Precision Electron Collision Spectroscopy of Highly Charged Ions

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Electron–ion collision resonances

Merged beams in storage rings

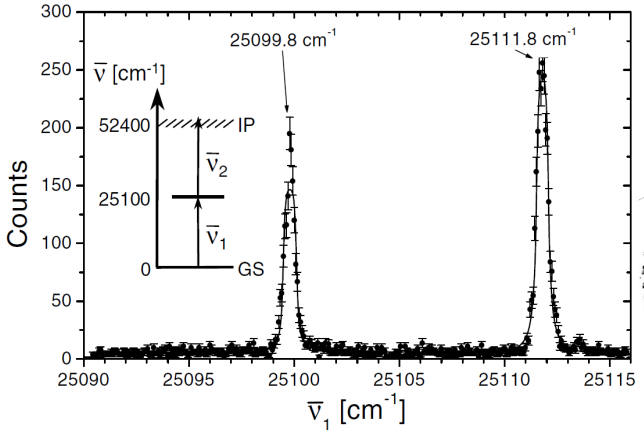
Precision measurements on low-energy resonances

Isotope shifts, QED contributions and hyperfine splitting in Li-like ions

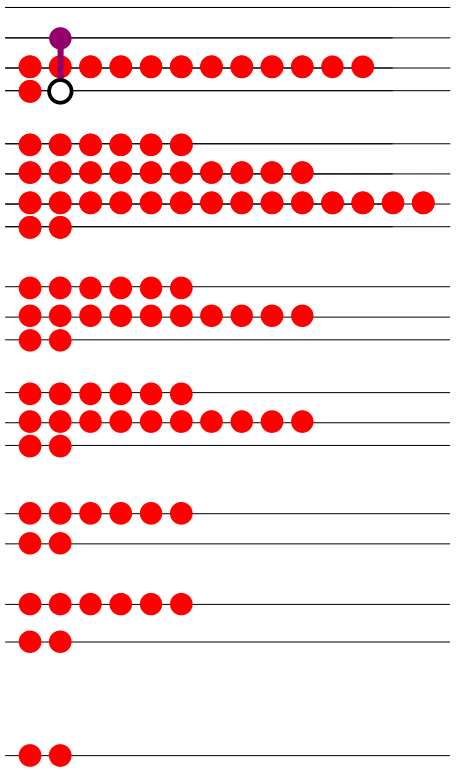
Collision resonances on Be-like and B-like cores

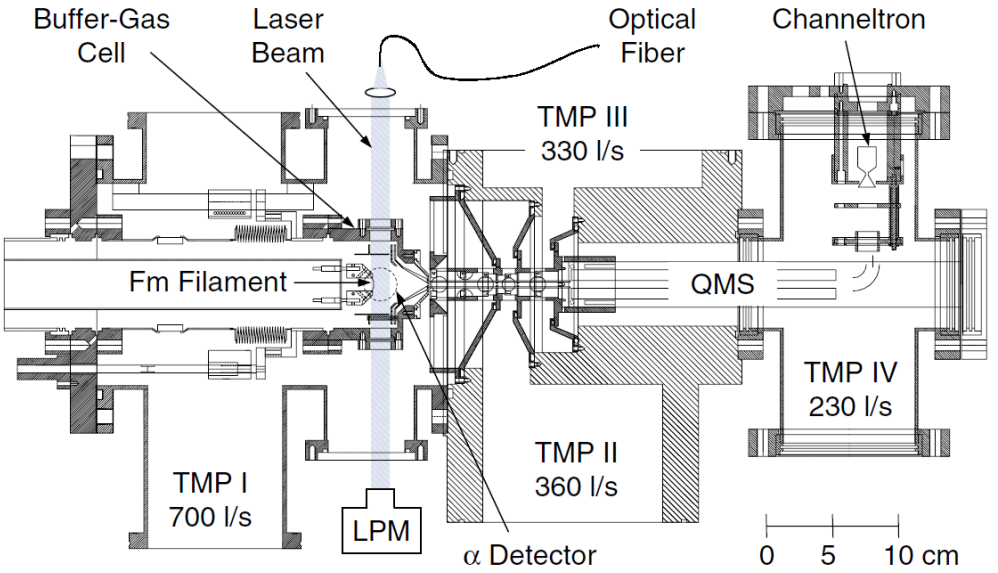
Ultra-low energy ion beams

Atomic physics studies of rare nuclides



$7s^2\ 5f^{12} \rightarrow 7s\ 5f^{12}\ 7p$





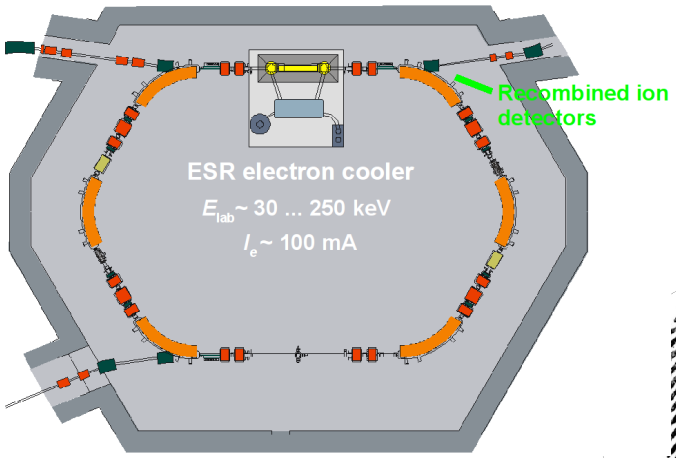
Resonance ionization spectroscopy

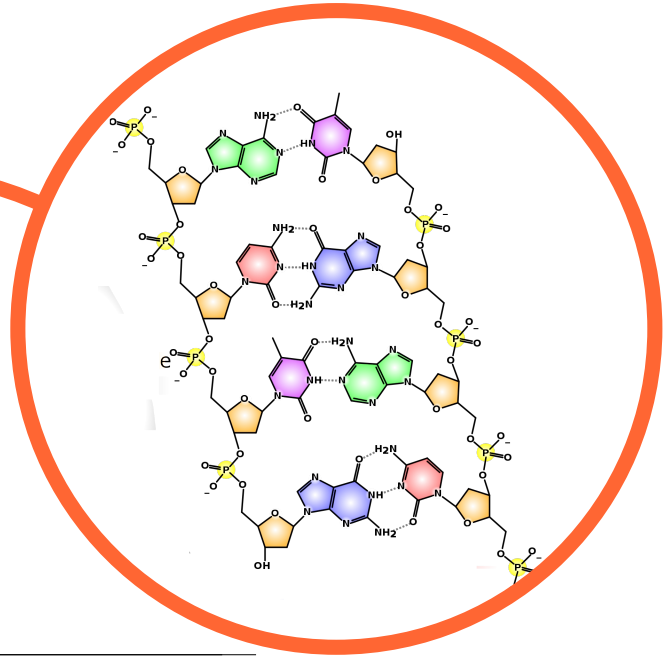
Sewtz, Backe et al.,
PRL 90, 163002 (2003)

