Precision Spectroscopy of HCI in the Dark

Precision Spectroscopy of Atomic Quantutm Levels without Detecting Emission of Photons or Electrons

R. Schuch, Stockholm University, AlbaNova Sweden

sparc
Stored Particles Atomic Physics Research Collaboration

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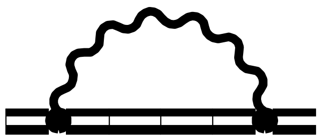
- Mass Measurements with High Precision in Penning Traps
- Resonant Coherent Excitation of Fast Ions in Crystals
- Collision Spectroscopy:
  Q-value in Electron Capture Measured Precisely by COLTRIMS
  Resonances in Electron Scattering by Dielectronic Recombination

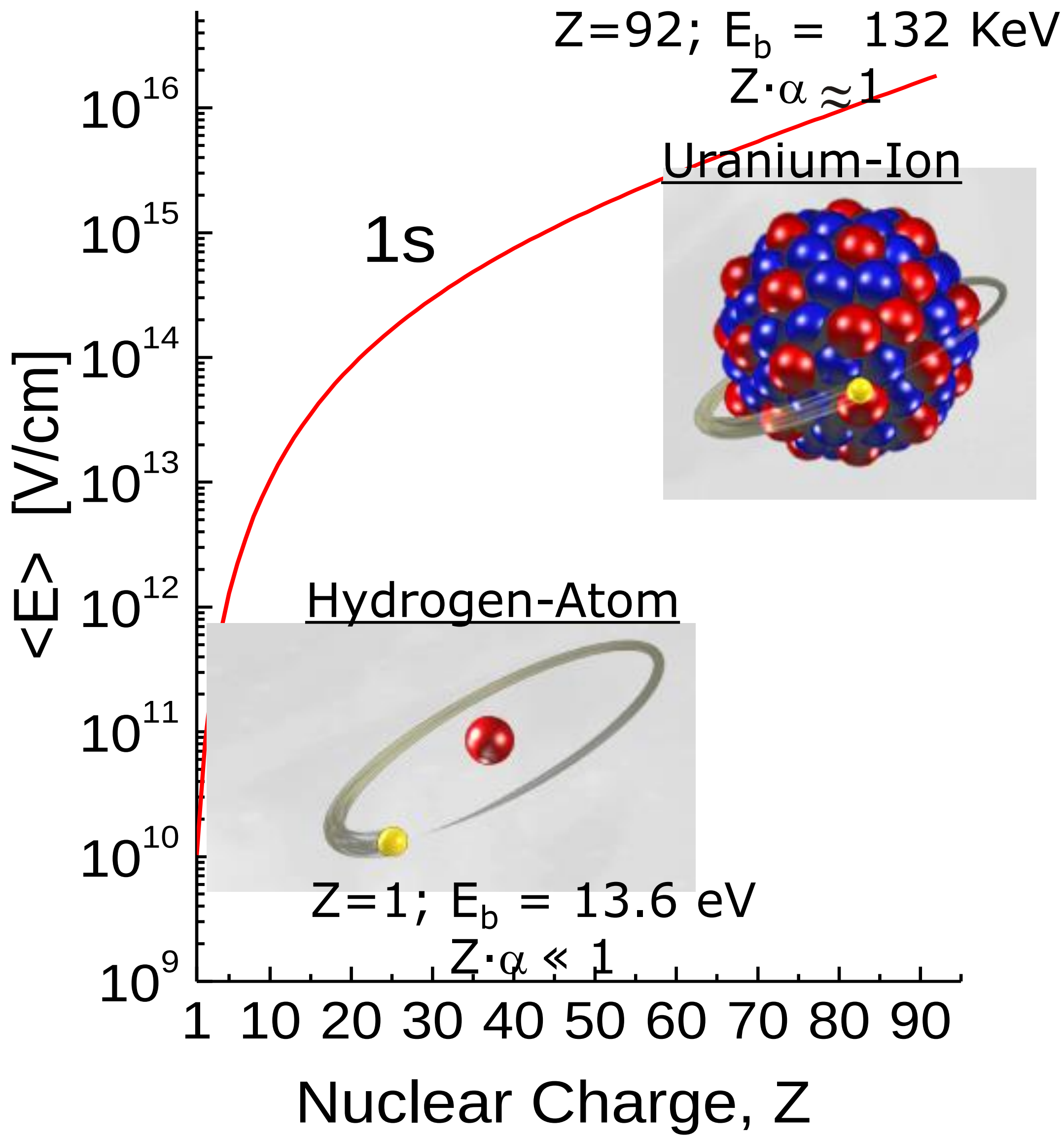
Motivation:

Atomic Physics in Extremly Strong Fields

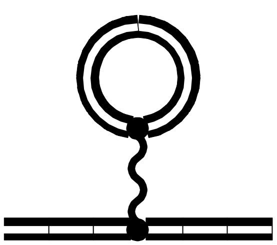
Self Energy



*Q*uantum
*E*lectro-
*D*ynamics



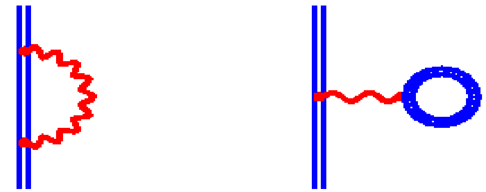
Vacuum Polarization



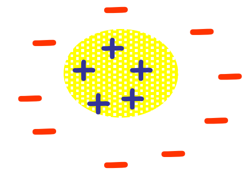
1s-ground state: increase of the electric field strength by six orders of magnitude

H-like "One Photon"

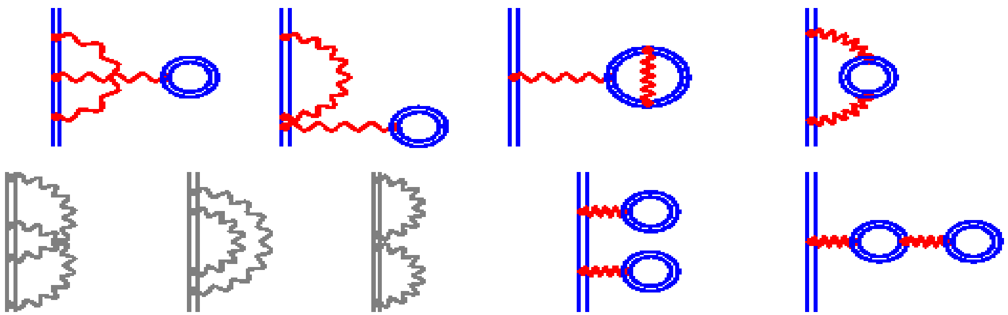
Self Energy



Vacuum Polarization



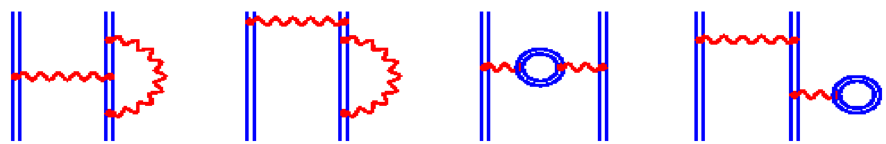
$m_{bare} \rightarrow m_{obs}$

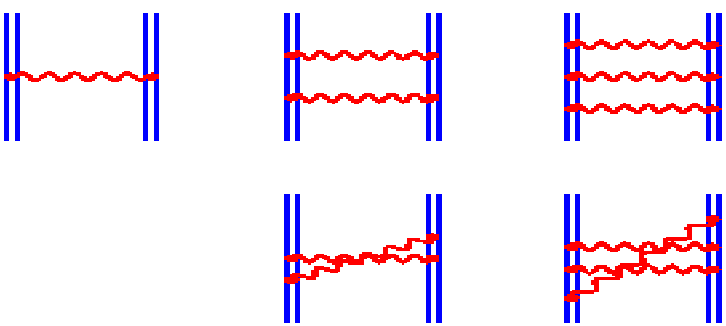


H-like ion "Two Photon" QED

"Screening of S.E. and V. P."

for ions with several electrons





Relativistic Many-Body Perturbation Theory (RMBPT)

Relativistic Configuration Interaction (CI)

+ QED

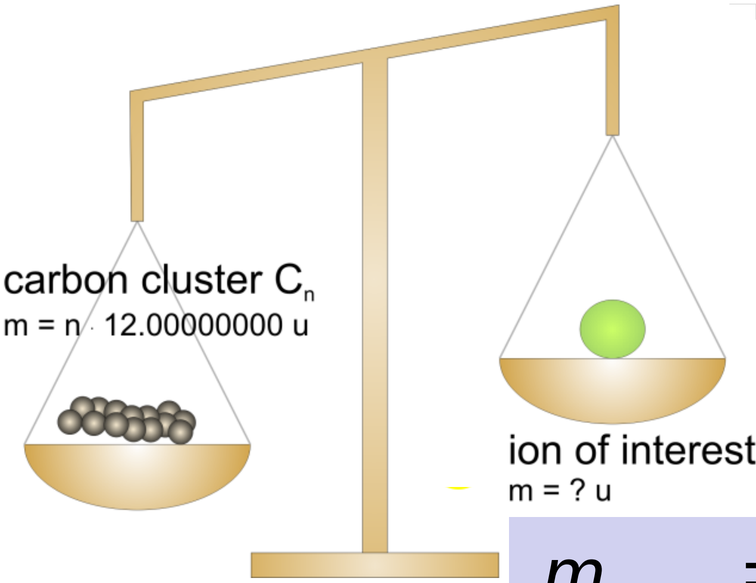
The structural aspect

The Problem: Many e^- (one – two – many!)

The Methods: Conservation of Misery

	Strength	Weakness
Configuration Interaction (CI) $$\Psi = \sum_i \xi_i \mid \Phi_1 \Phi_2 ... \Phi_N \rangle_i$$	Accuracy, strongly correlated systems	Scaling with # particles
Multi-Configuration Hartree/Dirac-Fock	Versatile! (FAC code)	Core-polarization
Perturbation Theory (RMPT) – Coupled Cluster	High accuracy for few e- ions!	Starting point, teadeous calculation

Mass Measurements with High Precision in Penning Traps for Binding Energy Determination



Using Einstein's $E = mc^2$, Confirmed to be correct to 0.00004% by Pritchard et al., in Trap (Nature 438, 1097 (2005))

$$m_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

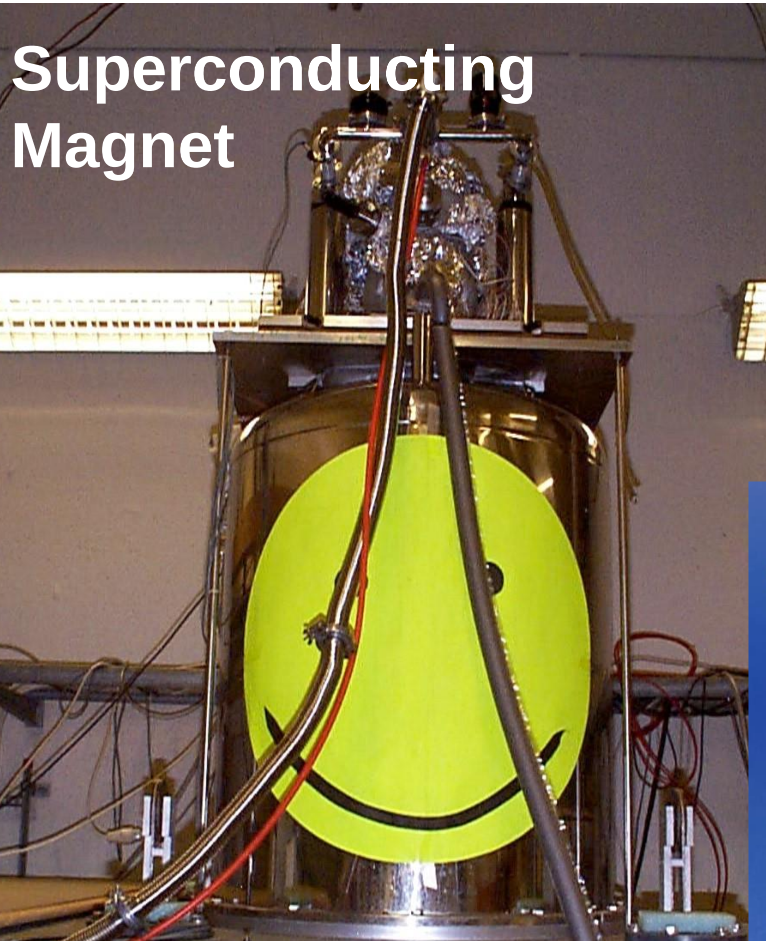
$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} - 10^{-8}$

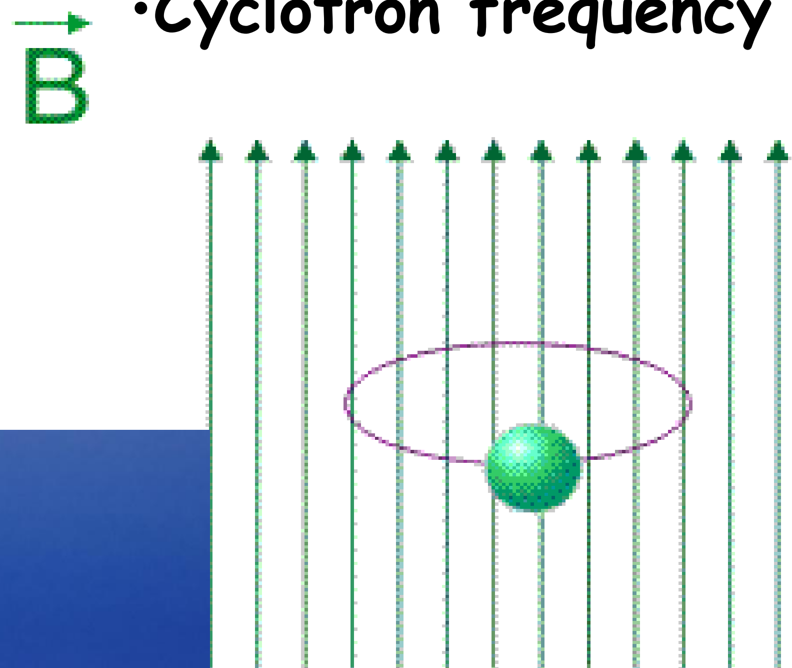
change number of electrons by using highy charged ions in different charge states

Keep B_{nucleus} fixed

High-precision mass measurements



- Cyclotron frequency

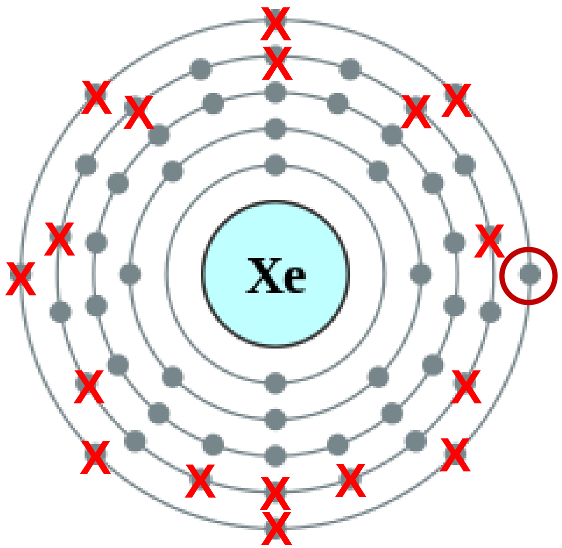


$$\omega_c = \frac{q}{m} \cdot B$$

known | determined

$$\frac{\omega_{ref}}{\omega_{ion}} = \frac{q_{ref}\, m_{ion}\, \cancel{B}}{q_{ion}\, m_{ief}\, \cancel{B}}$$

Weighing binding energies with PENTATRAP@MPIK

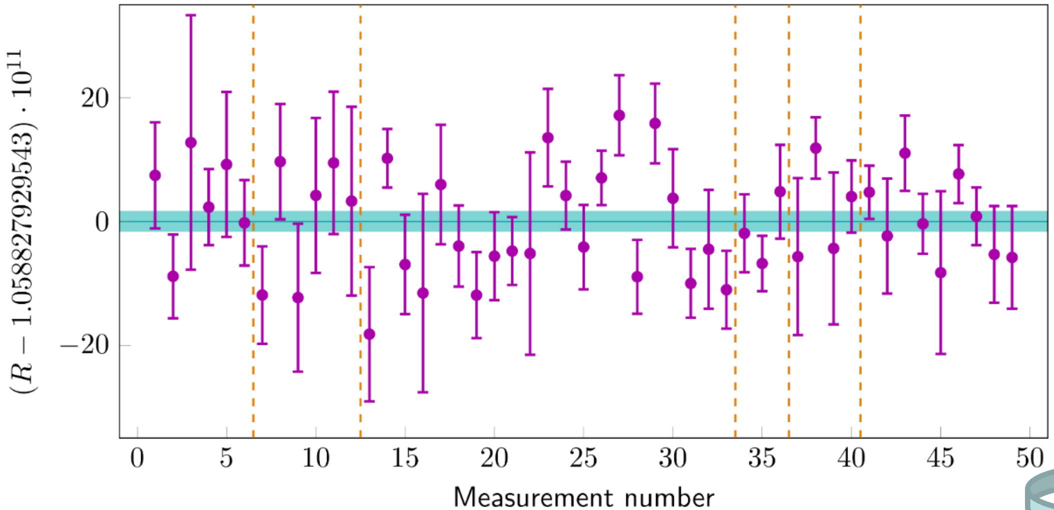


Electron configuration of Xenon (Z = 54):

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6$

Neutral Xe atom $[Kr]\ 5s^2\ 4d^{10}\ 5p^6$

Measure the mass difference of Xe^{17+} and Xe^{18+} yields the binding energy of the 18th electron.



