Measuring isotopic shifts in HCI with an EBIT

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TITAN Collaboration meeting and workshop

TRIUMF, Vancouver, June 10-11, 2005

Outline

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- Why study Highly Charged Ions (HCI) ?
- The production and trapping of HCI in an EBIT
- Isotopic shifts on dielectronic resonances / measurement
- Isotopic shifts on inner shell transitions / measurement
- $\delta <r^2> U^{233,238}$ measurement (S.R. Elliot *et al.)*
- Estimates for beam time

Why study nuclei with HCI ?

- Few body problem ↔ simpler for theory

  ↔ predictions with higher accuracy

- Scaling of physical effects with Z^x ($x \sim 1..10$)

  - transition probability A_{ik} :
    - E1 $\sim Z^4$
    - 2E1 $\sim Z^6$
    - M1 $\sim Z^{10}$
  - QED contributions (1s Lamb shift) $\sim Z^4$
  - nuclear size effects (1s Lamb shift) $\sim Z^6$

Why study nuclei with HCI ?

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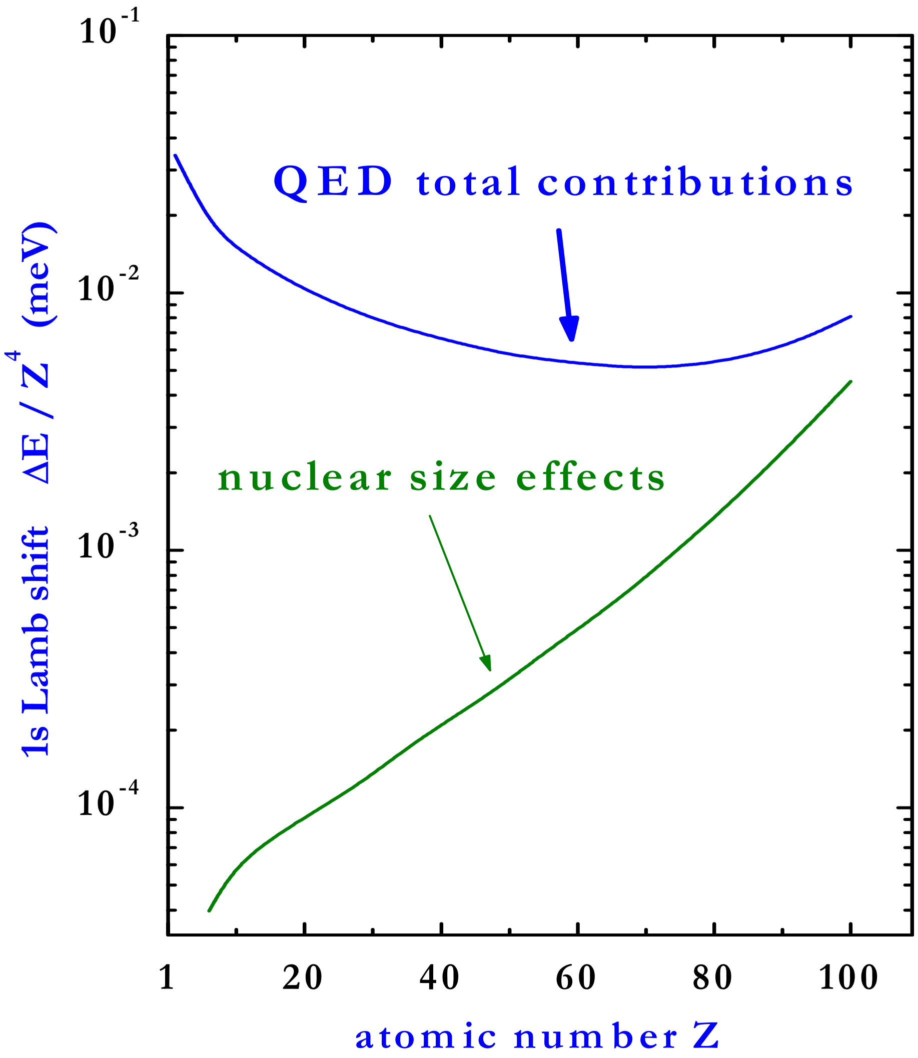
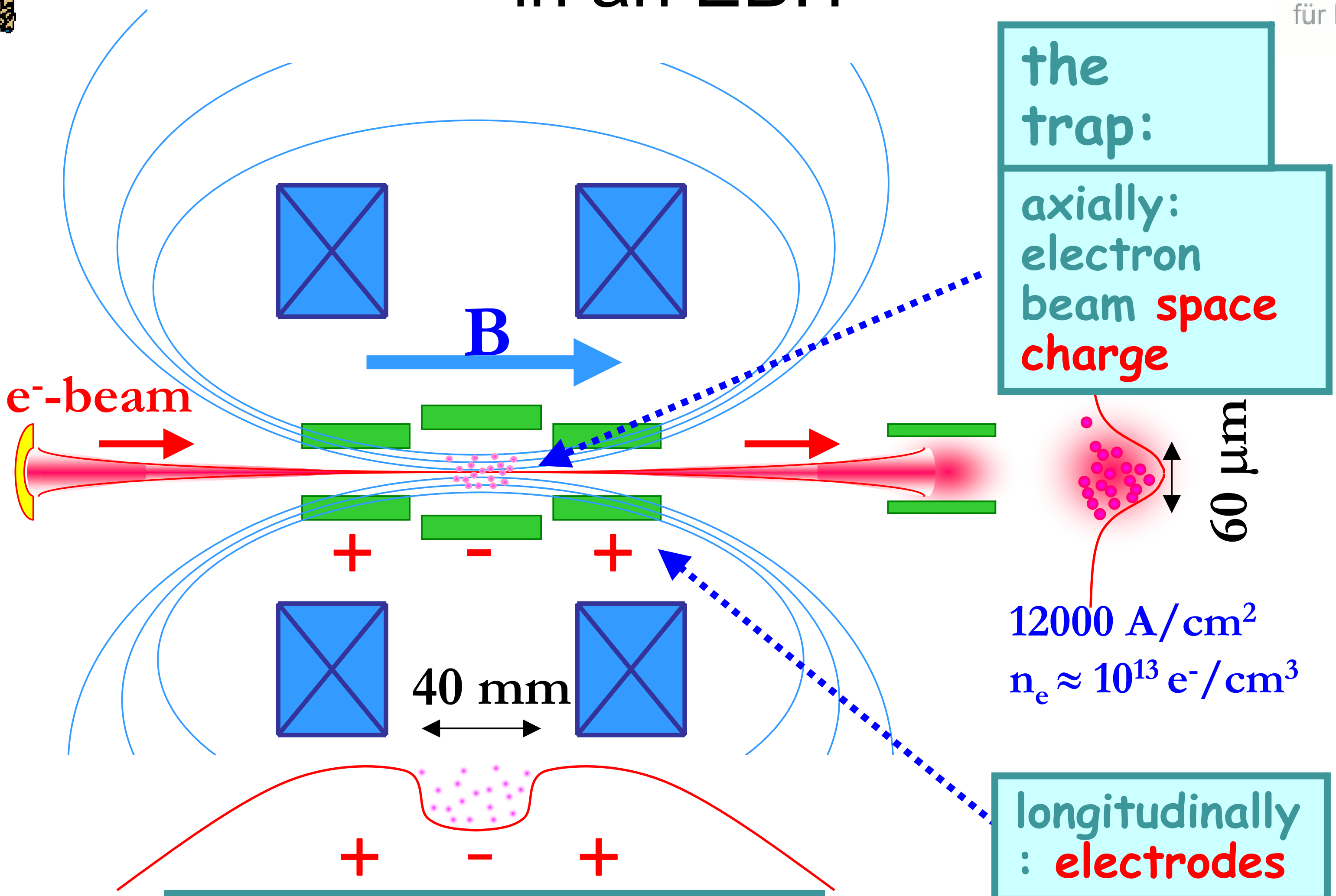
QED contributions on 1s-Lamb shift