^{255}Fm

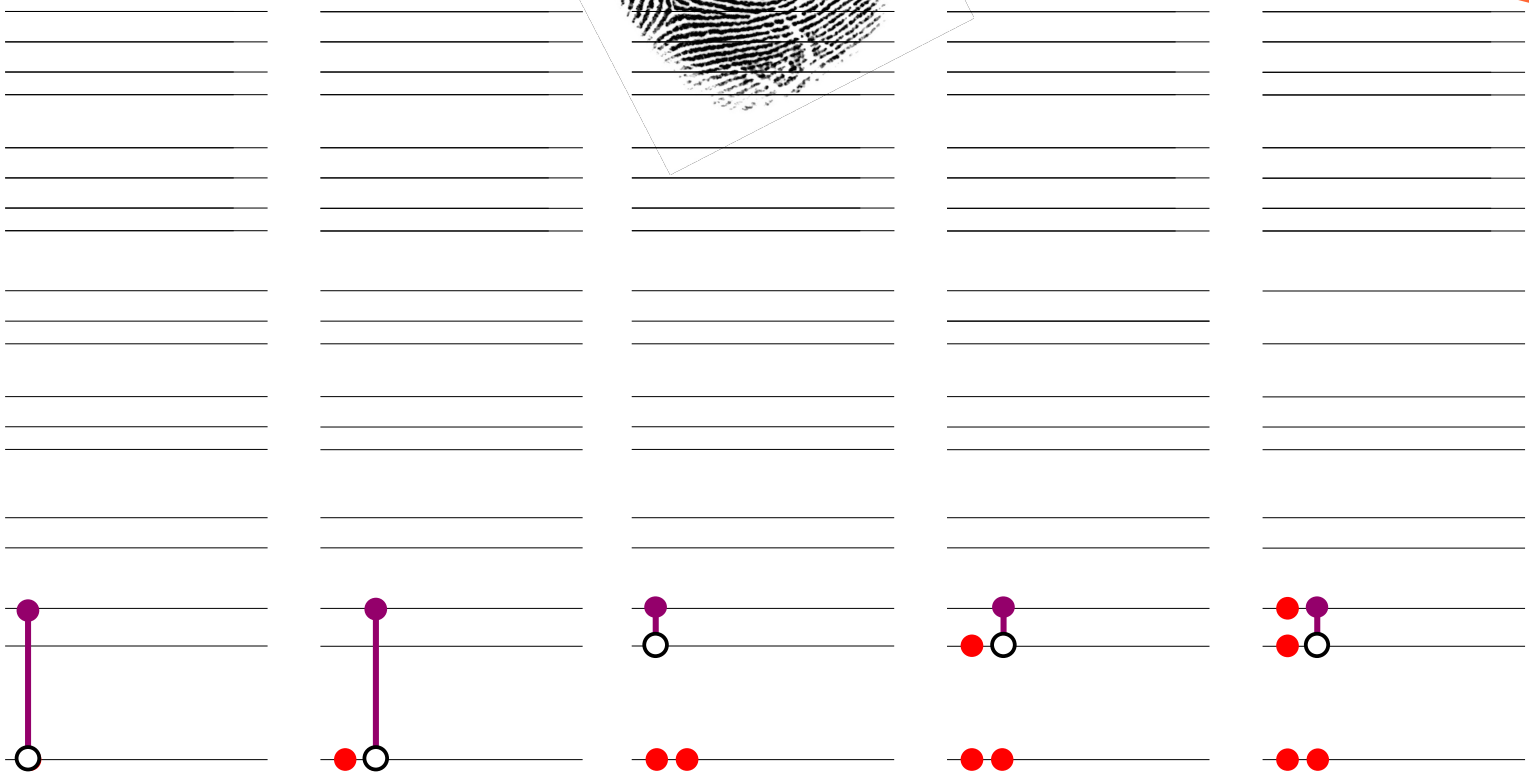
$t_{1/2}$ = 20.1 h

Few-electron ions



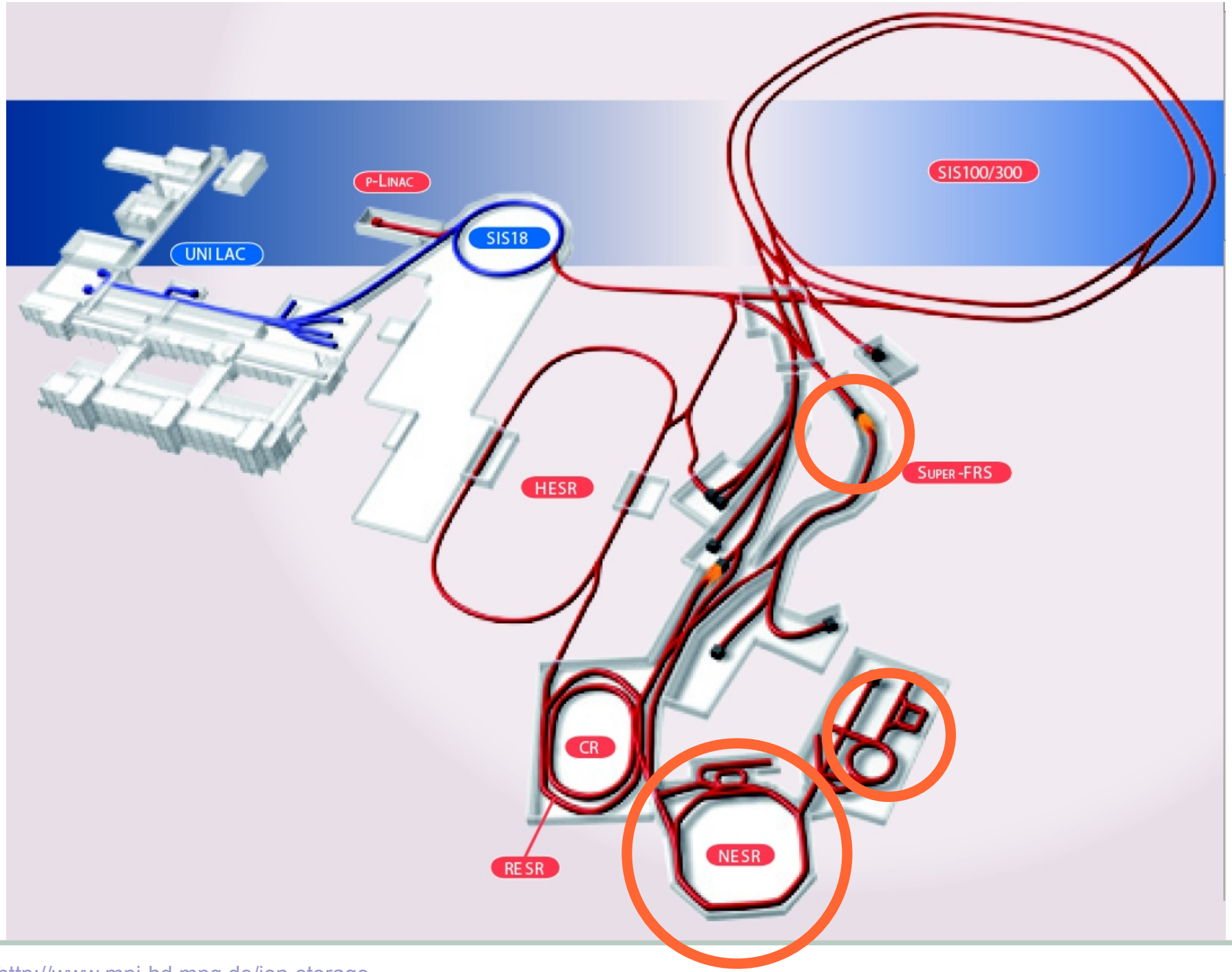


$^{A}Z^{q+}$



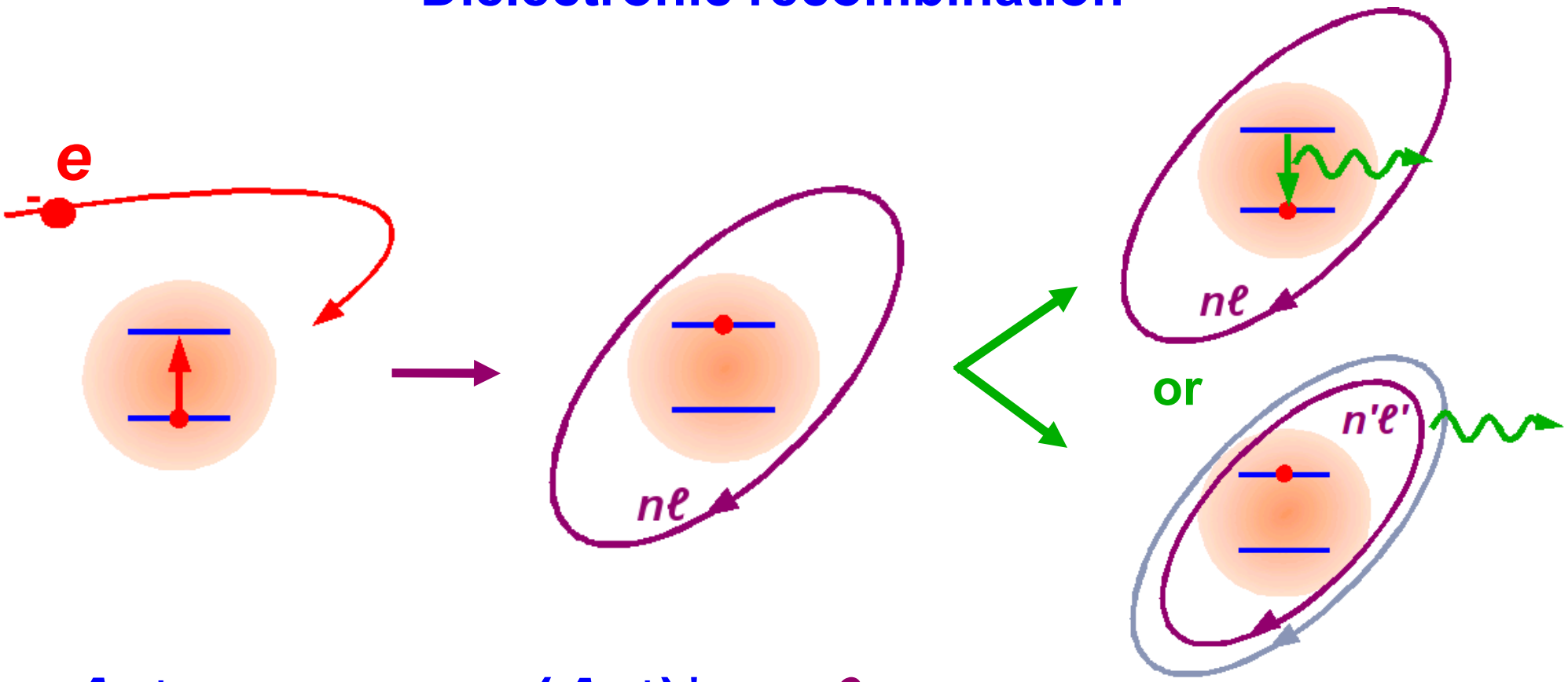
H-like ... B-like

Few-electron ions



Electron-ion collision resonances

Dielectronic recombination



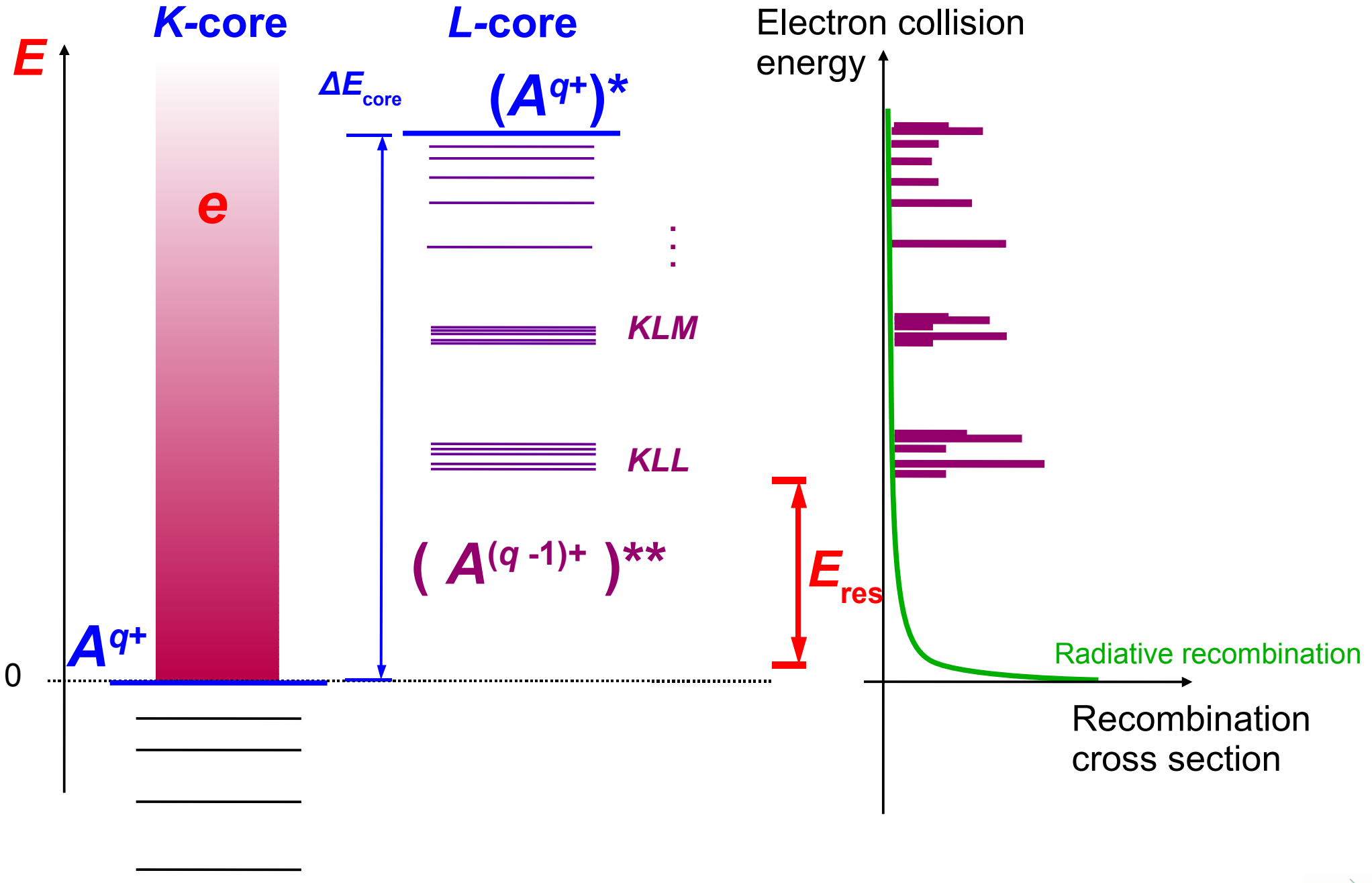
$A^{q+} + e$

$(A^{q+})^* + n\ell$

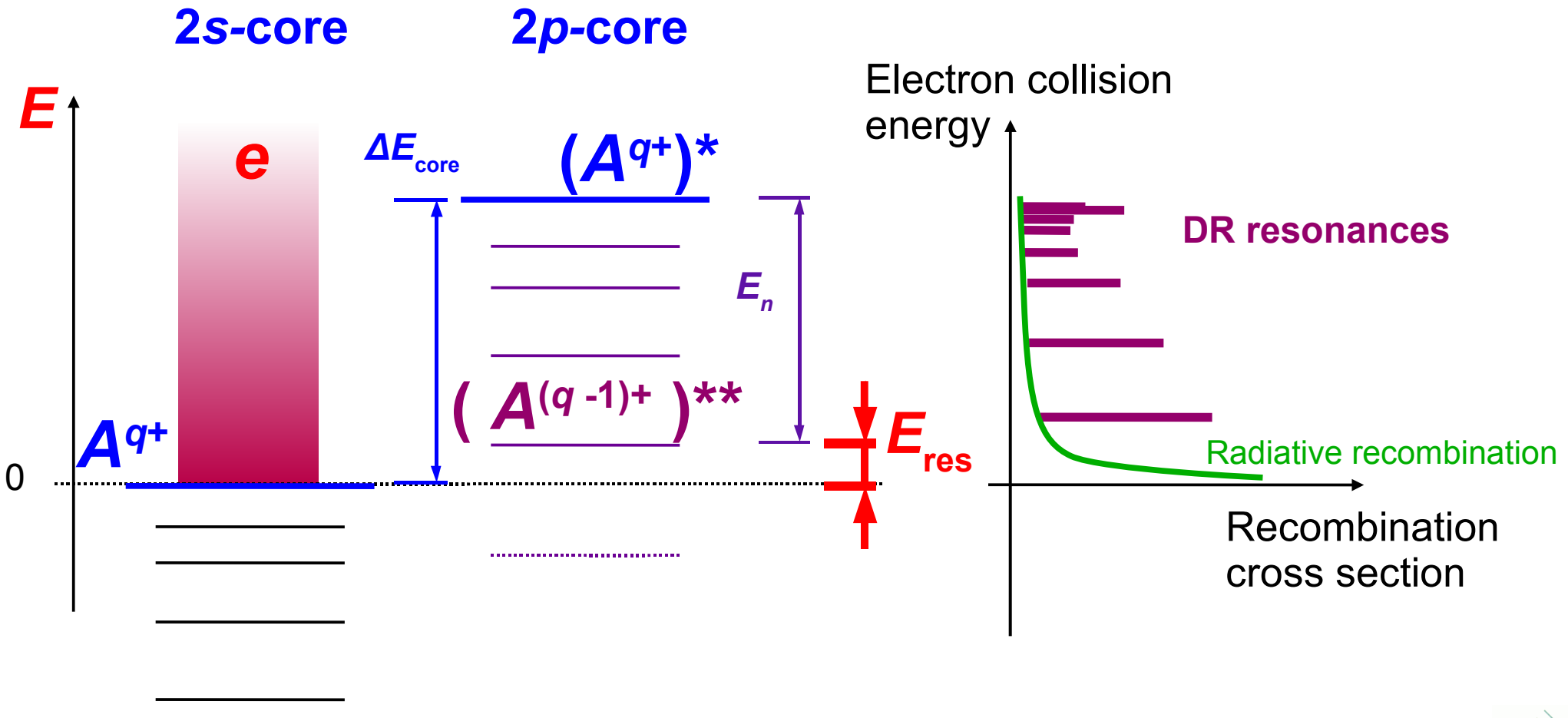
$(A^{(q-1)+})^{**}$

$(A^{(q-1)+})^* + h\nu$

High-energy dielectronic recombination

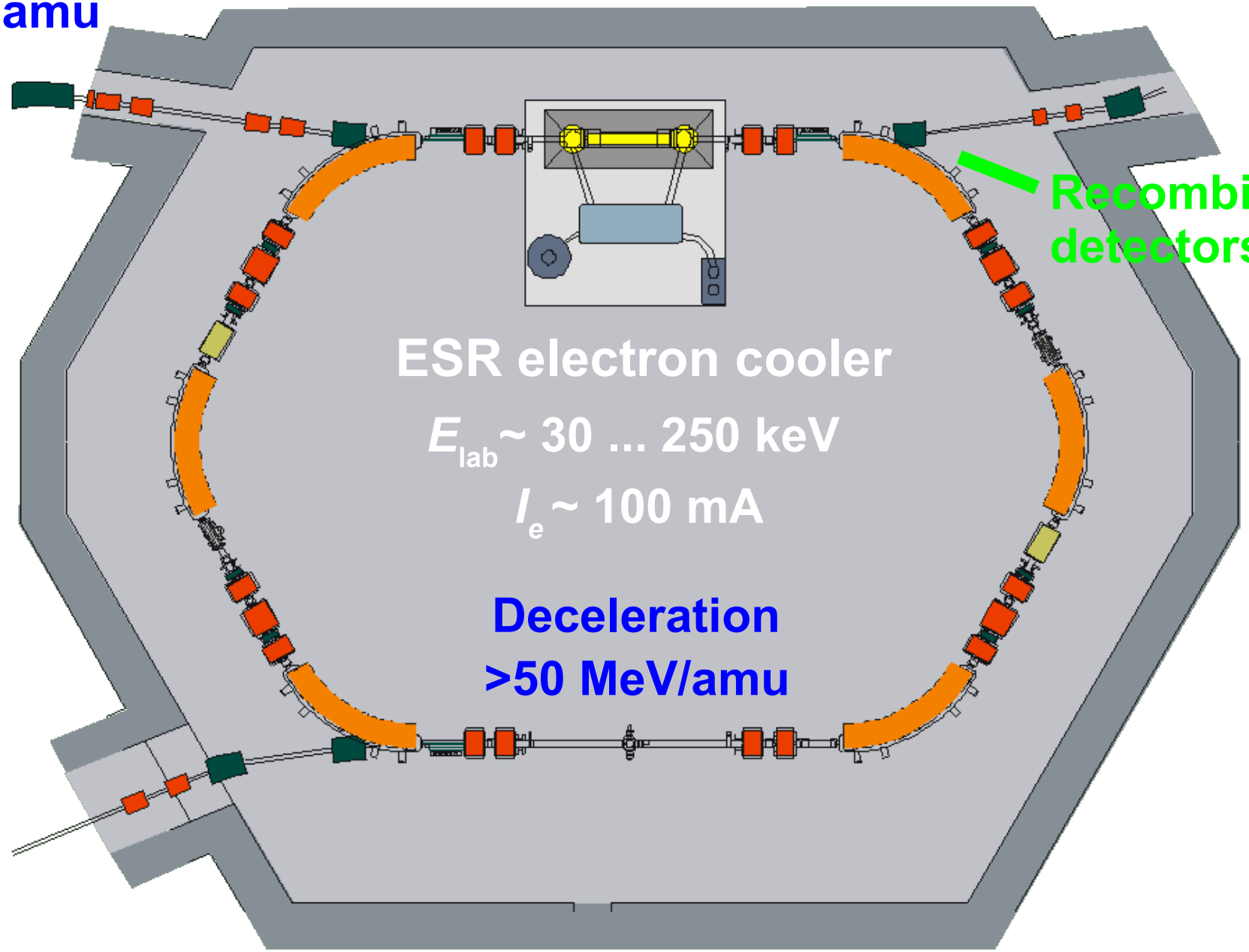


Low-energy dielectronic recombination

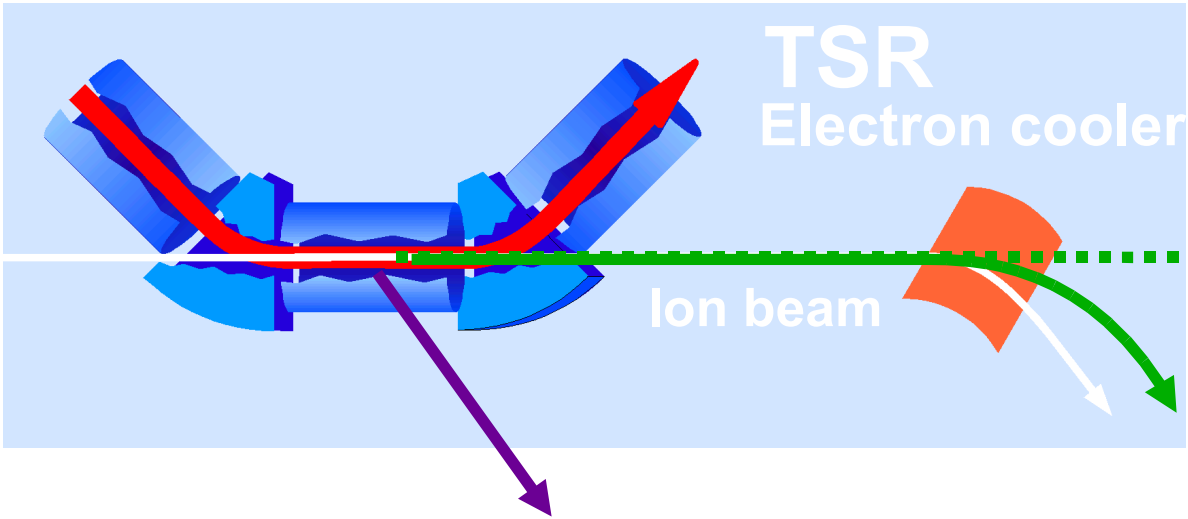


Merged beams in ion storage rings

Ion beam 200-600 MeV/amu



Merged beams in ion storage rings



Ion beam

~1...8 MeV/amu

In co-moving interaction region:

E_{lab} ~ 100 ... 7000 eV

I ~ 0.3 ... 100 mA

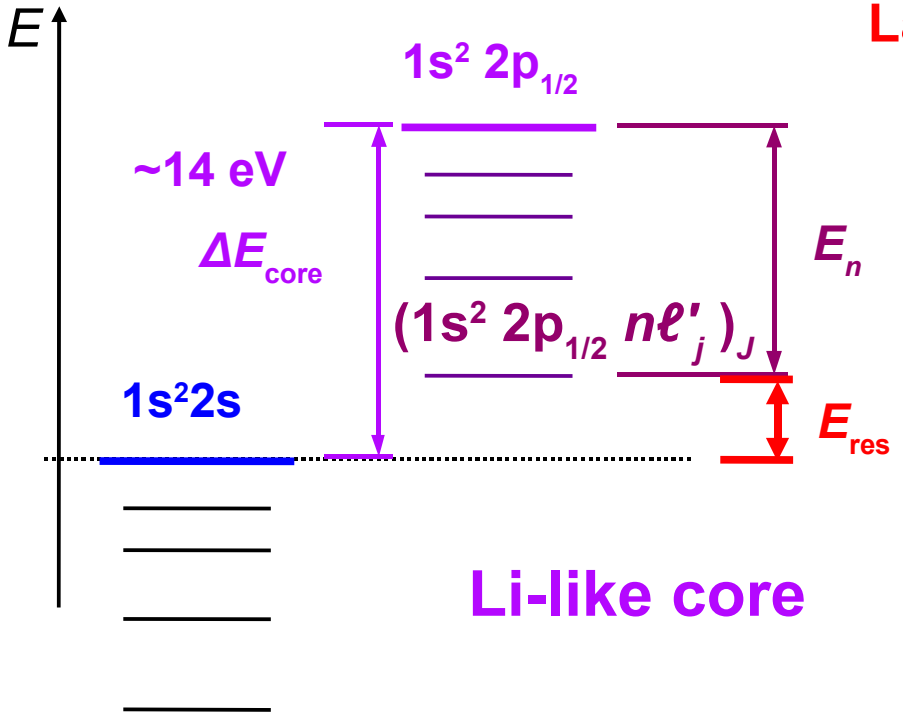
$n_e \sim 1 \cdot 10^7 \ \ldots \ 3 \cdot 10^8 \ \mathrm{cm}^{-3}$

$T_\perp$ ~ 1...100 meV

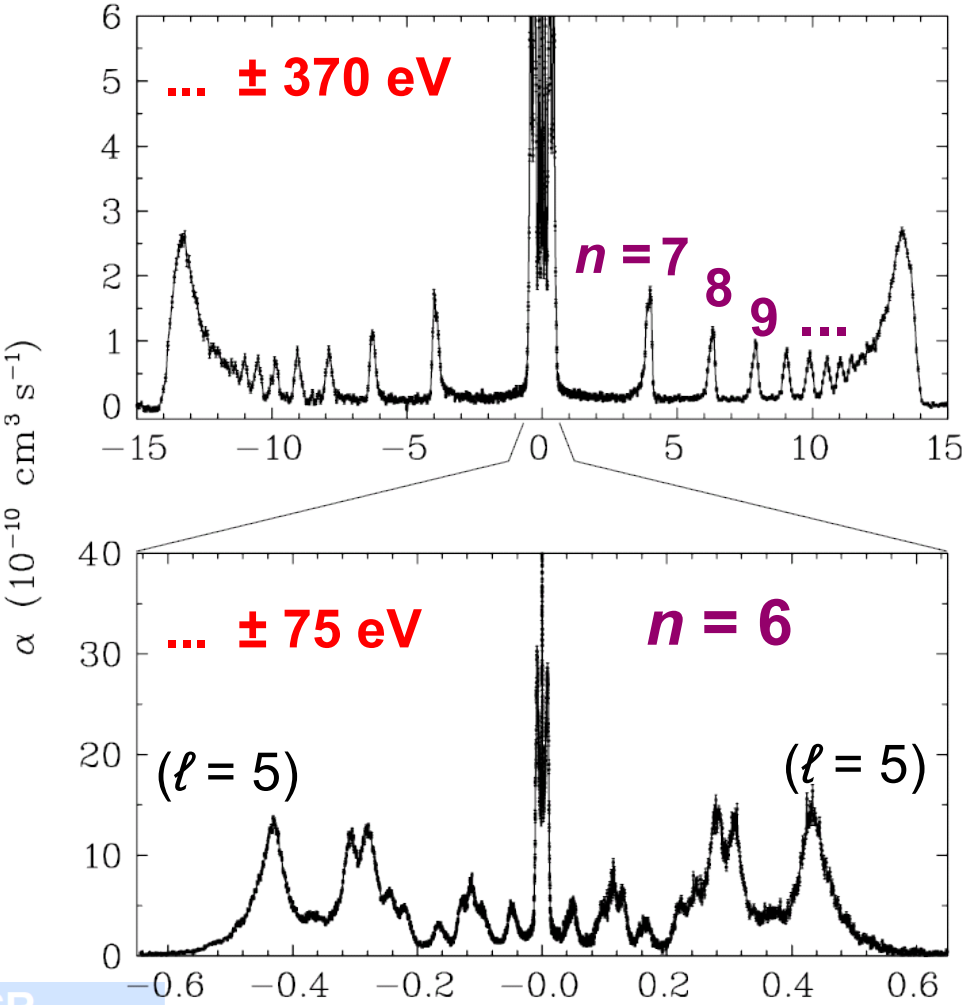
$T_\parallel$ ~ 0.02 meV $\quad (\sim e^2 n_e^{1/3})$

Magnetic field ~0.01...0.05 T

Low-energy dielectronic resonances



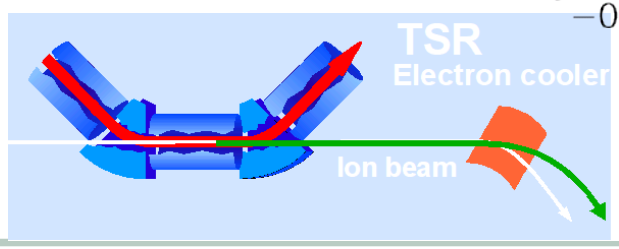
Laboratory electron energy: 2140 eV ...



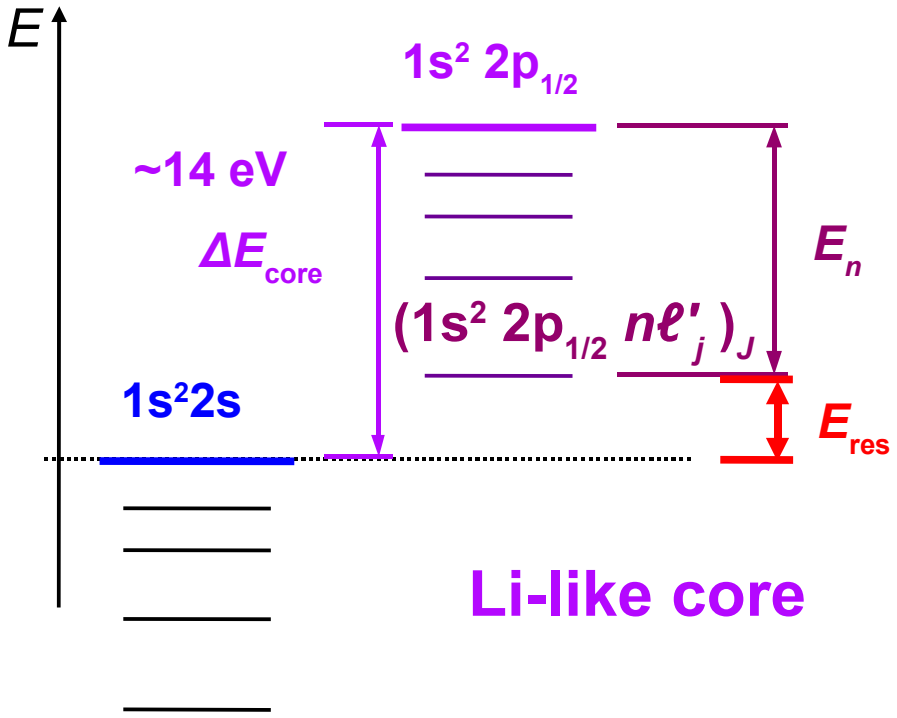
$^{19}F^{6+}$

TSR – 3.9 MeV/u

Tokman et al.,
PRA A 66, 012703 (2002)

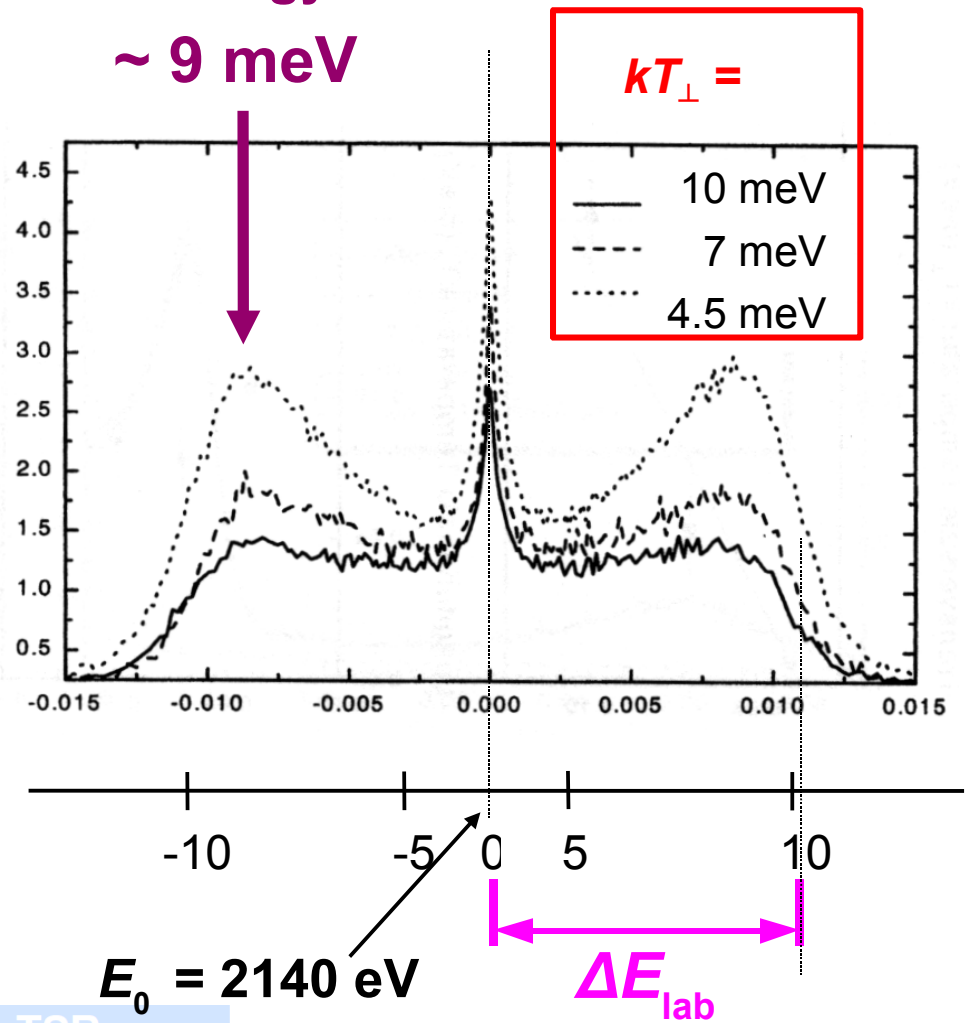


Low-energy dielectronic resonances



Resonance energy

~ 9 meV



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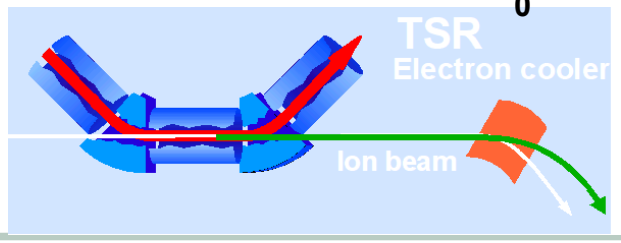
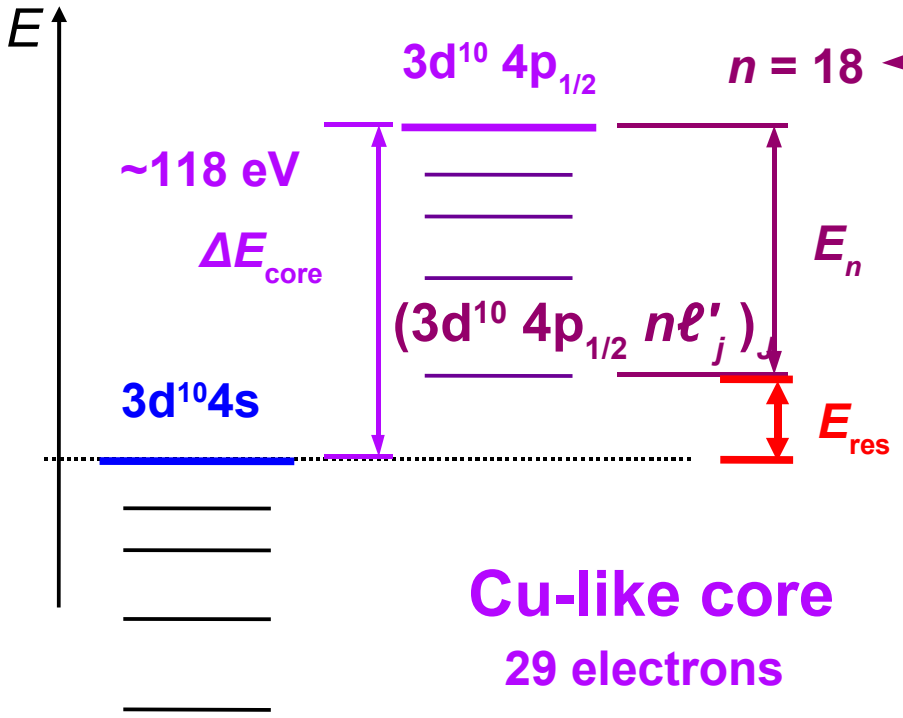


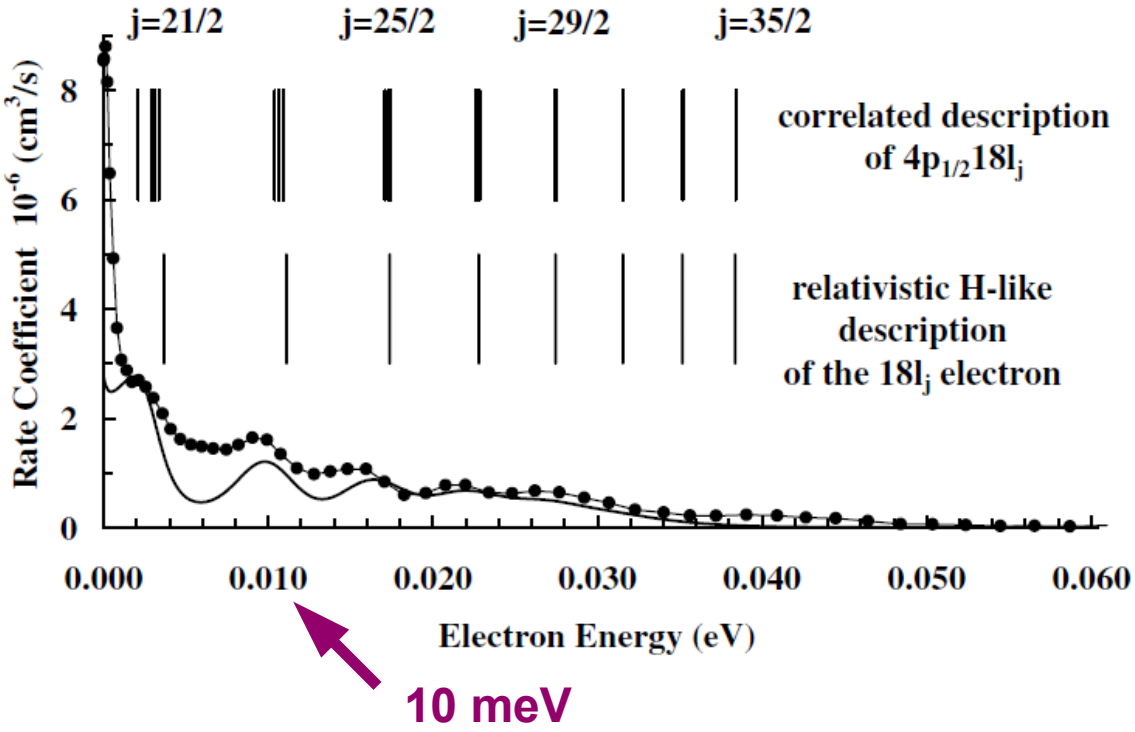
Low-energy dielectronic resonances



Relativistic many-body perturbation theory (RMBPT)

Cu-like core

29 electrons



10 meV

$^{208}Pb^{53+}$

CRYRING – 4.2 MeV/u

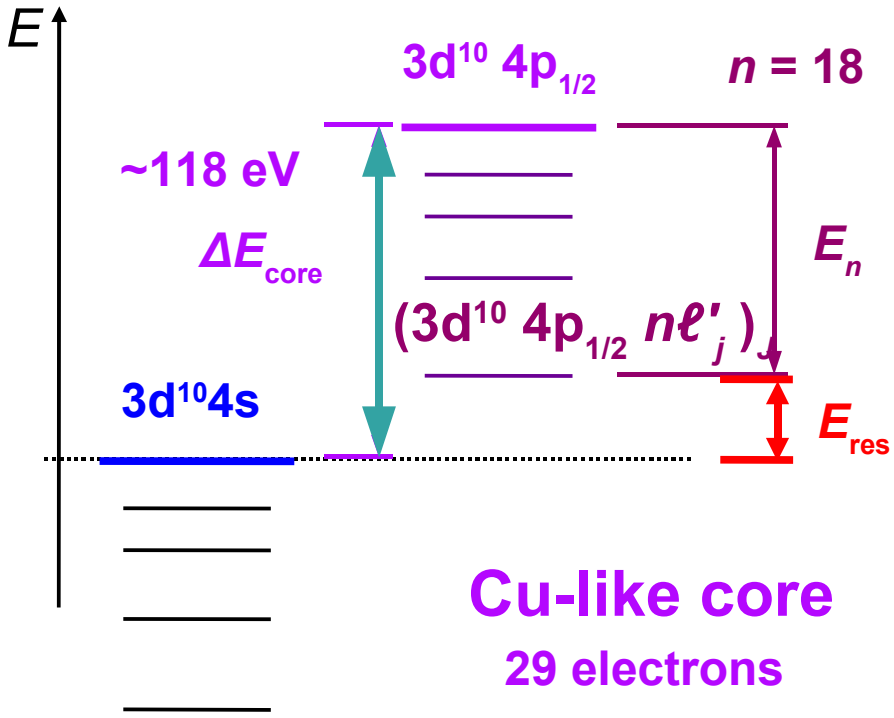
Lindroth et al.,
PRL 86, 5027 (2001)