PENTATRAP@MPIK:
$\delta m/m_{stat}$ = 1.1·10^{-11} (δm~ 1.4 eV)

<u>Exp.:</u> **$B(4d^1)_{Xe}$ = 432.4 (1.4)(3.4) eV**

<u>Theorie:</u> **$B(4d^1)_{Xe}$ = 432.4 (3.0) eV *(PI)***

$B(4d^1)_{Xe}$ = 435.1 (1.0) eV *(ZH)*

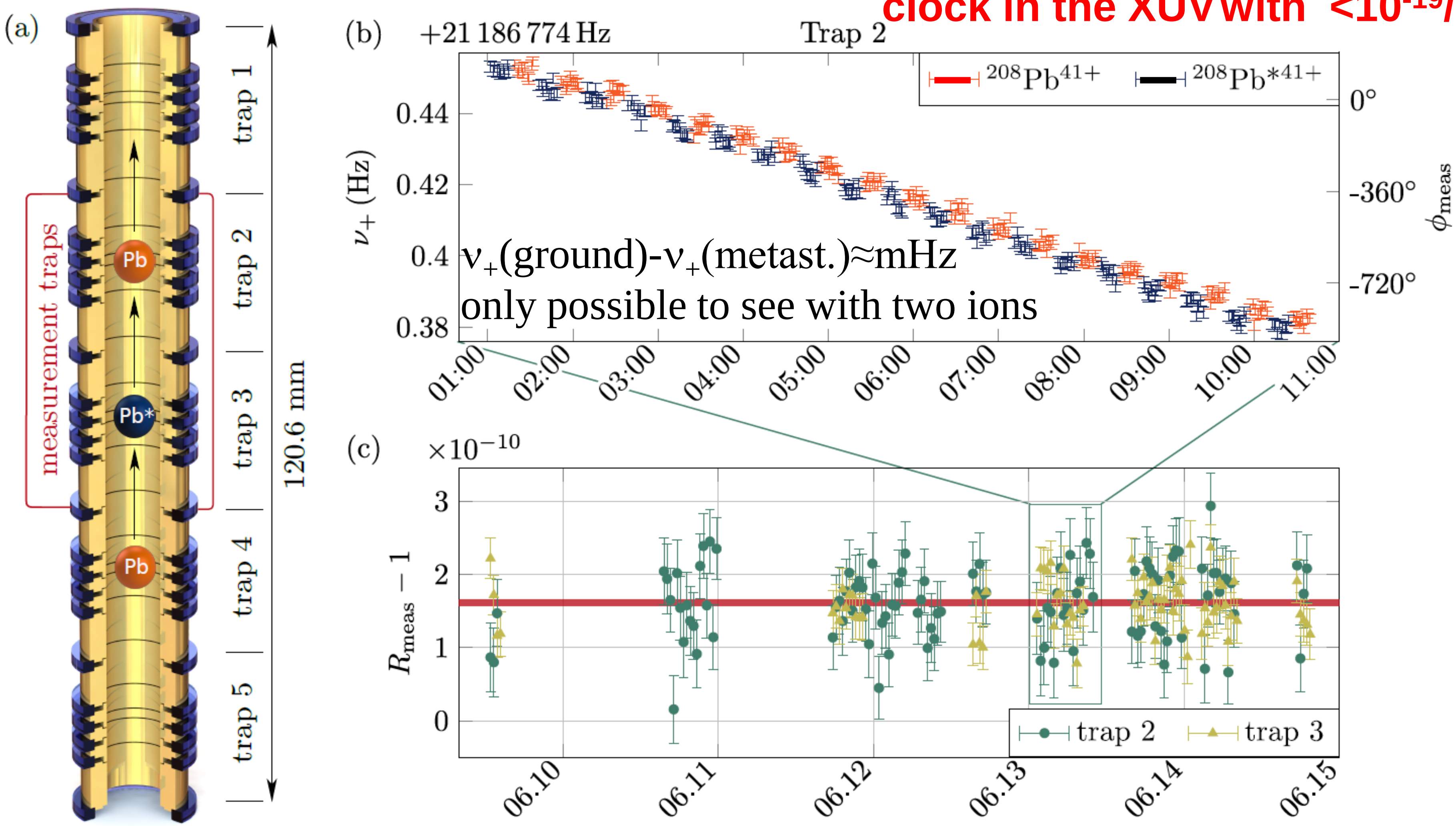
Test of many electron calculations

Rischka *et al.*, PRL **124**, 111301 (2020)

courtesey K. Blaum

Weighing binding energies with PENTATRAP@MPIK

Low-lying <u>metastable</u> electronic state in $^{208}Pb^{41+}$ → First step towards HCI clock in the XUV with $<10^{-19}/\sqrt{\tau}$



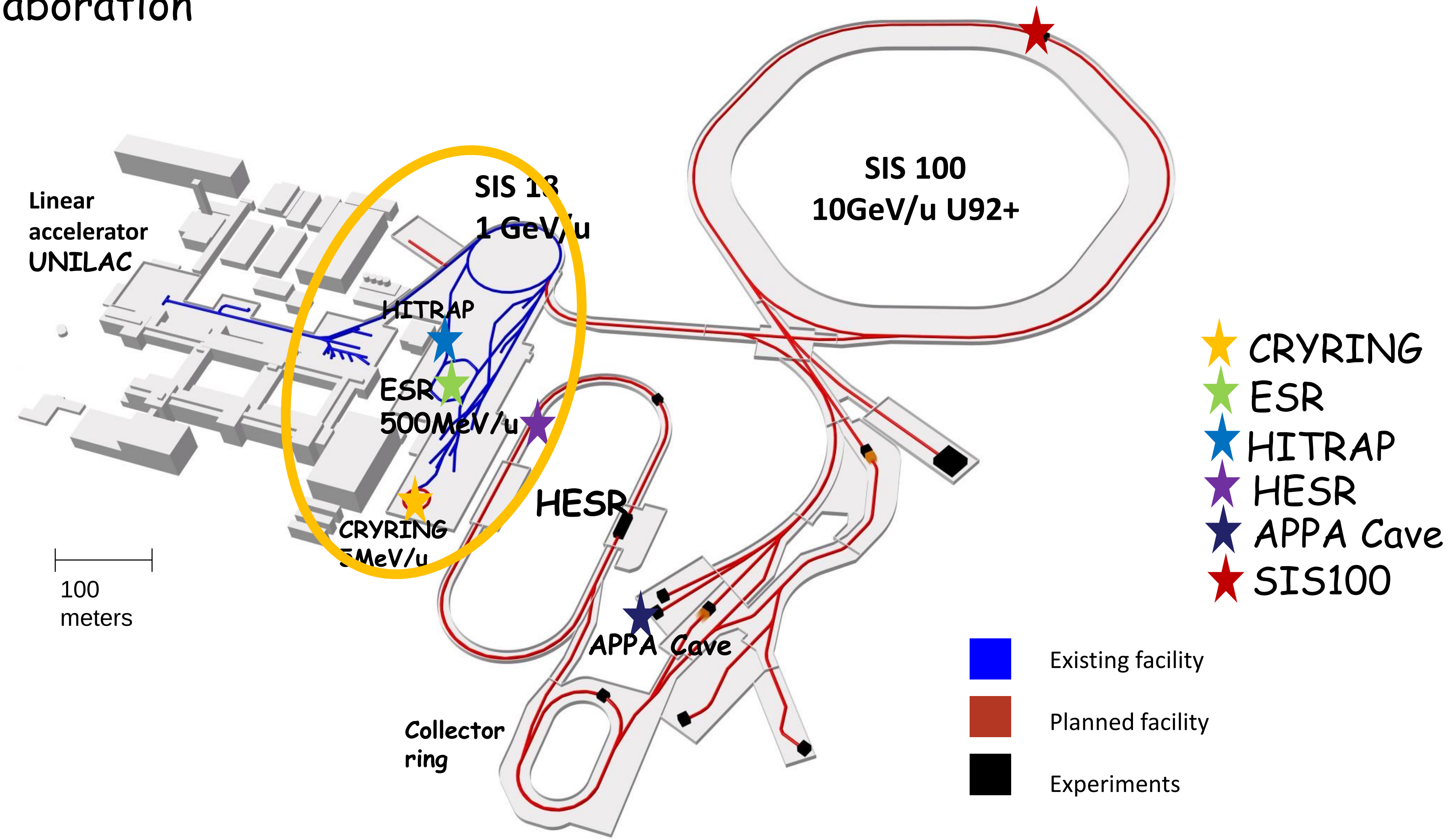
Ratio precision of $4 \cdot 10^{-12}$ Δm= 31.2 ±0.8eV=metastabl excitation energy
lifetime 26,5 d

Kromer *et al.*, arXiv:2310.19365v1 and PRL in print

Facilities of SPARC at FAIR

Stored Particle Atomic Research Collaboration

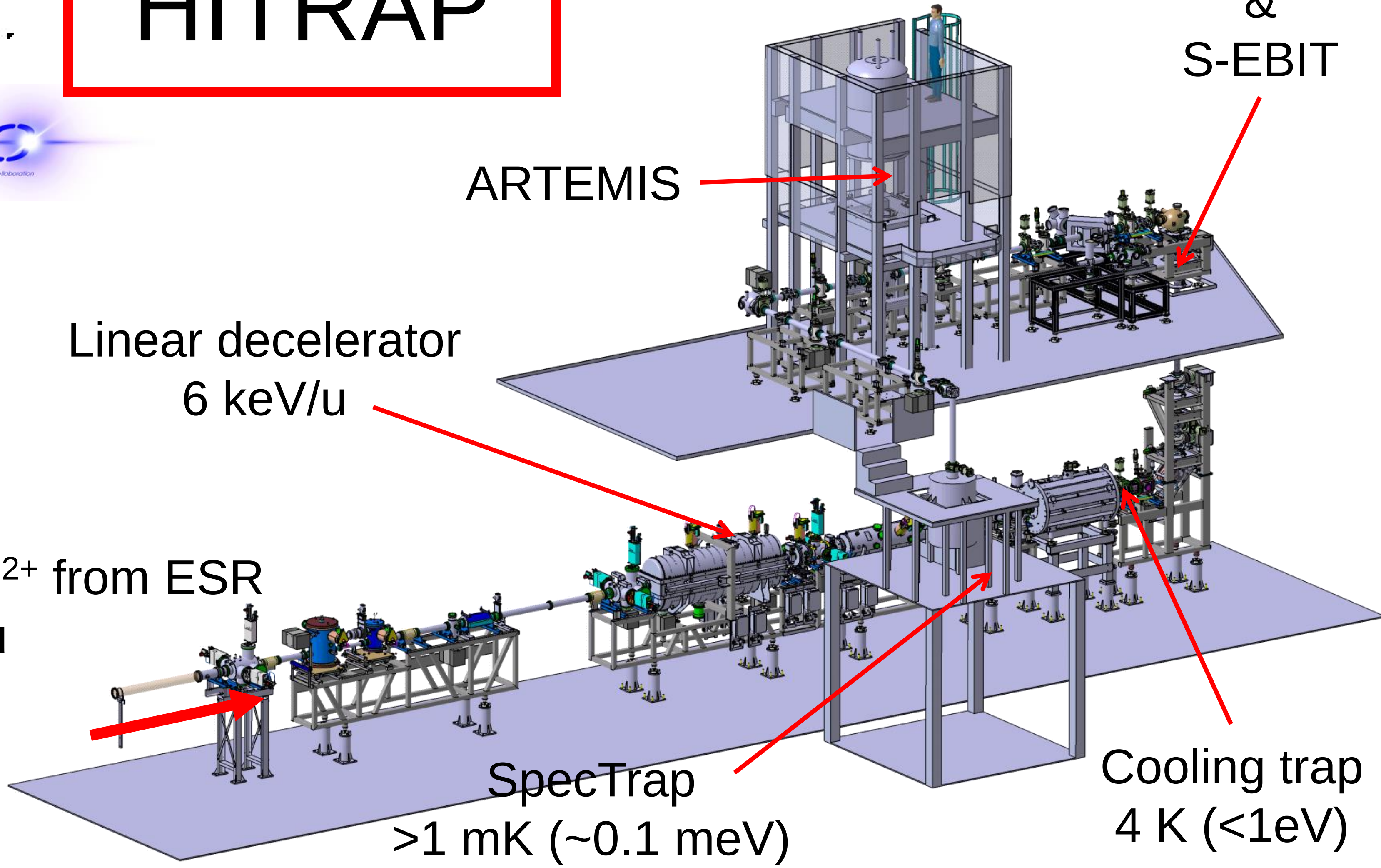
Facility for Antiproton and Ion Resear



Presently used by SPARC

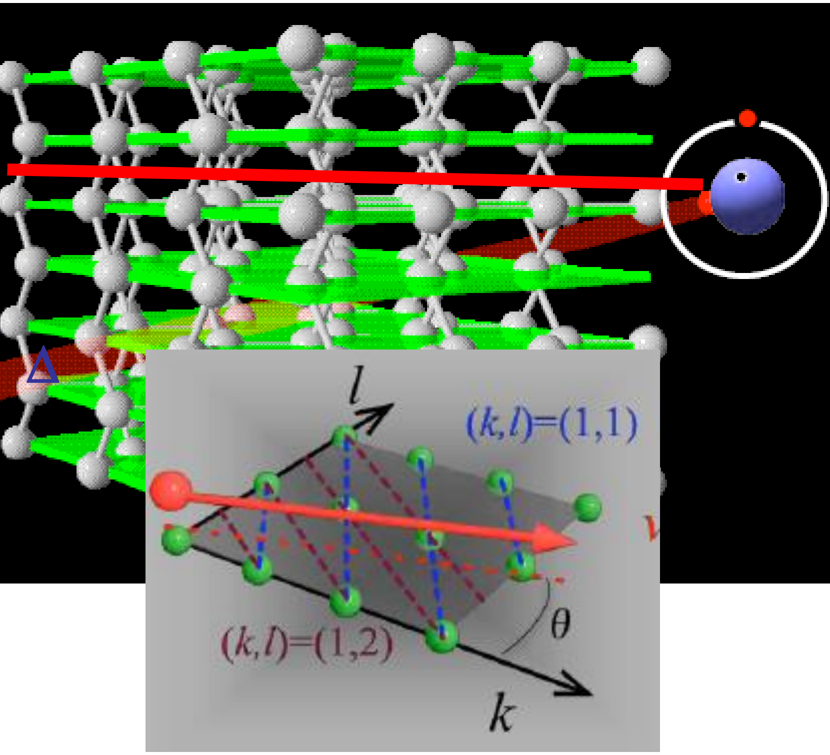
HITRAP

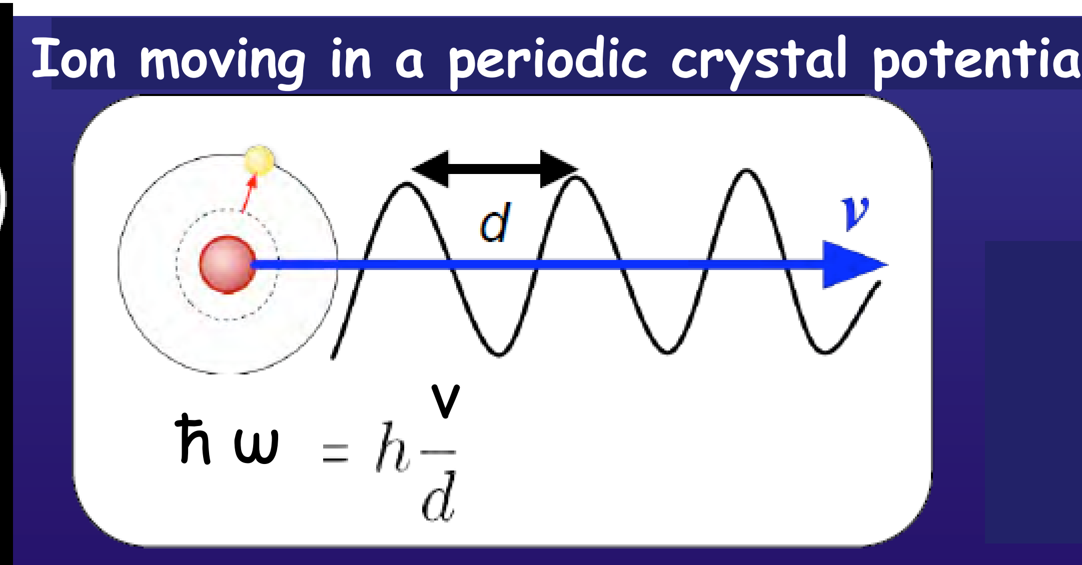
Presently commissioned



1s QED in U^{91+} ≈ 500eV → measure M of U^{92+} to U^{91+} to U^{90+} to 4.10^{-12} (in relative measurement)→ QED to <1eV to check high field and higher order

