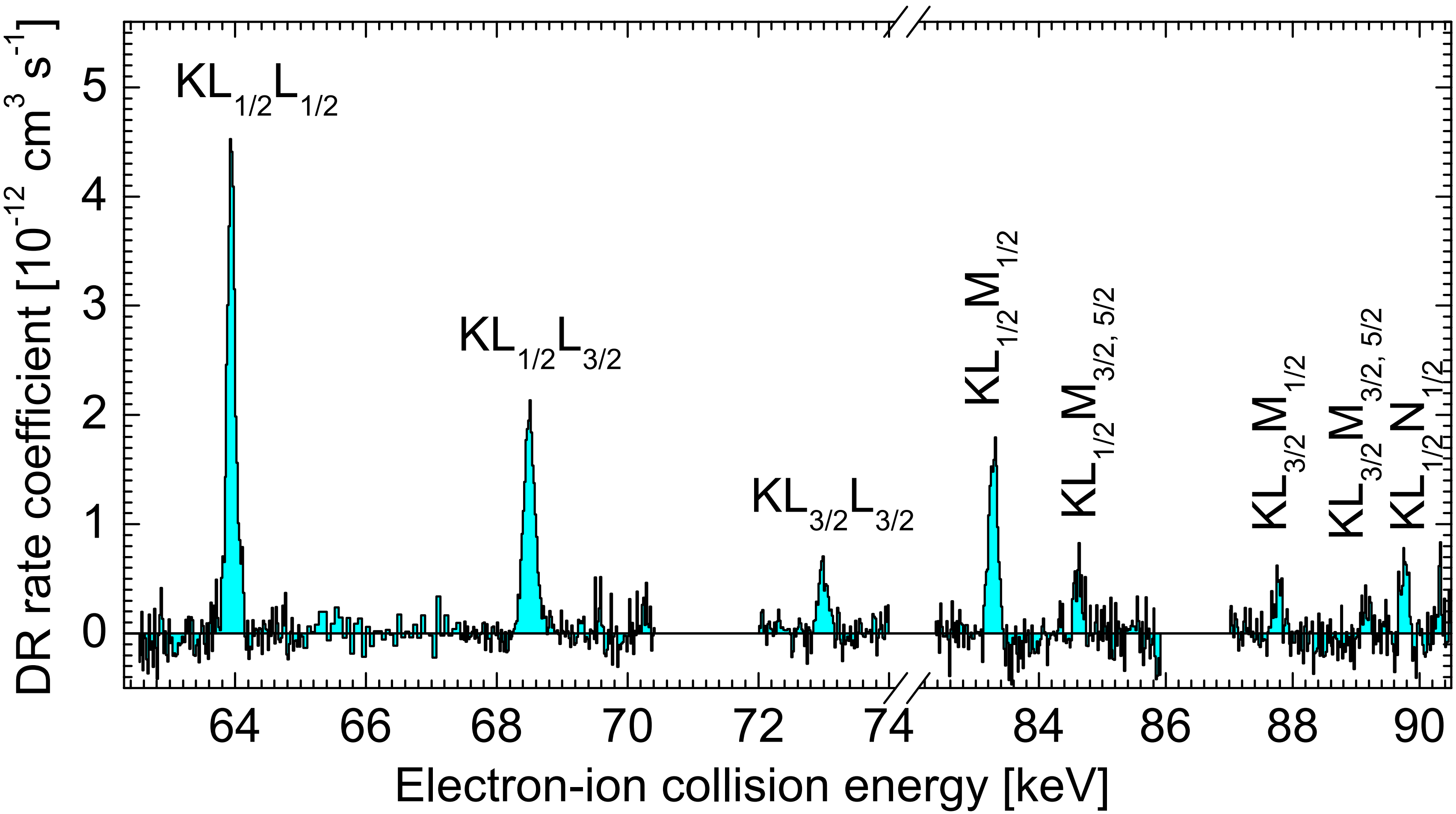
KLL-DR of H-like Xe^{53+}



C. Kozhuharov, C. Brandau et al., ICPEAC 2003

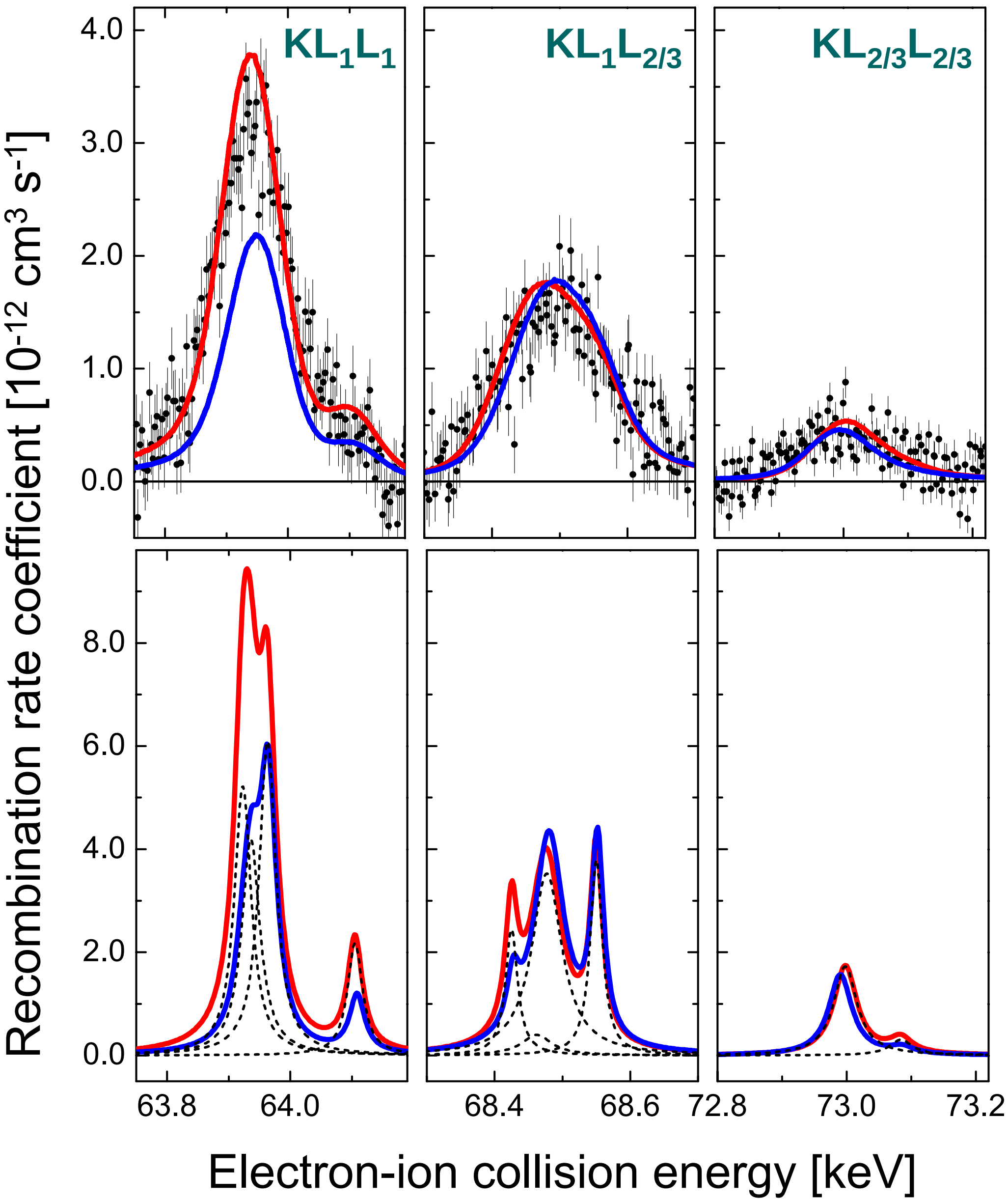
KLL-DR of hydrogenlike U^{91+}

stochastically cooled ion beam, electron cooler used as target only



ESR experiment: D. Bernhardt, C. Brandau, C. Kozhuharov, et al.