$\Delta E_{1s} \sim Z^4$



Nuclear size effects become as large as QED contributions

The production and trapping of HCI in an EBIT



trap potential $U_t \approx$ 100 V
($U_t \times$ ion charge) $\approx$ 5000 eV

Isotopic shifts on dielectronic resonances

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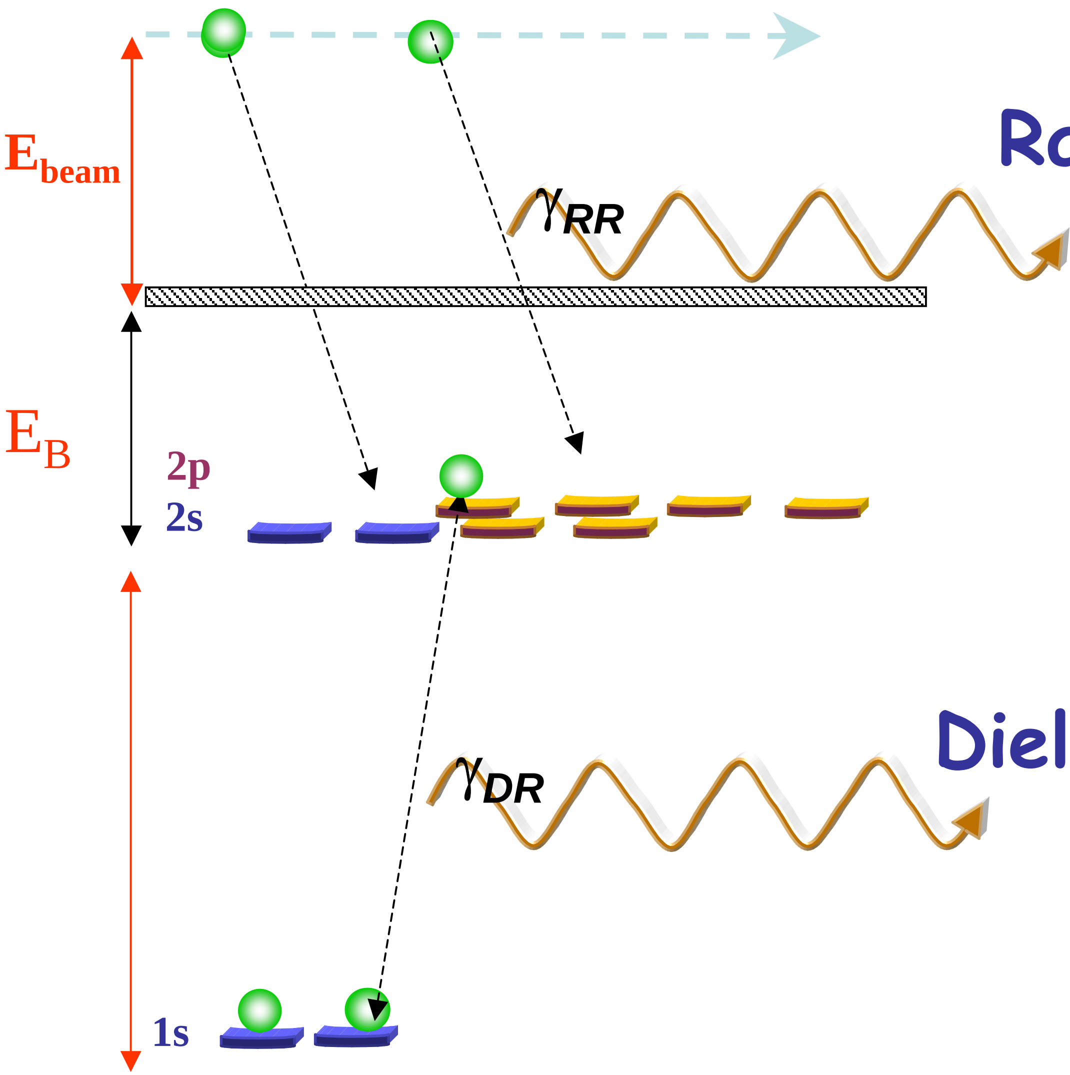
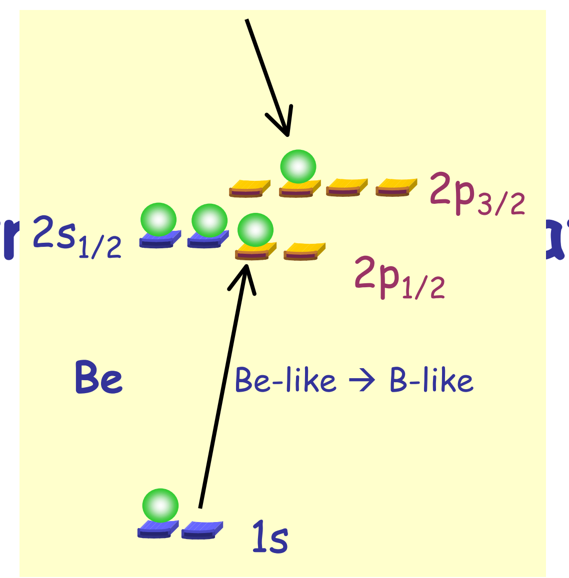