Precision Spectroscopy of 1s of Heavy Ion at High Energies GeV/u





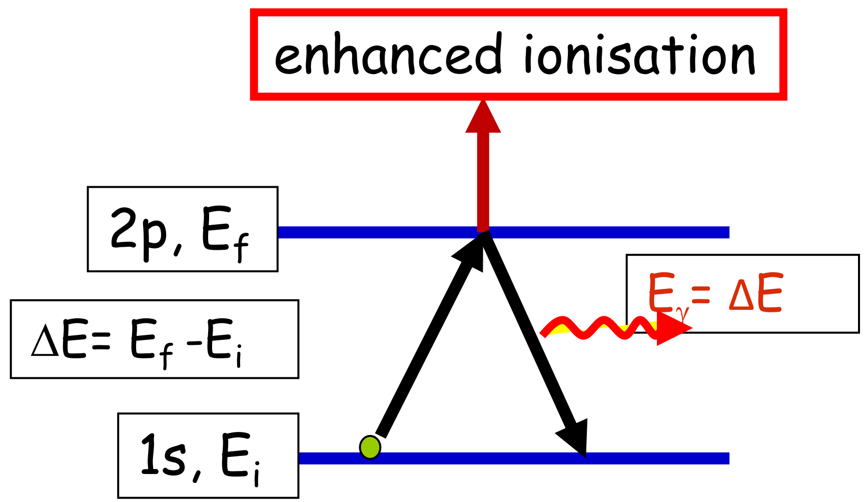
$$\hbar\omega = h\frac{v}{d}$$

$$\Delta E = \frac{\gamma h n v}{a}\left(\frac{k\cos\theta}{A} + \frac{l\sin\theta}{B}\right)$$

n order, γ Lorenz factor, a, k, l, A, B lattice constant
these are known, **θ measured** → ΔE

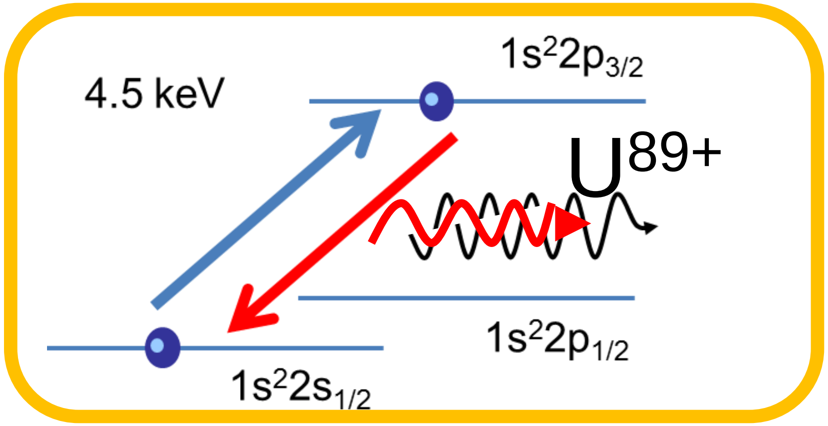
For relativistic ions, v ~ 10^{8} m/s, γ≈10, and atomic spacing 10^{-10} m, the oscillation frequency is ~ $10^{19}$$s^{-1}$ (100keV energy range)

Measurement with H-like Ion

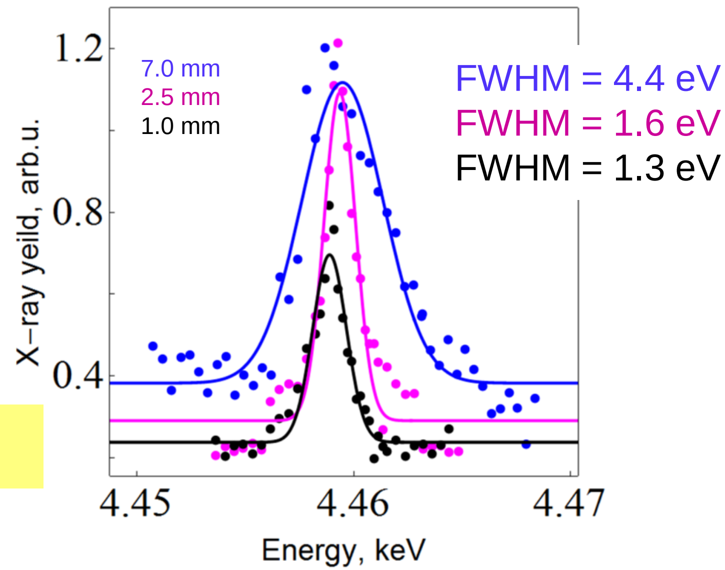


T. Azuma, et al.

Resonant Coherent Excitation at high energies (test with Li-like U @SIS18/ESR)



300MeV/u U^{89+} in Si crystal



Only moderate beam intensities are required !

major factors determining the resolution:

Momentum spread of ion beam $\Delta p/p$: $\sim 10^{-5} - 10^{-4} \rightarrow$ fraction of eV

Energy loss of ions in target: 10 MeV/(mg/cm²) $\rightarrow 1.4\cdot 10^{-4}\cdot$ Thickness (μm)

Number of atoms rows inducing the excitation: $1.6\text{x}10^{-5}$

Life time of the excited state: $1\text{x}10^{-14}$

$$\rightarrow \Delta E(v,\theta)/E(v,\theta) \sim \Delta v/v = \Delta p/p$$

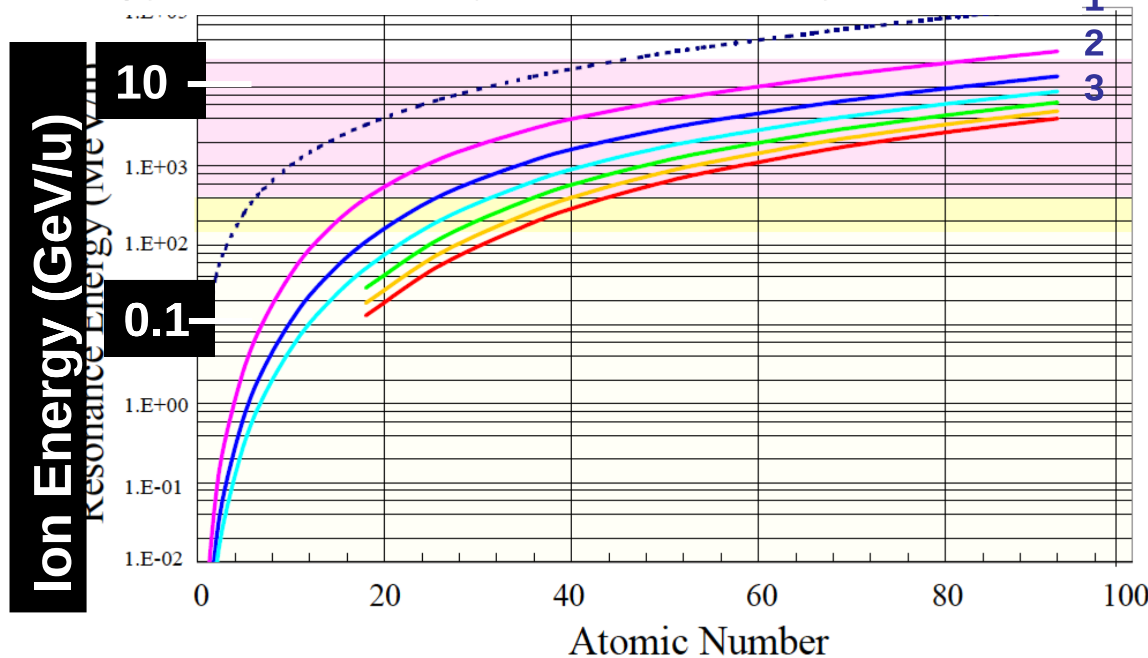
T.Azuma, A. Bråunig-Demain, et al.

Y. Nakano et al., PRA 86, 060501 (R) (2013)

Precision Spectroscopy of 1s of Heavy Ion at High Energies GeV/u

at SIS 100 relativistic ions $\gamma \rightarrow 10$, Z and q up to 92
RCE proposal Azuma et al. GSI, RIKEN

Ion Energy to excite 1s-2p in H-like Ion by RCE in Si



Issues to be solved: Beam cooling at 10 GeV/u (laser cooling?)

Energy loss at 10 GeV/u (probably reduced?)

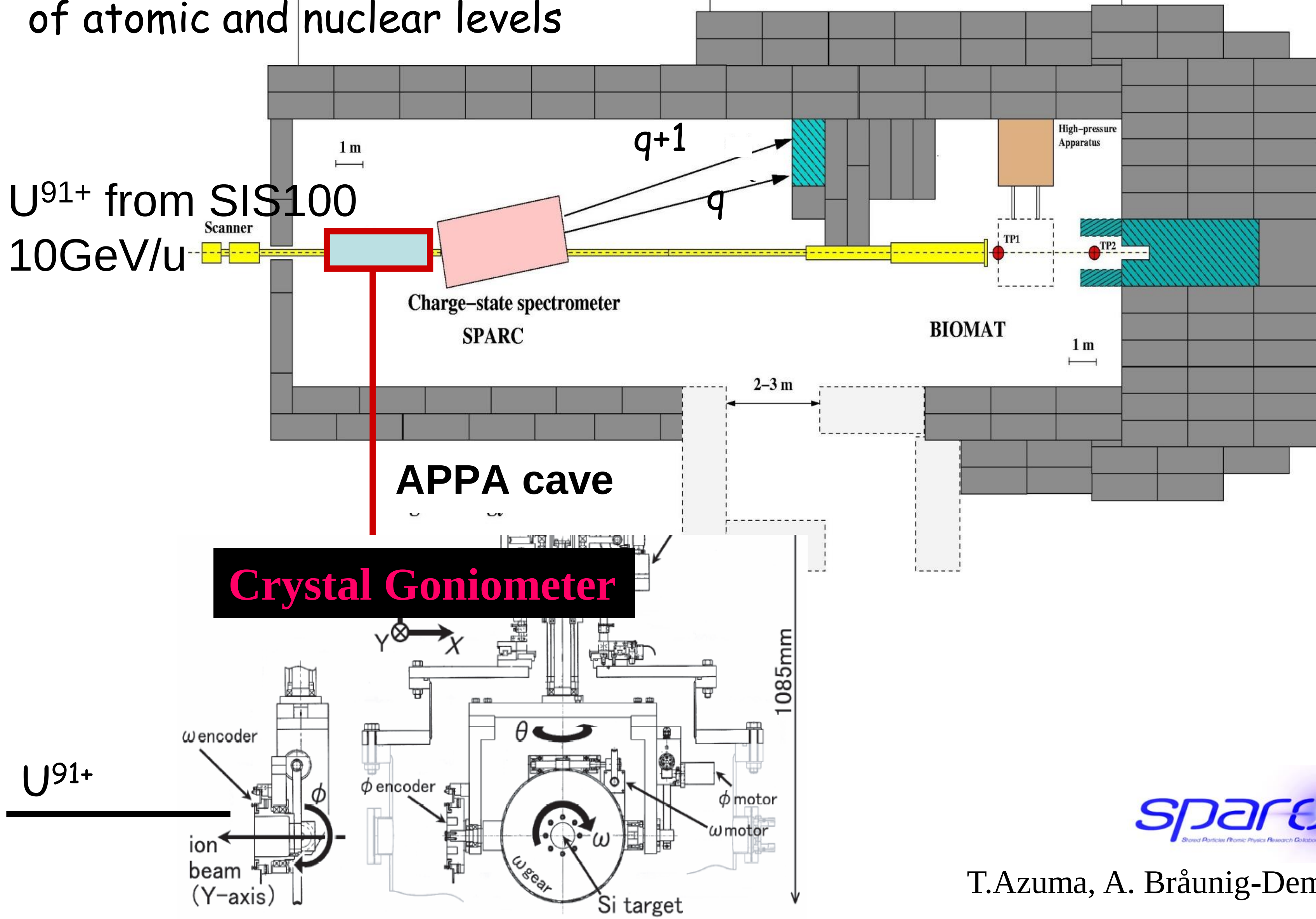
maybe $\Delta E/E \approx 10^{-5} \rightarrow$ 1 eV of 450 eV $\rightarrow$

10^{-2} of Lamb-shift in U^{91+}

For U^{91+} we need the APPA cave and SIS100

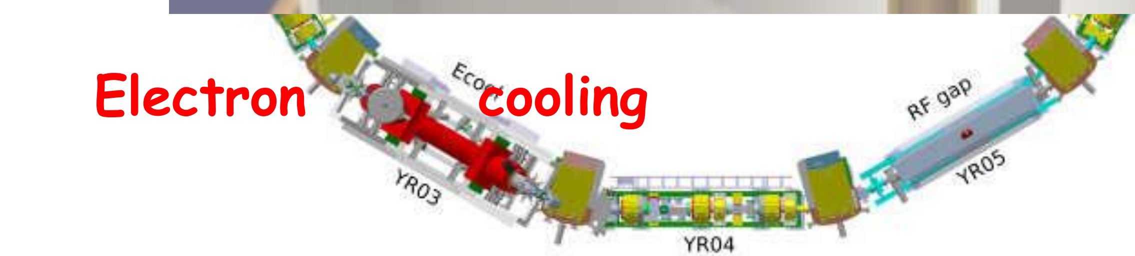
Precision spectroscopy by means of Resonant Coherent Excitation of atomic and nuclear levels

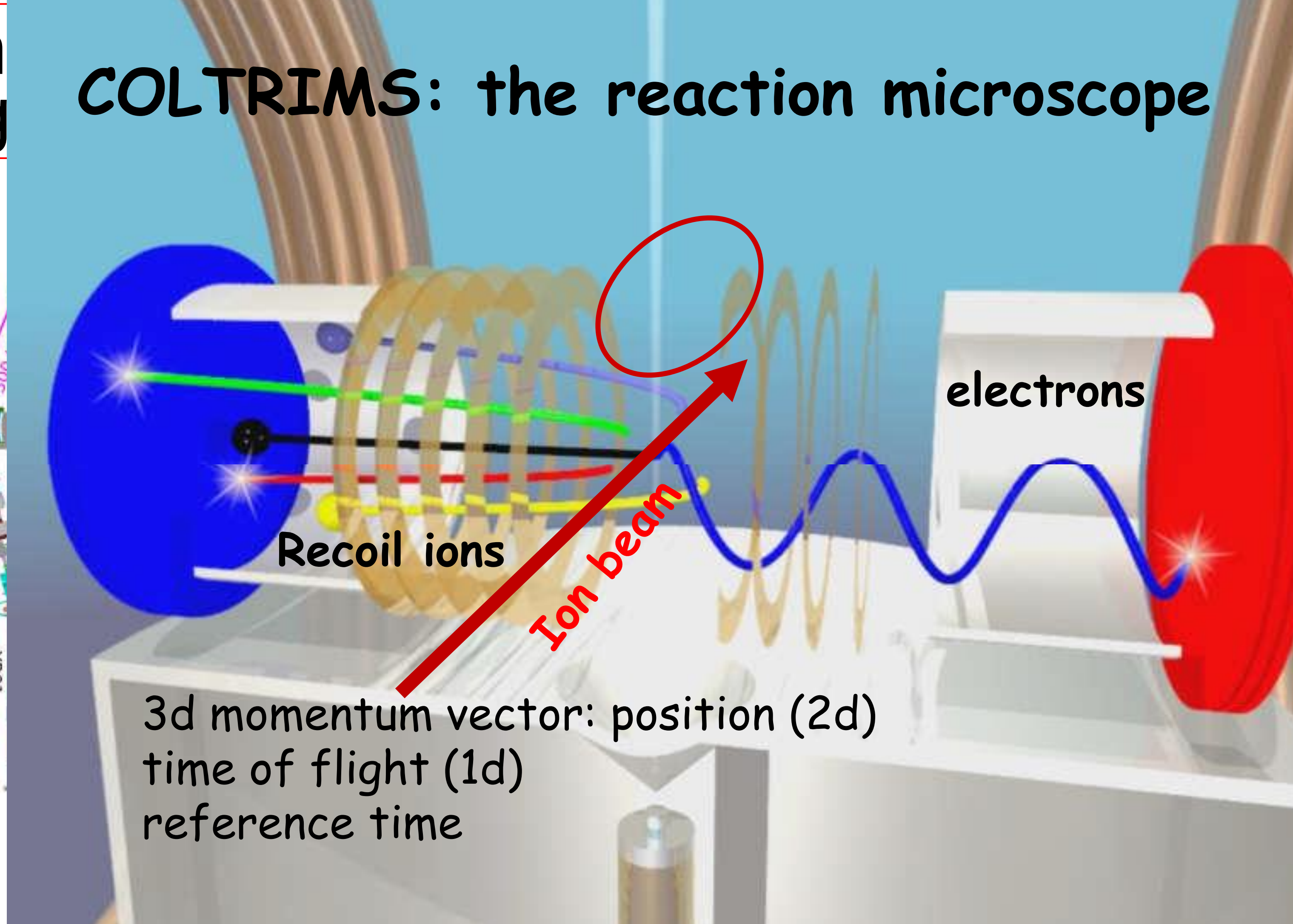
U^{91+} from SIS100
10GeV/u



T.Azuma, A. Bräunig-Demain, et al.