KLL-DR of U^{91+}: Comparison with theory



MCDF-calculations by
Z. Harman, T. Steih, W. Scheid et al.
Coulomb only
Coulomb + Breit

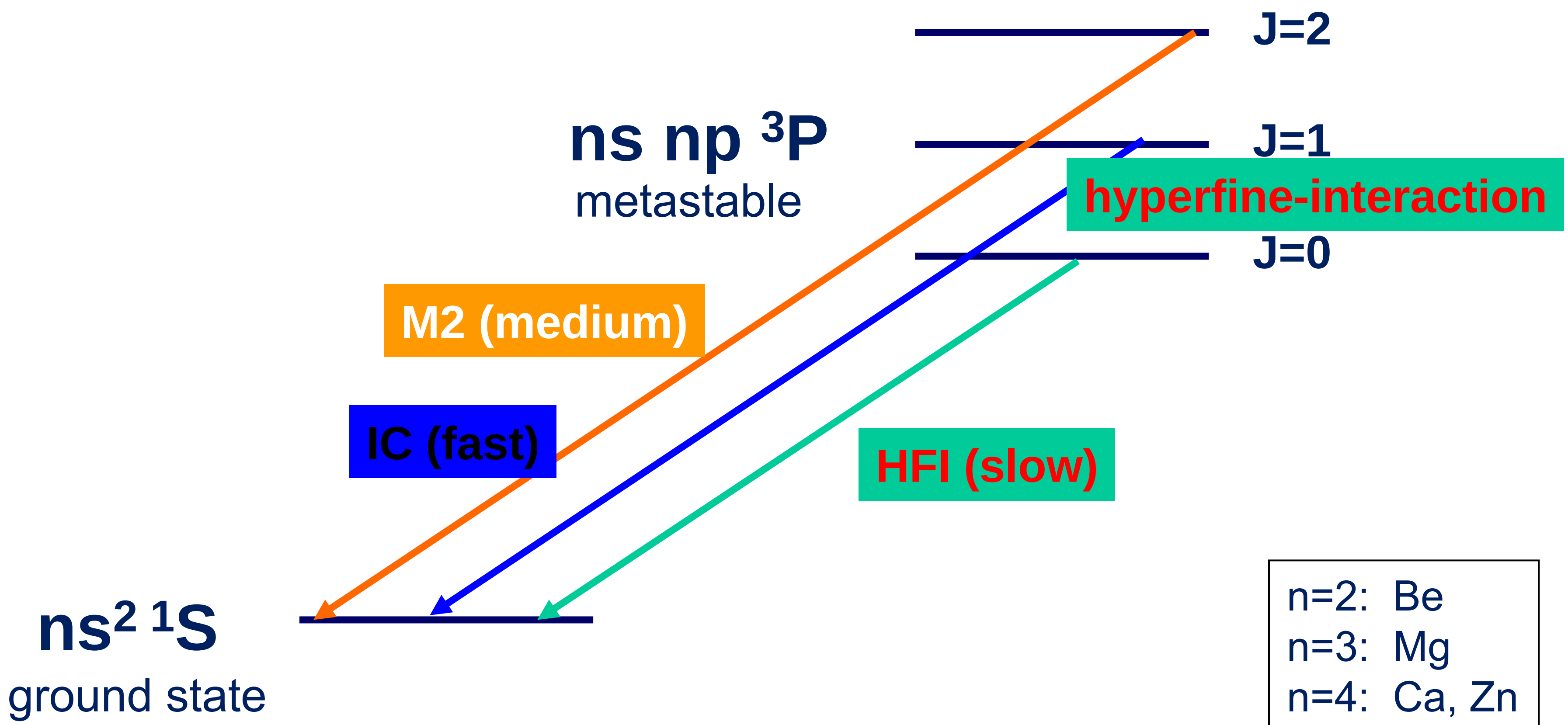
up to 44% Breit

experiment and theory
independently
on absolute scales

experimental resolution
close to