Radiative recombination

Dielectr … ation

Nomenclature of DR:

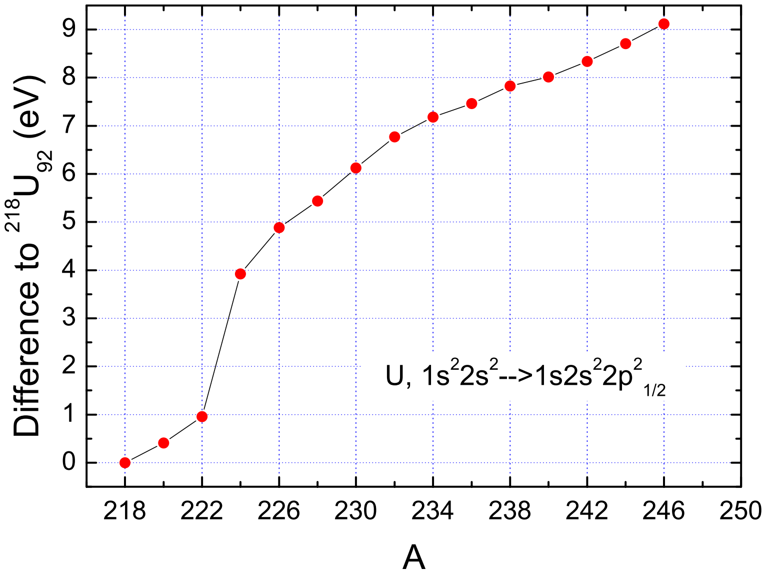
$KL_{1/2}L_{3/2}$



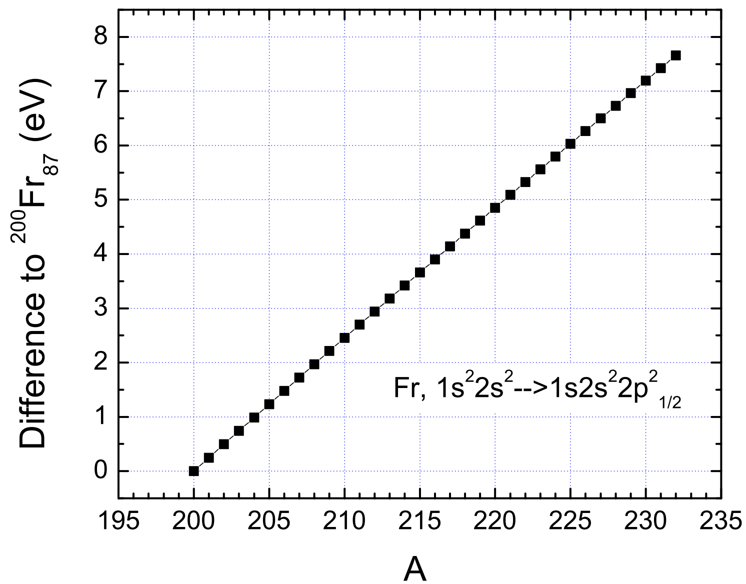
Isotopic shifts on DR in Be-like uranium and francium

Shabaev V. M. *et al.*
(homogenous charge distribution)

Uranium (E_{res}~ 67 keV)



Francium



R_{rms} Nerlo-Pomorska B. *et al.*

Semi-empirical estimate (Johnson and Soff)

$$R_{rms} = 0.836A^{1/3} + 0.570[fm]$$

small energy shifts ↔ high precision measurements needed (ppm)

Energy of dielectronic resonances (electron beam)

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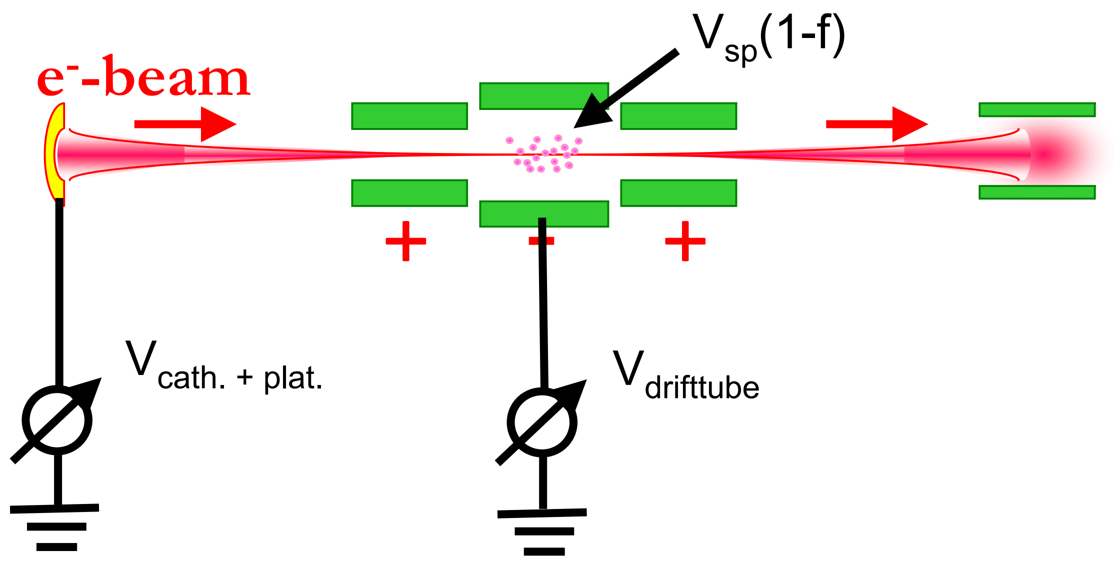