Collision
using





Electron cooling

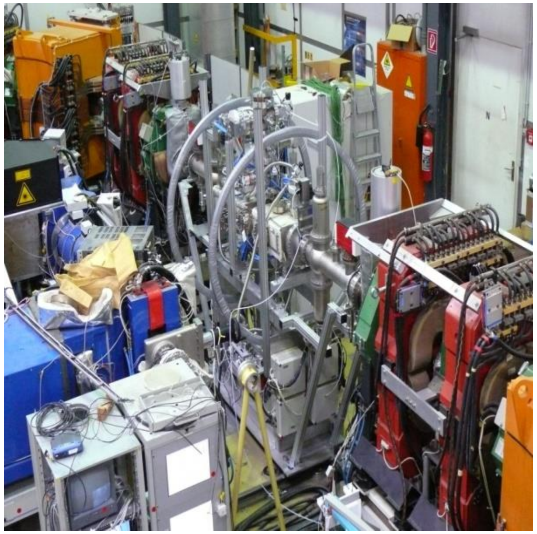
CRYRING@ESR

Collision Spectroscopy on Highly-Charged Ions using Ion Storage Ring and COLTRIMS

CRYRING@
Stockholm RIMS

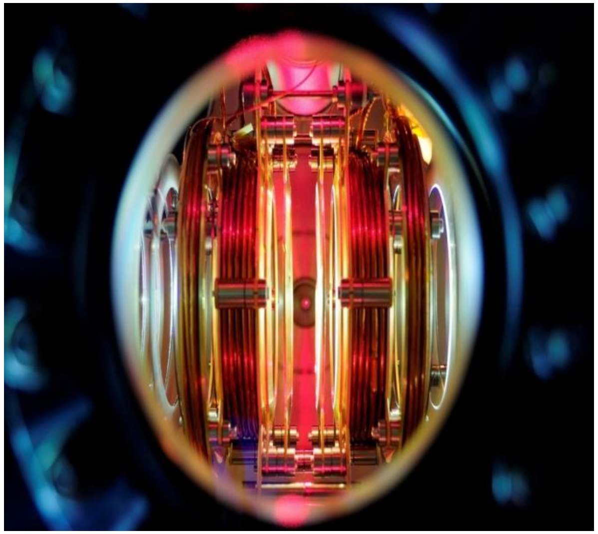
commissioned 1997

TSR, Heidelberg
ion-electron coincidences



commissioned 2009

TSR, Heidelberg
Ion-electron concidence
optically trapped target



commissioned 2011

H. Schmidt et al., Phys. Rev. Lett. 89, (02), 163201

K. Schneider et al., Phys. Rev. Lett. 110 (11), 113201

R. Hubele, et al, Phys. Rev. Lett. 110 (13), 133201

Coming soon: Next generation COLTRIMS at CRYRING@ESR
(M. Schöffler, D. Fischer et al., Uni Frankfurt/Rolla)

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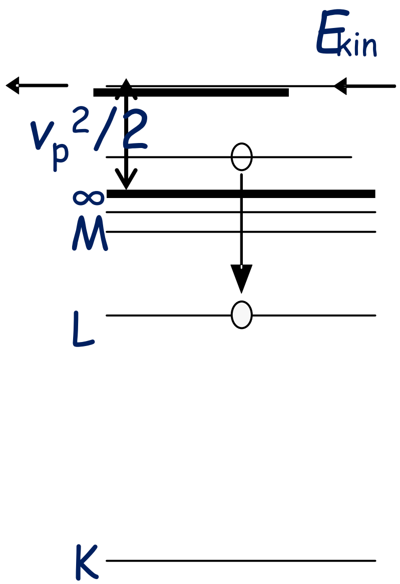
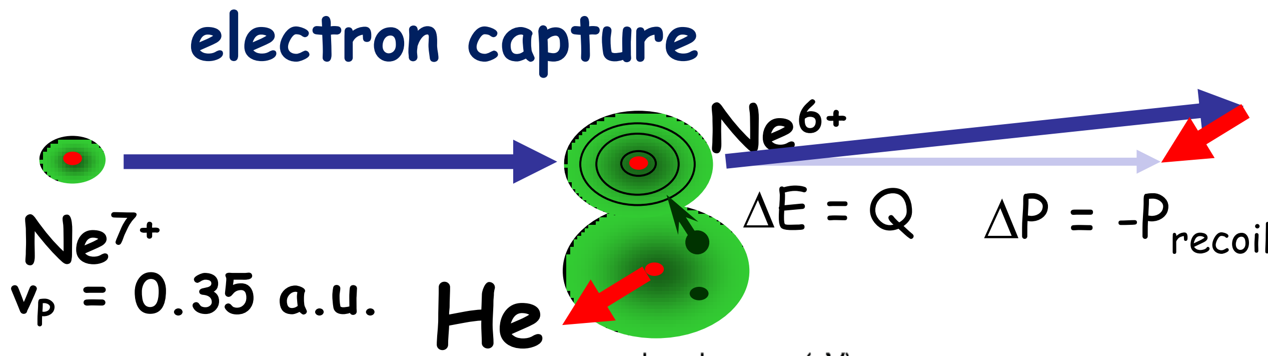
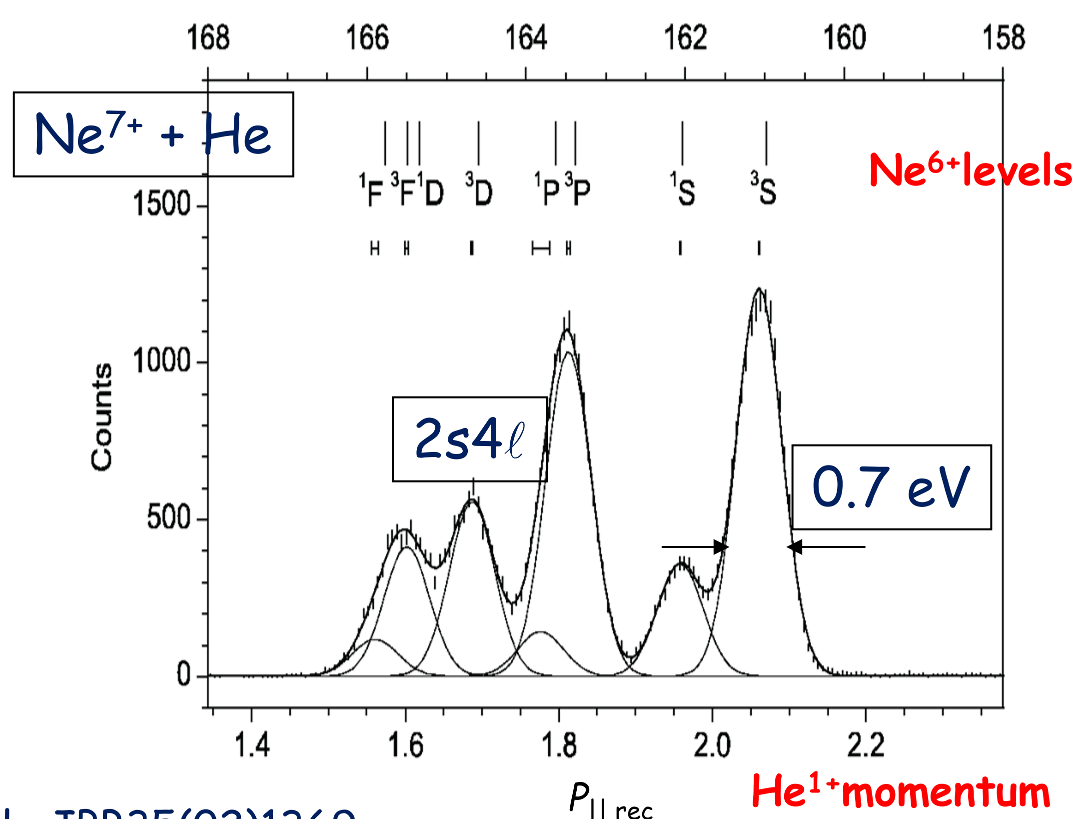
FAIR

Collision Spectroscopy on Highly-Charged Ions







Advantages:

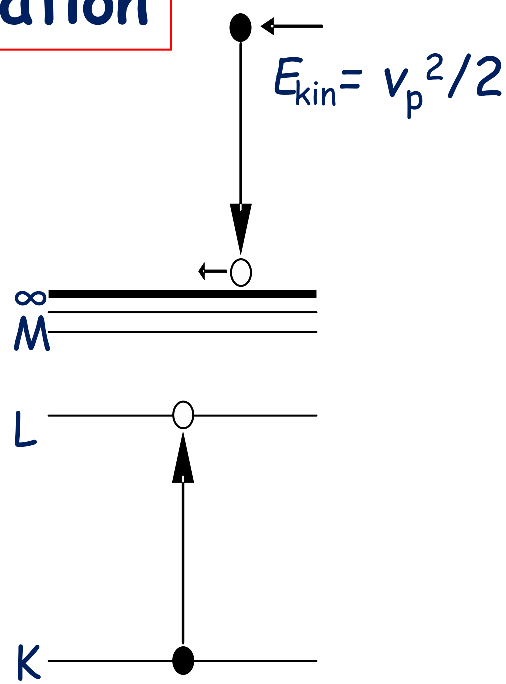
- 4π solid angle
- no selection rules, direct energy determination
- Energy precision ~ 1 meV

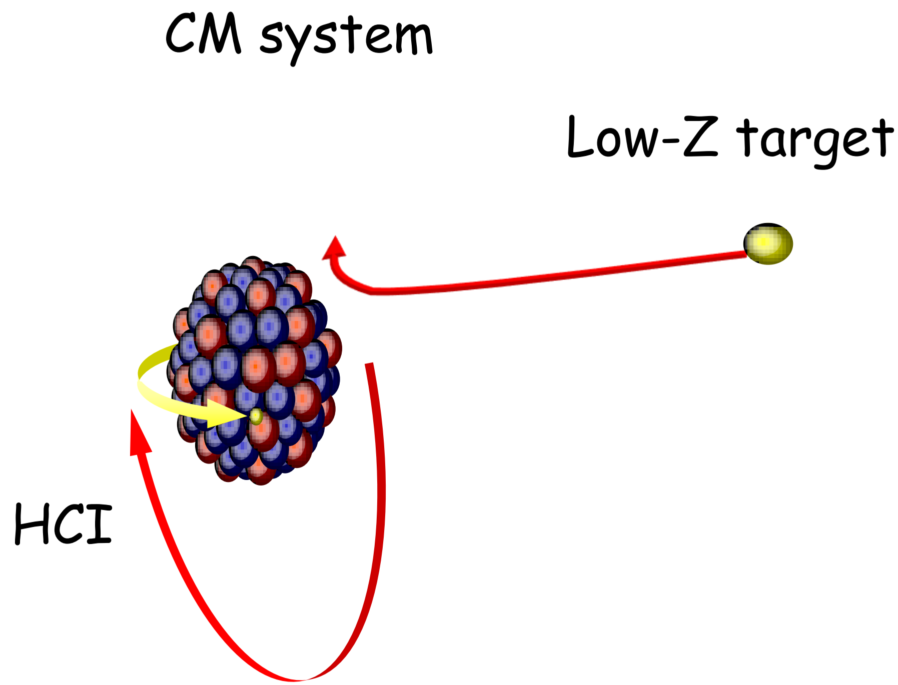
$$\Delta E_{kin} = \Delta E_{Bind}$$

D. Fischer et al., JPB35(02)1369

Collision Spectroscopy on Highly-Charged Ions

excitation



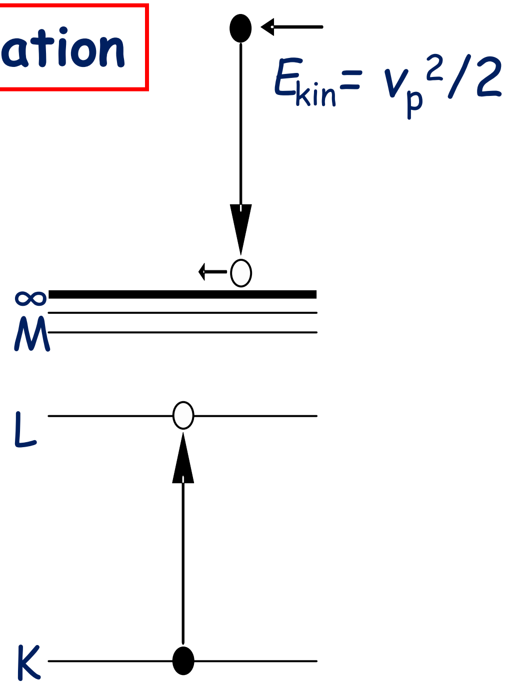


$$\Delta E_{kin} = \Delta E_{exc}$$

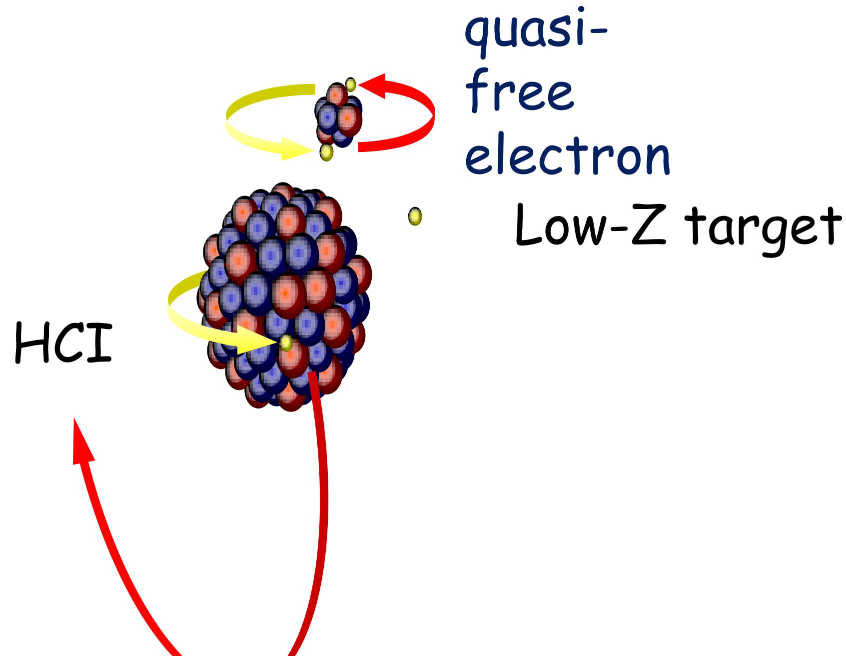
courtesey D. Fischer

Collision Spectroscopy on Highly-Charged Ions

excitation



$\Delta E_{kin} = \Delta E_{exc}$



Example: Xe^{53+}

$1s_{1/2}$-$2p_{1/2}$ exc. energy ~ 31 keV
$2p_{1/2}$ - $2p_{3/2}$ splitting ~ 430 eV
cross section σ~10^{-23} cm^2

recoil momentum resolution <0.01 a.u.
energy resolution <10 eV

New technique with:

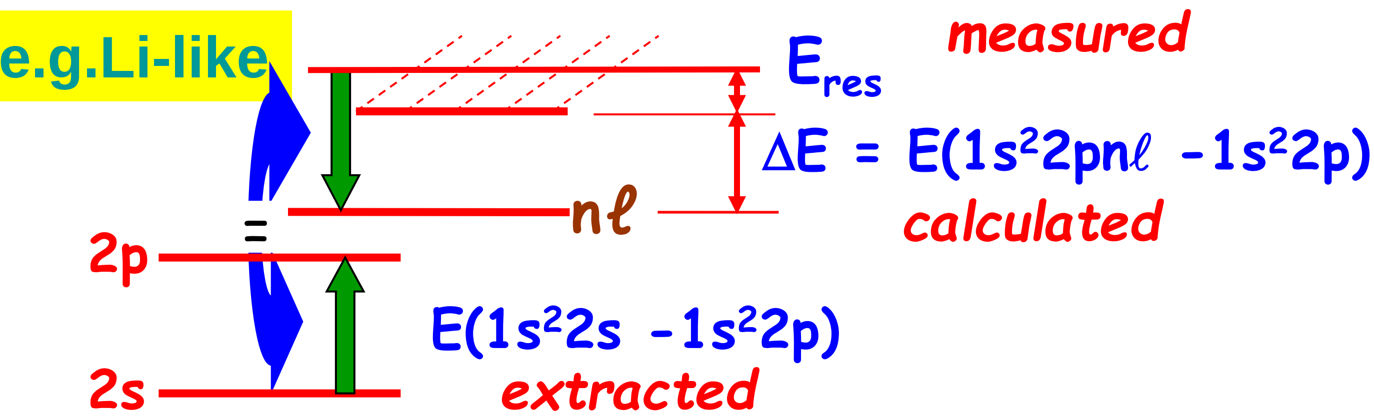
- 4π solid angle acceptance
- excellent energy resolution
- all ionic states: $Z_P \leq 92$

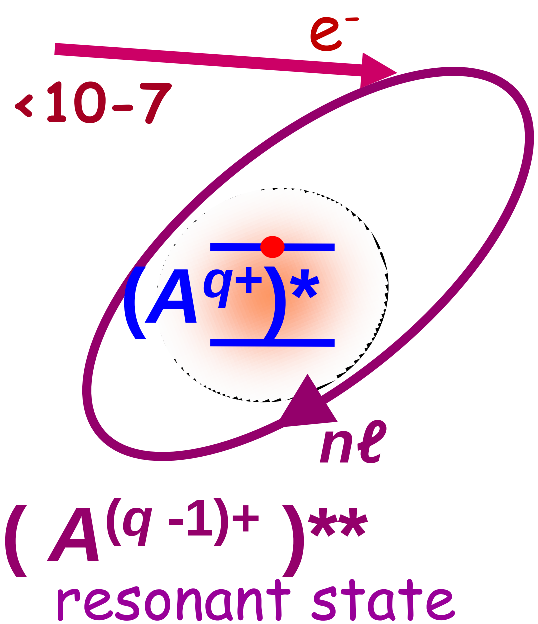
D. Fischer et al., SPARC collaboration

Collision Spectroscopy by Electron-Ion Recombination

Test QED in many e^- enviroment, e^- correlation, nuclear properties (Hyperfine Interaction, Nuclear Size,....)

Method: $E_{res} = \Delta E - E_{nl} \approx 0 \Rightarrow \Delta E$ with $E_{res} / \Delta E < 10-7$



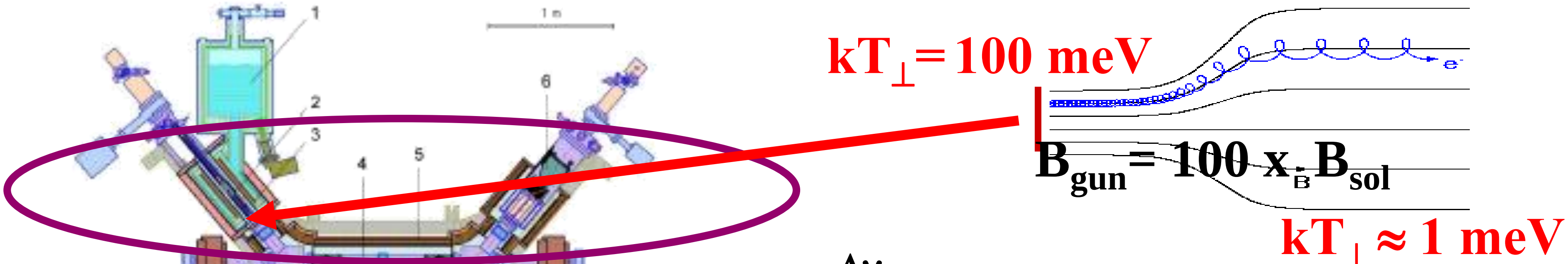


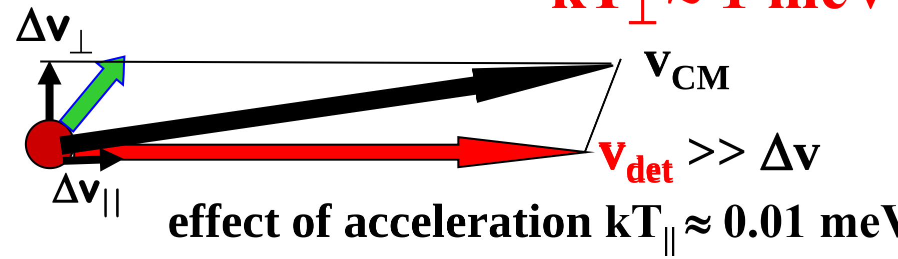
Calculate E_{nl} with e.g. Relativistic Many-Body Perturbation Theory (RMBPT) to any accuracy

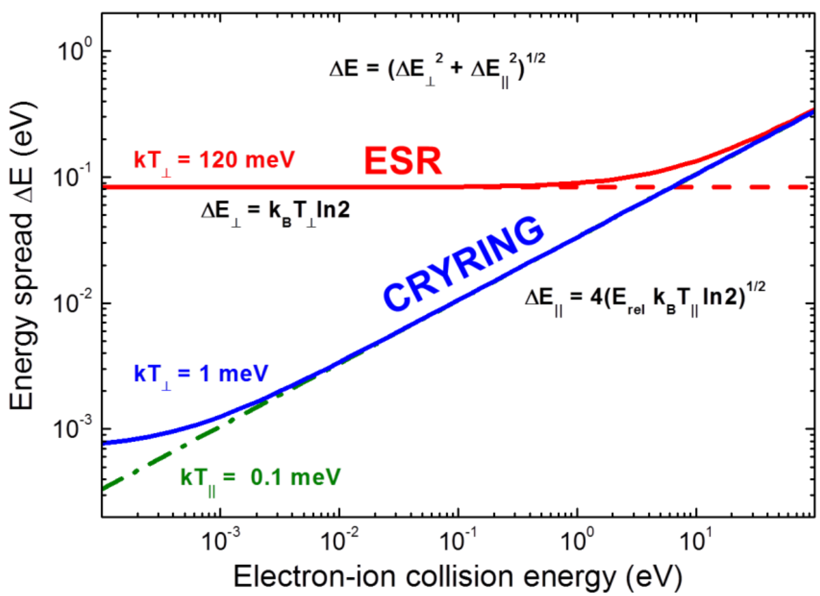
Examples medium-Z (Kr^{33+}) and high-Z (Pb^{53+}, Pb^{78+}) ions

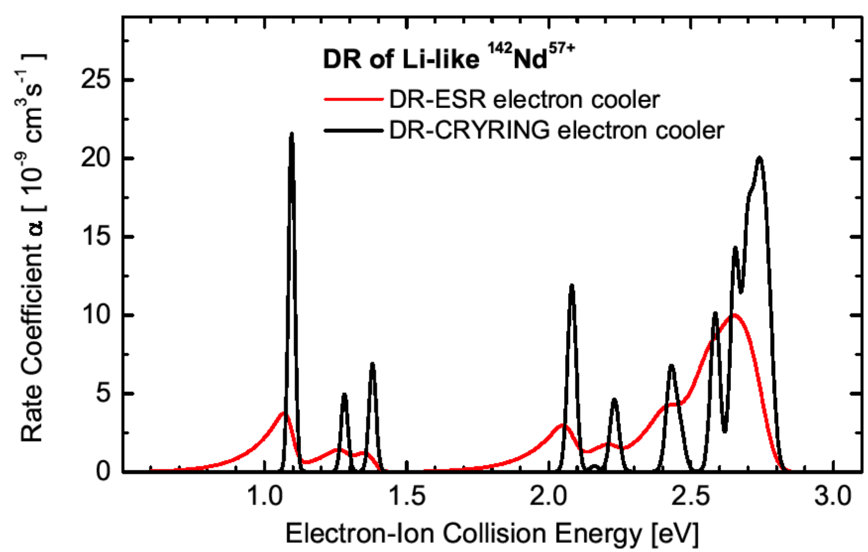
Important Ingrediences: Storage Ring for Ions and Electron Cooler/Target