natural linewidths

D. Bernhardt, C. Brandau et al.
(to be published)

Transitions in divalent atoms and ions



n=2: Be
n=3: Mg
n=4: Ca, Zn
n=5: Sr, Cd
n=6: Ba, Hg
n=7: Ra

The challenge

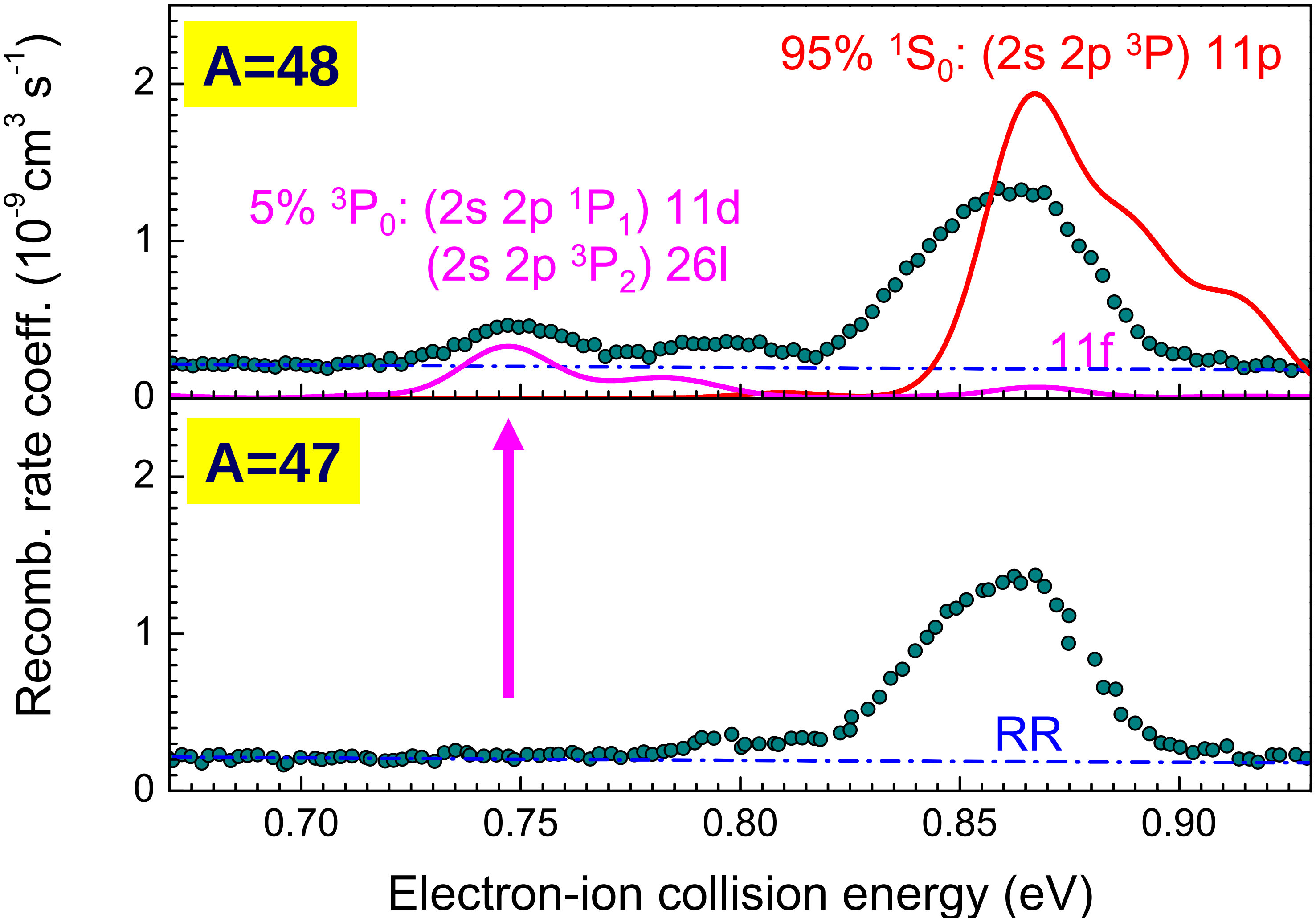
measurement of an extremely long lifetime