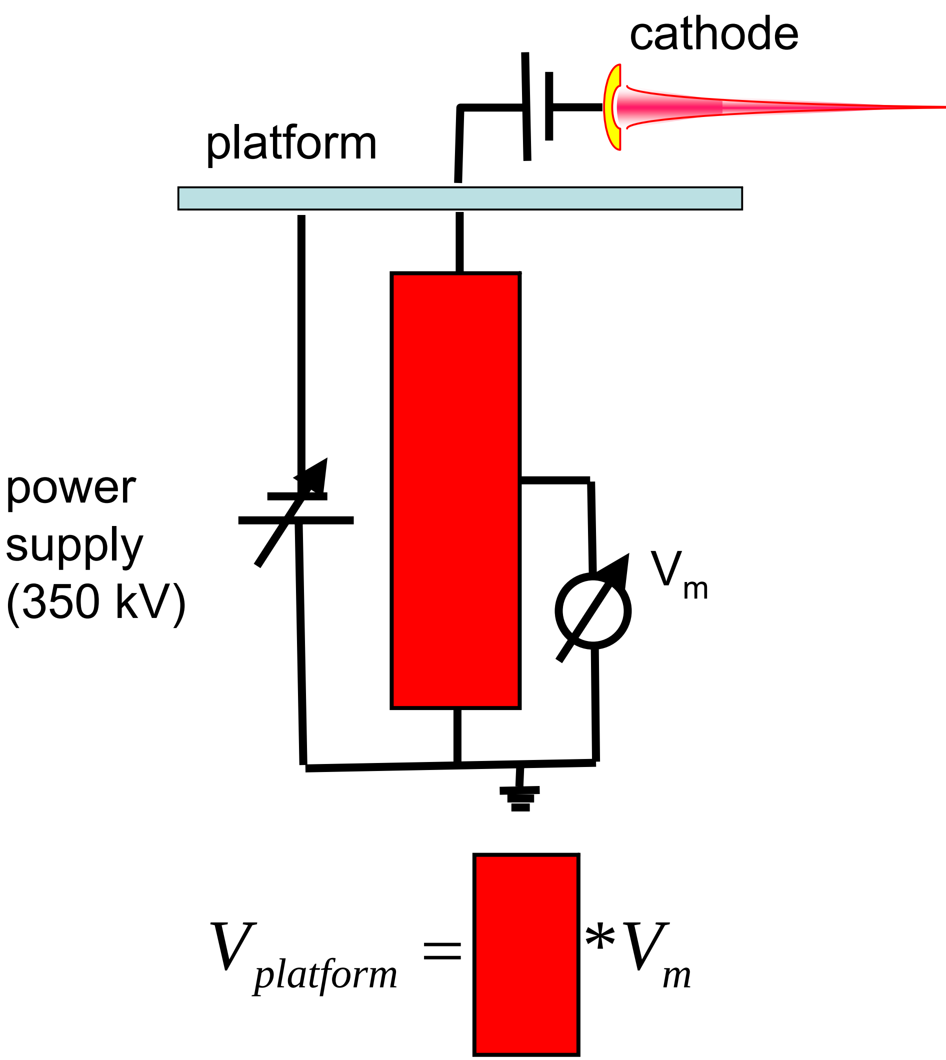
$$E_{resonance} = -V_{cathode} - V_{platform} + V_{driftfube} + V_{sp}(1\text{-}f)$$

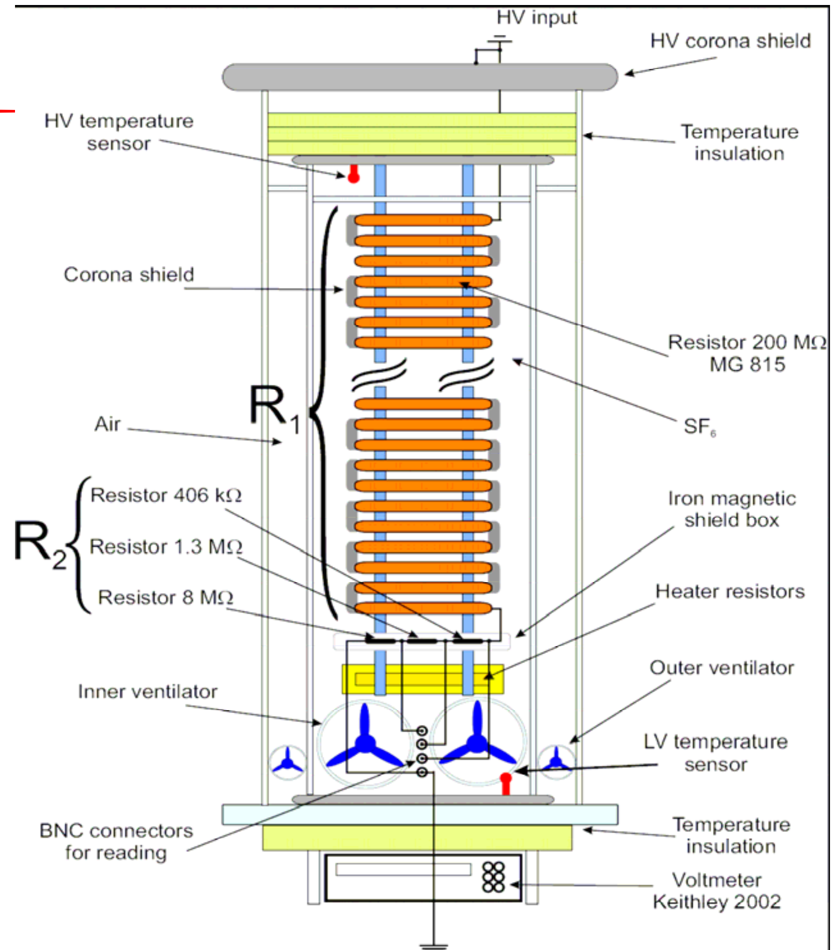
$$V_{sp} = V_{sp}(I, r_e, r_{dt}, E_e)$$