CRYRING + Electron Cooler



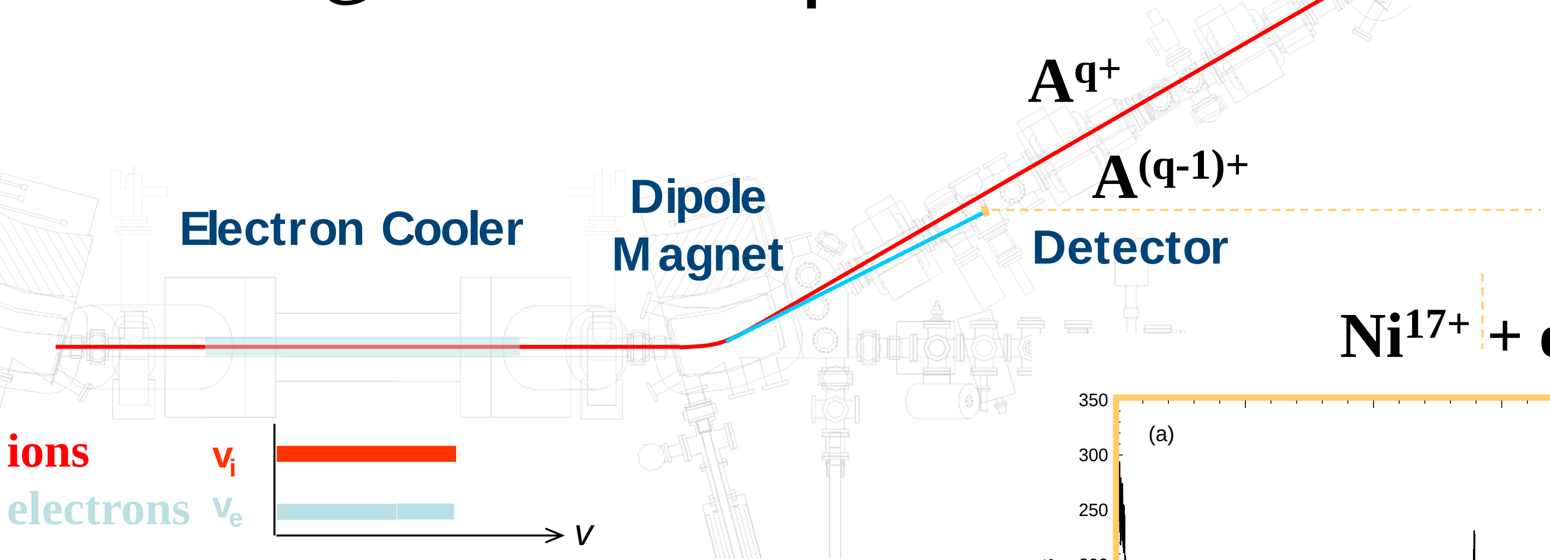




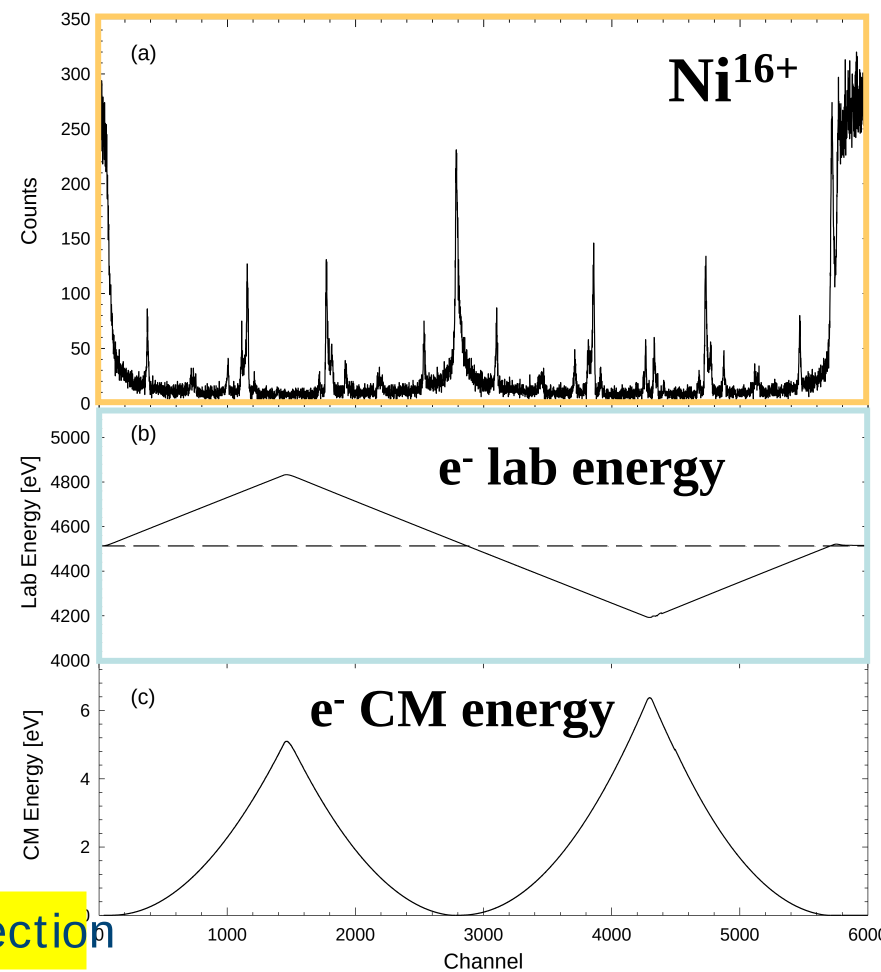


Great physics opportunities in CRYRING using beams from the ESR

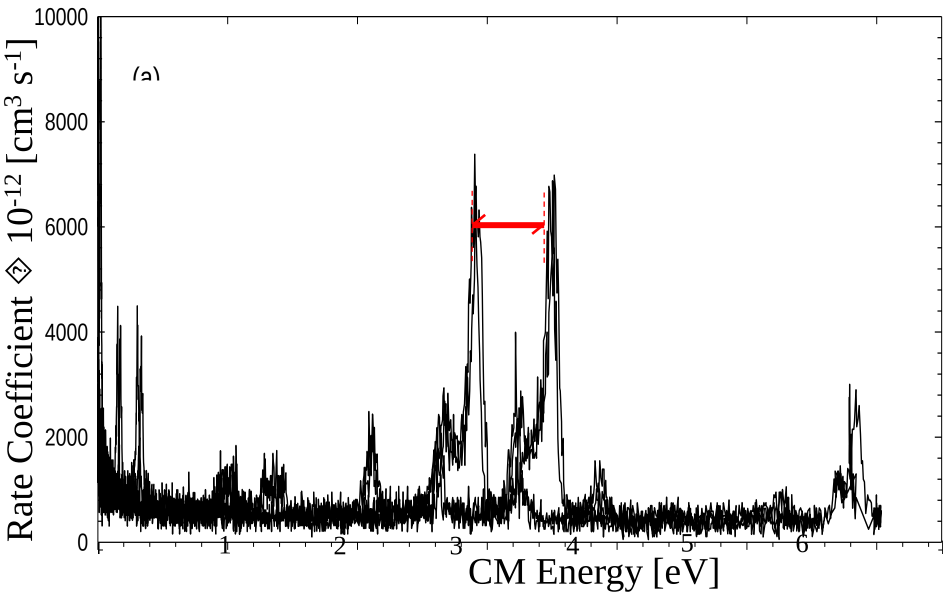
CRYRING@Stockholm Experimental Method



$Ni^{17+} + e^- \rightarrow$

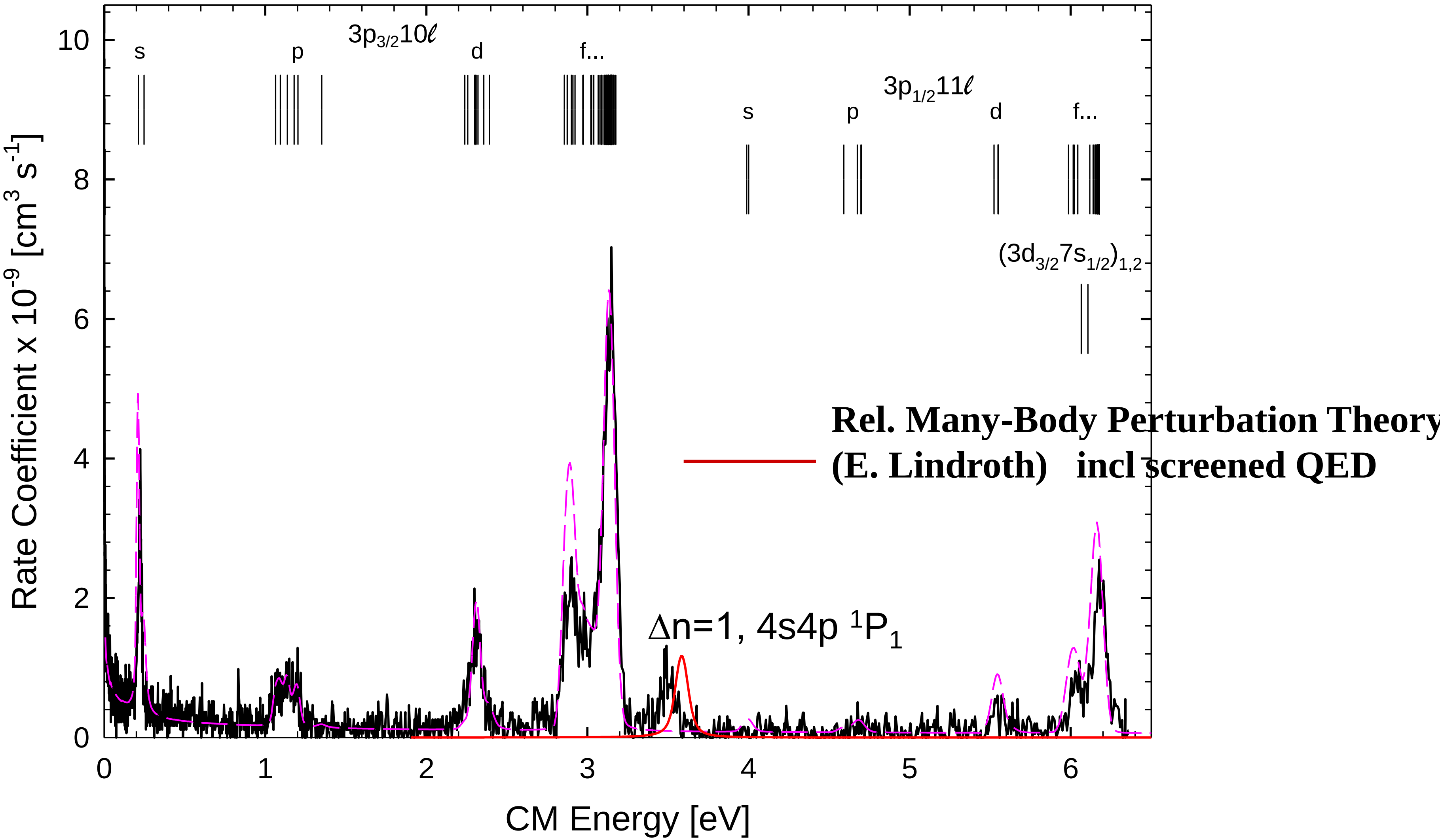


Drag Force Correction



Electron gun voltage + Space Charge Correction

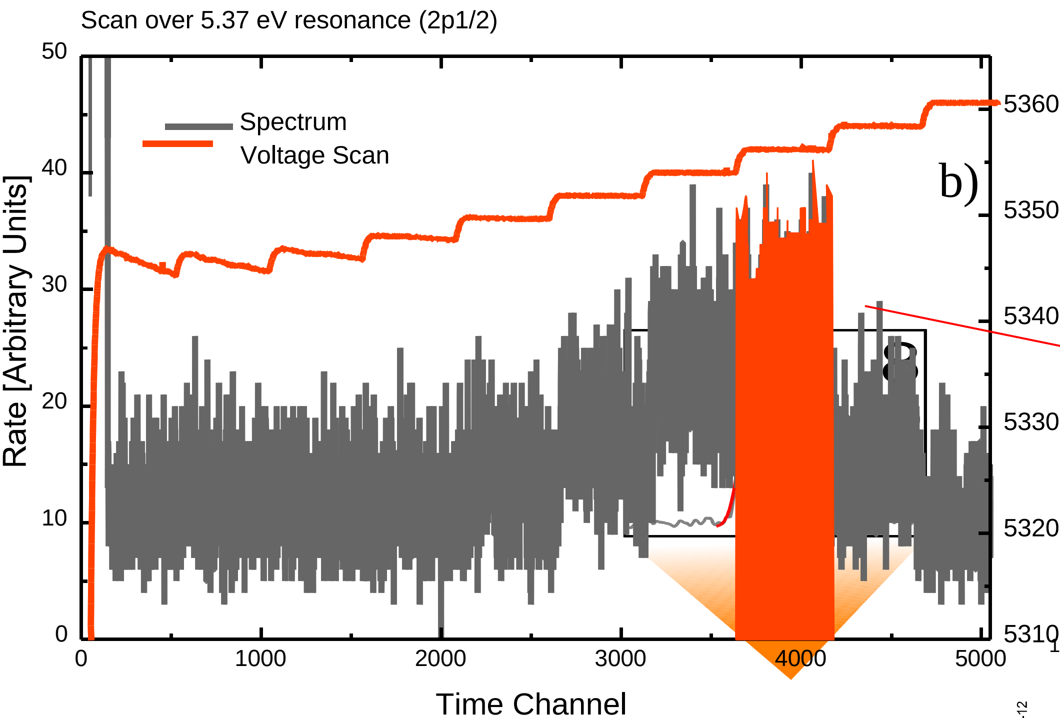
Na-like $Ni^{17+}(3s) + e^- \rightarrow (Ni^{16+})^{**} \rightarrow Ni^{16+} + h\nu$

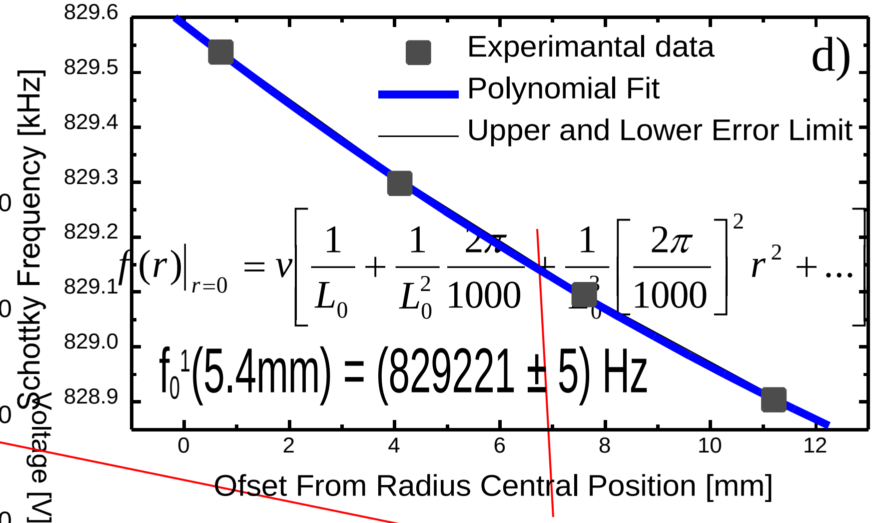


Estimated accuracy of the center of mass electron energy scale $\delta E/E \approx 10^{-2}$
Method to improve the center of mass electron energy calibration by Schottky frequency and storage ring orbital length measurements:

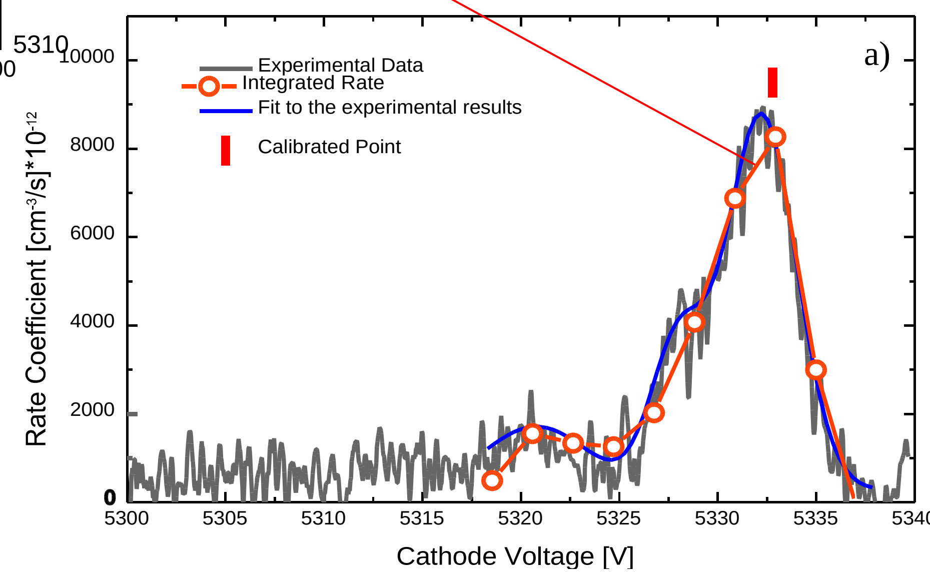
Kr^{33+} $1s^2 2s_{1/2} + e^- \rightarrow 1s^2 2p_{1/2} 15l_j$

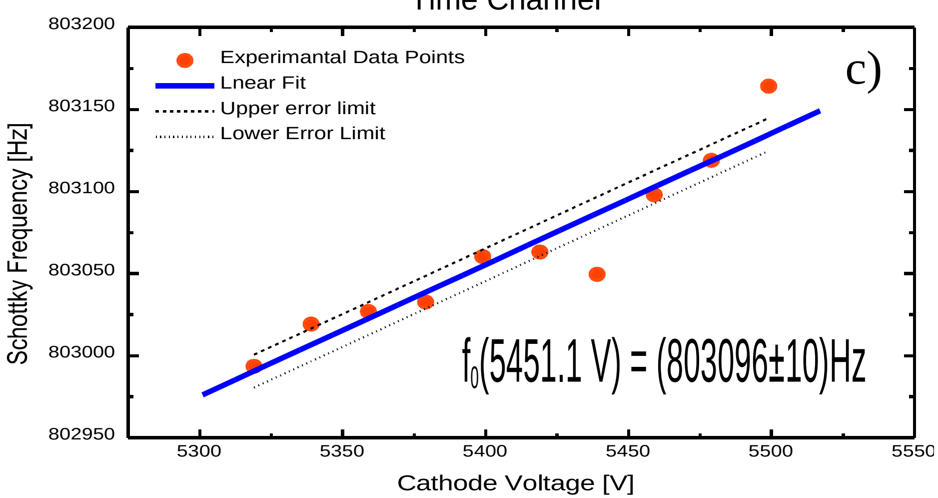
calibration by Schottky frequency





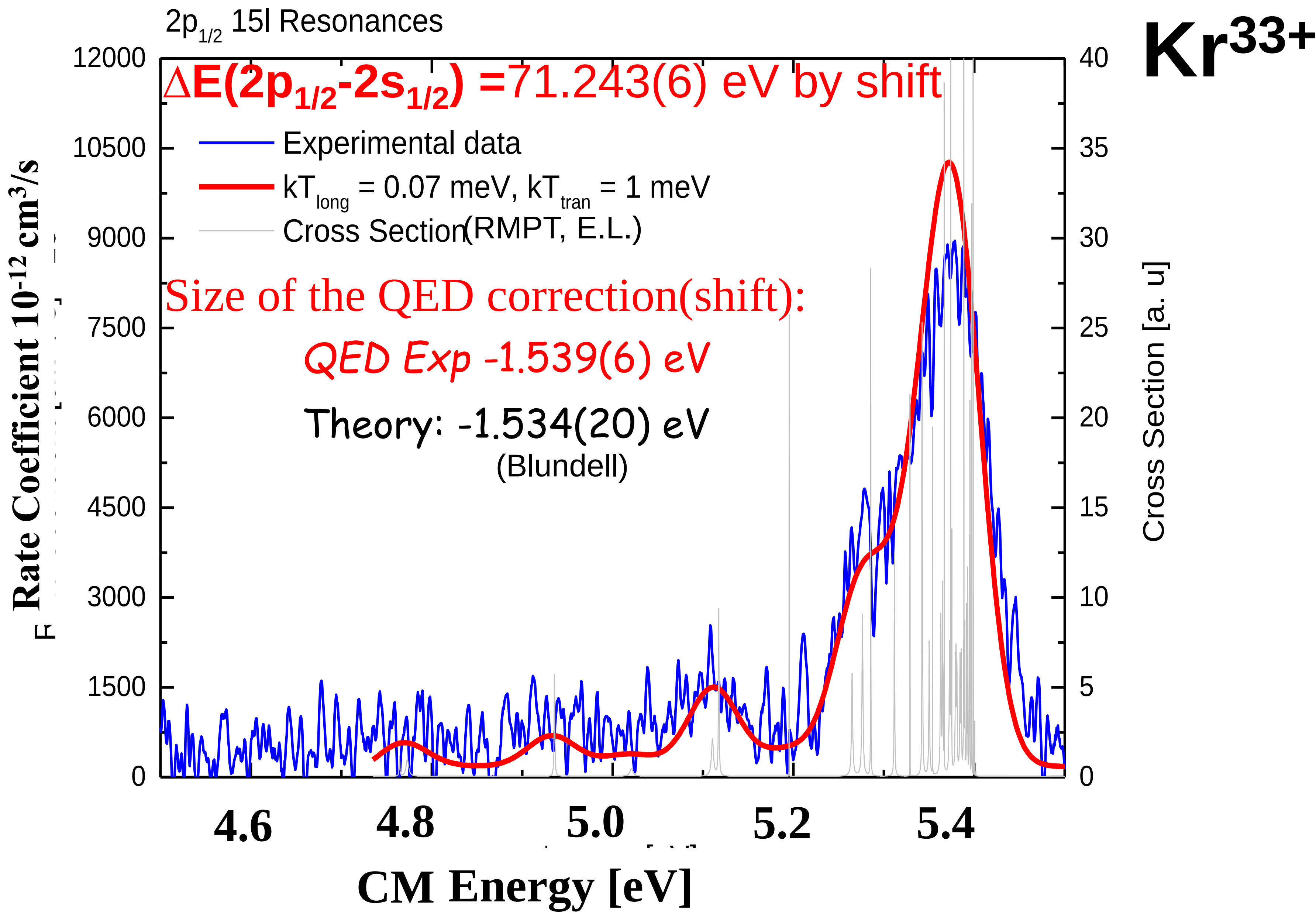
$$\Delta v = (f_0^1 - f_0)L$$





Madzunkov et al. P.R.A65 (02)032505

Collision Spectroscopy by Electron-Ion Recombination



Madzunkov et al. P.R.A65 (02)032505

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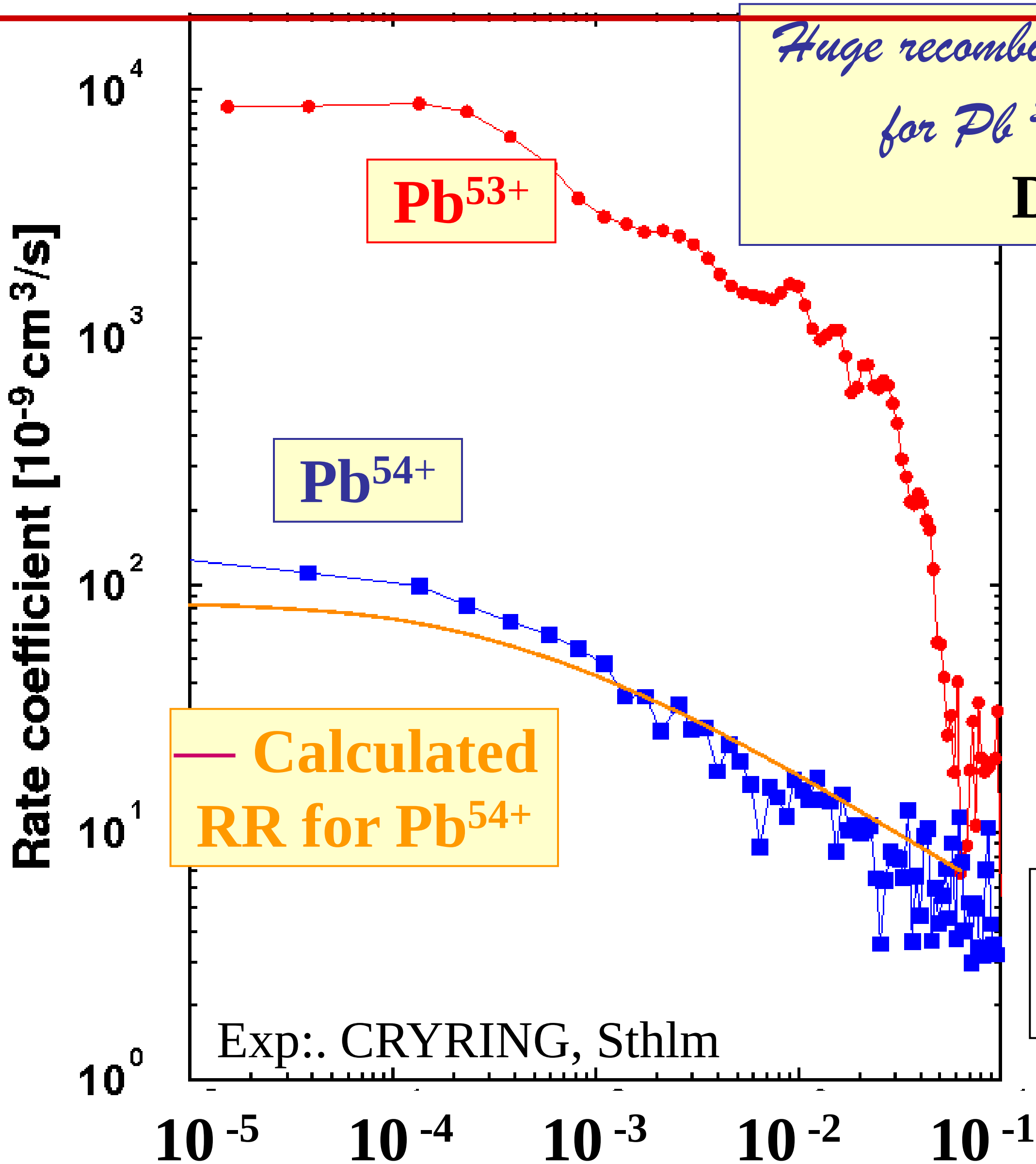