prediction for the $^{47}Ti^{18+}(2s2p\ ^3P_0)$ state: τ = 2.8 s

theory by Marques et al., PRA 47 (1993) 929

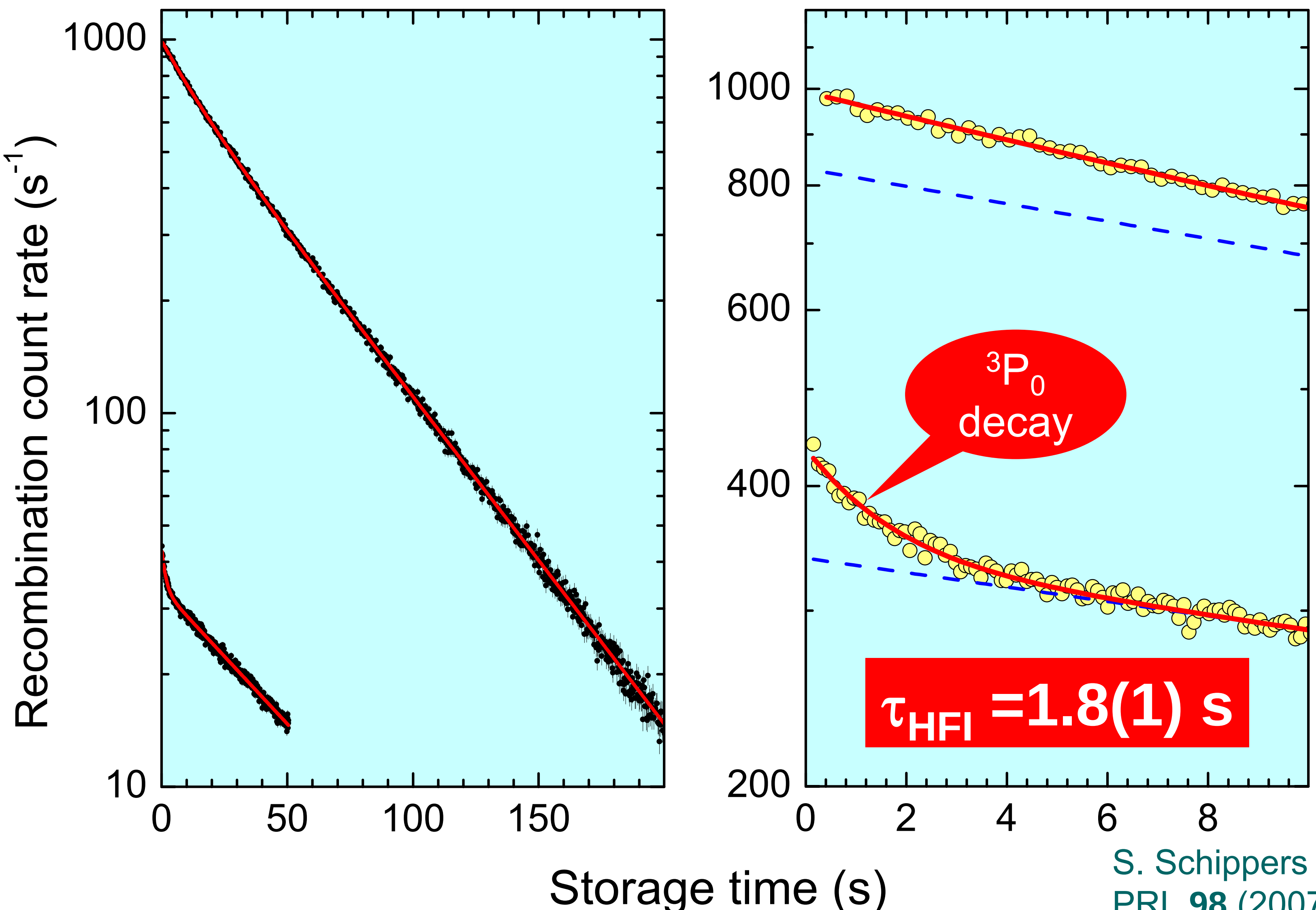
needs well defined environment without significant disturbance of the long living state