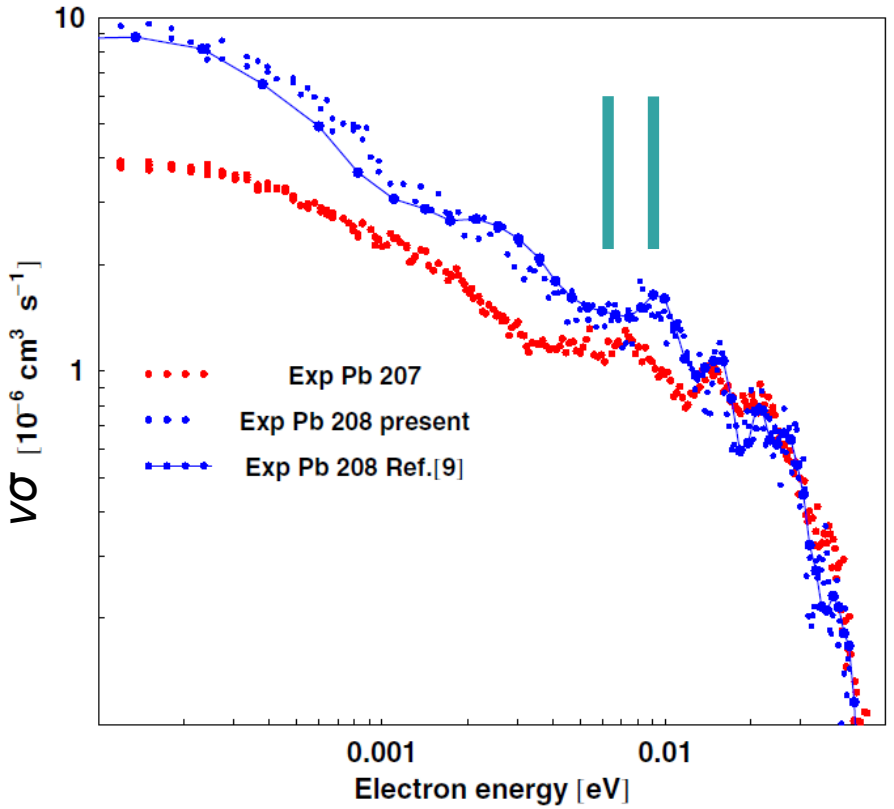
Experimental core excitation energy from theoretical binding energy E_n

ΔE_{core} = 118.010 ± 0.001 eV

ΔE_{QED} =~ −40 meV

Low-energy dielectronic resonances





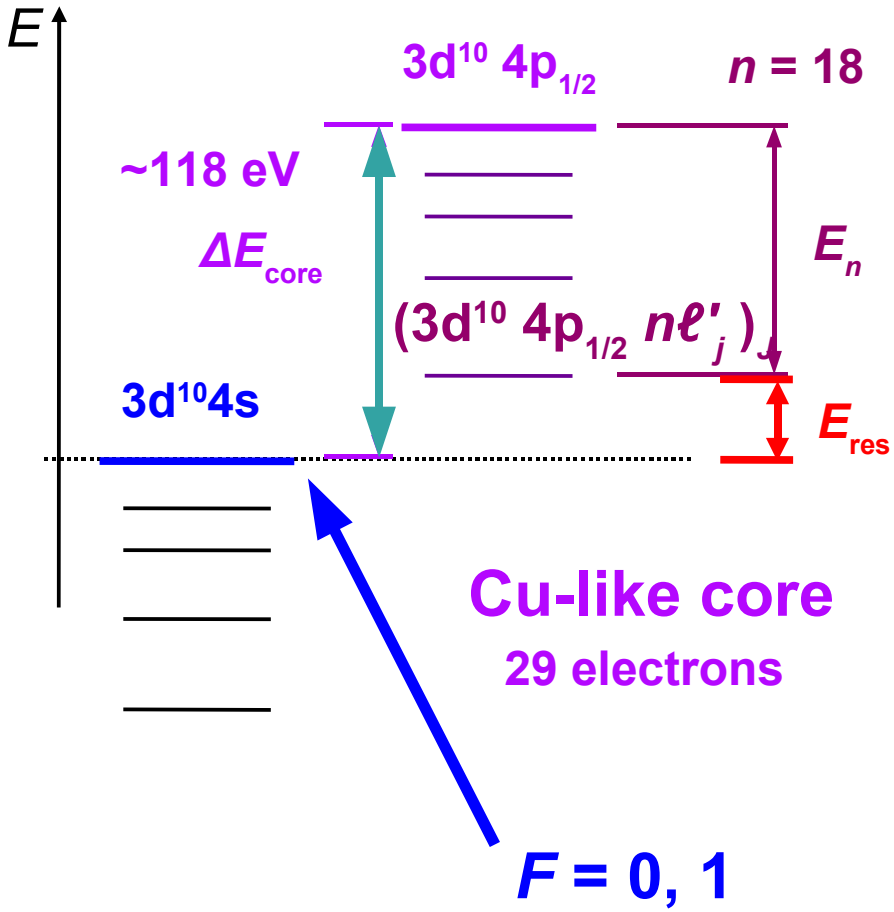
Isotope shift of ΔE_{core} – $4s_{1/2}$-$4p_{1/2}$

$^{207,208}Pb^{53+}$

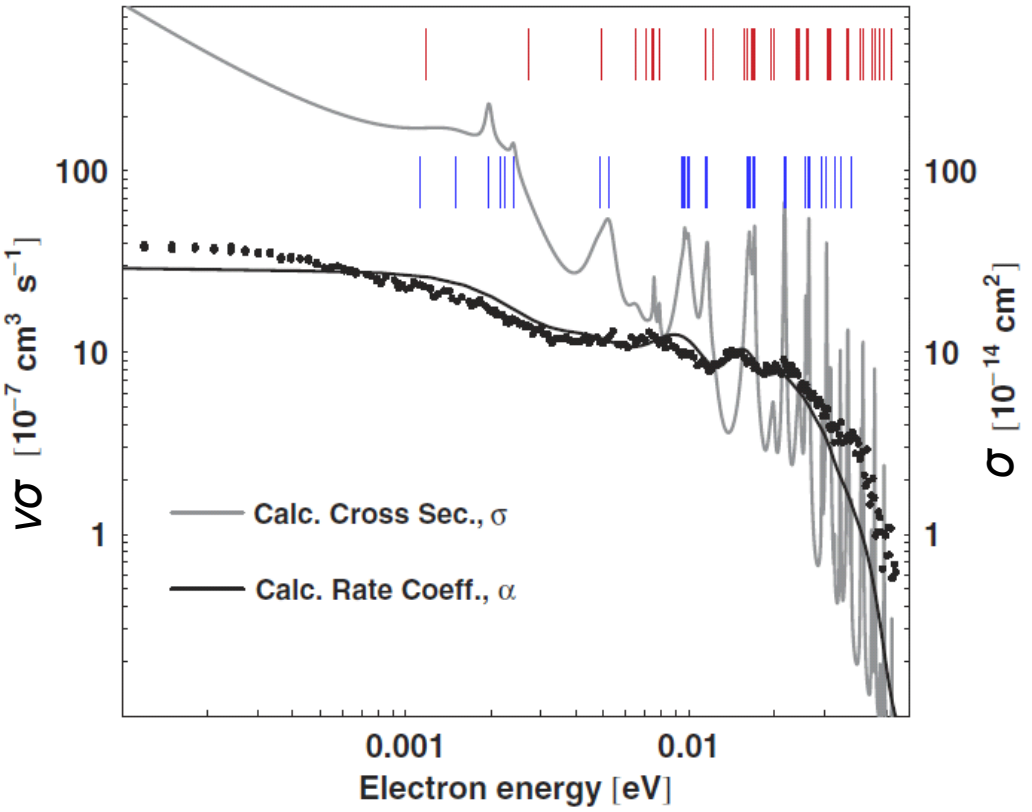
CRYRING – 4.2 MeV/u

Schuch et al.,
PRL 95, 183003 (2005)

Low-energy dielectronic resonances



Relativistic many-body perturbation theory (RMBPT)
E. Lindroth



Isotope shift of ΔE_{core} – $4s_{1/2}$-$4p_{1/2}$

Hyperfine structure splitting of the $3d^{10}\,4s$ ground state

$a_{4p,1/2}$ ~ 4.8 meV

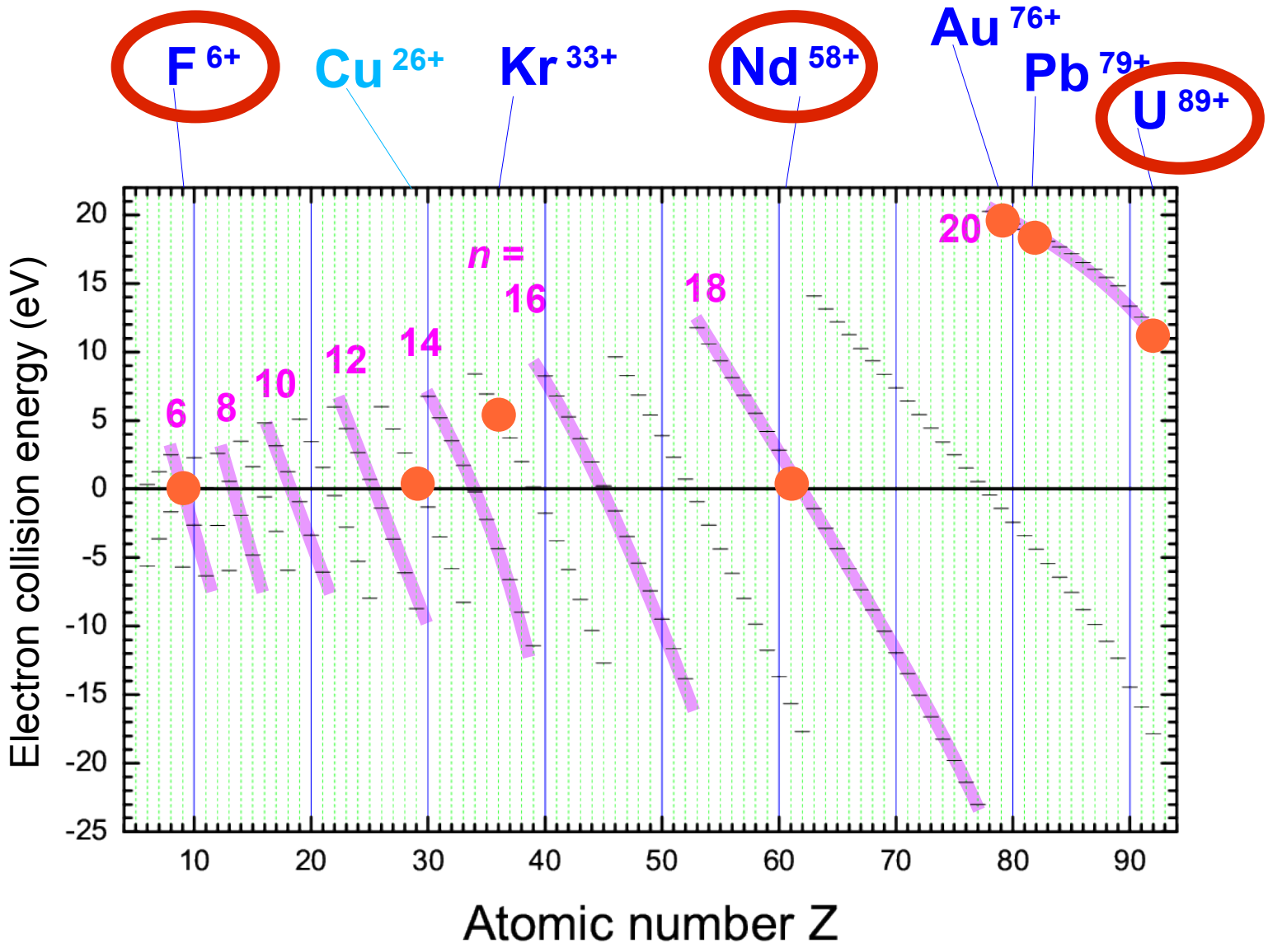
$^{207}Pb^{53+}$ (I = 1/2)

CRYRING – 4.2 MeV/u

Schuch et al.,
PRL 95, 183003 (2005)

Low-energy resonances with Li-like core

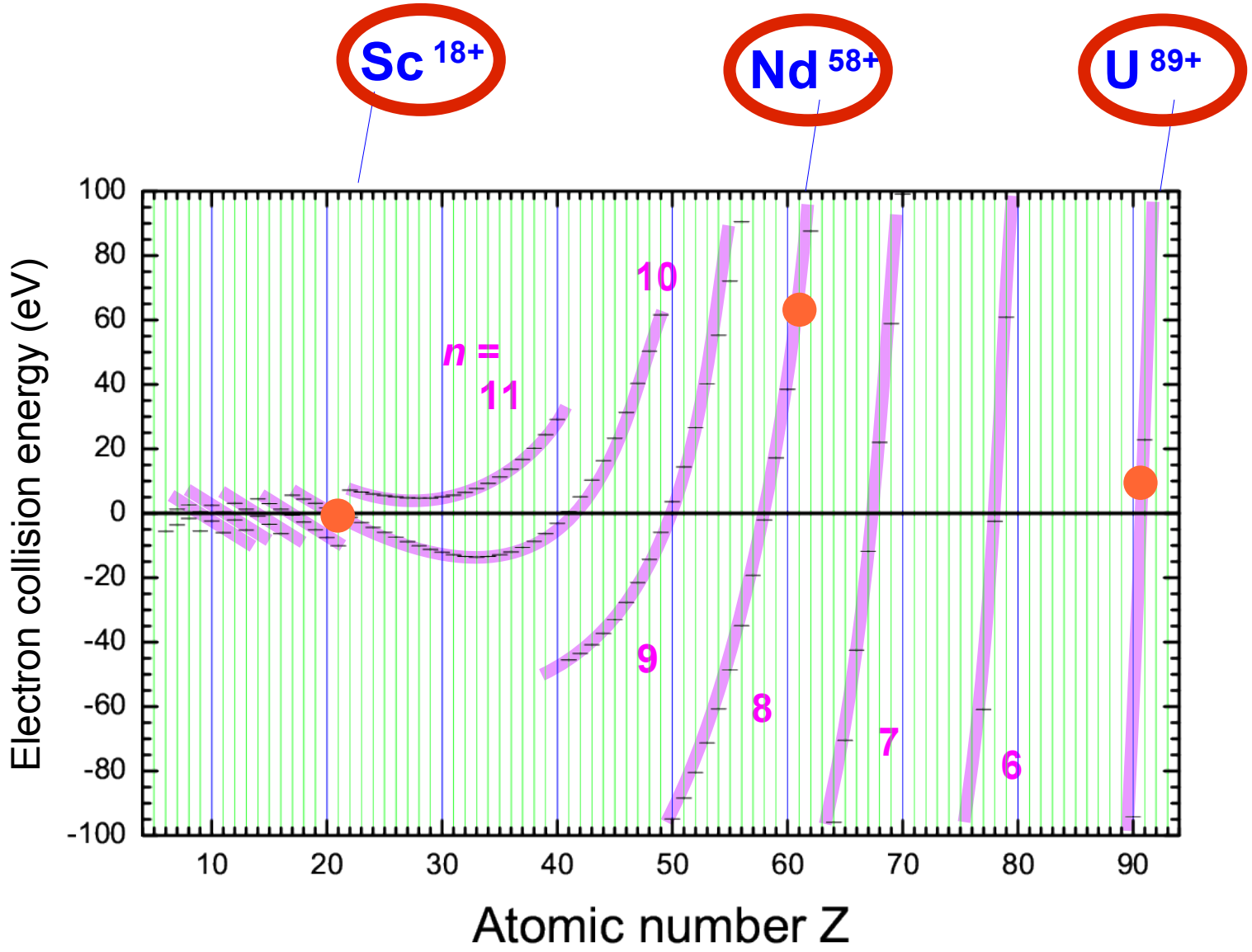
$2p_{1/2}$



Rydberg resonance positions **Li-like $2s - 2p_{1/2}$**

Low-energy resonances with Li-like core

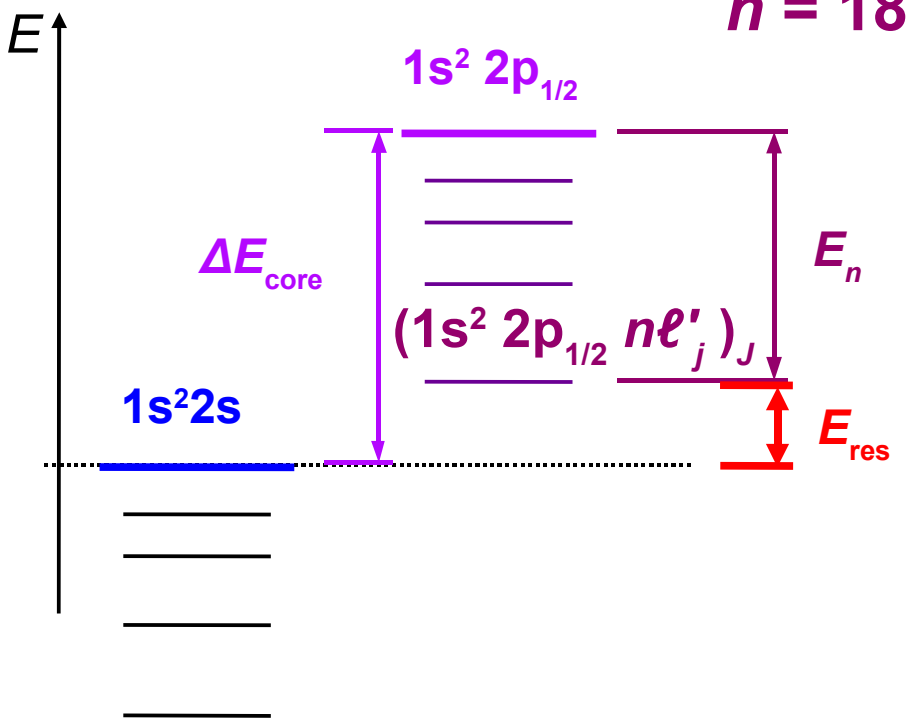
$2p_{3/2}$

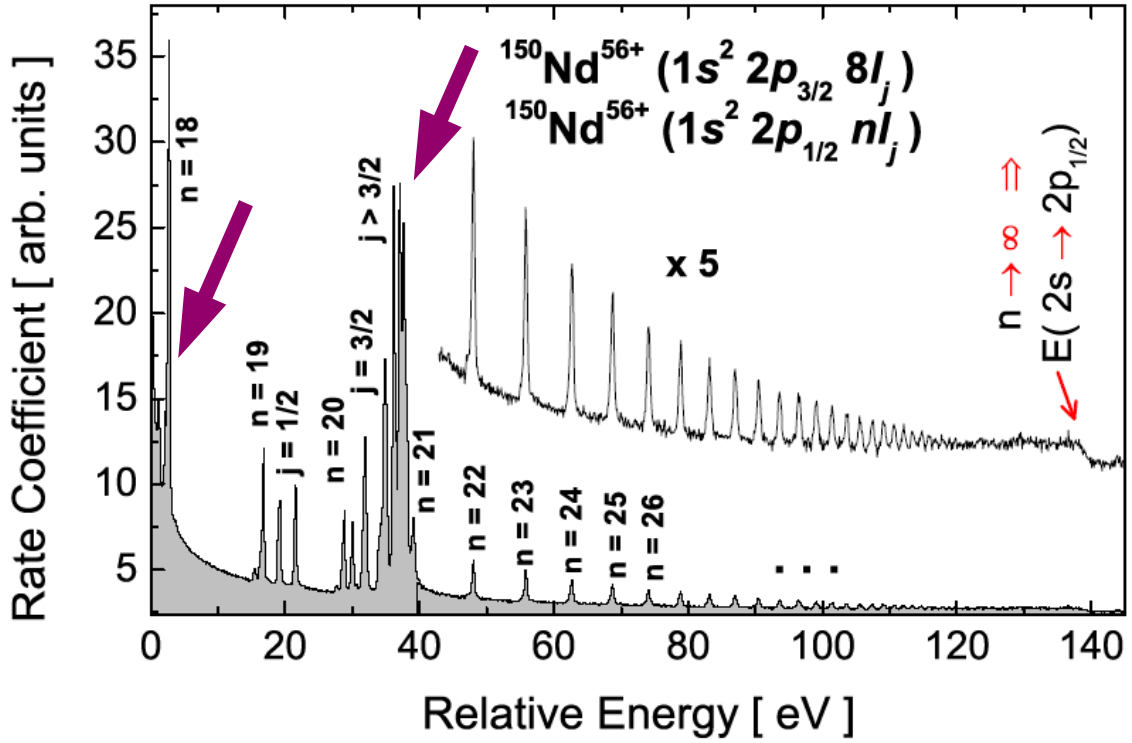


Rydberg resonance positions **Li-like $2s - 2p_{3/2}$**

Isotope shifts from dielectronic resonances

n = 18 (j = 1/2), 8 (j = 3/2)

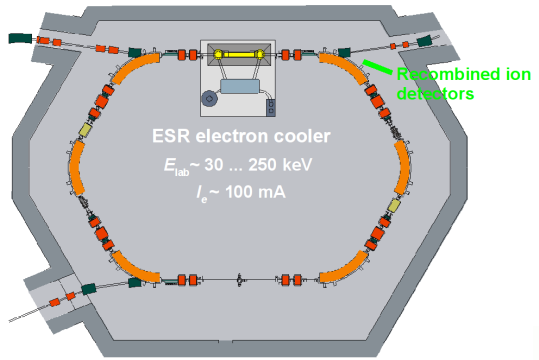




142,150Nd58+

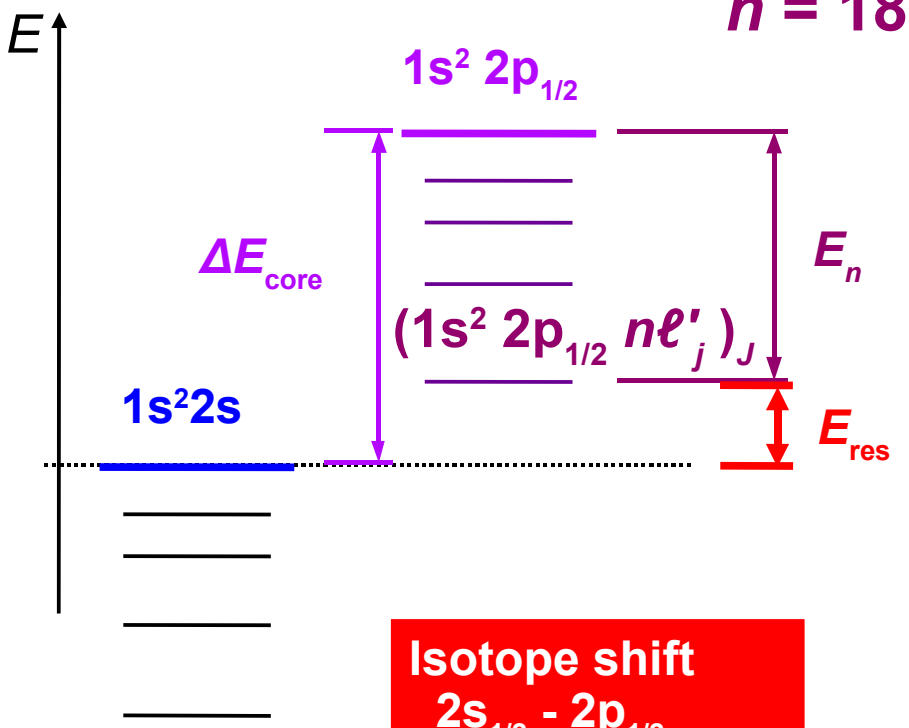
ESR – ~90 MeV/u

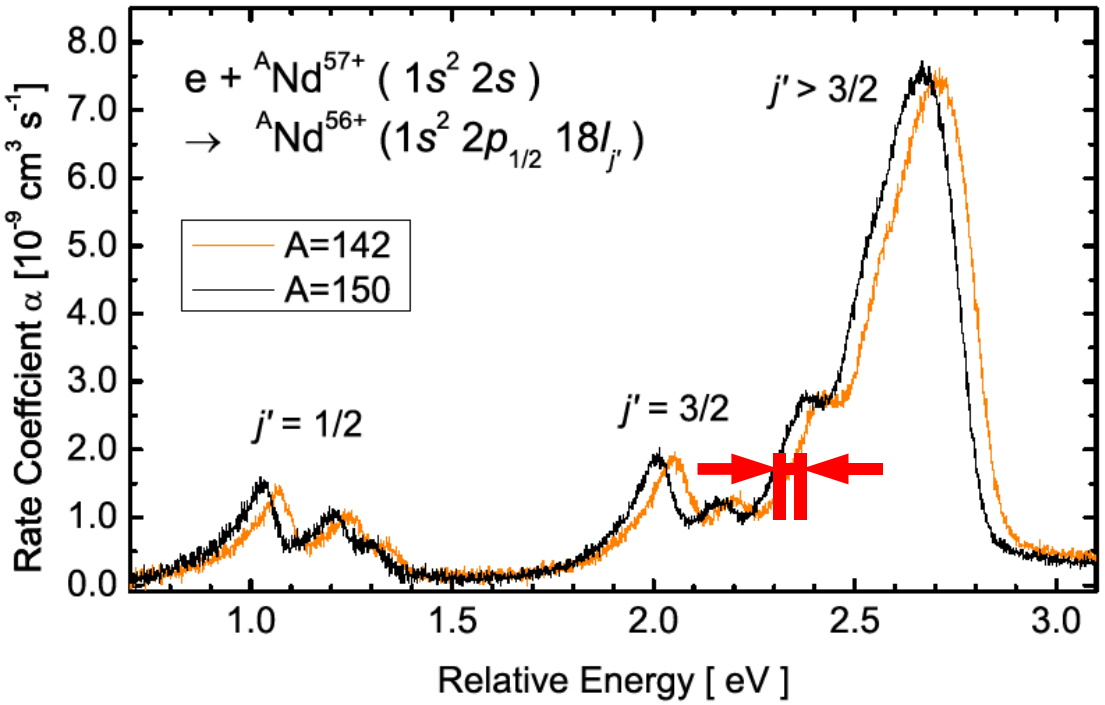
Brandau et al., Phys. Rev. Lett. 100, 073201 (2008)