Conditions:

- same amount of positive charge in the trap
- or measure with different currents (extrapolate)

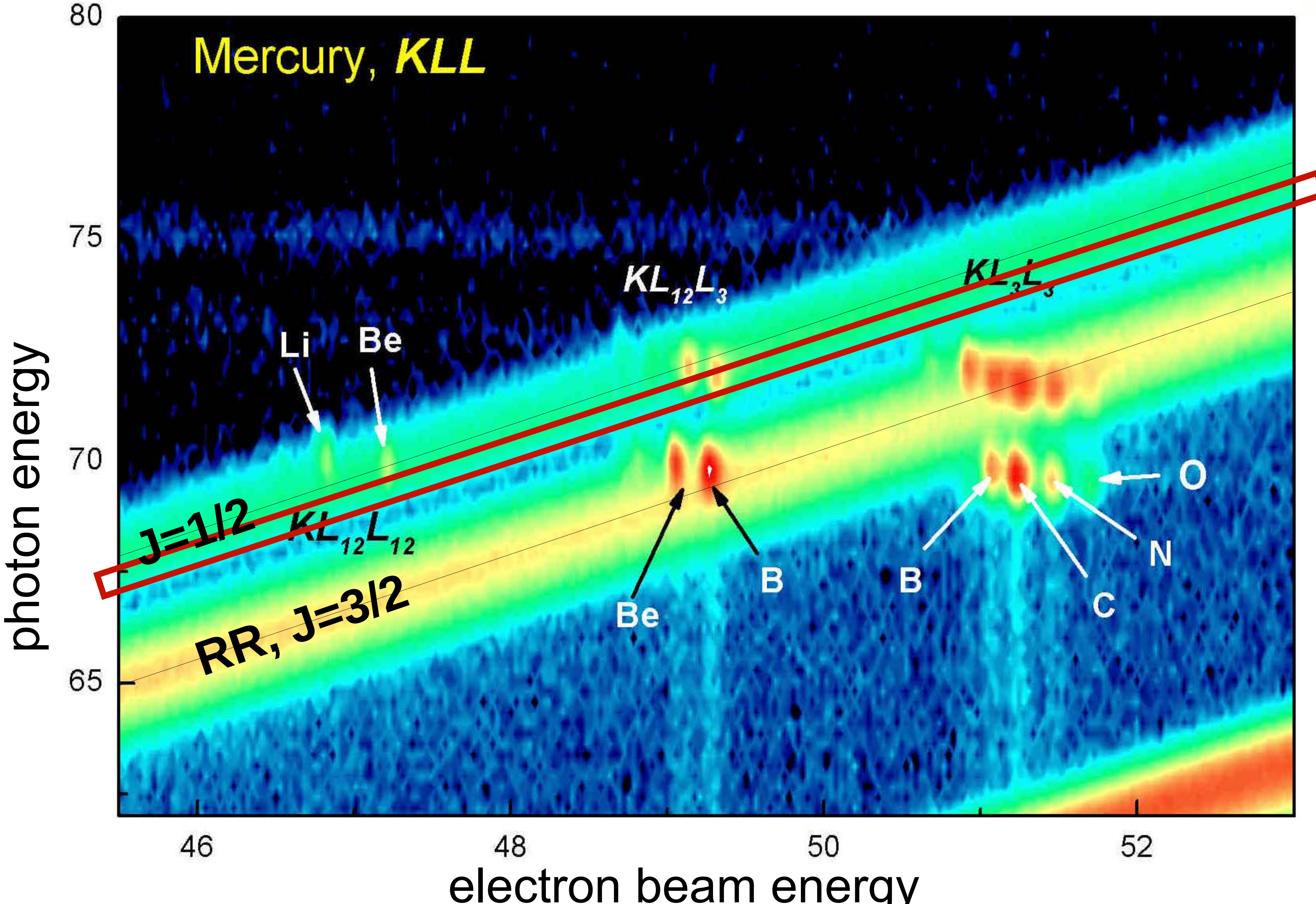
Voltage divider
(Antonio González Martínez)



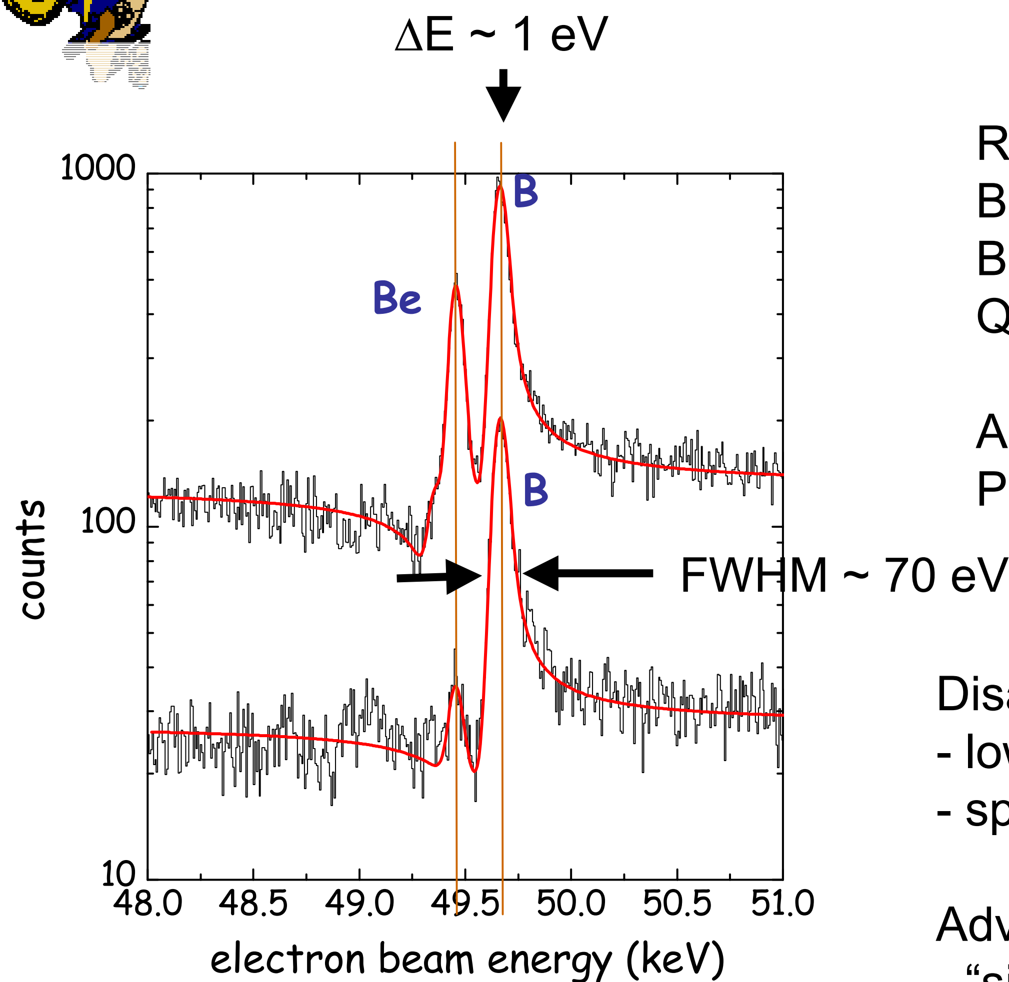


Temperature stability: ± 0.02 K

Plot of the scanned data



Determination of the resonances



Results:
Be- like Hg: 49.349(6) keV
B- like Hg: 49.557(4) keV
Quantum Interference

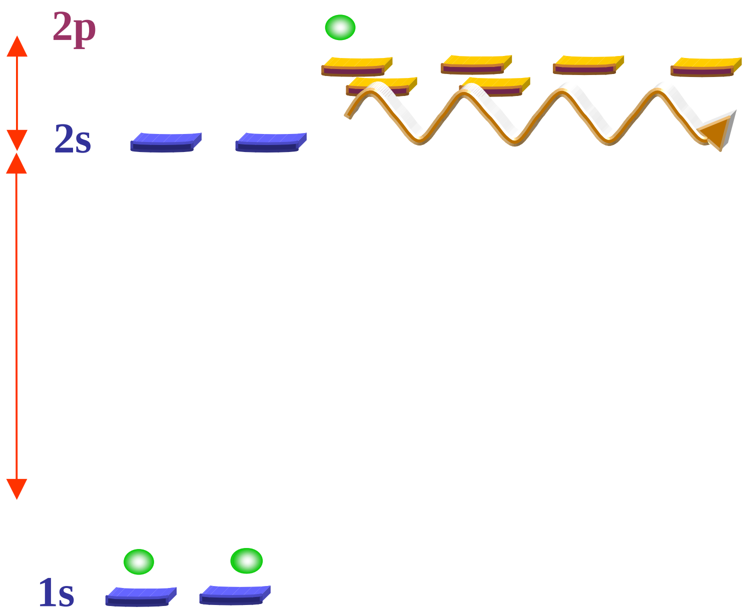
A.J. González Martínez *et al.*,
PRL 94, 203201 (2005)

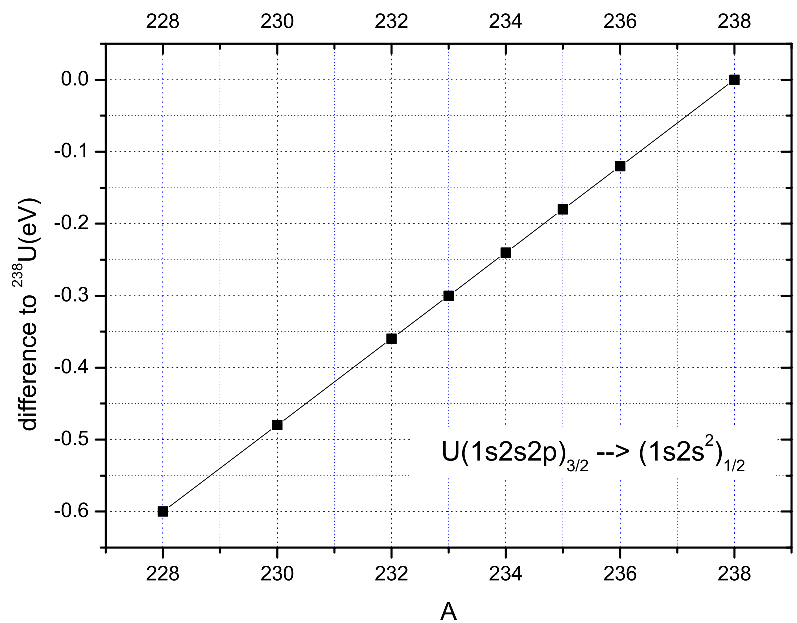
Disadvantages:
- low resolution
- space charge shift (extrapolate to 0 mA)

Advantages:
- “simple” setup
- high x-ray flux

Time: 100 h
- scan region ~ 10
- TITAN factor ~ 10 !?

Isotopic shifts on inner shell transition $(2p_{3/2} - 2s_{1/2})$

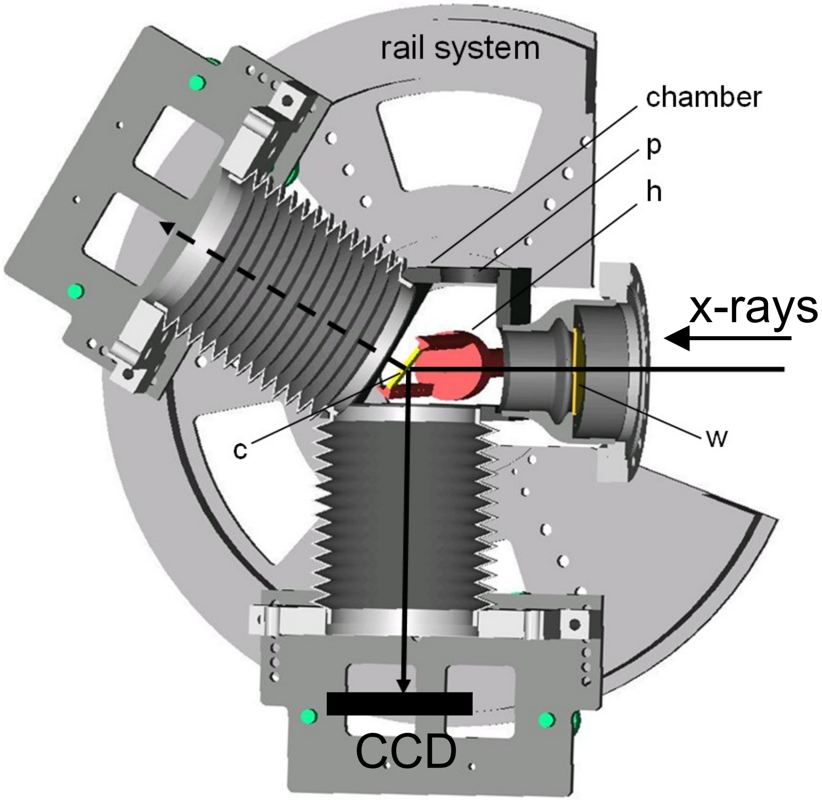




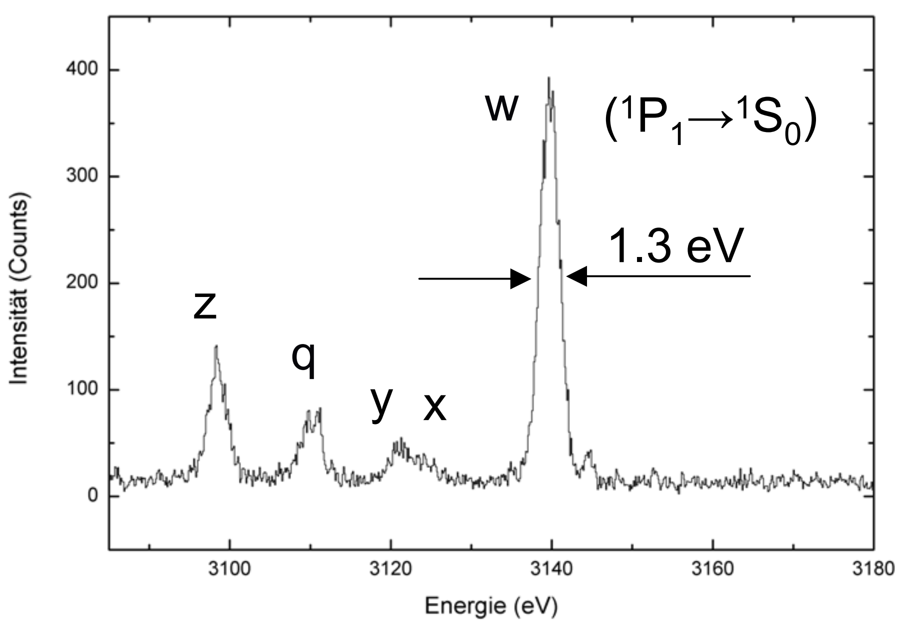
energy: ~ 4.5 keV (Li-like U)
shift: ~ 0.3 eV ($U^{233,238}$) ~ 67 ppm

Compare to:
KLL-DR Resonance U
energy: ~ 70 keV
shift: ~ 1.1-1.7 eV ($U^{233,238}$) ~ 21 ppm

Flat crystal x-ray spectrometer



He- like Argon



Range:
Si111 2.26 keV - 4.1 keV
Si220 3.69 keV - 6.66 keV
Submitted: Rev. Sci. Instr.
J. Braun, H. Bruhns, *et al*.

Resolution:
Si111 1.3 eV at 3.14 keV

$\delta\langle r^2\rangle$ $U^{233,238}$ measurement

S.R. Elliot, P. Beiersdorfer, M.H. Chen, PRL 76 (1996) 1031

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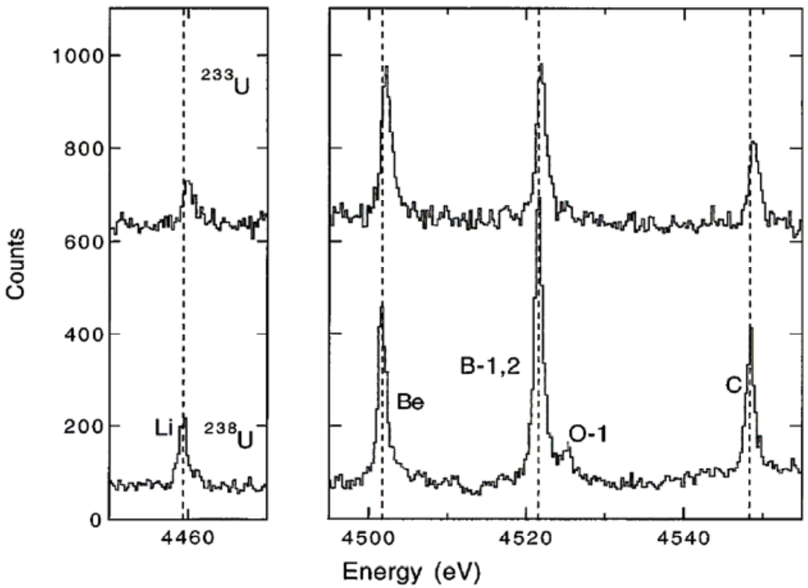


TABLE III. A summary of $\delta E_{\rm Coul}$ and the deduced $\delta\langle r^2\rangle^{233,238}$ values for each charge state. The uncertainties listed are entirely statistical.