Ti^{18+} DR spectrum at low energies



S. Schippers et al.
JPC **58** (2007) 137

Recombination signal at 0.75 eV vs. time

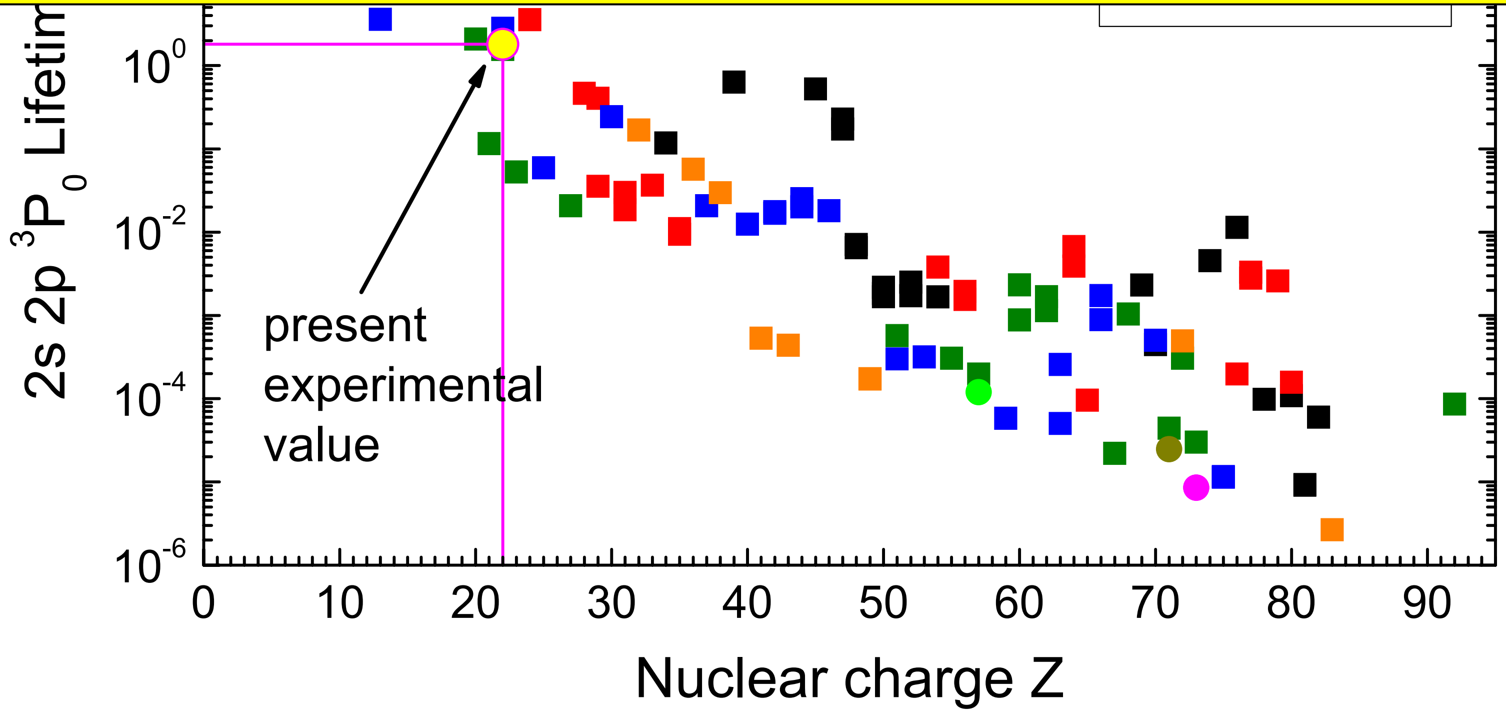


S. Schippers et al.
PRL **98** (2007) 033001

Theoretical 2s2p $^3P_0$ lifetimes

Ti^{18+} values

1993 theory:	**2.812 s**	Marques et al. PRA 47 (1993) 929
2007 experiment:	**1.8(1) s**	Schippers et al., PRL 98 (2007) 033001
2008 theory:	**1.487 s**	Cheng et al., PRA 77 (2008) 052504
2009 theory:	**1.476 s**	Andersson et al., PRA 79 (2009) 032501
2010 theory:	**1.51 s**	Li & Dong, Plas. Sci. Technol. 79 (2010) 032501



J. P. Marques, F. Parente & P. Indelicato, Phys. Rev. A **47** (1993) 929

Summary

- **High-resolution studies of low-energy DR**
  - **Hyperfine split DR resonances**
  - **$2s_{1/2}$–$2p_{3/2}$ splitting in Li-like Sc^{18+} determined with 4.6 ppm accuracy**
  - **Sensitive to few-body effects on radiative corrections**
  - **Isotope shifts of DR resonances**
- **Stochastically cooled ion beam at the ESR**
  - **KLL-DR of H-like Xe^{53+} and U^{91+}**
  - **Absolute determination of contribution by Breit interaction**
  - **Natural linewitdhs almost resolved**
- **Hyperfine induced transions in Be-like ions**
  - **First laboratory measument with Ti^{18+}-ions**
  - **New theoretical results in better agreement than older ones**