Isotope shifts from dielectronic resonances

$n = 18\ (j = 1/2),\ 8\ (j = 3/2)$



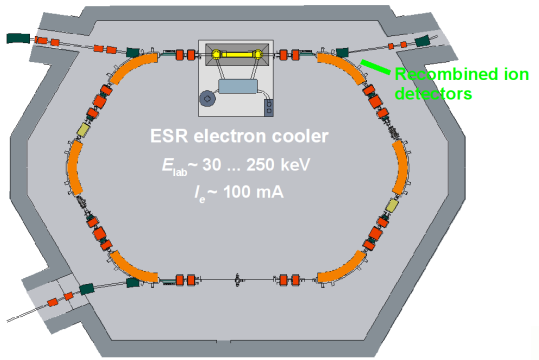


Isotope shift
$2s_{1/2}$ - $2p_{1/2}$

40.2(3)(6) meV

100 meV

$T_{\perp}$ ~ 100 meV
$T_{\parallel}$ ~ 0.2 meV



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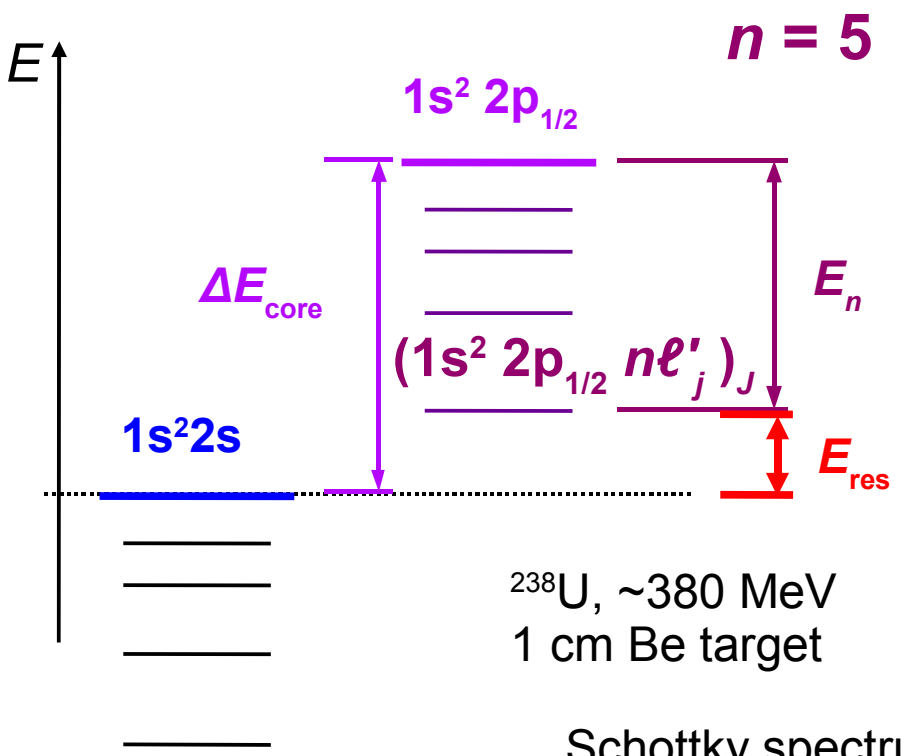
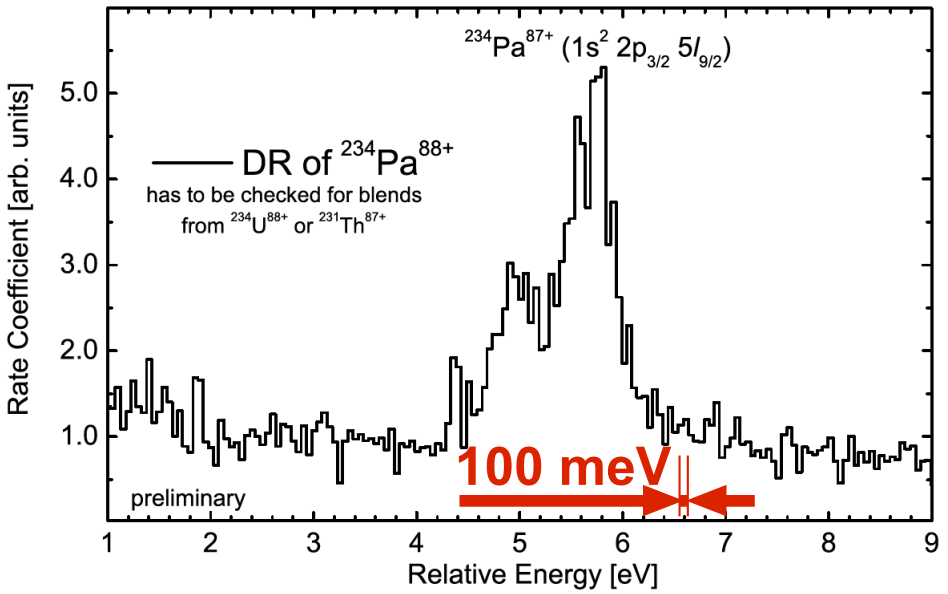
Isotope shifts from dielectronic resonances

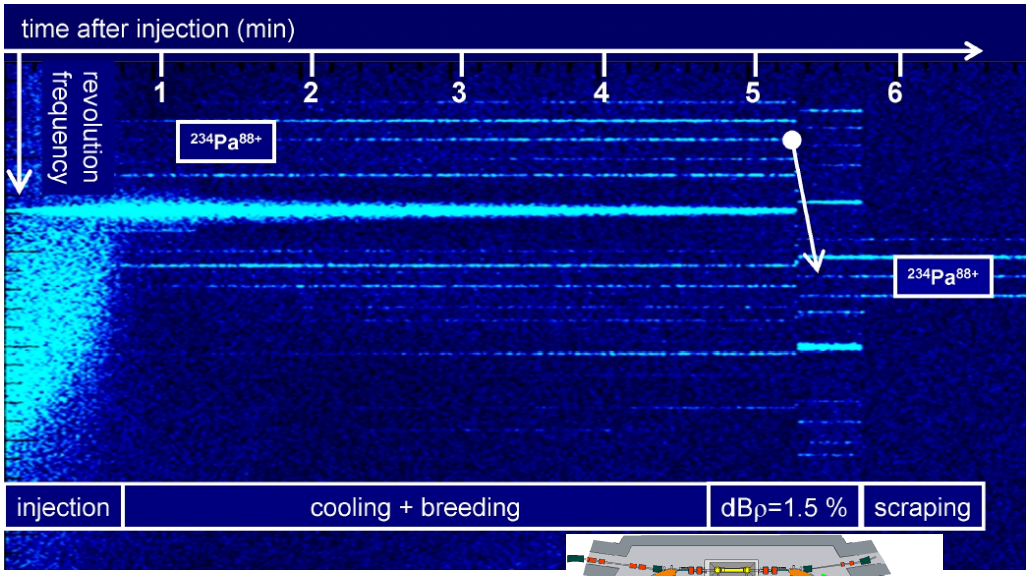


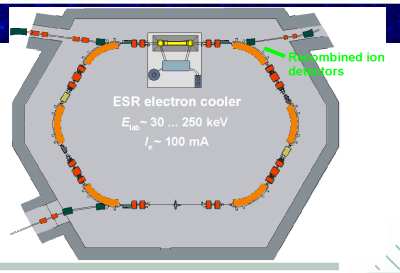
^{238}U, ~380 MeV
1 cm Be target

Schottky spectrum of
product ions in ESR

C. Brandau et al. (2009)







^{234}Pa^{88+}

ESR – ~185 MeV/u

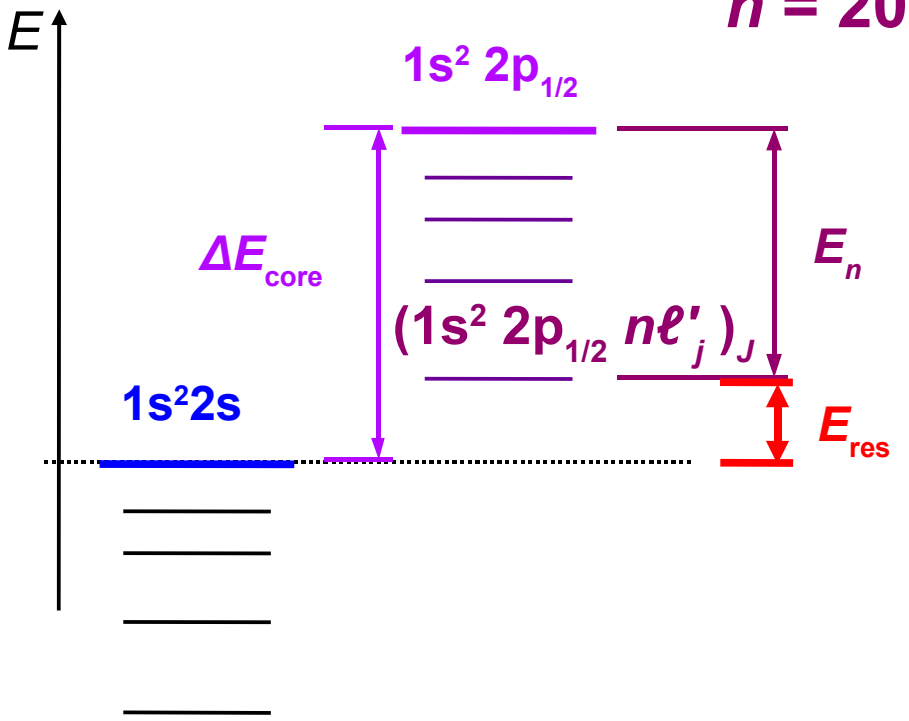
~ 2-3 × 10^4 ions

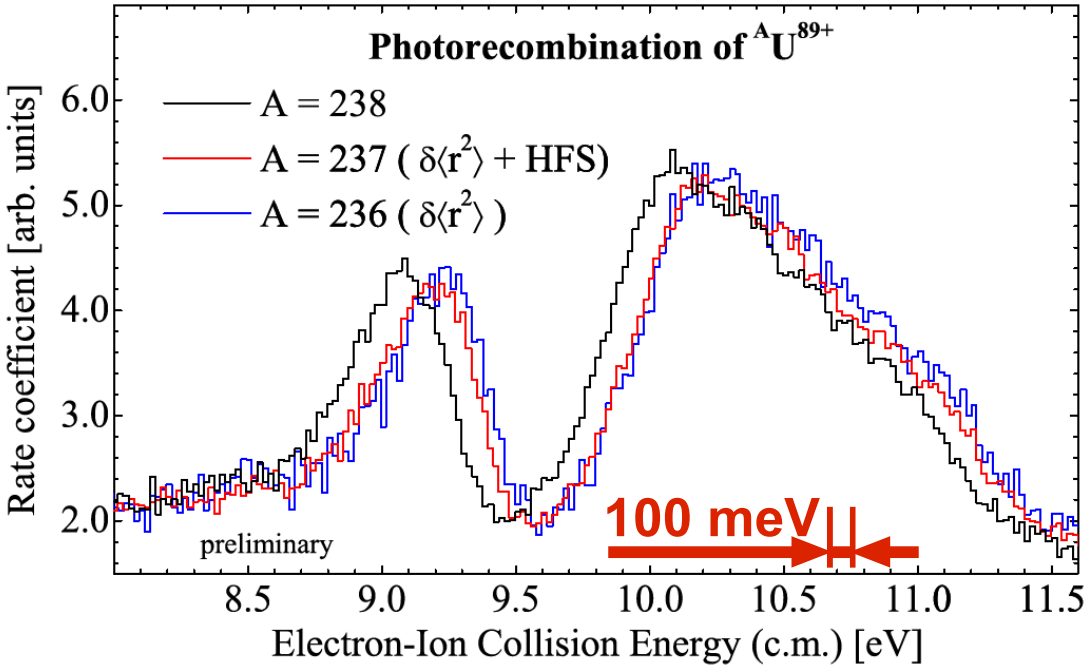
$T_\perp$ ~ 100 meV

$T_{||}$ ~ 0.2 meV

Isotope shifts from dielectronic resonances

$n = 20\ (j = 1/2),\ 5\ (j = 3/2)$



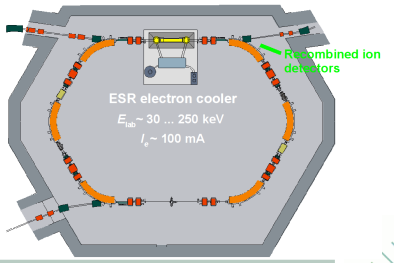


C. Brandau et al. (2009)

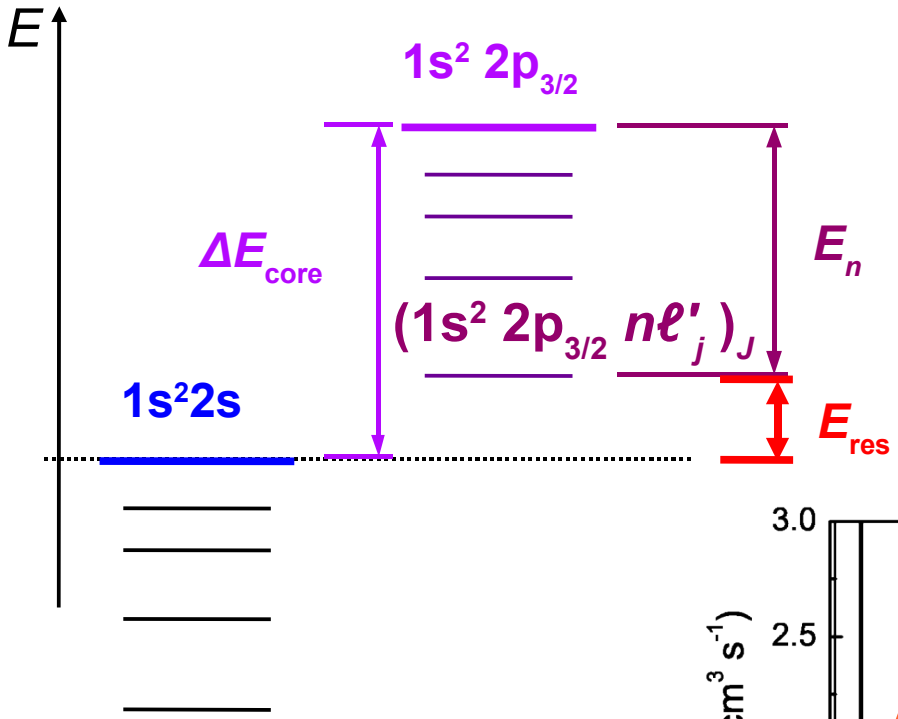
$^{236,237,238}U^{89+}$

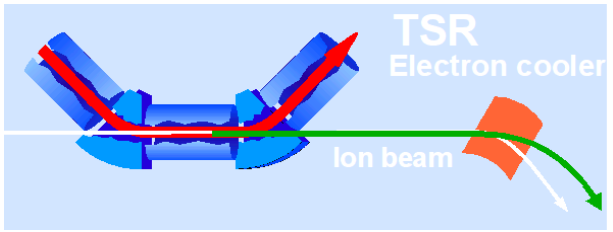
ESR

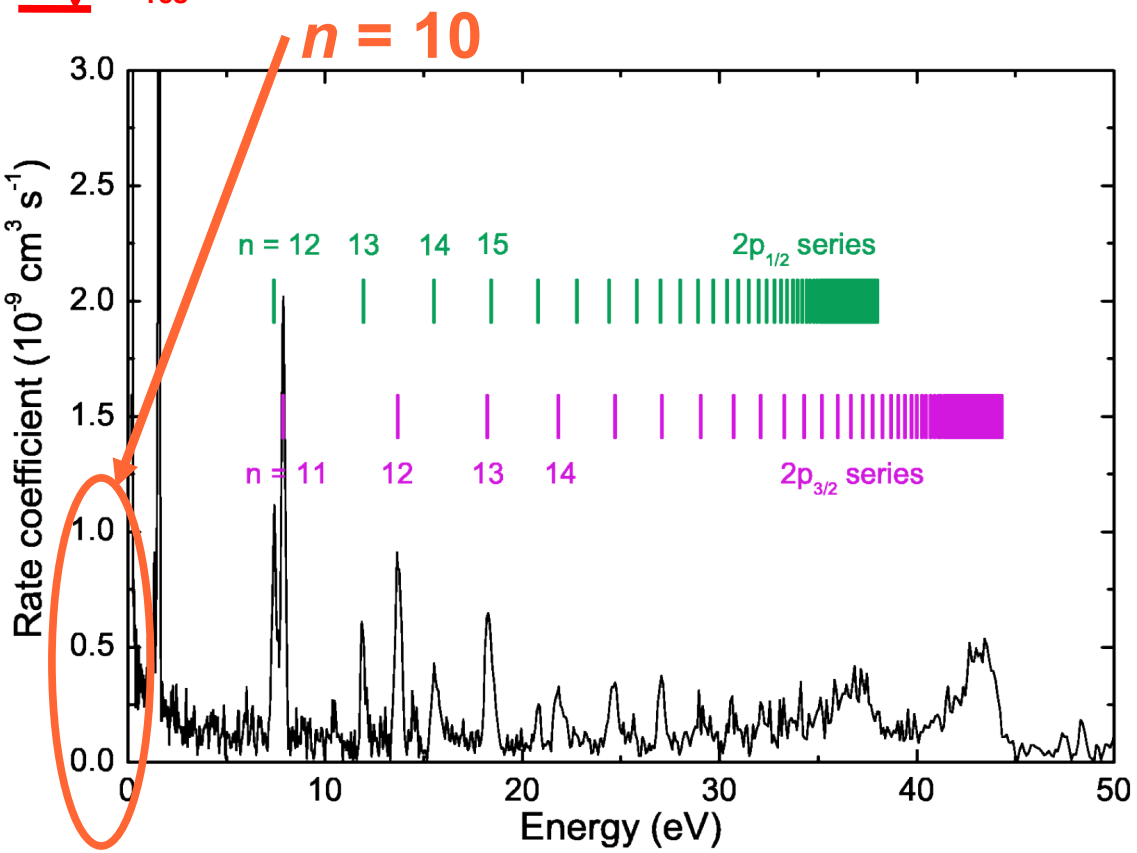
$T_{\perp}$ ~ 100 meV
$T_{\parallel}$ ~ 0.2 meV



QED shifts and hyperfine structure





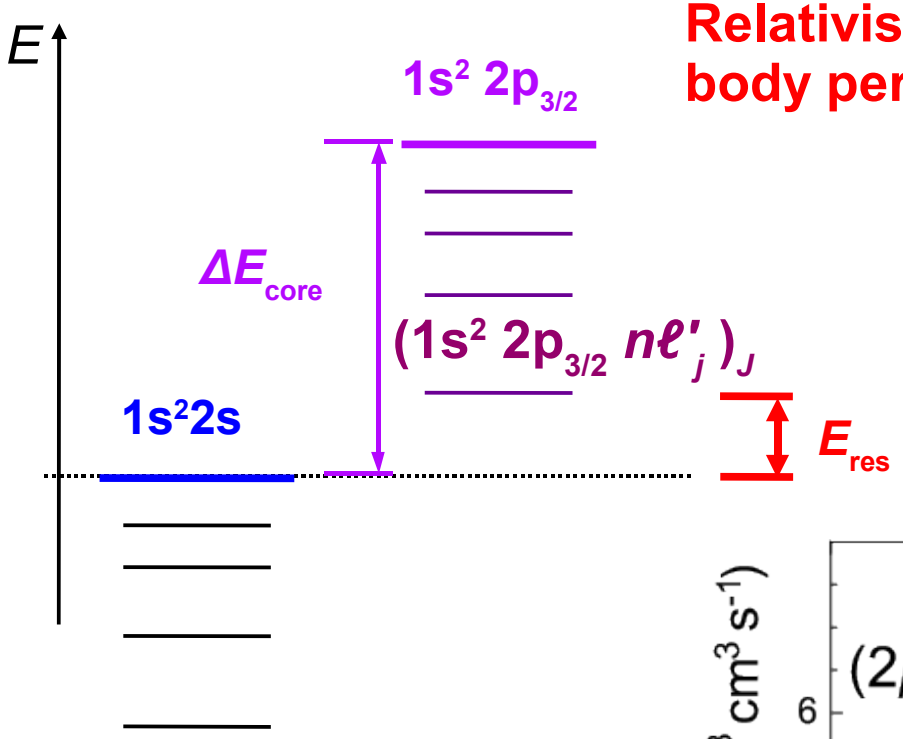


$^{45}Sc^{18+}$

TSR – 4 MeV/u

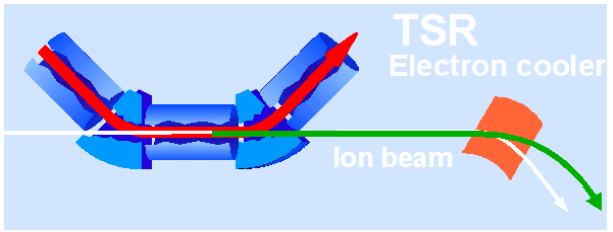
Kieslich et al.,
PRA 70, 042714 (2004)

Core excitation energies ΔE (2s–2p)



Relativistic many body perturbation theory (RMBPT)

E. Lindroth



Electron cooler

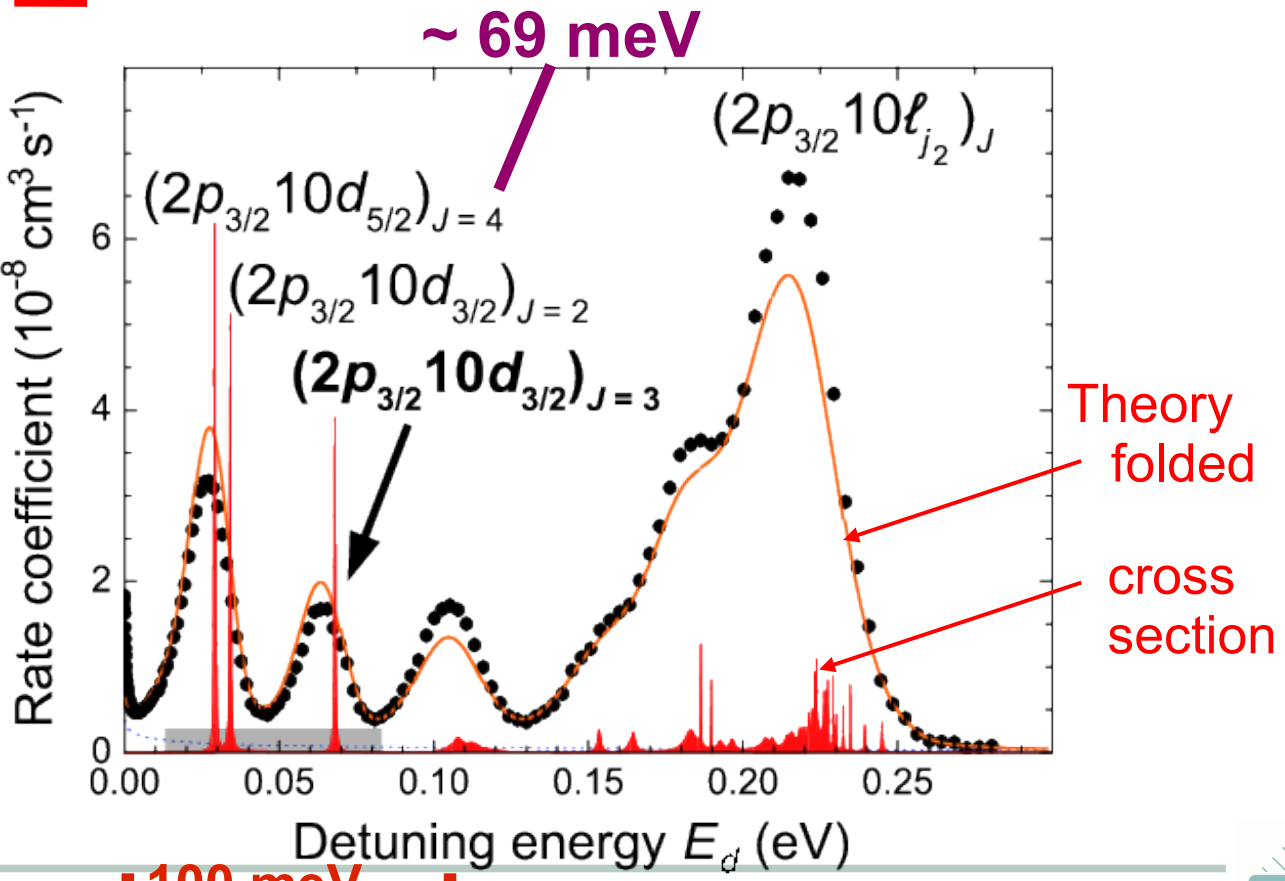
$T_{\perp}$ = 7.2 meV

$T_{||}$ ~ 0.18 meV

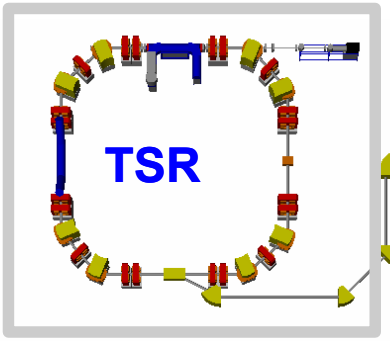
$^{45}Sc^{18+}$

TSR – 4 MeV/u

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



Electron–ion merged beams at the TSR Heidelberg



Cl^{17+}
Ge^{28+}
Au^{50+}

Photocathode electron "target"