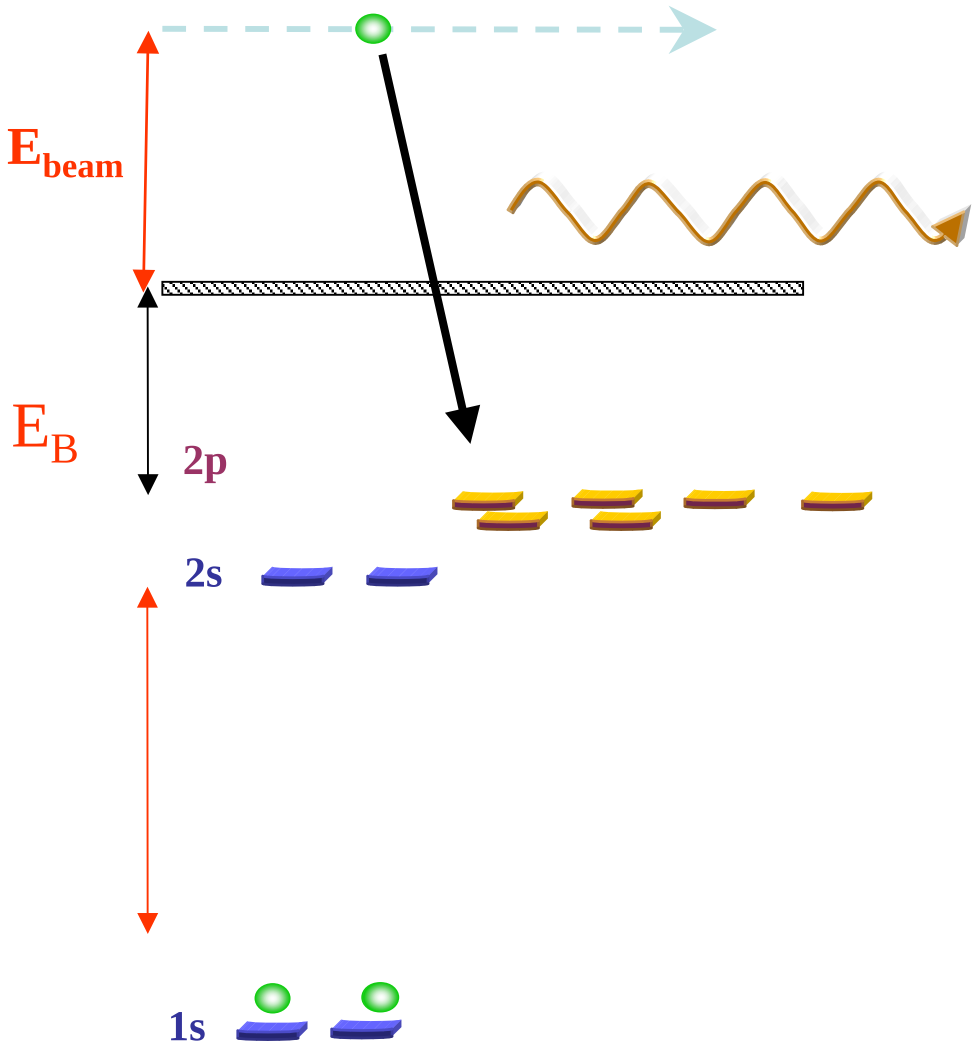
Key	$\delta E_{\rm Coul}$ (meV)	$\delta\langle r^2\rangle^{233,238}$ (fm^2)
Li	280 ± 118	−0.364 ± 0.153
Be	324 ± 61	−0.436 ± 0.081
B-1,2	344 ± 52	−0.455 ± 0.068
C	386 ± 62	−0.515 ± 0.083
Average		−0.457 ± 0.043
Previous	$K\alpha$ [12,13]	−0.383 ± 0.044
	Muonic atoms [11]	−0.520 ± 0.081

TABLE I. Summary of the measured energy shifts. The ^{238}U energy values and the nomenclature for the key are from Ref. [15]. All transitions decay to the ground state of the respective ion.

Key	Ion	Upper level	^{238}U energy (eV)	ΔE (meV) ^{233}U-^{238}U
Li	U^{89+}	$(2p_{3/2})_{j=3/2}$	4459.37 ± 0.35	256 ± 118
Be	U^{88+}	$(2s_{1/2}2p_{1/2})_{j=1}$	4501.72 ± 0.27	300 ± 61
B-1,2	U^{87+}	$(2s_{1/2}2p_{1/2}2p_{3/2})_{j=1/2,3/2}$ blend	4521.39 ± 0.22	320 ± 52
C	U^{86+}	$(2s_{1/2}2p_{1/2}^2 2p_{3/2})_{j=1}$	4548.32 ± 0.20	362 ± 62
O-1	U^{84+}	$(2s_{1/2}2p_{1/2}^2 2p_{3/2}^3)_{j=2}$	4525.26 ± 0.25	

Current results are statistically limited → precision which is limited by the nuclear polarization calculations can in principle be achieved

Estimates of measuring time



Mercury
Beam current: 160 mA

8 cps (RR into $2p_{3/2}$ of Hg)

- charge distribution (Li, Be,...)
- crystal distance ~ 500mm (TITAN)
- crystal reflectivity ~ 4.4* 10^{-4} (measured)
- CCD efficiency ~ 0.6 – 0.7
- resolution FWHM ~ 1.3 eV
- statistical accuracy ~ 20 meV
- excitation rate factor ~ 100-1000

Time per Isotope: 10-100 h (150 h U)
TITAN factor ~ 10

Conclusion

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- Isotopic shifts can be measured via DR
- Isotopic shifts can be measured via inner shell transitions
- Combine both measurements (beam time)
- TITAN & ISAC ↔ unique tool !

EBIT Group in Heidelberg

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- Sascha Epp (PhD)
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- Alexandra Rohr (diploma thesis)
- Günther Sikler (post doc)
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- Joachim Ullrich

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Vladimir Mironov
Christopher Osborne
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Thank you for your attention!