DR – resonances at threshold

$Pb^{53+}(..3d^{10})4s + e^- \rightarrow$
$Pb^{52+}(..3d^{10})4p\ 18\ell_j \rightarrow$
$Pb^{52+}(..3d^{10})\ 4s^2 + \hbar\omega$

Detected Pb^{52+}

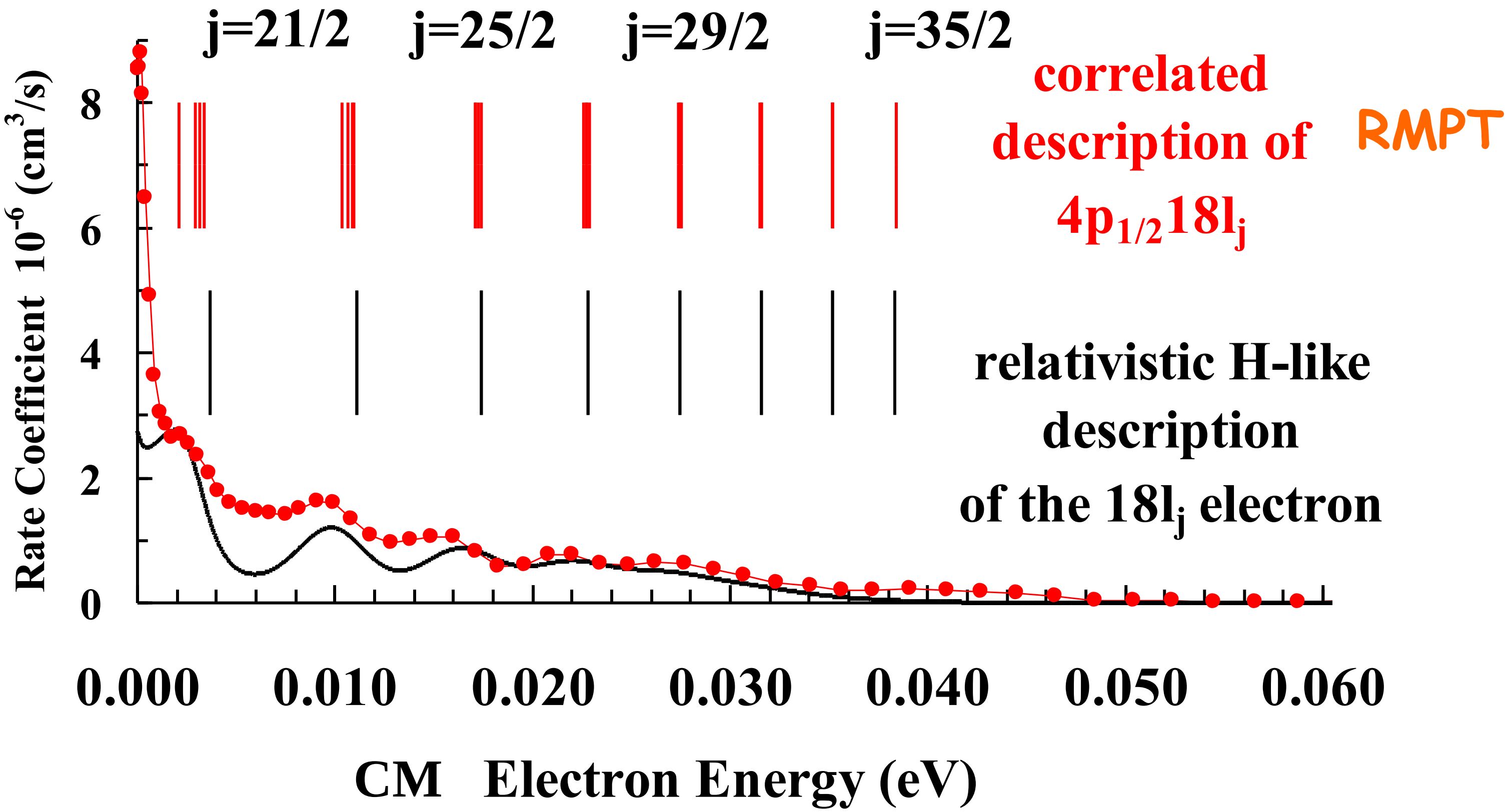
RR -non resonant

$Pb^{54+}(..3d^{10}) + e^- \rightarrow$
$Pb^{53+}(..3d^{10})4s + \hbar\omega$

Detected Pb^{53+}

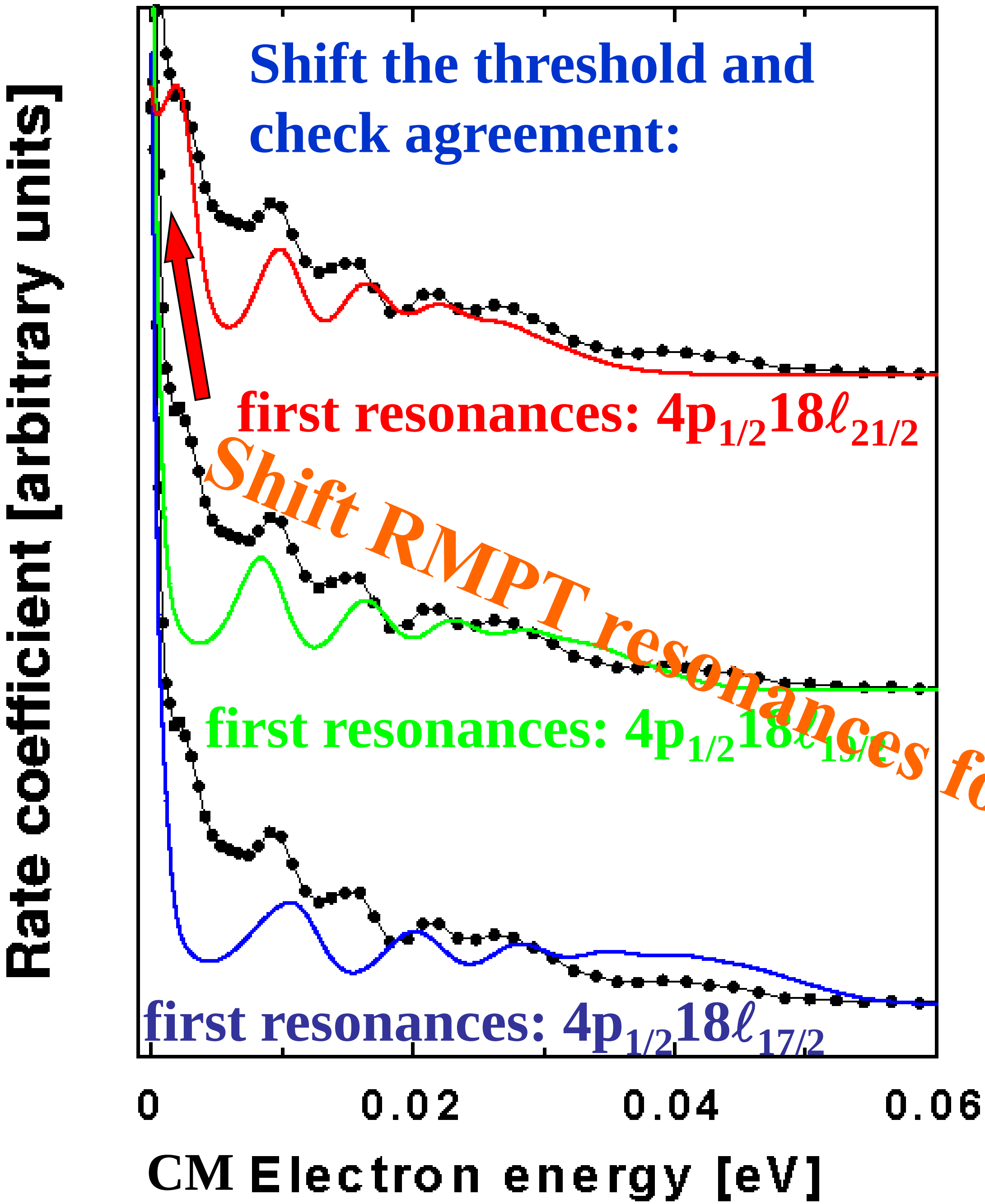
Lindroth et al. PRL 86, (01)5027

$\varepsilon = Pb^{52+}\,(4p_{1/2}\ 18\ell_j) - Pb^{53+}\,(4s_{1/2}) \approx Pb^{53+}\,(4p_{1/2} - 4s_{1/2}) + \Delta E(18\ell_j)$



Had to shift RMPT resonances for QED in Pb^{53+}

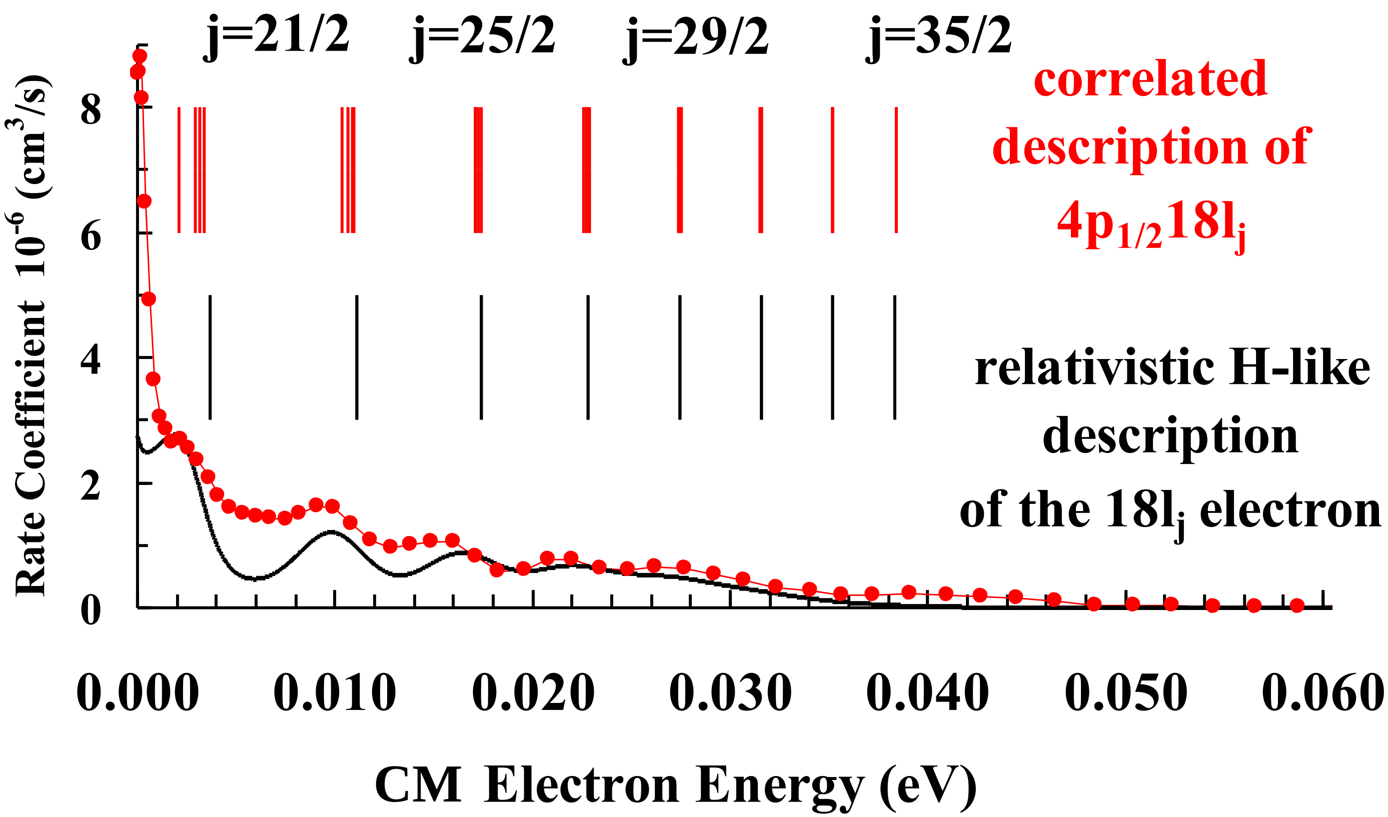
Lindroth et al. PRL 86, (01)5027



Best fit

Shift RMPT resonances for QED *in Pb* $^{53+}$

$\varepsilon = Pb^{52+} (4p_{1/2}\ 18\ell_j) - Pb^{53+} (4s_{1/2}) \approx Pb^{53+} (4p_{1/2} - 4s_{1/2}) + \Delta E(18\ell_j)$



From QED correction adjusted so theoretical spectrum best fit experiment

$\Rightarrow Pb^{53+}\ \Delta E\ (4s_{1/2}-4p_{1/2}) = 118.010(1)$ eV rel. uncertainty $8\cdot10^{-6}$

QED part is: -2.044(1) eV (from exp.)

•Theoretical values: -2.008(40) eV (P. Indelicato) -2.05 (1) eV (Blundell)

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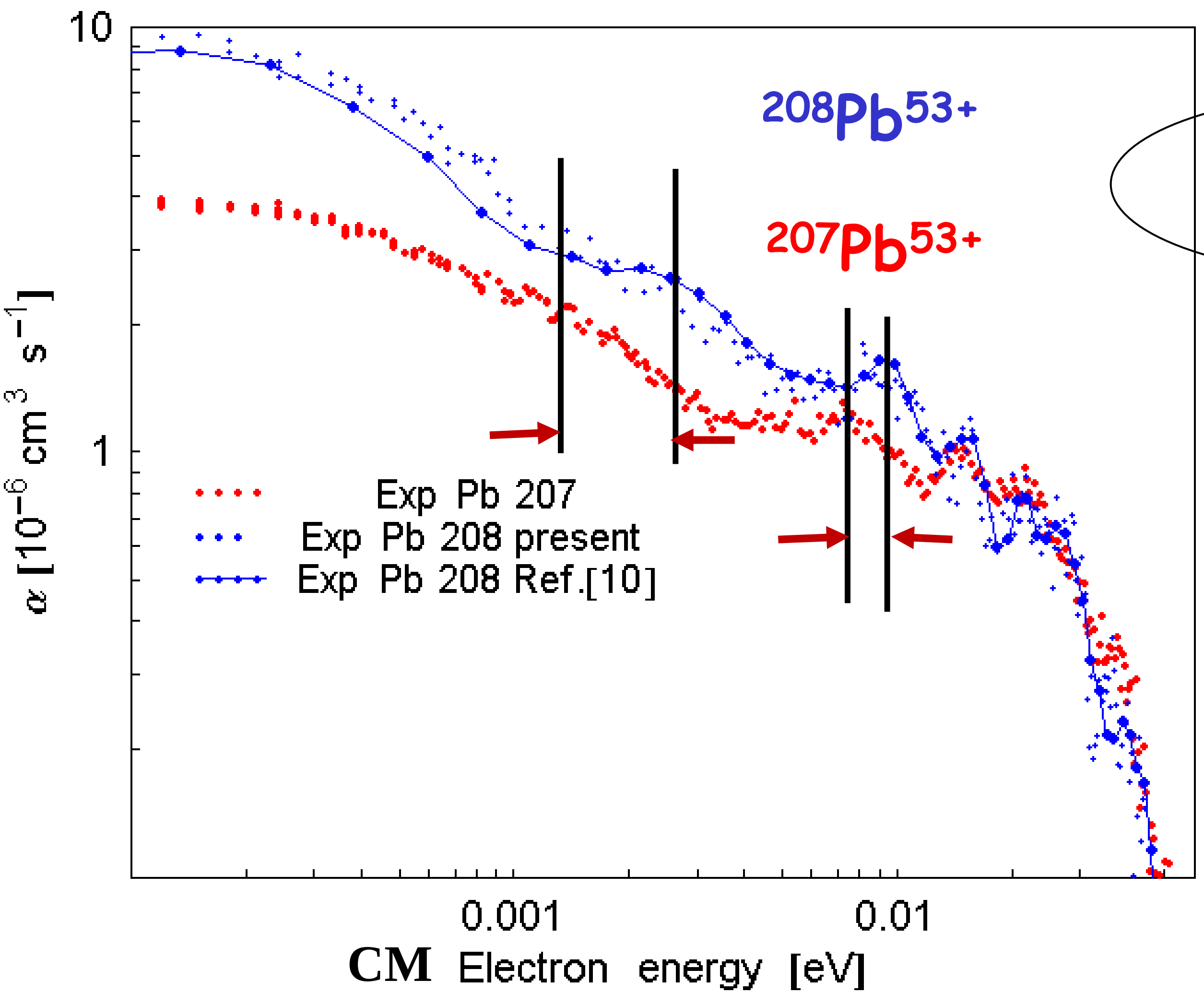
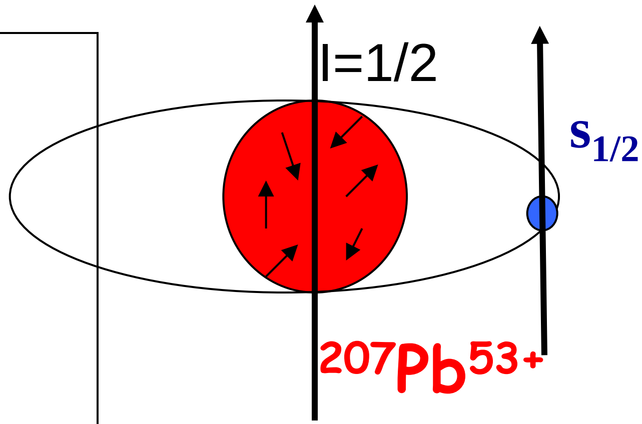
Hfs seen by DR!

$Pb^{53+}(4s)+e^{-} \rightarrow Pb^{52+}(4p_{1/2}18l_j) \rightarrow \gamma$



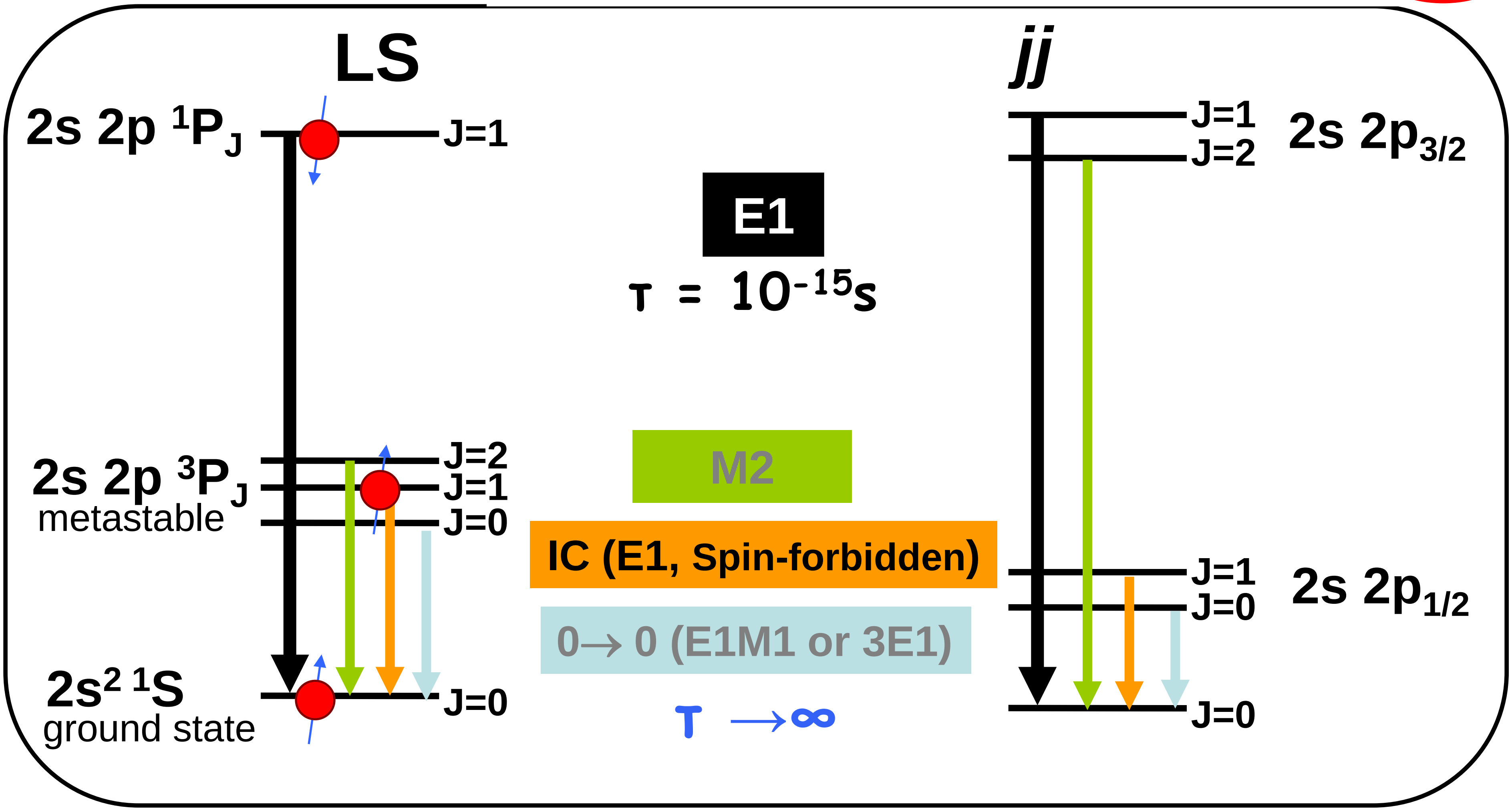


exp. $\Rightarrow$a= 4.6(3)meV sensitive to nuclear polarization (0.4) and volume shift (1.6).

method attractive for radioactive beams, needs low electron-beam energy spread!

CRYRING R.S. et al.,PRL. ***95,(05) 183003***

Be-like Ions: Ne^{6+}, Si^{10+}, Ar^{14+}, Ti^{18+}, Kr^{32+}, Xe^{50+}, Pb^{78+}

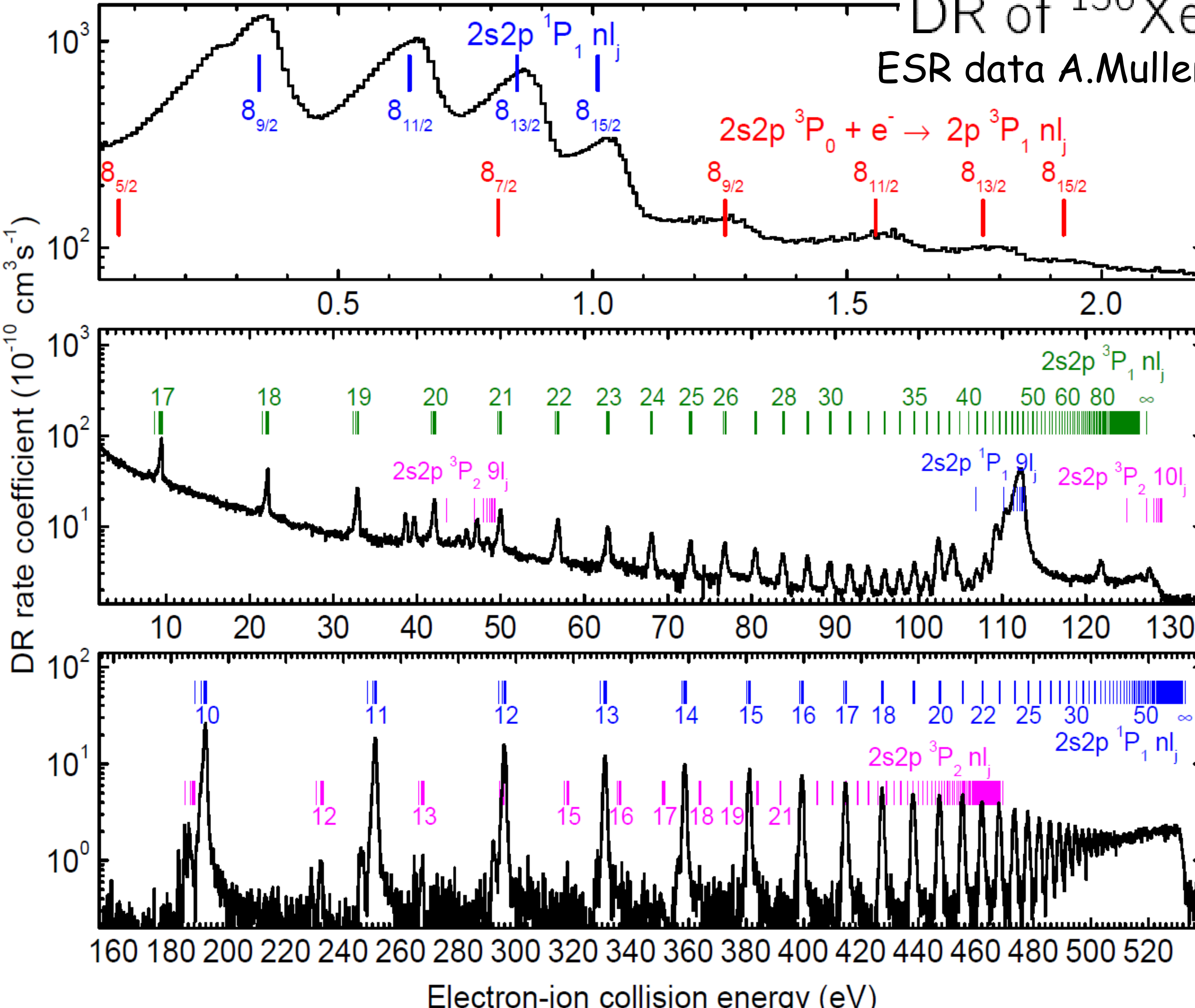


Possible to study:

- lifetimes, energies to test atomic structure codes
- collisional & B- field quenching (astro & codes)
- breading of metastable ions under controlled conditions

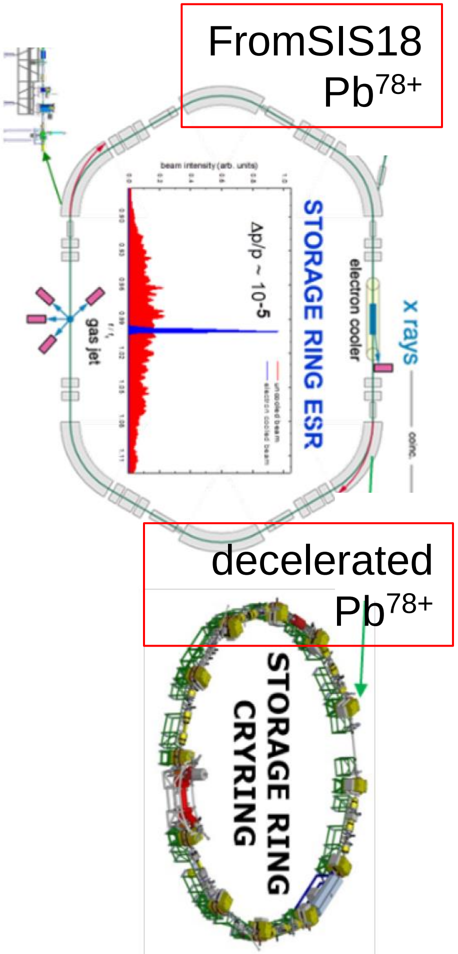
DR of $^{136}Xe^{50+}$

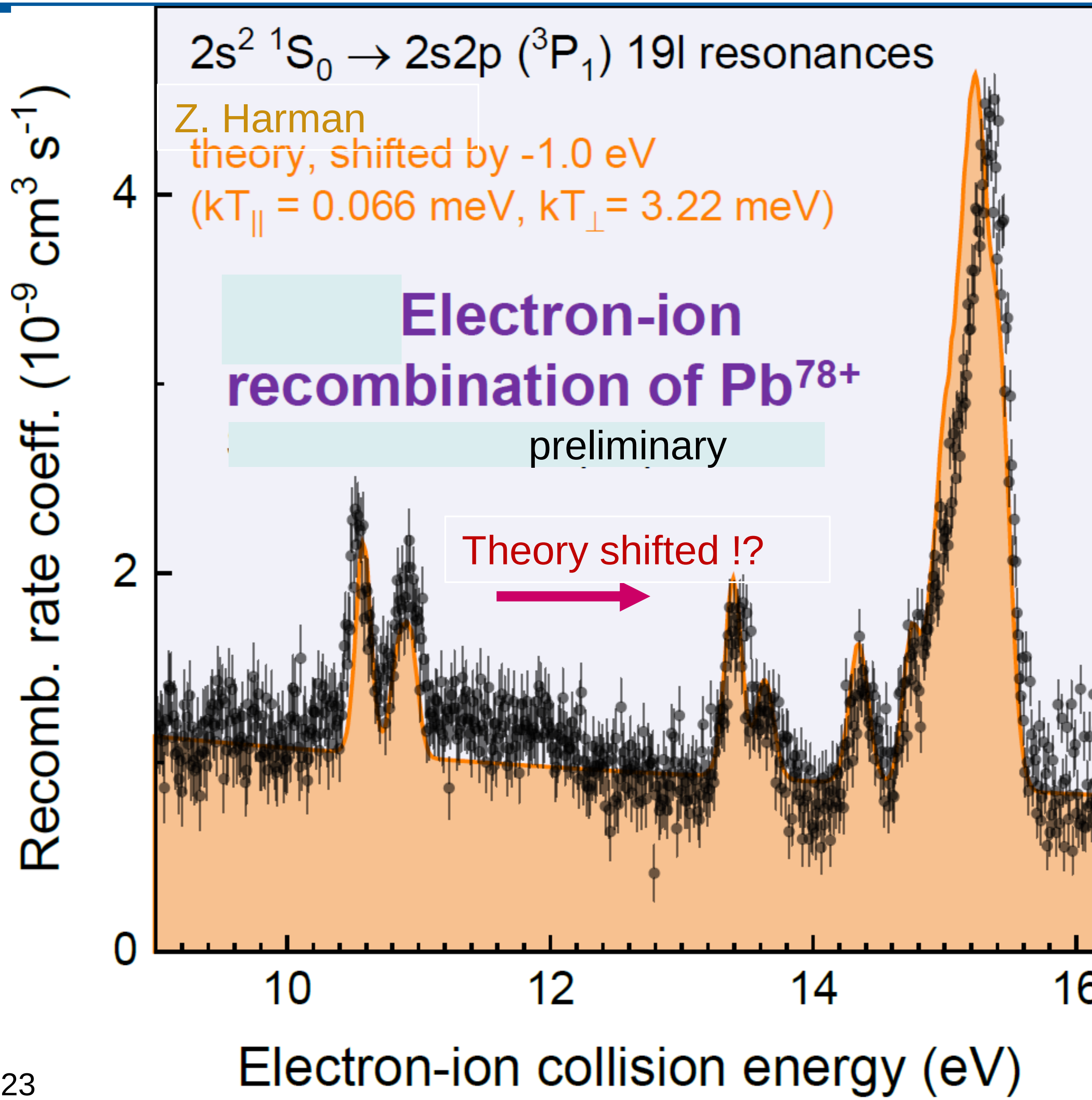
ESR data A.Muller et al.



High-resolution electron-ion collision spectroscopy of beryllium-like heavy ions in CRYRING@ESR

S. Schippers et. al.
to be publ.





Conclusions

•Spectroscopy in the dark can reach high precision and accuracy- compares well with photon spectroscopy

•Has several advantages and is complementary to photon spectroscopy:

•High detection efficiency, needs fewer ions (sometimes only one)

•Observes long lived states with traps (rings)

•Very clean experimental conditions (low background)

• Can be used to detect optically not allowed transitions

Many thanks to all collaborators over the years!