$v_e \neq v_i$

12 m

10 m

25 MV cavity linac

Recombination detector

Electron cooler

$v_e = v_i$

$kT_e \sim$ 4 meV

$kT_e \sim 1$ meV

~10^6-10^8 stored ions

Translational and internal cooling

0.5 MV RFQ linac

12 MV tandem accelerator

Ion sources

2.5 MeV pelletron

Extracted ions
Coulomb explosion beamline

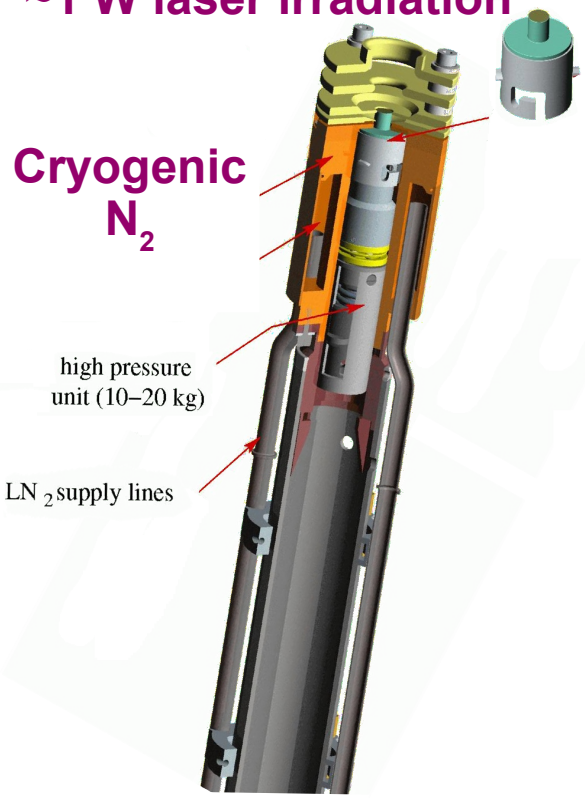
~1...8 MeV/amu

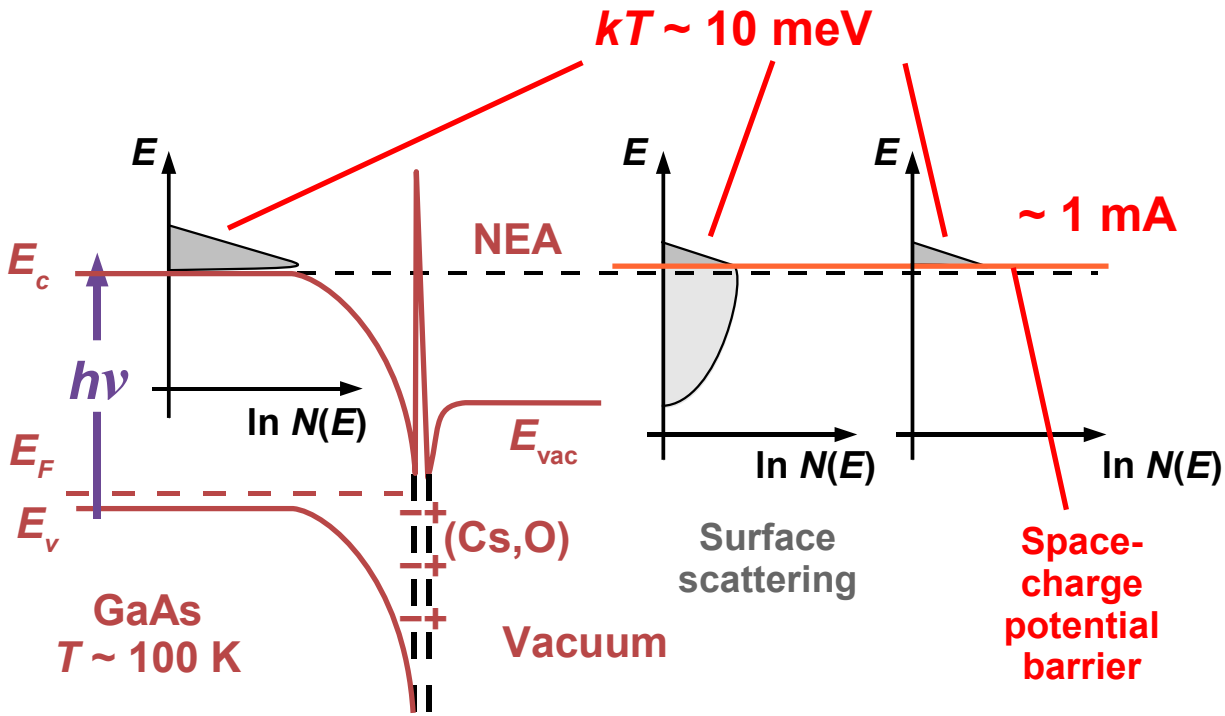
High-resolution electron target

Photocathode electron target

GaAs photocathode ~100 K

~1 W laser irradiation



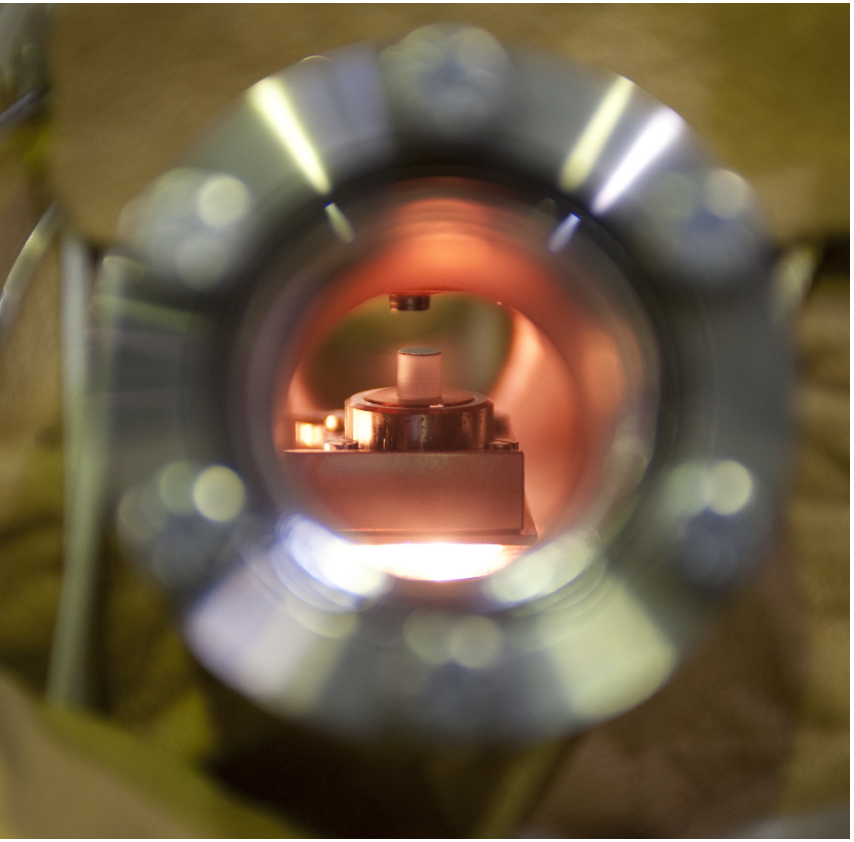


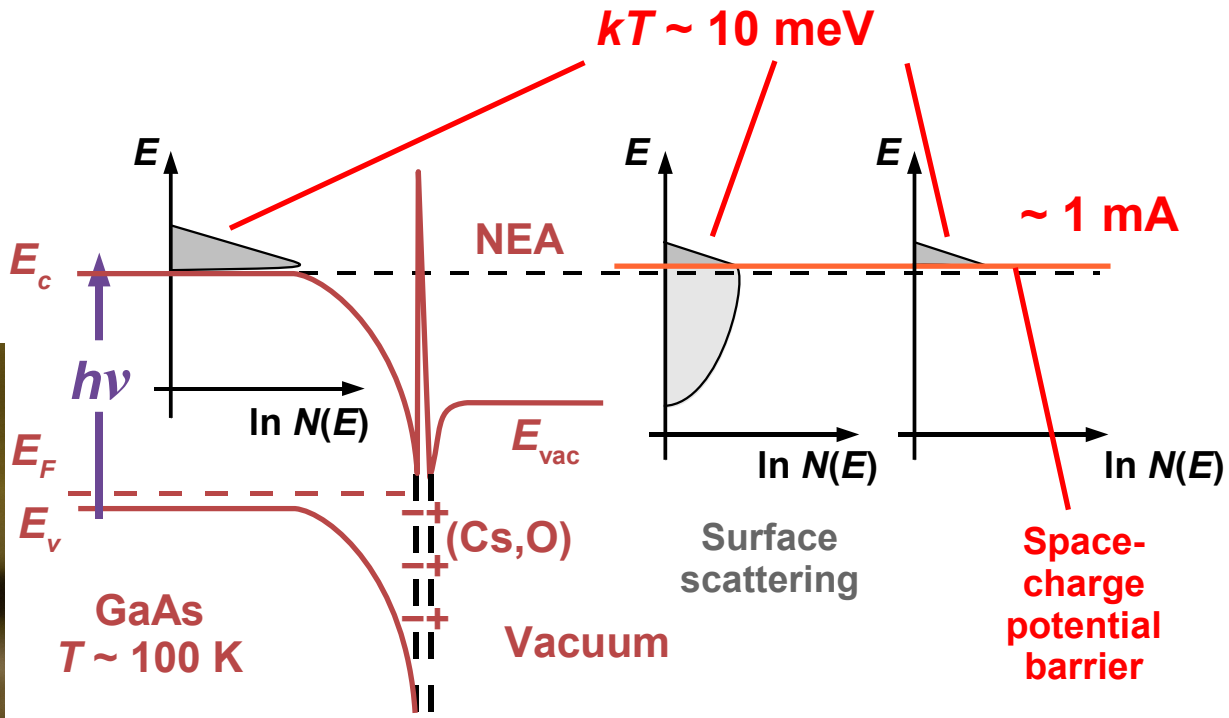
- Magnetic expansion (~0.4 T → 0.02 T) yields 0.5...1 meV electron temperature (~5...10 K)
- Cathode lifetime typ. 24 h
- ~4 cathodes under vacuum in closed-cycle operation since >2 years
- 2008: Beam transport down to < 1 eV with 10 µA current (0.01 T guiding field)

D. A. Orlov, C. Krantz, A. Shornikov, et al.
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

High-resolution electron target

Photocathode electron target





- Magnetic expansion (~0.4 T → 0.02 T) yields 0.5...1 meV electron temperature (~5...10 K)

- Cathode lifetime typ. 24 h

- ~4 cathodes under vacuum in closed-cycle operation since >2 years

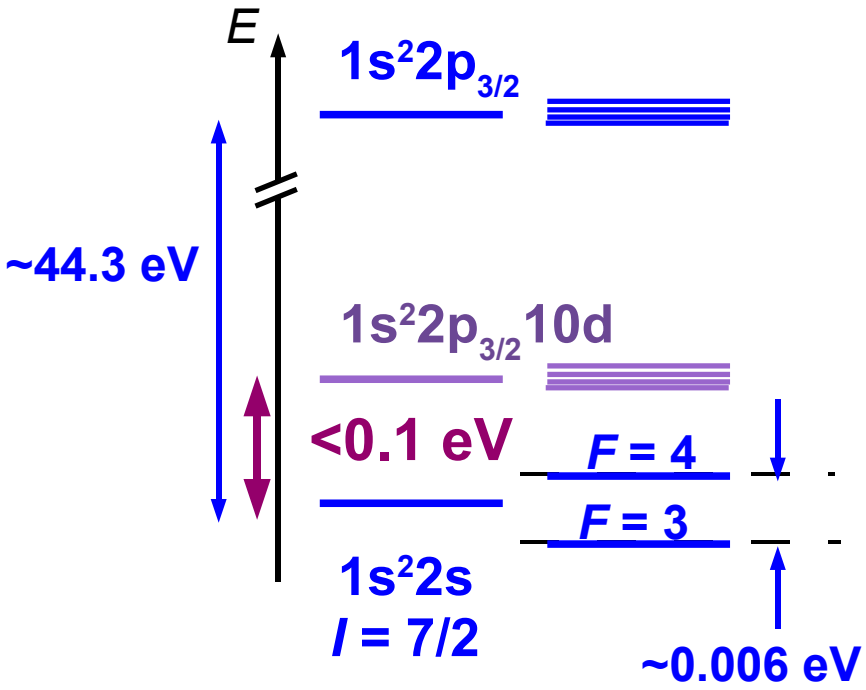
- 2008: Beam transport down to < 1 eV with 10 µA current (0.01 T guiding field)

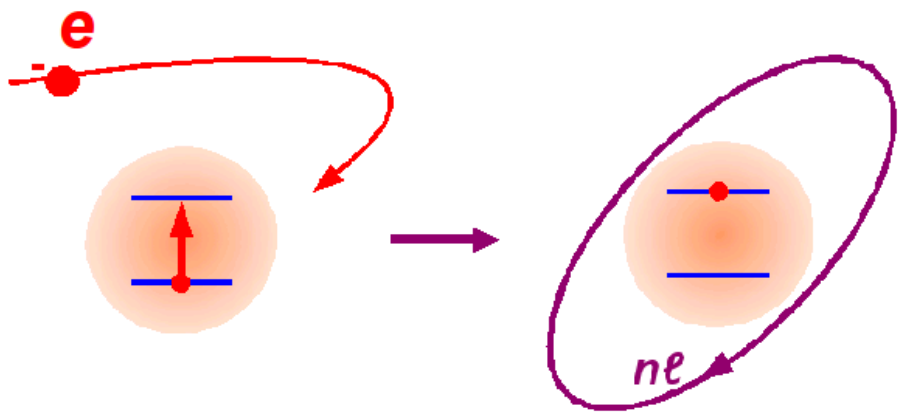
D. A. Orlov, C. Krantz, A. Shornikov, et al.
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

Hyperfine-resolved electron collisions

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

Rydberg resonances and hyperfine splitting of Sc^{18+} ($1s^2 2s$)





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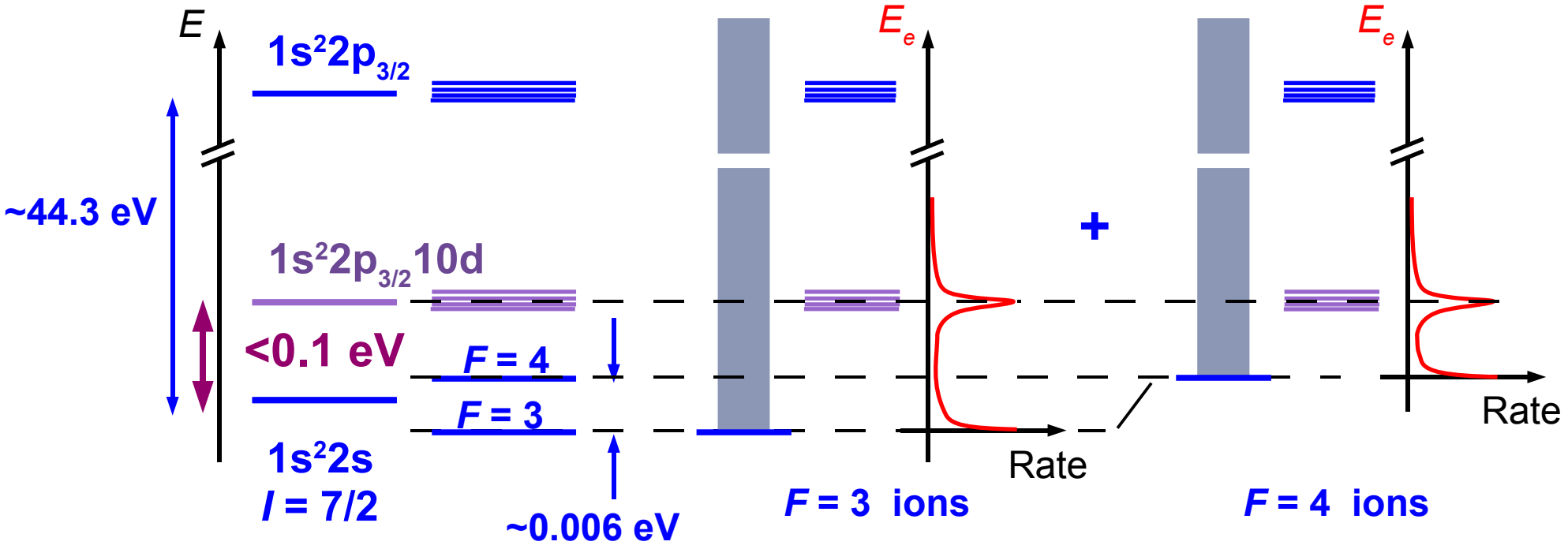

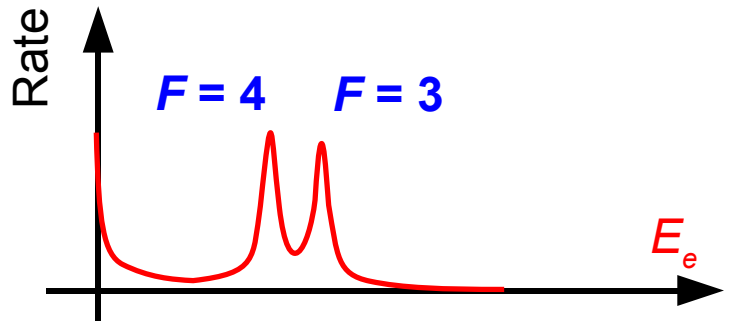

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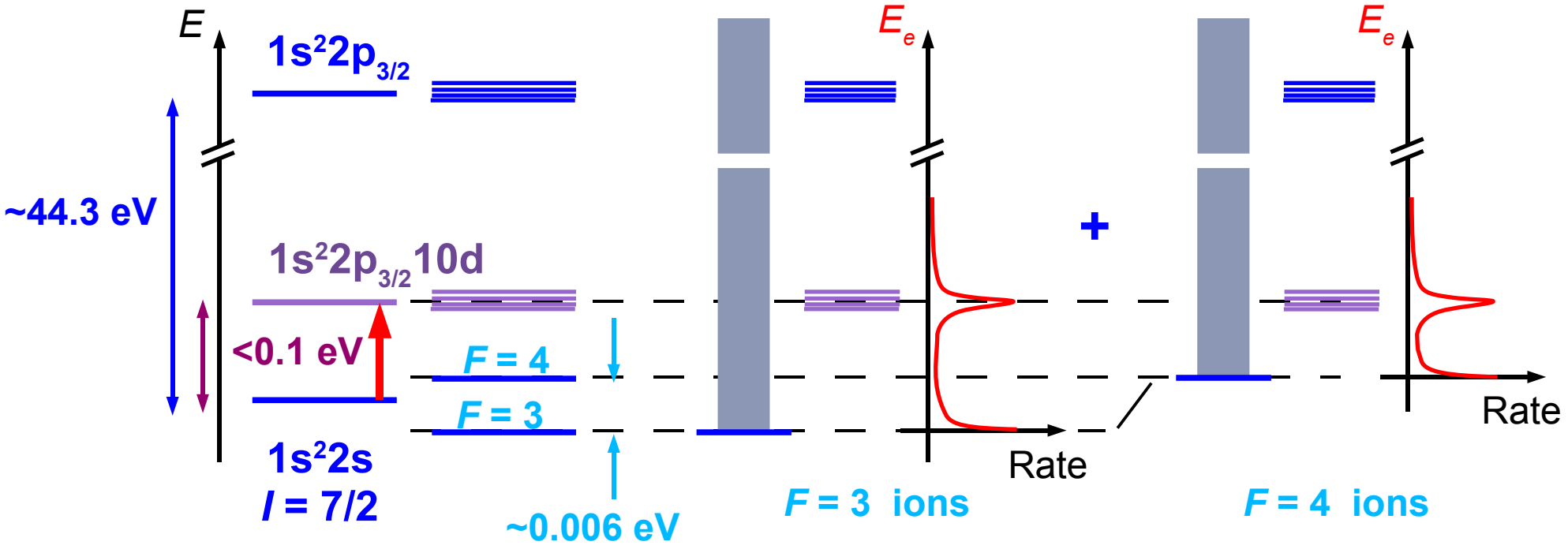
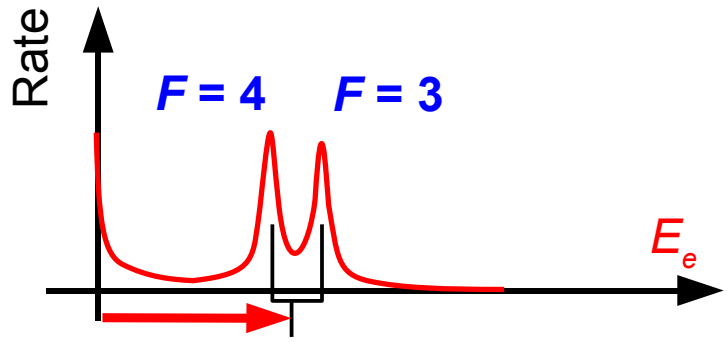
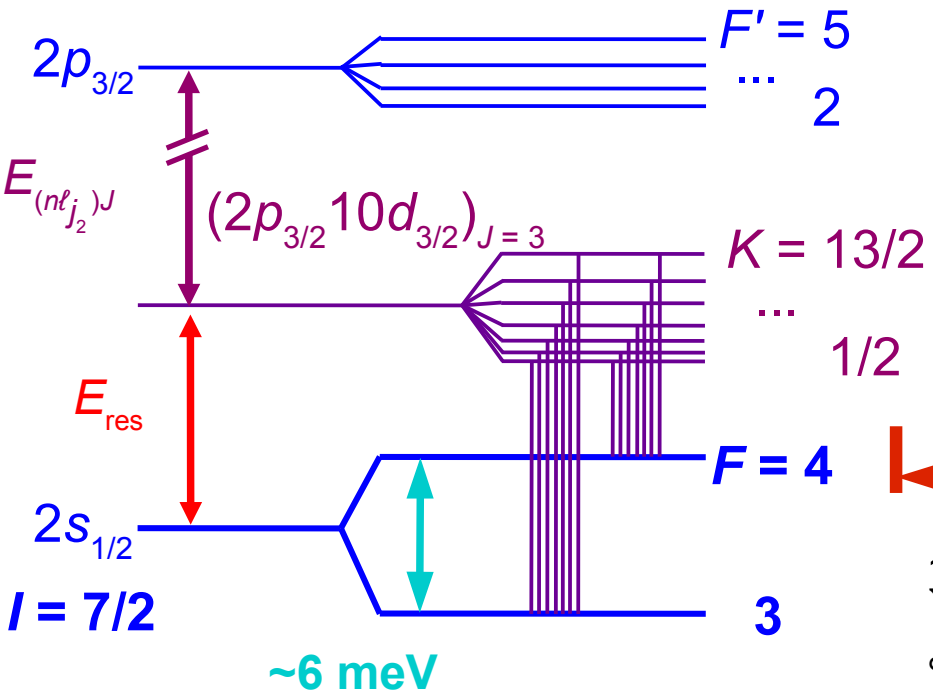