Collaborators

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and
F. J. Currell (Belfast), Z. Stachura (Krakow), A. S. Terekov (Novosibirsk)

Non-comprehensive list of $\delta\langle r^2 \rangle$ values for the isotope pair ^{142}Nd - ^{150}Nd

about 20 publications (optical, muonic, K_α x-ray, e-scattering), a few examples :

Method	$\delta\langle r^2 \rangle$
„combined“ analysis:	**1.291 fm² [1]**
muonic atoms:	1.324 fm² [2]
e-scattering, high energy:	1.345 fm² [3]
e-scattering, low energy:	-0.569 fm² [4]
e-scattering, [4]] reanalysed:	0.765 fm² [5]
e-scattering, low energy (II):	0.220 fm² [6]
optical IS	1.205 fm² [7]
optical IS	1.259 fm² [8]
optical IS	1.220 fm² [9]
optical IS	1.205 fm² [10]
K_α x-ray	1.259 fm² [11]
K_α x-ray	1.353 fm² [12]
-IS (Brandau et al.)	**1.36(1)(3) ….**

[1] I. Angeli, ADNDT 87 (2004) 185
[2] G. Fricke, et al., ADNDT 60 (1995) 177
[3] N.P. Heisenberg, et al., NPA 164 (1971) 340
[4] D.W. Madsen, et al., NPA 169 (1971) 97
[5] L.S. Cardman, et al., NPA 216 (1973) 285
[6] R. Maas, et al., Phys. Lett. B 48 (1974) 212
[7] E. W. Otten, Treat on Heavy-ion Sci., Vol.8
[8] M. Wakasugi, et al., J Phys. Soc. Jap, 59 (1990) 2700
[9] W.H. King et al., Z Phys 265 (1973) 207
[10] M. Hongliang, et al., PRA 44 (1991) 1843 / J Phys B, 30 (1997) 3355
[11] S.K. Battacherjee, et al., PR 188 (1969) 188 / P.L. Lee and F. Boehm, PRC 8 (1973) 819
[12] O.I. Sumbaev, et al., Sov. J. Nucl. Phys. 5 (1967) 387

C. Brandau, et al., PRL **100** (2008) 073201

$^{A}Nd^{57+}$ DR iostope shifts and change in mean square radius

7 data sets for 0 - 3.5 eV: $^{A}Nd^{56+}(1s^2\ 2p_{1/2}\ 18\ l_j)$

3 data sets for 12 - 24 eV: $^{A}Nd^{56+}(1s^2\ 2p_{1/2}\ 19\ l_j)$
$^{A}Nd^{56+}(1s^2\ 2p_{3/2}\ 8\ l_{1/2})$

1 data set for 25 - 41 eV: $^{A}Nd^{56+}(1s^2\ 2p_{1/2}\ 20\ l_j)$
$^{A}Nd^{56+}(1s^2\ 2p_{3/2}\ 8\ l_{j>/2})$
$^{A}Nd^{56+}(1s^2\ 2p_{1/2}\ 21\ l_j)$

154 „values“ for $2s_{1/2}$ - $2p_{1/2}$ $\Rightarrow \Delta E$ (A =142 – 150) = 40.2 (3)(6) meV
45 „values“ for $2s_{1/2}$ - $2p_{3/2}$ $\Rightarrow \Delta E$ (A =142 – 150) = 42.3 (12)(25) meV

+ full QED calculations (Z. Harman, Y.S. Kozhedub)
+ NP 0.3 meV for A=150 (2^+-state,130.21 keV, B(E2↑) = 2.760 e^2b^2)

Extraction of $\delta\langle r^2\rangle$(142-150) = 1.36 (1)(3) fm^2

C. Brandau, et al., PRL **100** (2008) 073201
Y.S. Kozhedub, et al., PRA **77** (2008) 032501; Z. Harman et al., (to be published)