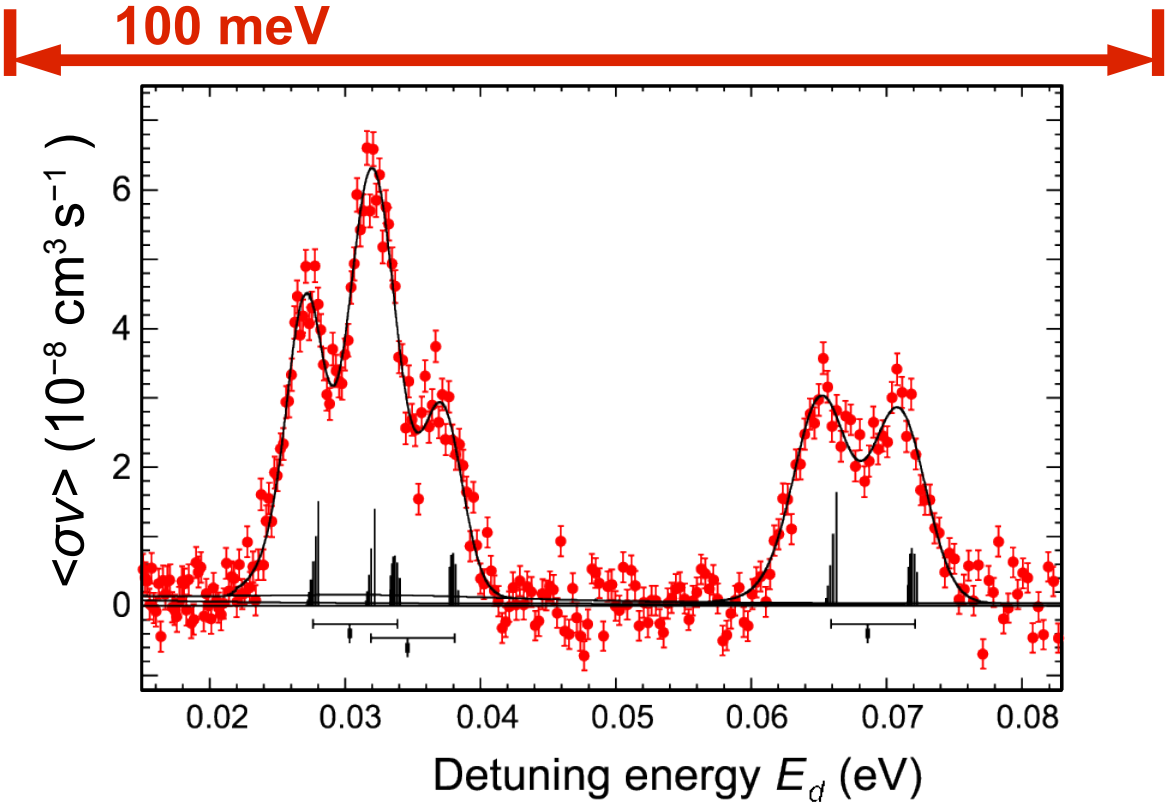
Electron spectroscopy →

- **Resonance energy**
- **Initial-state energy splitting and population**



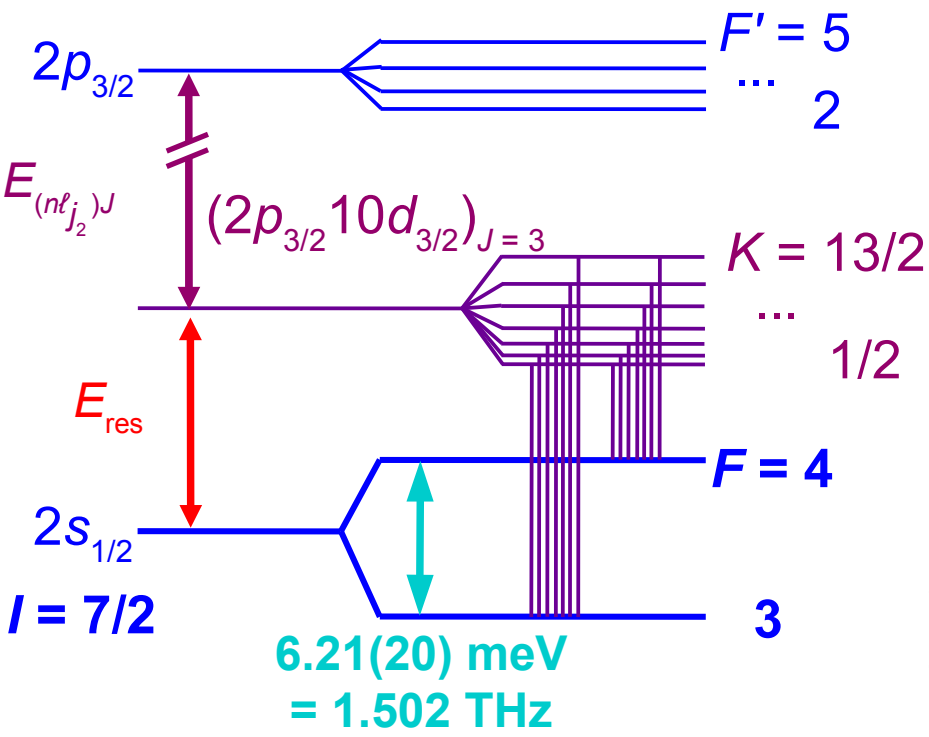
Hyperfine-resolved electron collisions

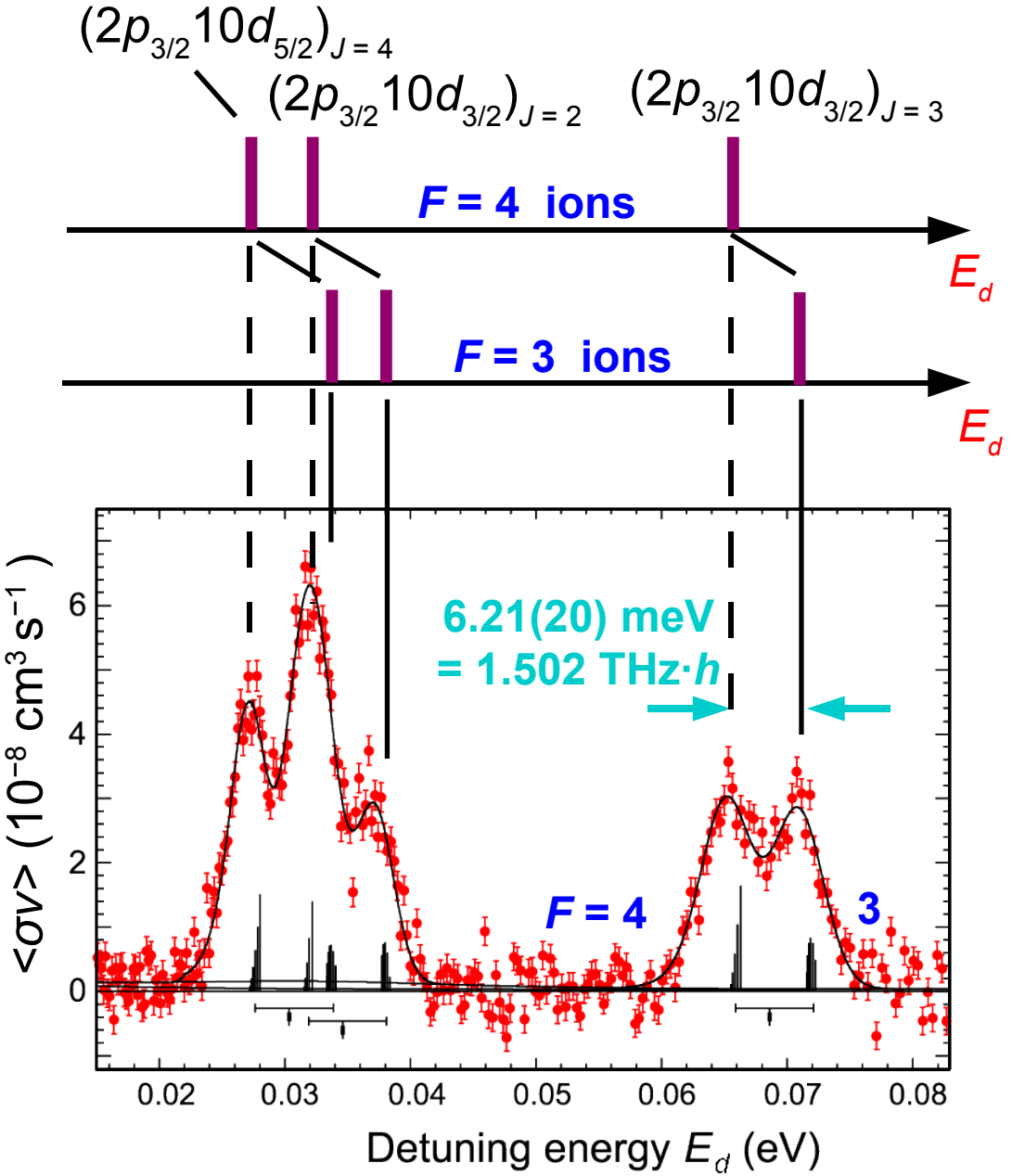




M. Lestinsky et al., PRL 100, 033001 (2008)

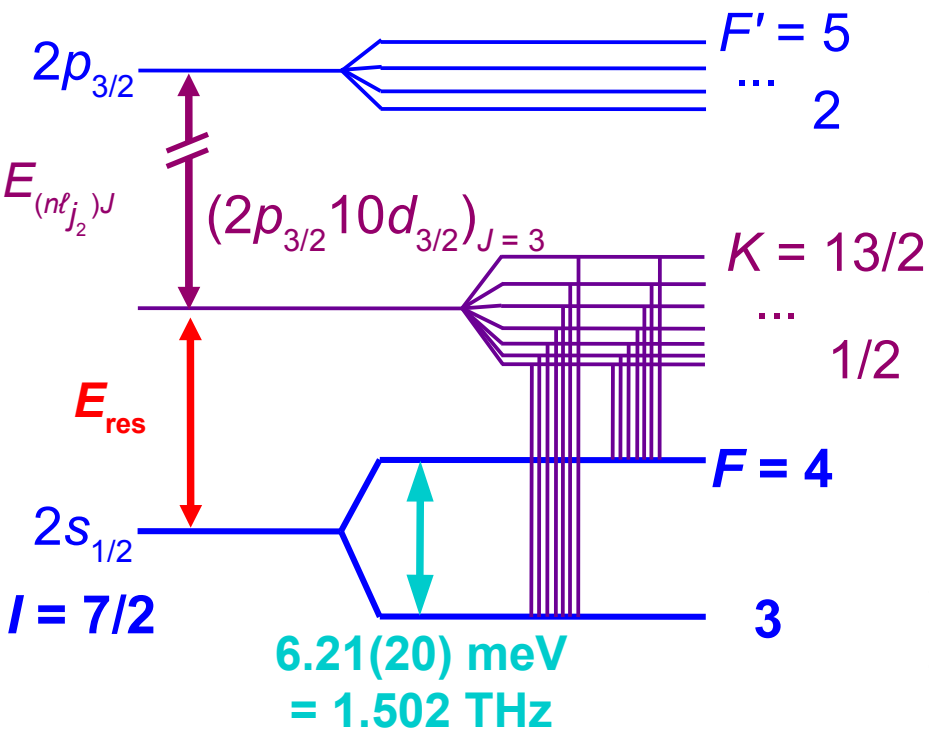
Hyperfine-resolved electron collisions

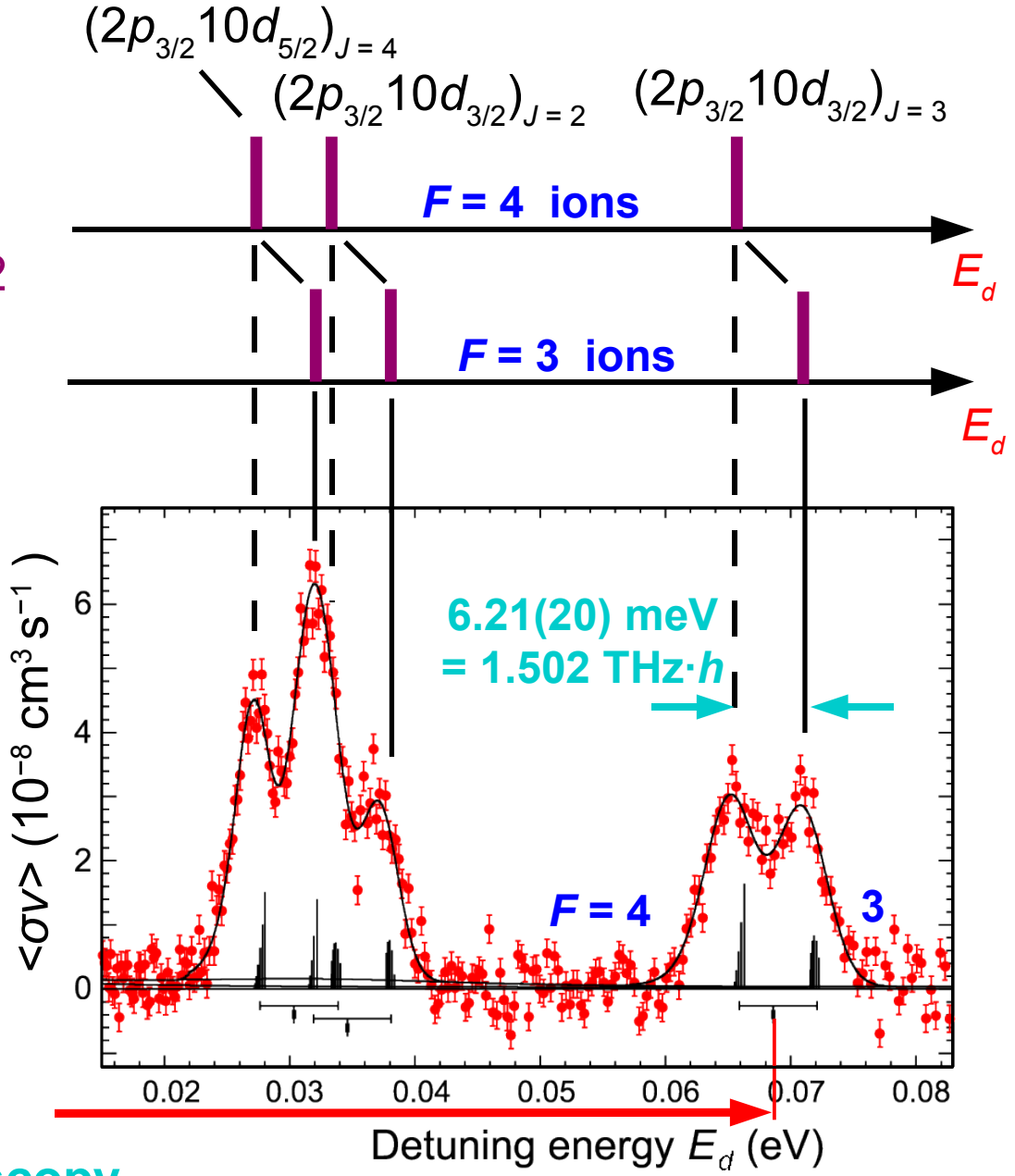




M. Lestinsky et al., PRL 100, 033001 (2008)

Hyperfine-resolved electron collisions





Hyperfine-averaged resonance energies ±0.1 meV

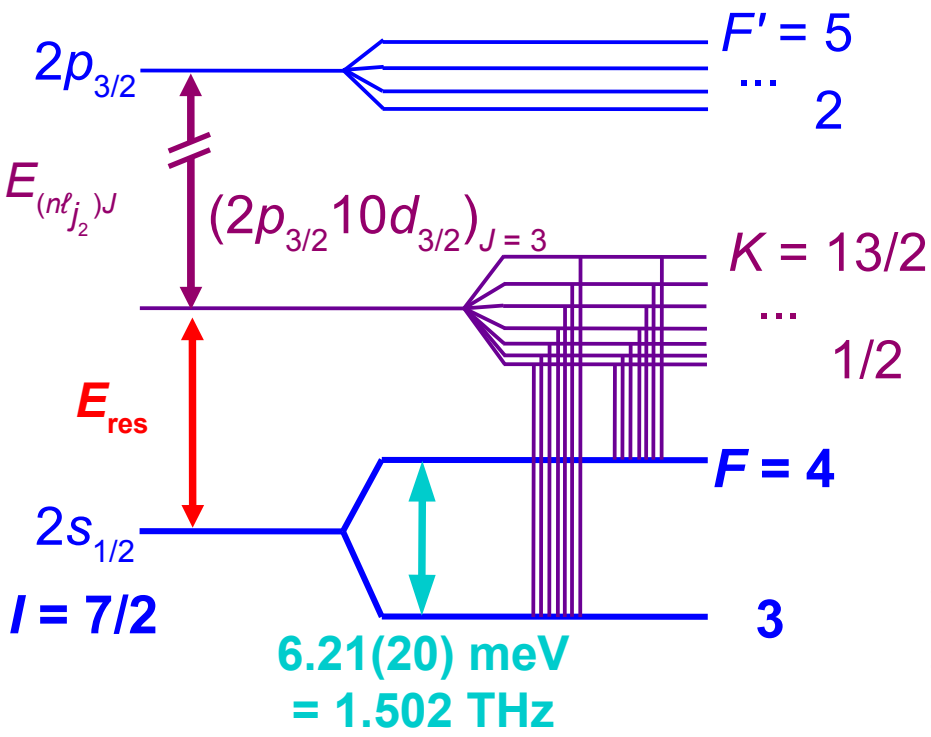
Hyperfine level populations in stored ion beam

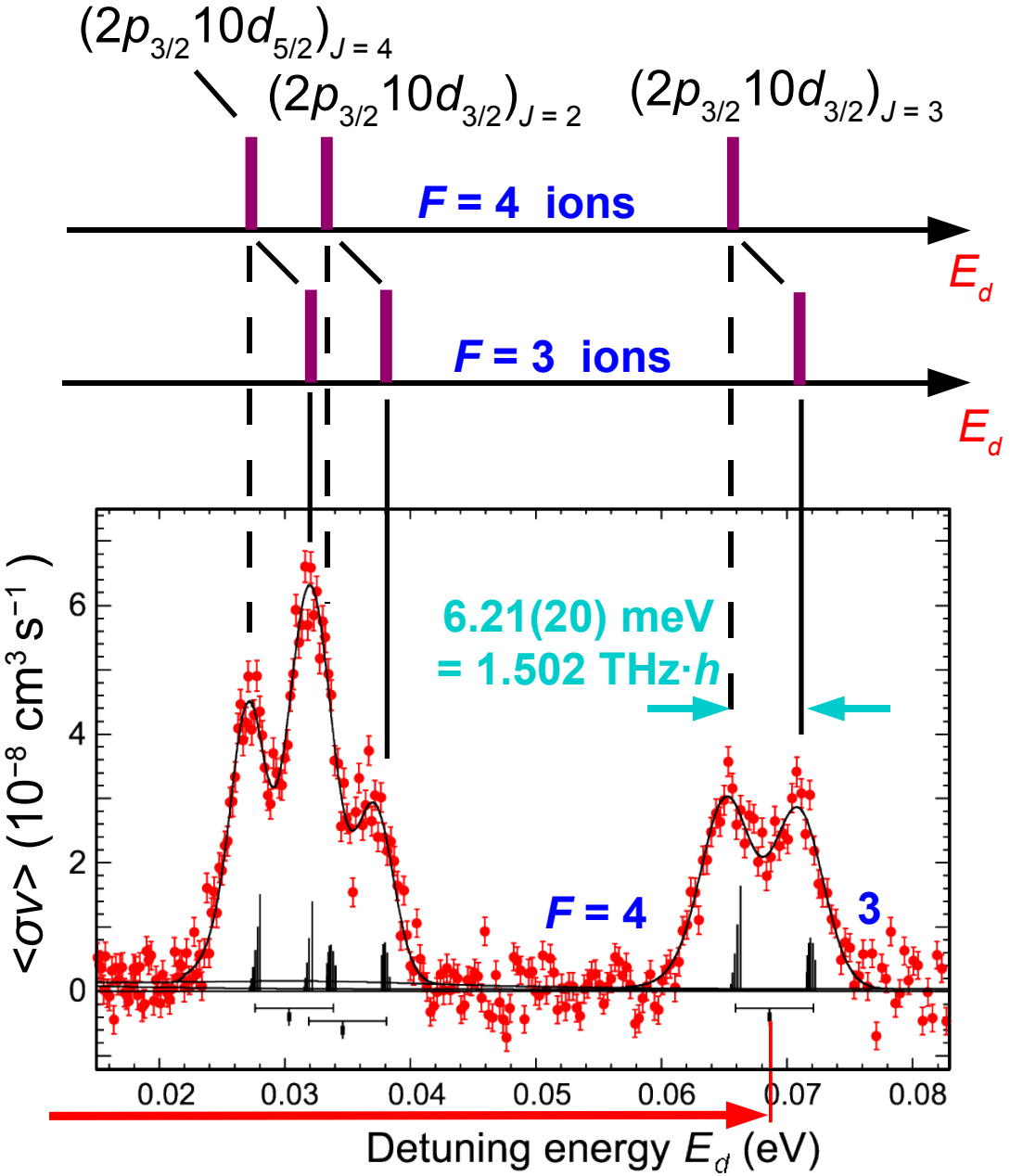
Thermal (Boltzmann) population T = 410(100) K

Tool for double-resonance spectroscopy

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

Screened QED in Li-like ions





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

$Z = 21$, $2s_{1/2}$-$2p_{3/2}$ E. Lindroth

RMBPT $(nl)J$ binding energies

Using 3 resonance positions:

$J = 4$: 44.30952(15) eV
$J = 2$: 44.30945(15) eV
$J = 3$: 44.30932(15) eV

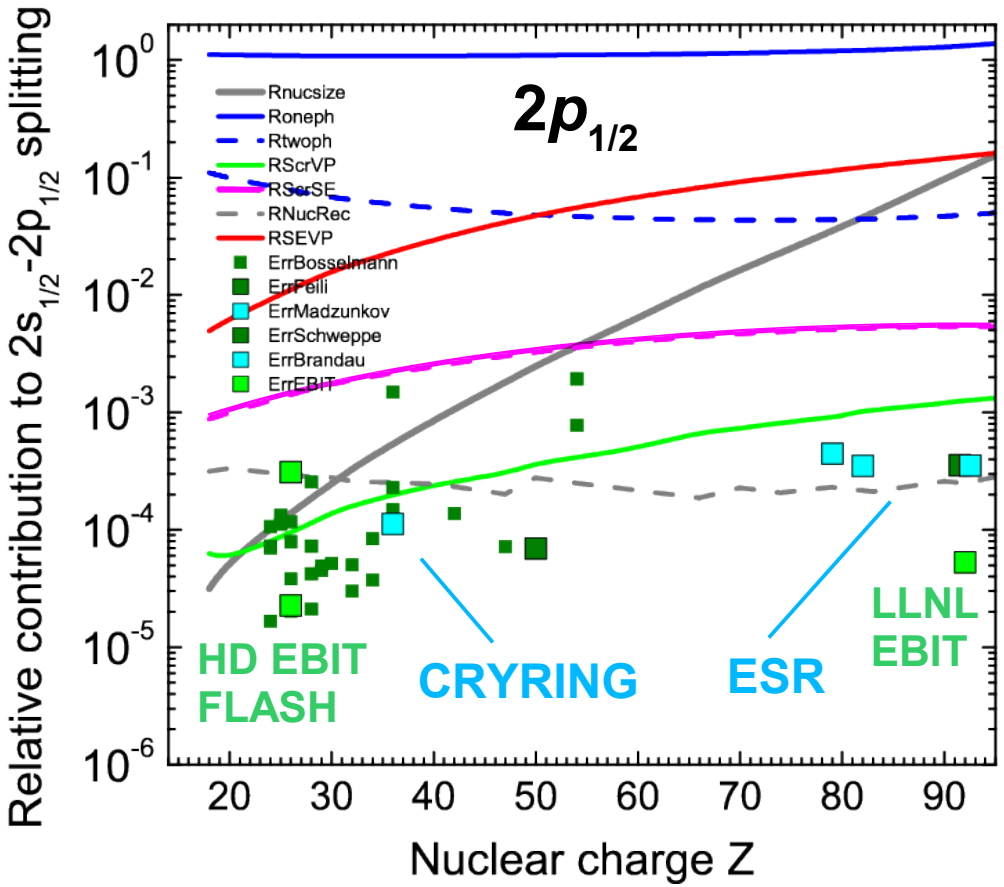
±0.2 meV

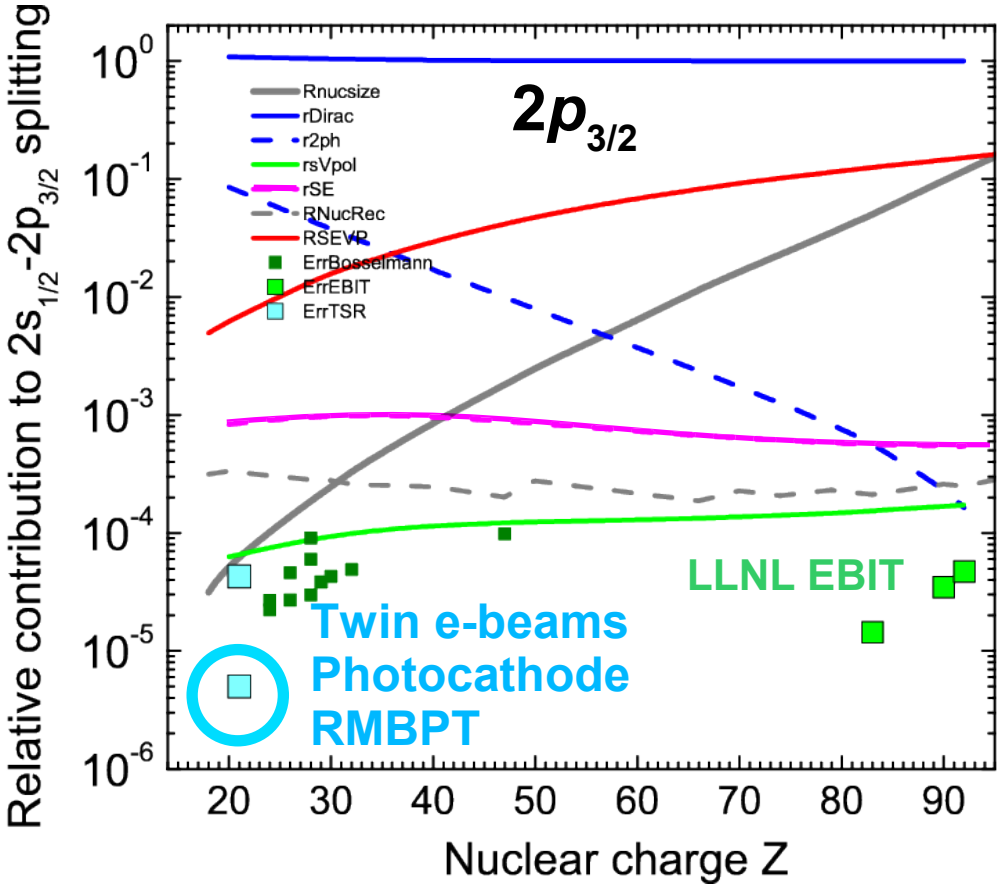
→ 44.30943(20) eV

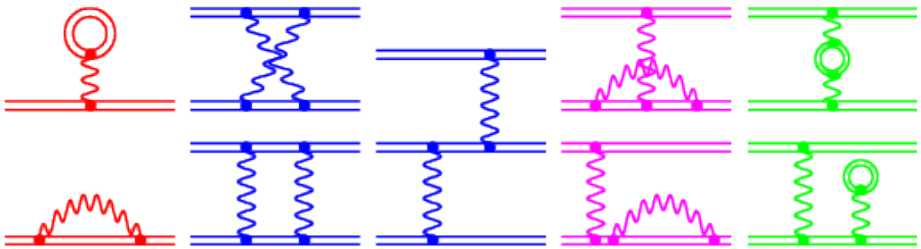
QED: 0.22 eV

Core excitation energies ΔE ($2s$–$2p$) – QED contributions

compared to experimental relative accuracy





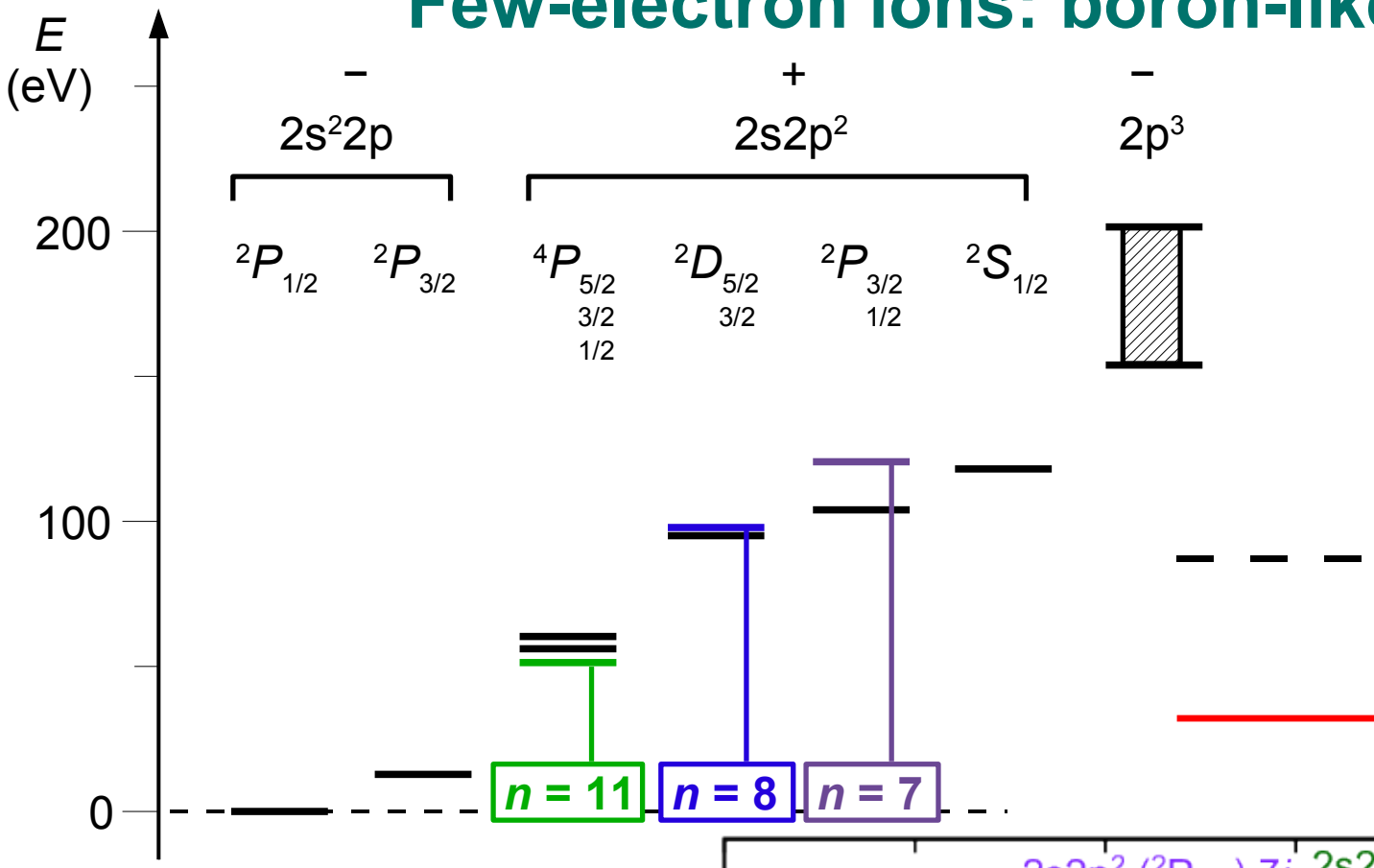


Screened self-energy

Screened vacuum polarisation

(Compilation: S. Schippers)

Few-electron ions: boron-like core



Fe^{21+}

$1s^2\,2s^2\,2p$

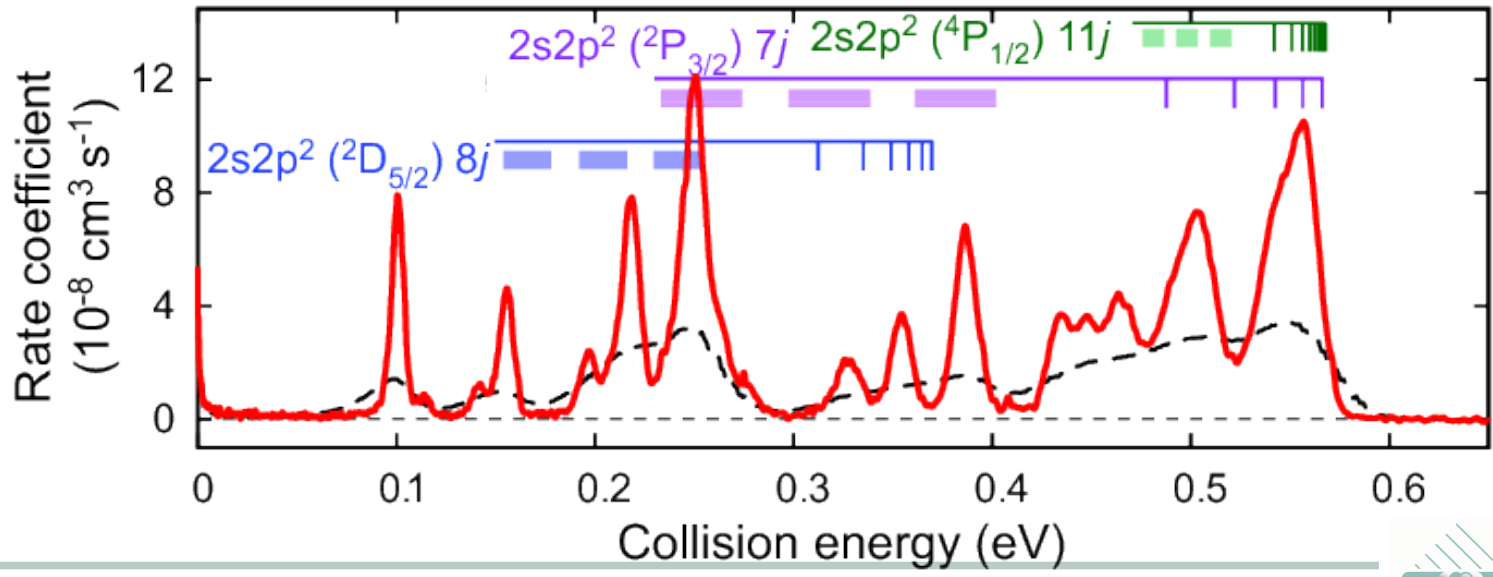
$Z = 26$

TSR / Electron cooler

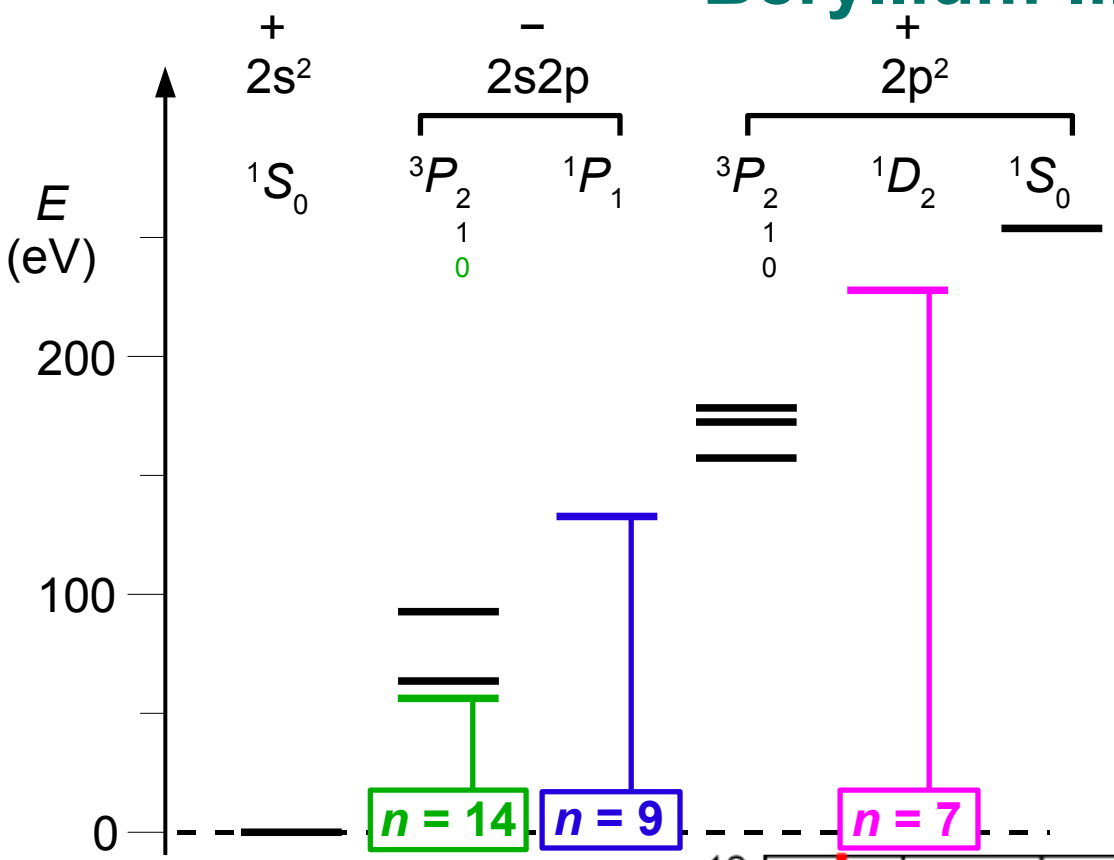
D. W. Savin et al., Astrophys. J. Suppl. 147, 421 (2003)

TSR / Photocathode

C. Krantz et al., J. Phys. Conf. Ser. 163, 012059 (2009)



Beryllium-like ions



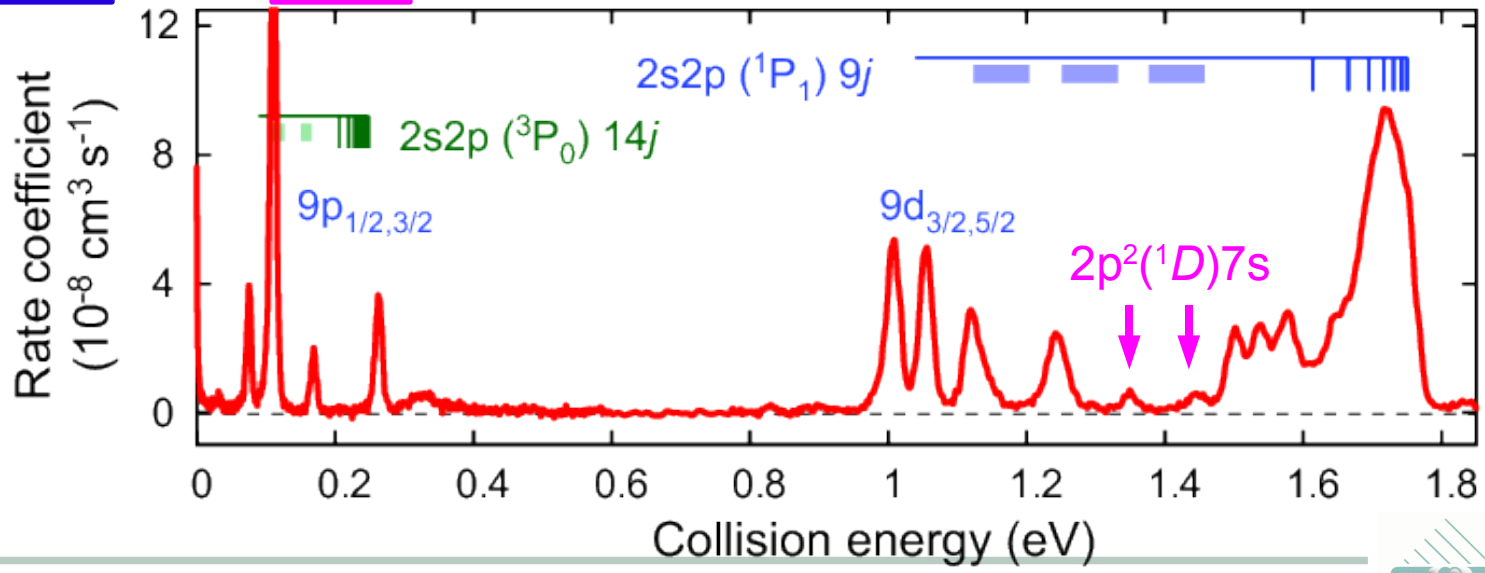
Ge^{28+}

$1s^2\,2s^2$

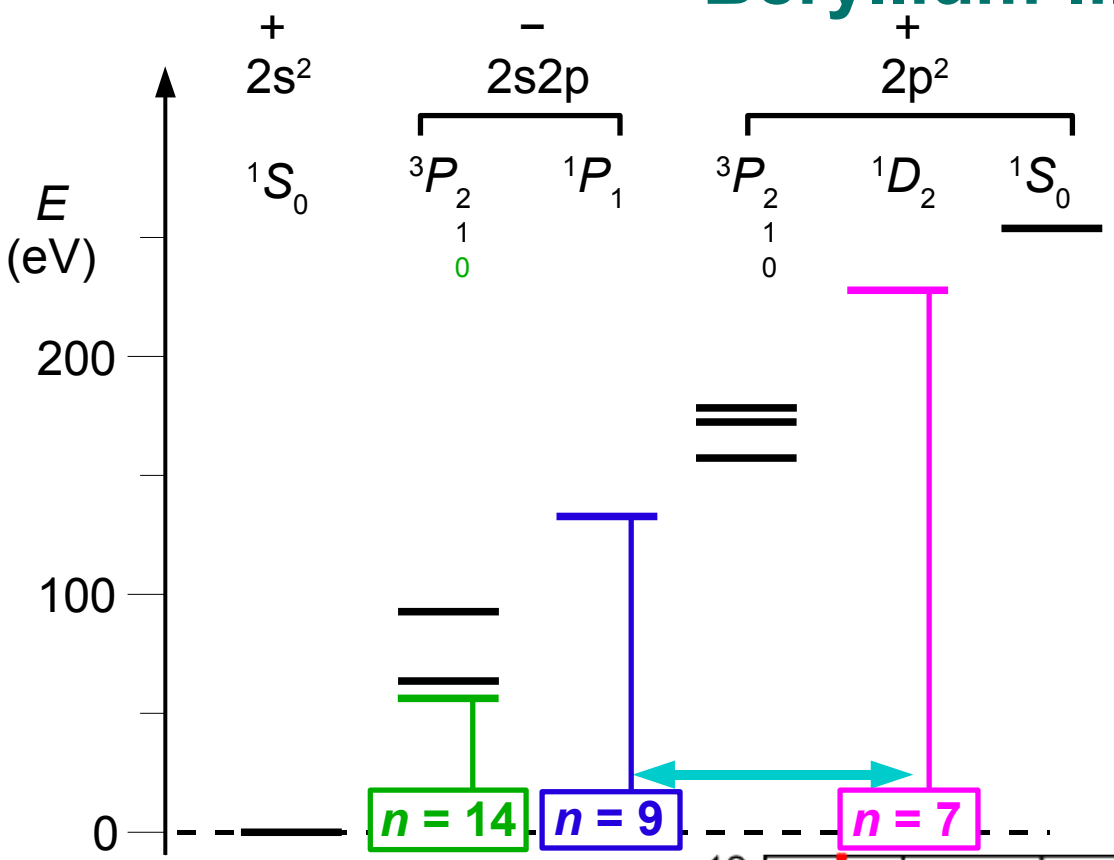
$Z = 32$

TSR / Photocathode

D. A. Orlov et al., J. Phys. Conf. Ser. 163, 012058 (2009)



Beryllium-like ions



Ge^{28+}

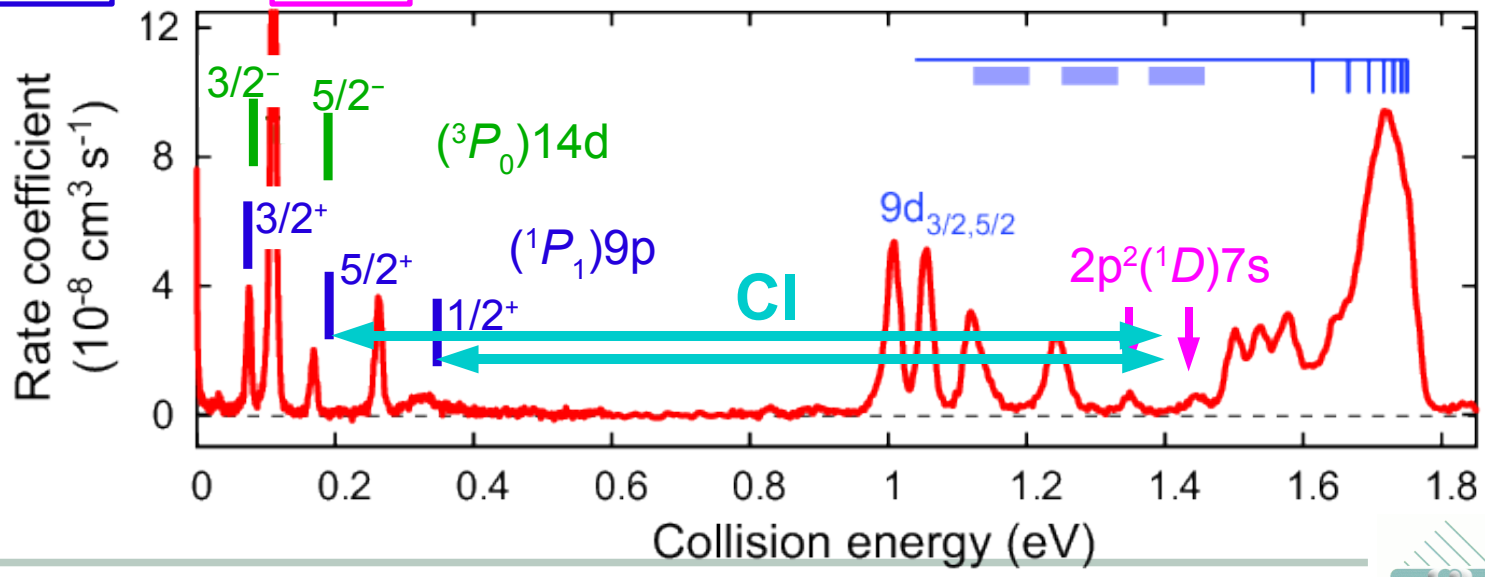
$1s^2\,2s^2$

$Z = 32$

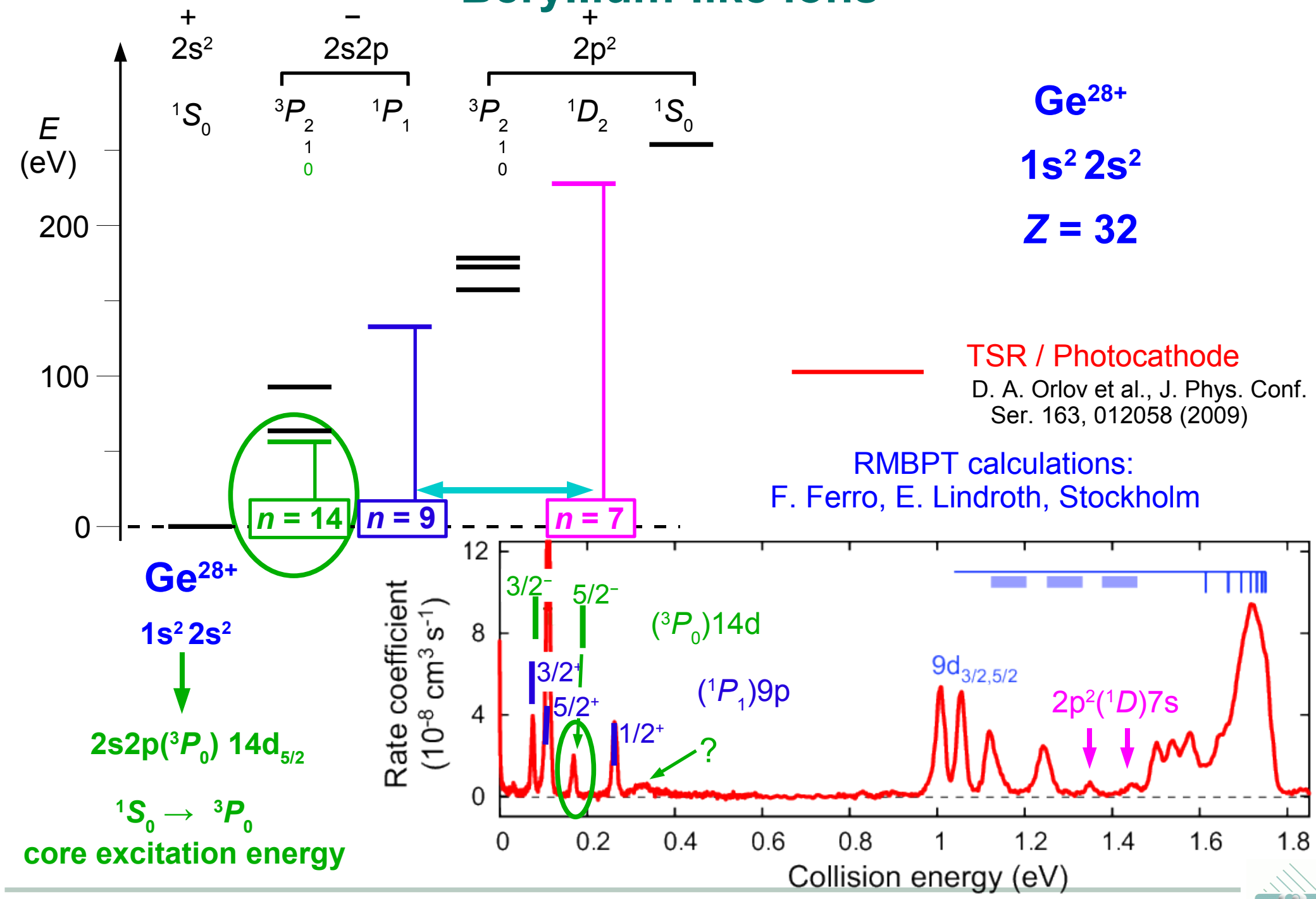
TSR / Photocathode

D. A. Orlov et al., J. Phys. Conf. Ser. 163, 012058 (2009)

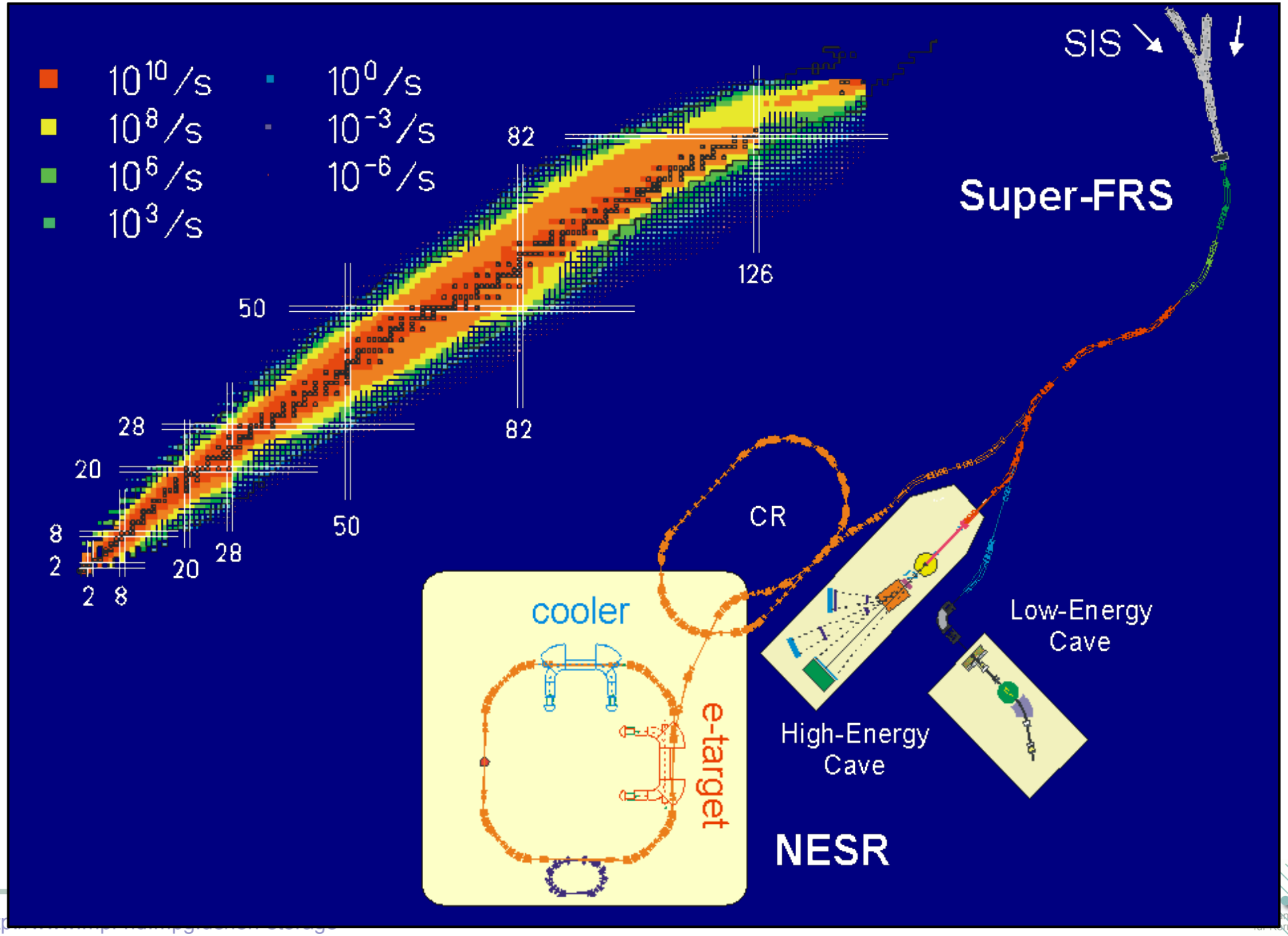
RMBPT calculations:
F. Ferro, E. Lindroth, Stockholm



Beryllium-like ions

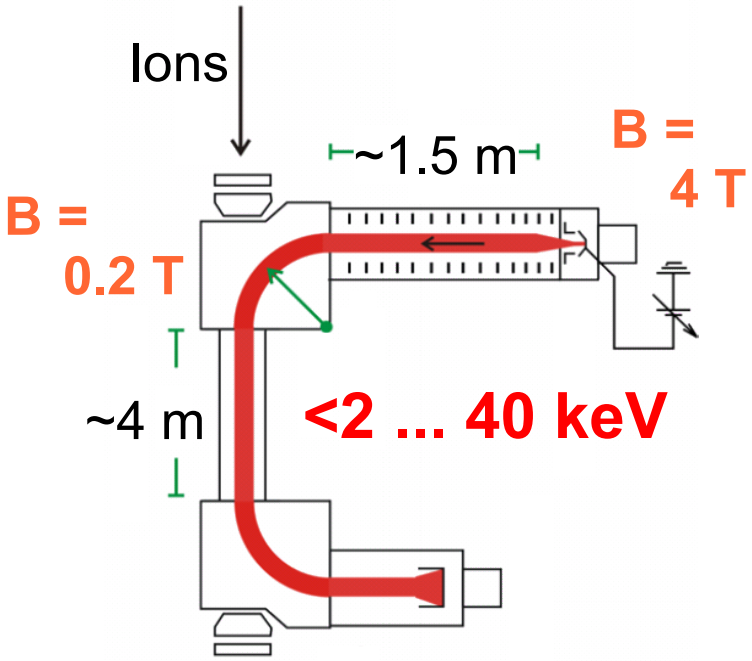


Electron collisions at the NESR



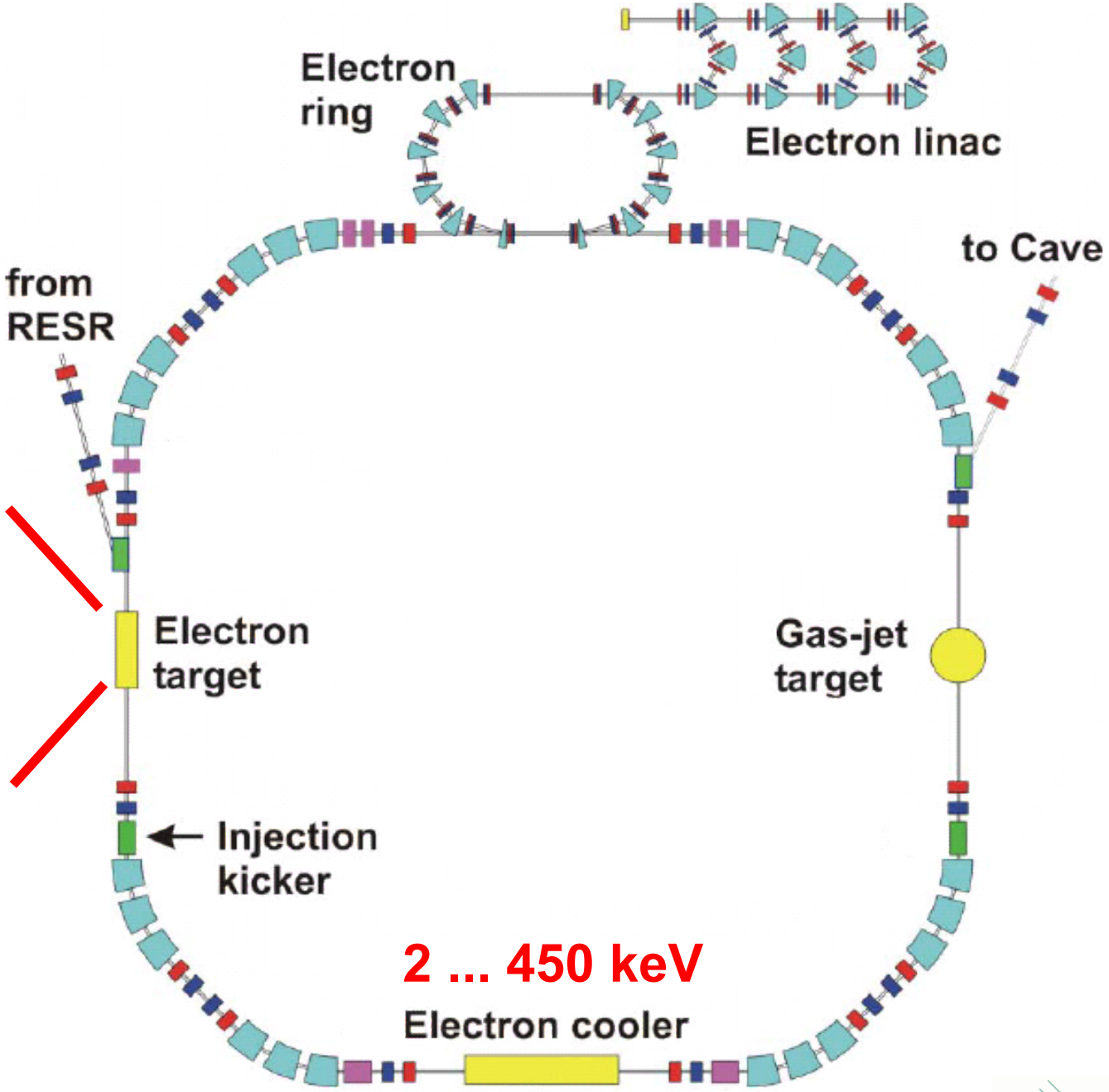
Electron collisions at the NESR

$T_{\perp}$ ~ 5 meV
$T_{\parallel}$ ~ 0.02 meV

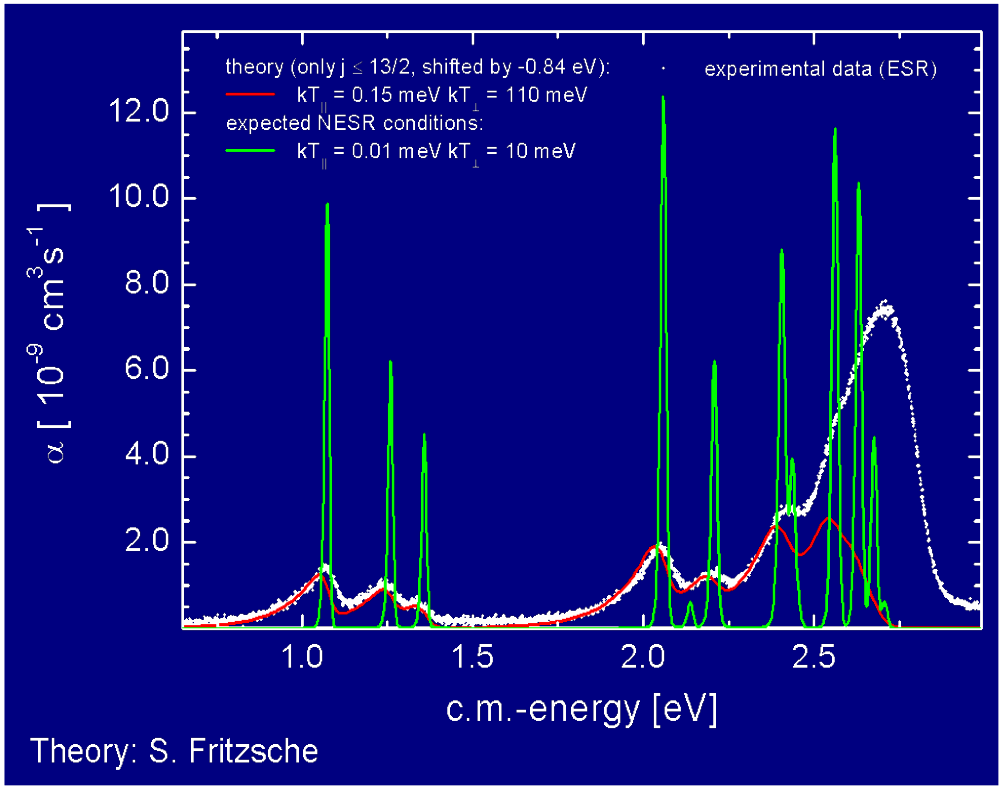


Magnetic expansion

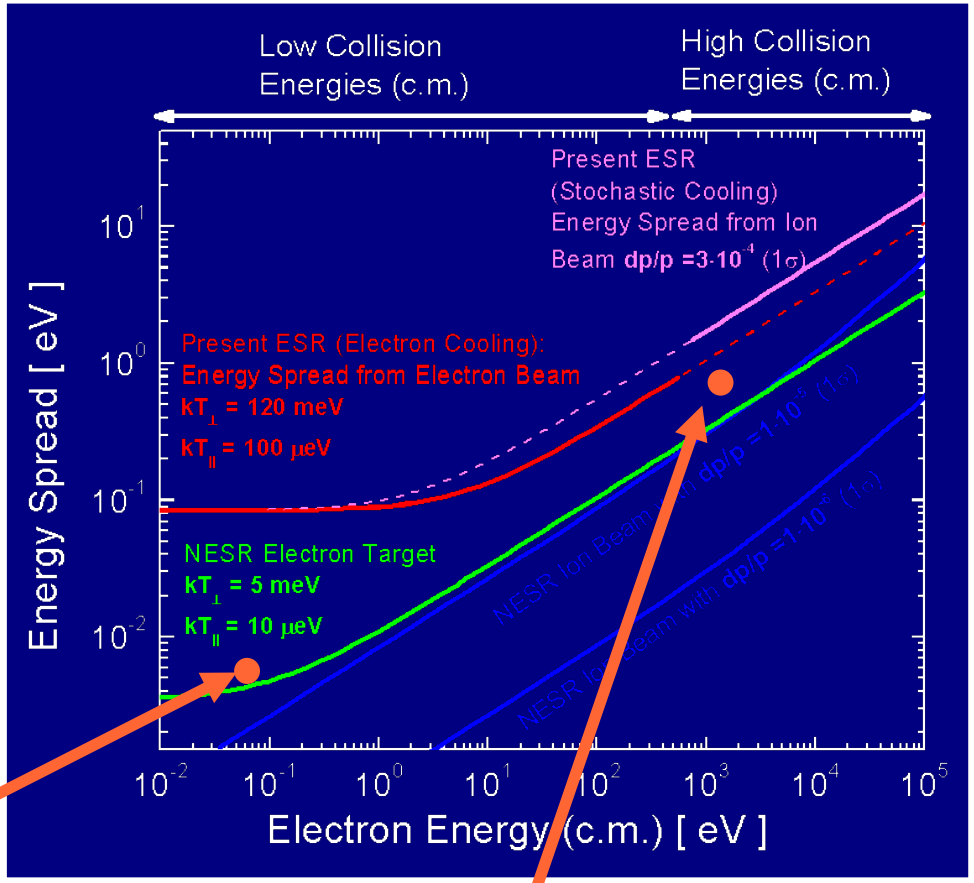
Two-step acceleration



Projections for NESR electron target performance



$^{150}Nd^{58+}$

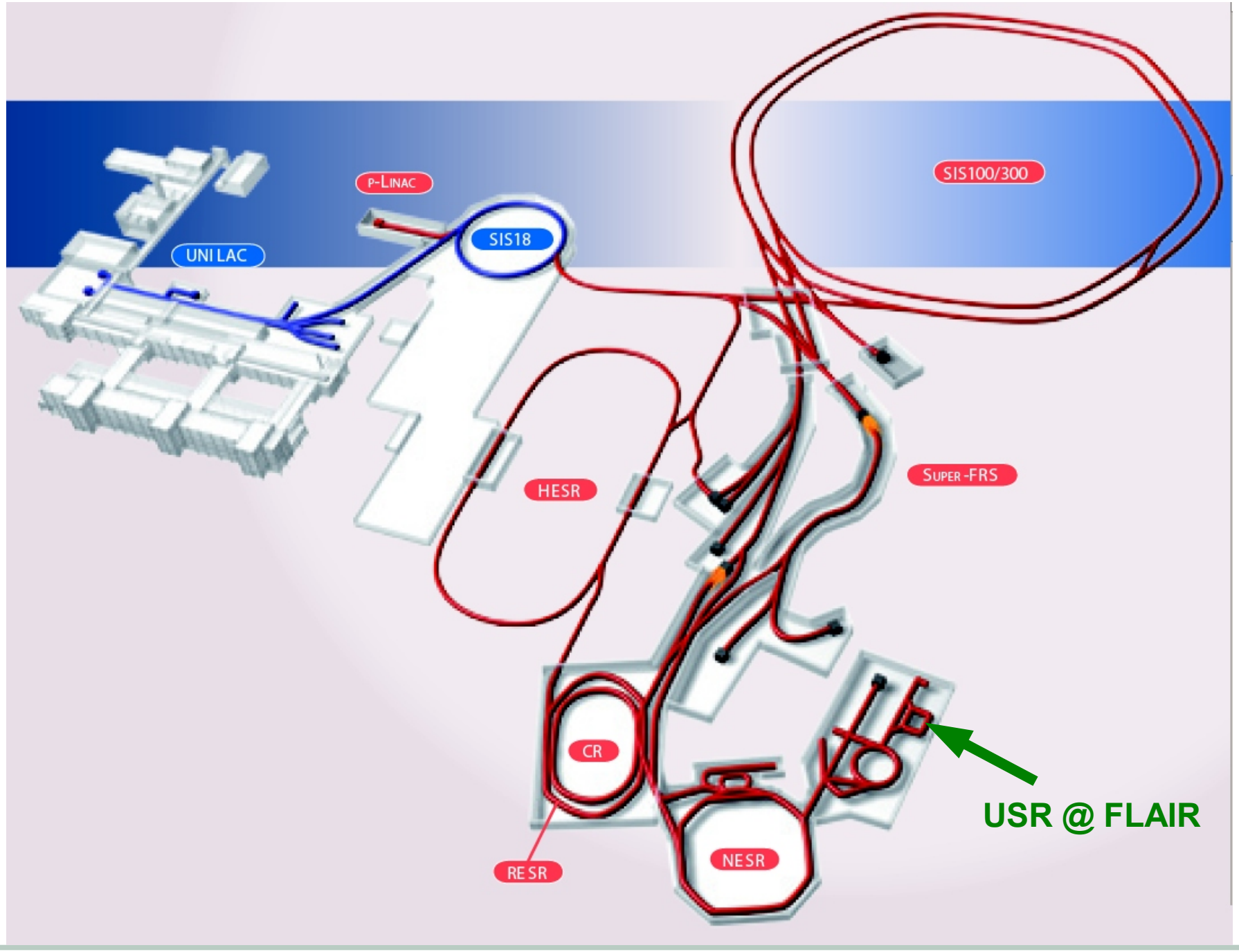


TSR twin electron beams

4 MeV/u Sc^{18+} (photocathode)

4 MeV/u Mg^{11+} (thermocathode)

Stored ion beams with keV energies



Cryogenic electrostatic storage ring CSR

Highly charged ions, large molecules, clusters (cations, anions)
Under construction at MPIK, Heidelberg

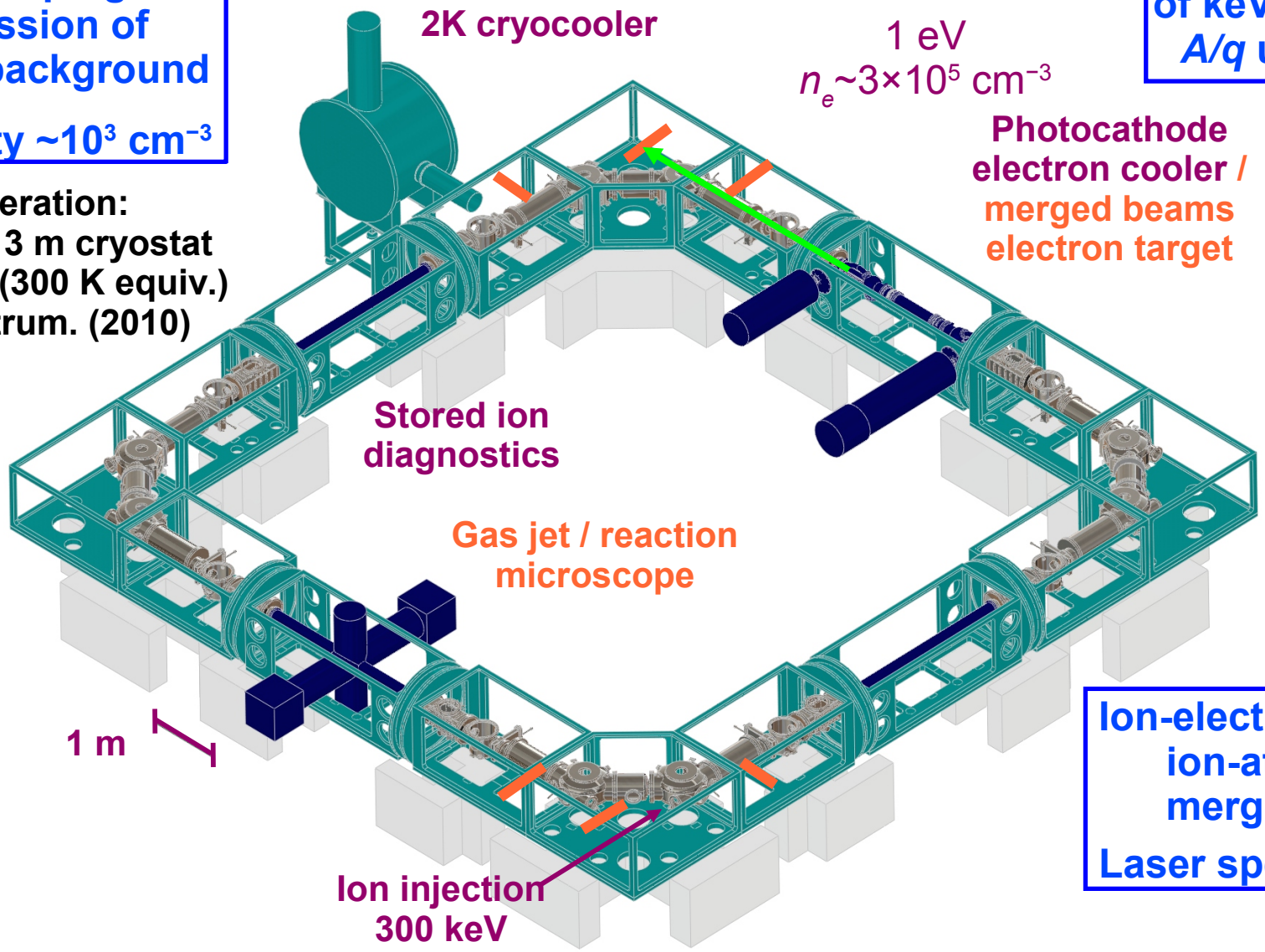
2 K cryopumping and suppression of radiation background

Gas density ~10^3 cm^{-3}

Prototype operation:
keV ion trap, 3 m cryostat
1×10^{-13} mbar (300 K equiv.)
Rev. Sci. Instrum. (2010)

Electron cooling of keV ion beams
***A/q* up to ~160**

D. A. Orlov, C. Krantz, A. Shornikov et al.



Ion-electron and ion-atom merged beams

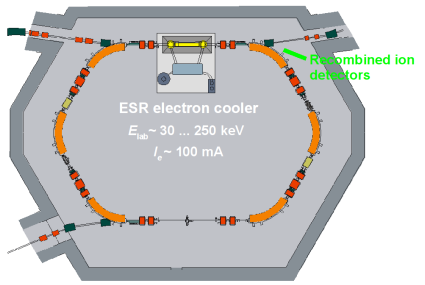
Laser spectroscopy

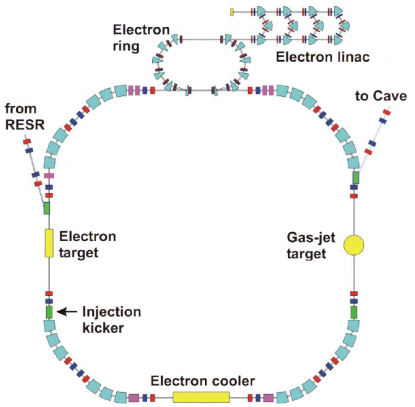
CSR construction

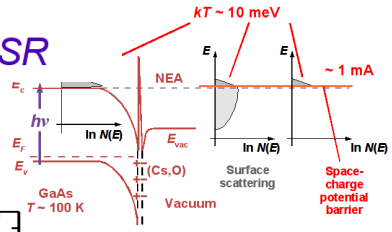
Summary

Electron capture resonances on few-electron heavy ions

Energy resolution 1-100 meV for resonances at ~0.1...10 eV





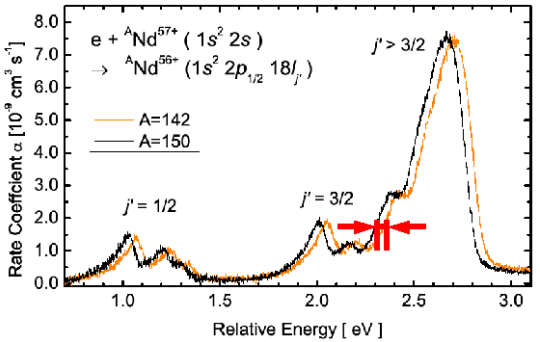


Rydberg electrons probing core excitation:

Isotope shifts of heavy nuclei $^{142,150}Nd^{58+}$, $^{236\text{-}238}U^{89+}$

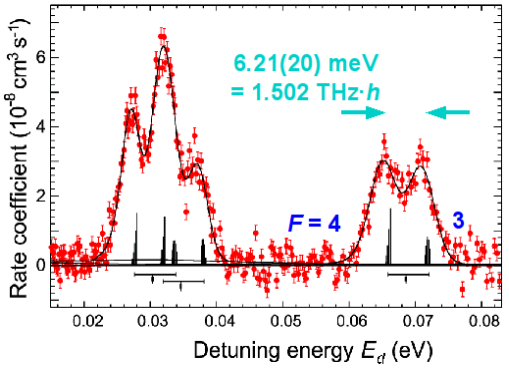
Hyperfine splitting and screened QED in $^{238}Sc^{18+}$

Towards Be-like systems: $^{74}Ge^{28+}$



Merged electron-ion beams at NESR

Ultra-low energy beams (eV-keV/amu) at FLAIR



Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

Stored and Cooled Ions (K. Blaum)

Highly charged ion collisions

Atomic and molecular quantum dynamics

Atomic and molecular physics	**A. W.** **D. A. Orlov** A. Petrignani B. Jordon-Thaden
Electron target	**C. Krantz**
Photocathode	**A. Shornikov** D. Bing M. Mendes M. Berg J. Stützel

Stored and cooled ion instrumentation

TSR and accelerator	**M. Grieser** **R. von Hahn** **R. Repnow** **R. von Hahn**

Collaborations

Univ. Giessen, Germany
D. Bernhard **S. Schippers**
E. W. Schmidt **A. Müller**

Columbia Univ., NYC
M. Lestinsky **D. Wolf Savin**
O. Novotný

Univ. of Stockholm, Sweden
E. Lindroth **F. Ferro**

GSI, Darmstadt
C. Brandau **C. Kozhuharov**

www.mpi-hd.mpg.de/blaum/molecular-qd
storage-rings

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK