Accurate spectroscopy of excited levels in He-like uranium

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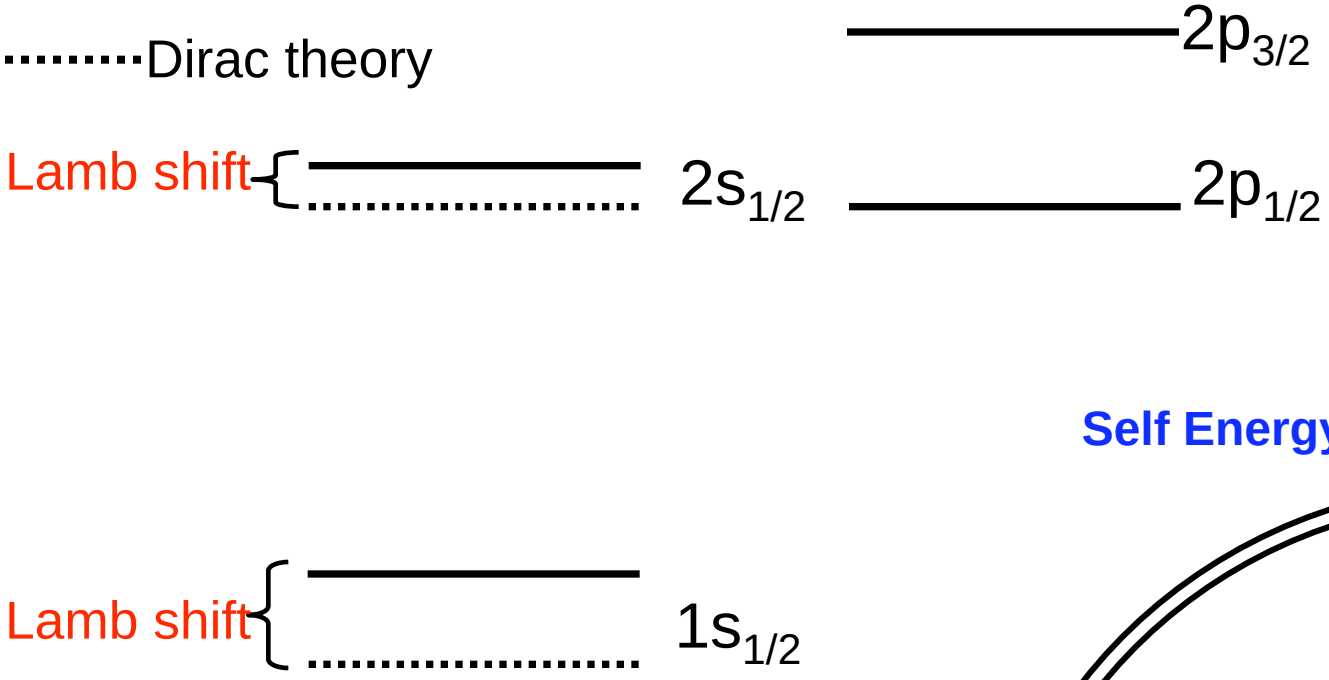
Institute of NanoSciences of Paris, France

Experiment made at the Gesellschaft für Schwerionenforschung as Alexander Von Humboldt fellow

Atomic structure of highly charged ions
H-like ions

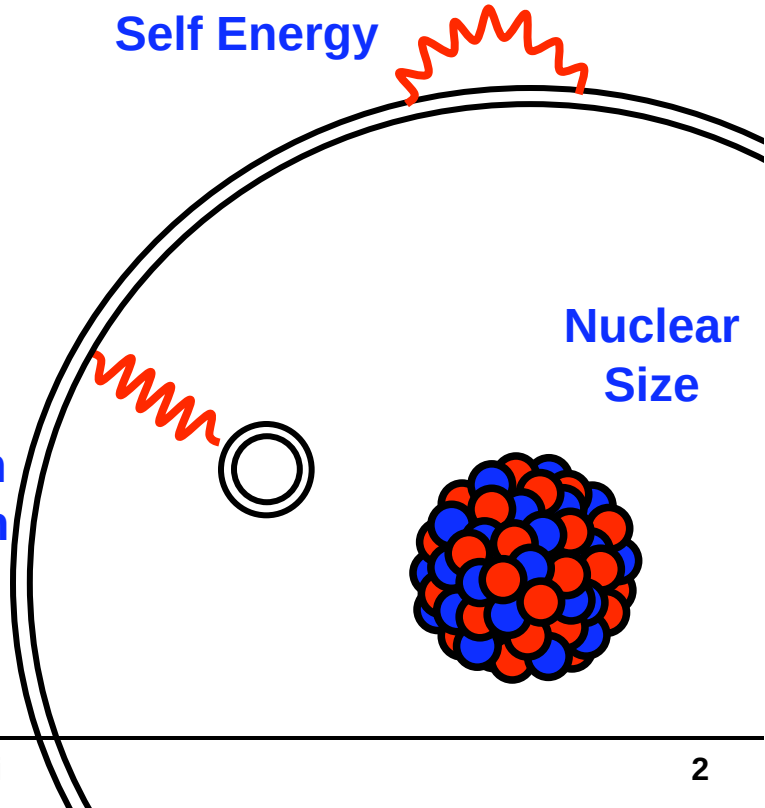


QED corrections

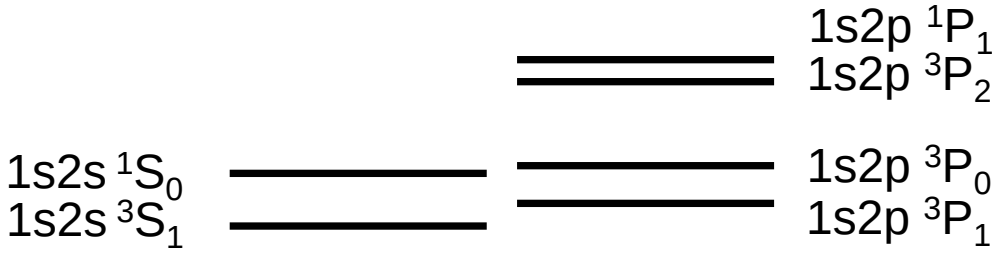
$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

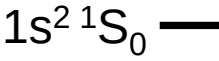
Important for s-states

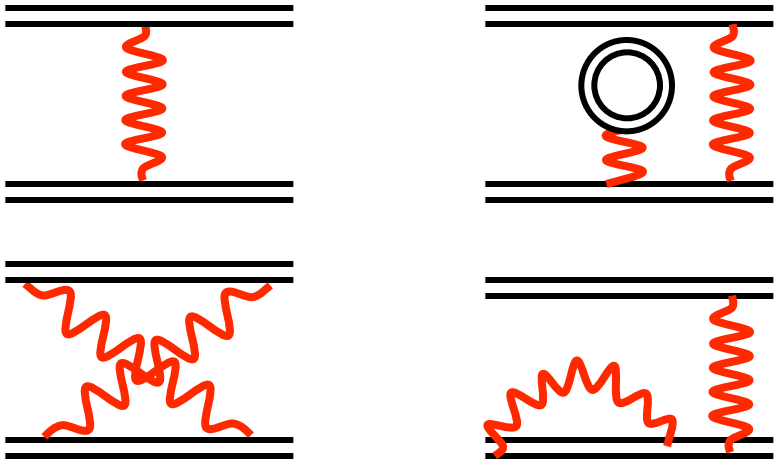


Atomic structure of highly charged ions
He-like ions



Electron-electron interaction

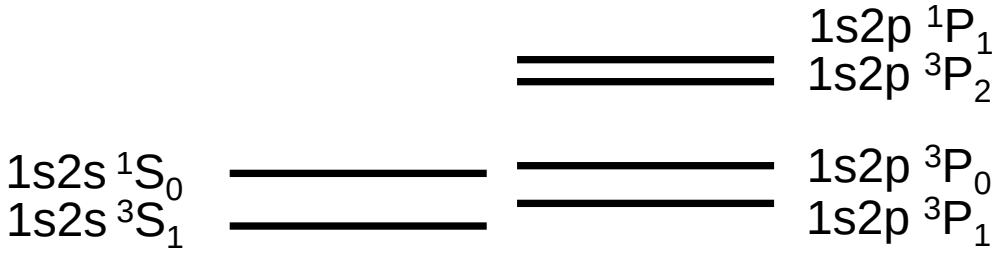




Non-radiative QED

Radiative QED

Atomic structure of highly charged ions
He-like ions



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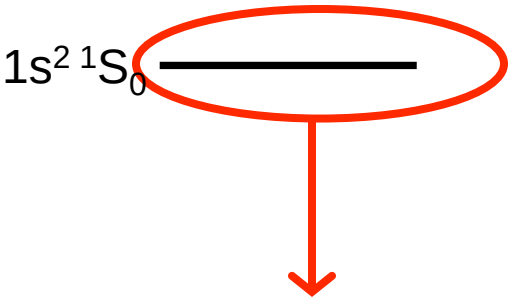
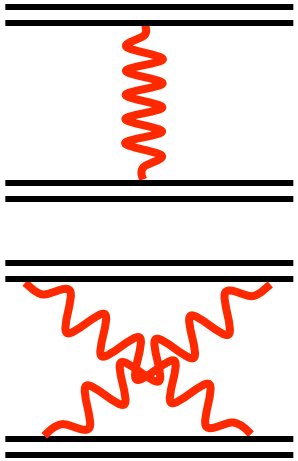


A. Gumberidze et al., Phys. Rev. Lett. **92**, 203004-4 (2004).



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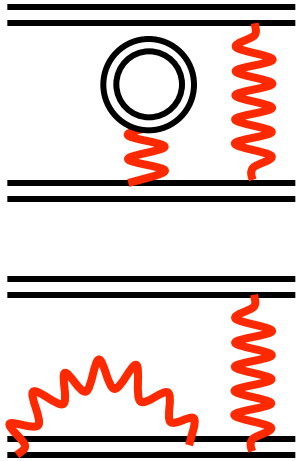

Radiative QED

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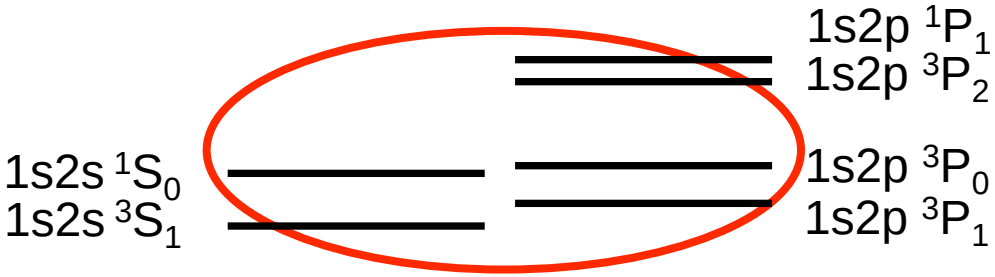

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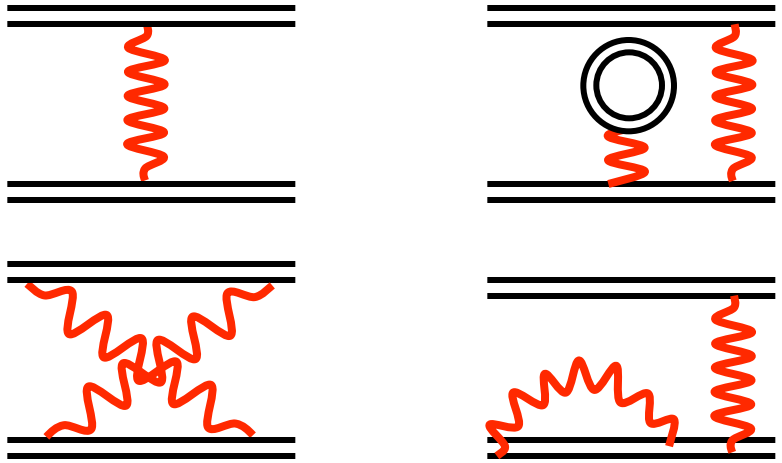

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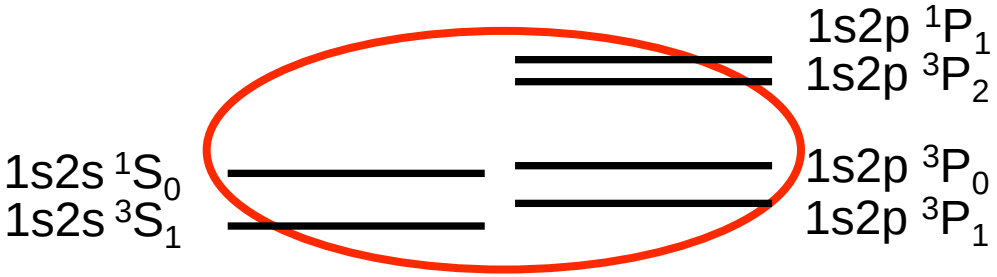
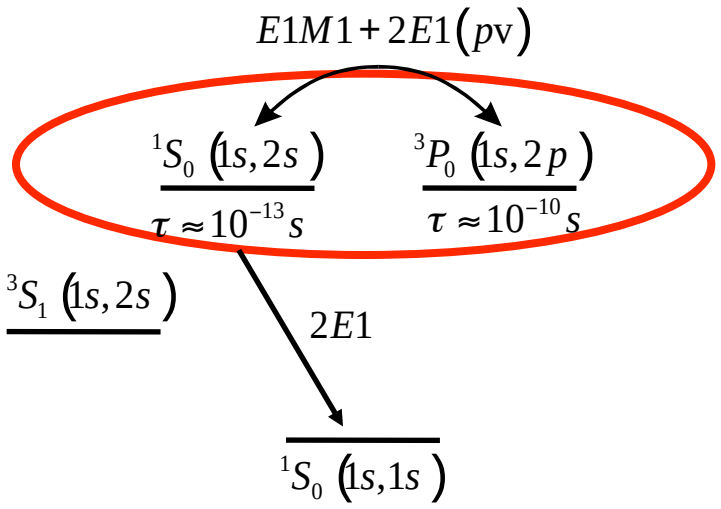


Parity violation in He-like ions experiment

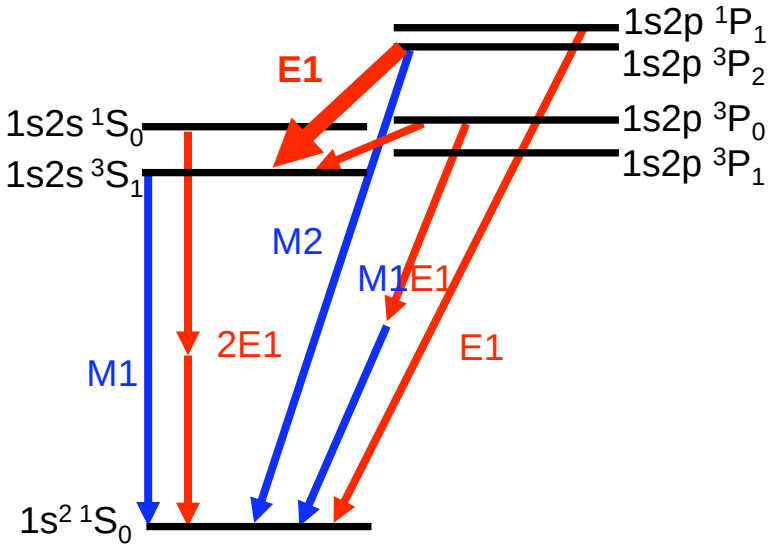
$1s^2\ ^1S_0$



[1] A. Schäfer *et al.*, Phys. Rev. A **40**, 7362 (1989).

Intra-shell transition spectroscopy

Heavy He-like ions



Intra-shell transition:
4.50 keV in Uranium

Intra-shell transition spectroscopy

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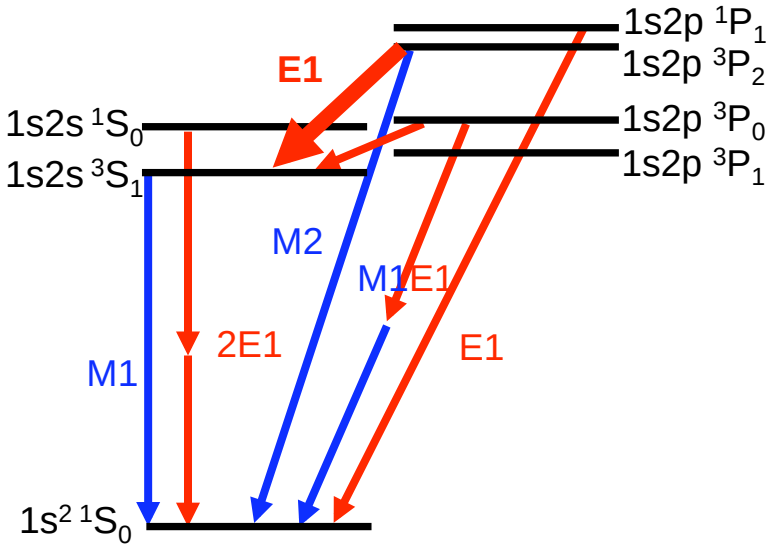
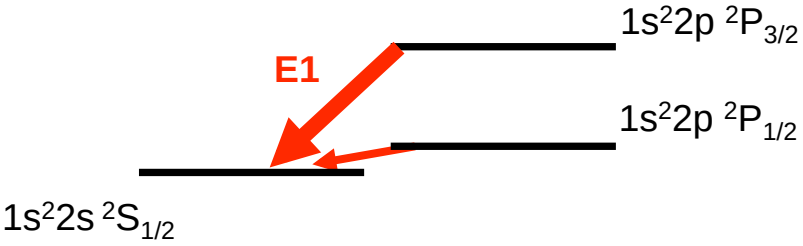


Heavy Li-like ions

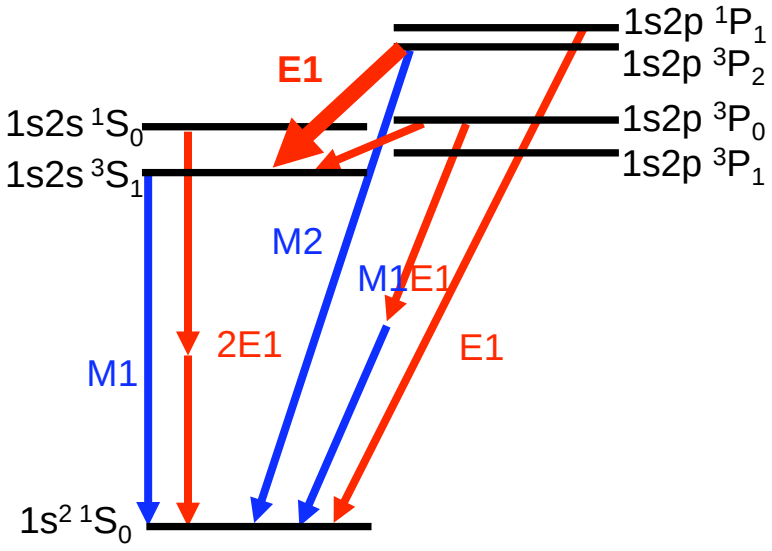


Intra-shell transition:
4.50 keV in Uranium

Intra-shell transition:
4.46 keV in Uranium

Intra-shell transition spectroscopy

Heavy He-like ions



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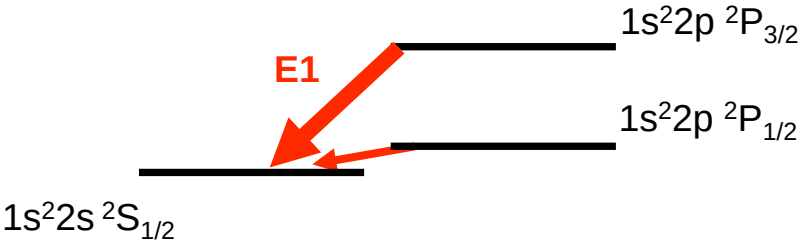
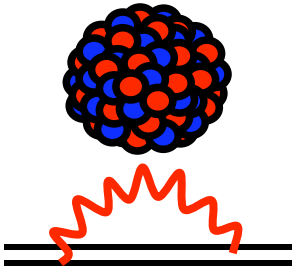




- Same nucleus
- Same 1 el. QED contribution

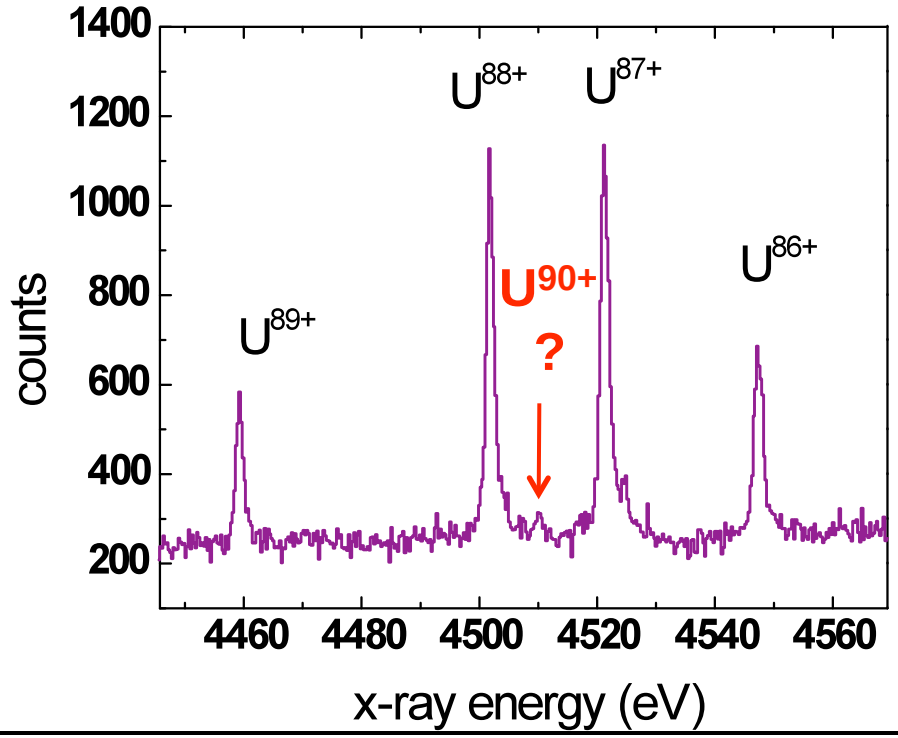
⇒ Reduction of the systematic uncertainties in the theoretical predictions

Intra-shell transitions at Super-EBIT

PHYSICAL REVIEW A VOLUME 53, NUMBER 6 JUNE 1996

Search for $1s2s\ ^3S_1 - 1s2p\ ^3P_2$ decay in U^{90+}

P. Beiersdorfer, S. R. Elliott,* A. Osterheld, Th. Stöhlker,† J. Autrey,‡ G. V. Brown,§ A. J. Smith,‡ and K. Widmann
Department of Physics and Space Technology, Lawrence Livermore National Laboratory, Livermore, California 94550
(Received 20 December 1995)



Uranium Intra-shell transitions at the super-EBIT

The population of the $^3P_2$ level by electron impact excitation was not sufficient for measuring the transition energy in U^{90+}!!

Intra-shell transitions at Super-EBIT

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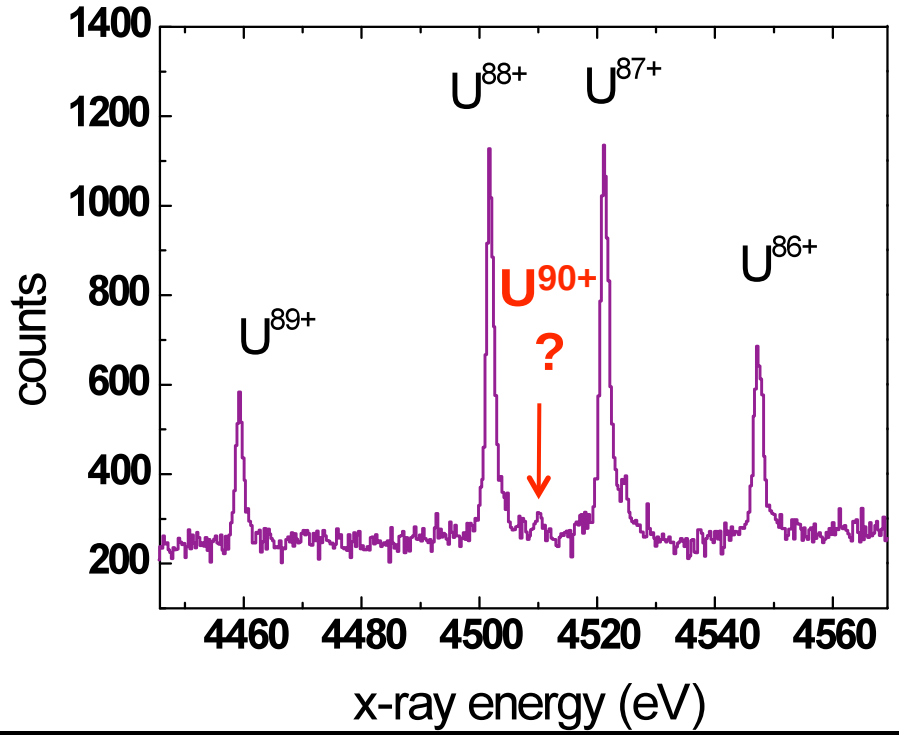

Uranium Intra-shell transitions at the super-EBIT

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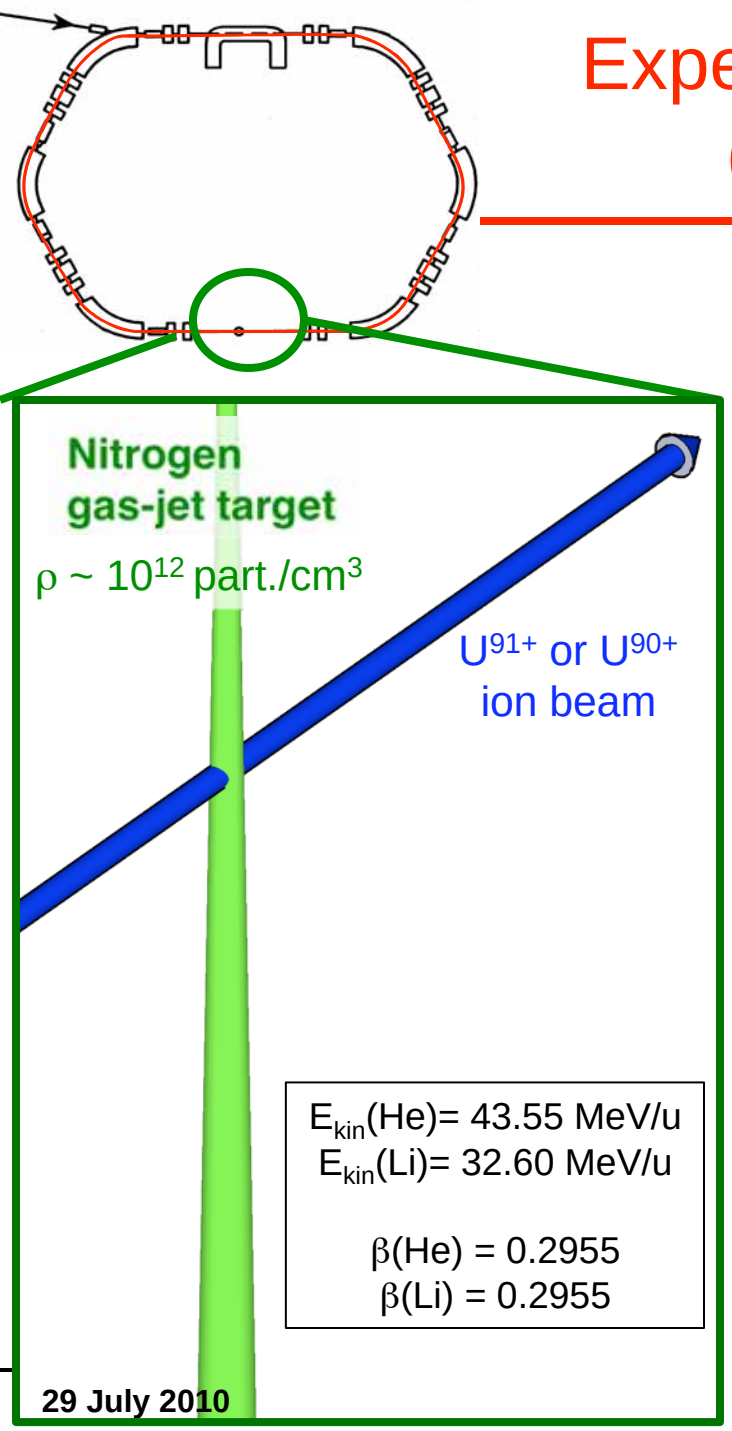
➔ Electron capture at GSI!

Experiment at the ESR (August 2007)



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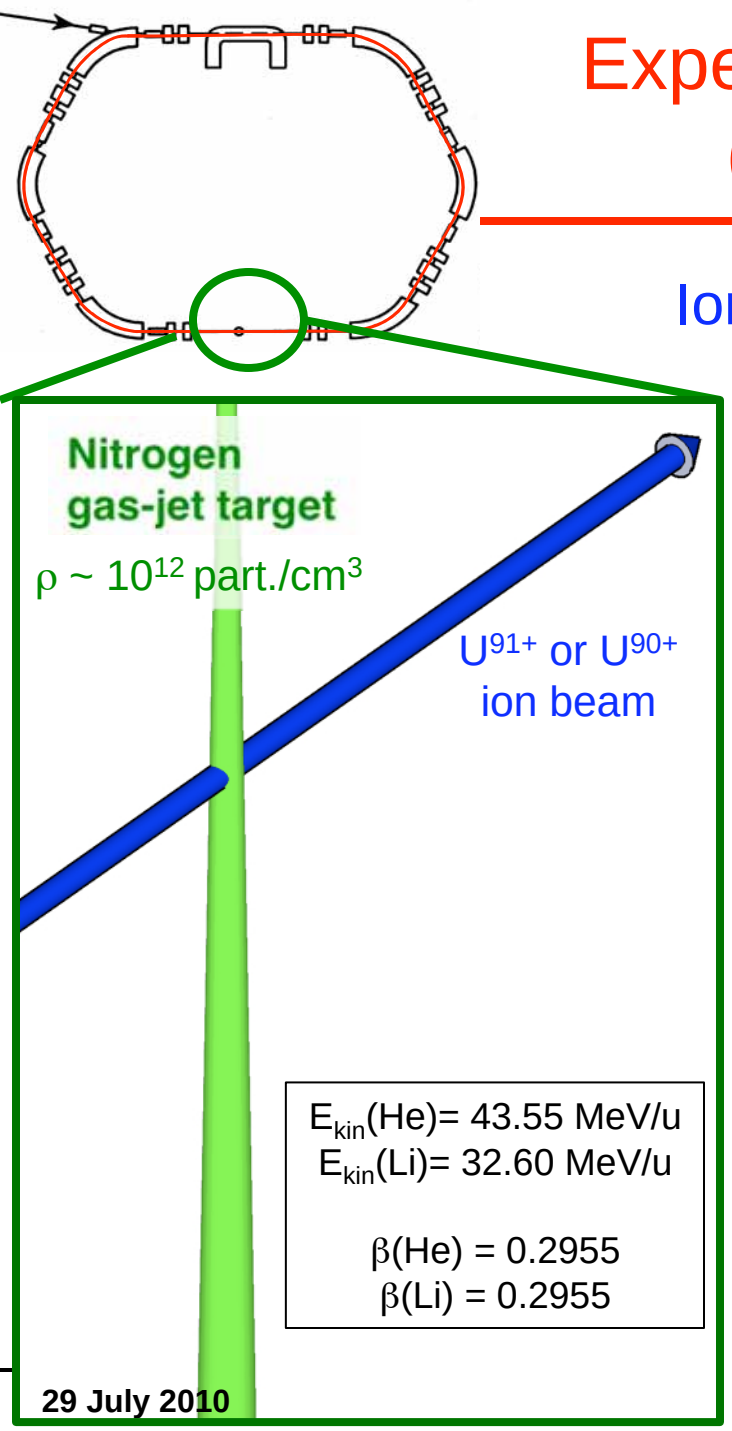


Ion velocity modulation

⇩

Low ion velocity
(+ low-Z target)

⇩

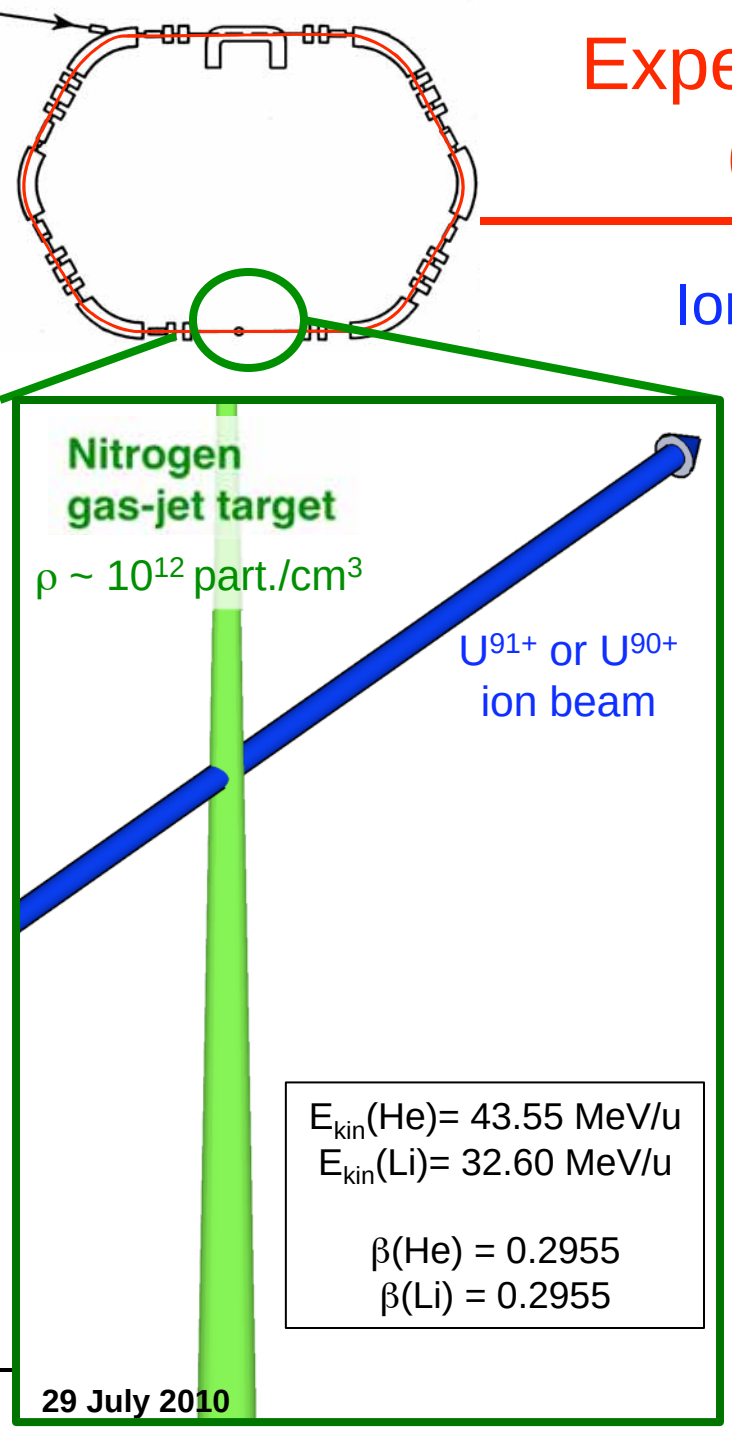
Electron capture
in n = 2-5 levels

$U^{91+} + N_2 \rightarrow U^{90+} + N^+ + \ldots$

⇩

Efficient population of the
1s2p state

Experiment at the ESR (August 2007)



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$U^{91+} + N_2 \rightarrow U^{90+} + N^+ + \ldots$

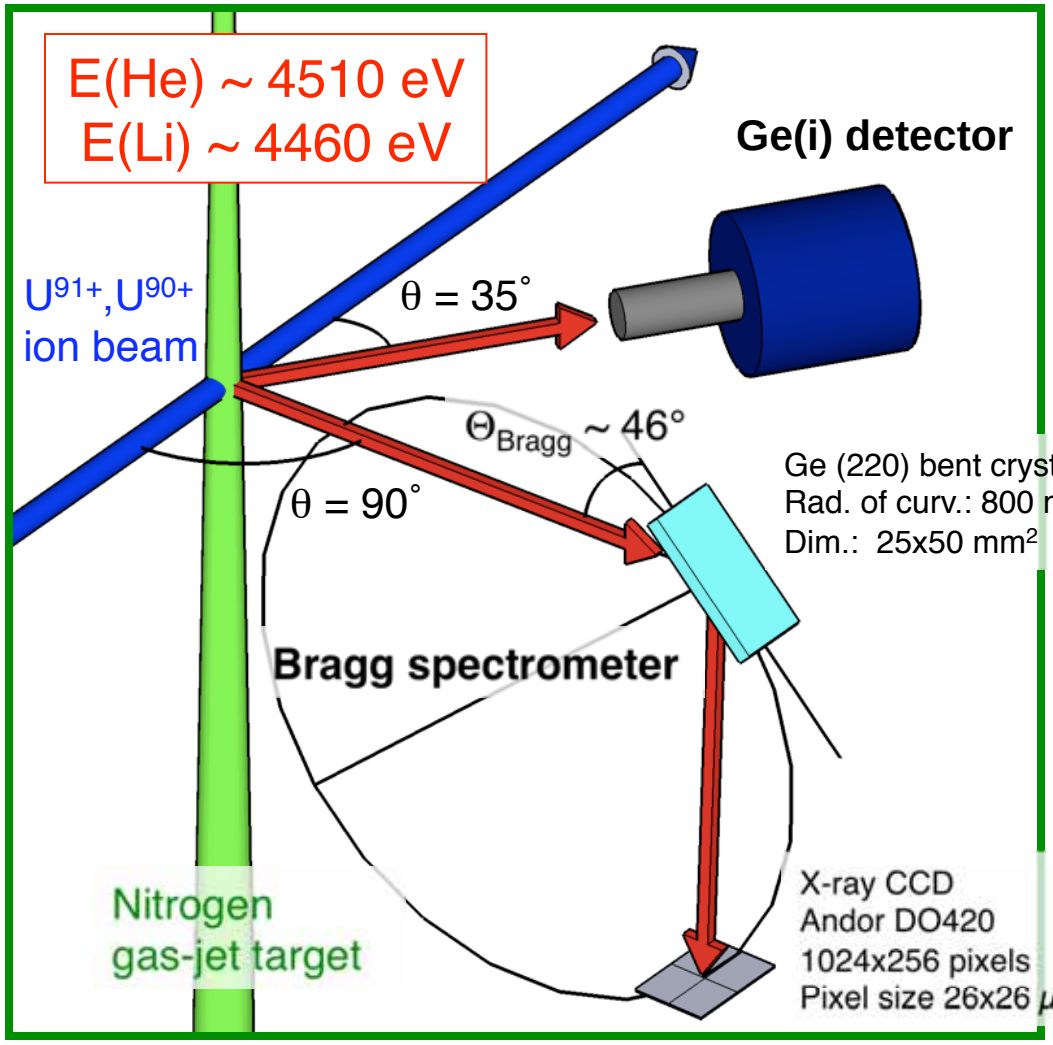
Efficient population of the 1s2p state

Ion charge selection

Comparison between He- and Li-like U ions using Doppler tuning

Drastic reduction of the systematic uncertainties

Detectors system



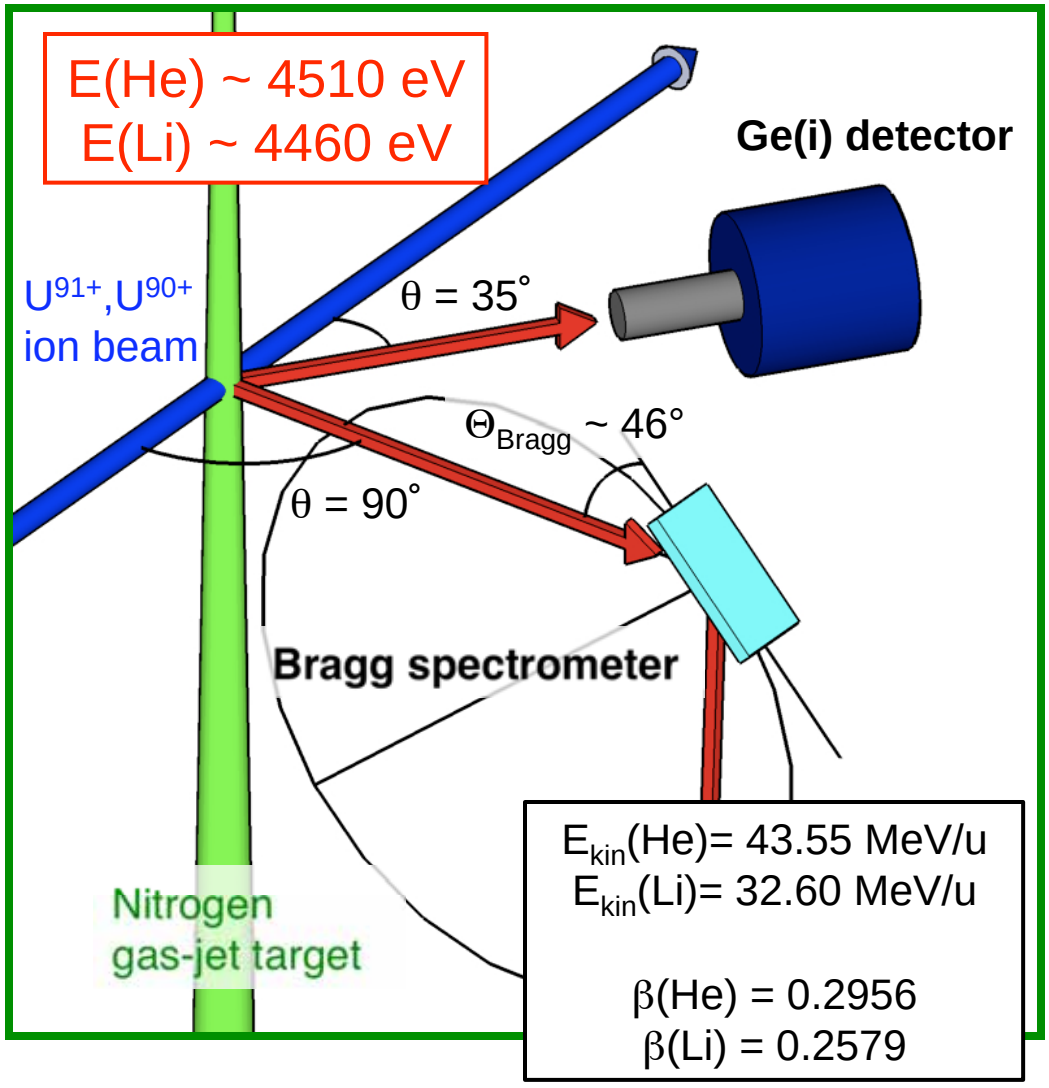
Solid state detector

- Intrinsic germanium detector
- Efficiency: ~ 2 x 10^{-5}
- Large observable energy range
- Resolution: 250 eV at 5.9 keV

Bragg crystal spectrometer

- Efficiency: ~ 5 x 10^{-7}
- Small observable energy range
- Resolution: few eV at 4-5 keV

Detectors system and Doppler tuning



Solid state detector

- Intrinsic germanium detector
- Efficiency: ~ 2×10^{-5}
- Large observable energy range
- Resolution: 250 eV at 5.9 keV

E_{lab}(He) = 5689 eV, E_{lab}(Li) = 5462 eV

Bragg crystal spectrometer

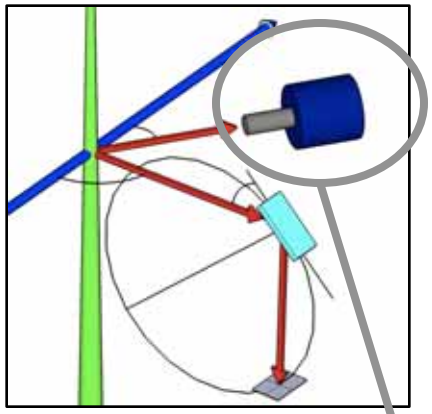
- Efficiency: ~ 5×10^{-7}
- Small observable energy range
- Resolution: few eV at 4-5 keV

E_{lab}(He) = E_{lab}(Li) = 4308 eV

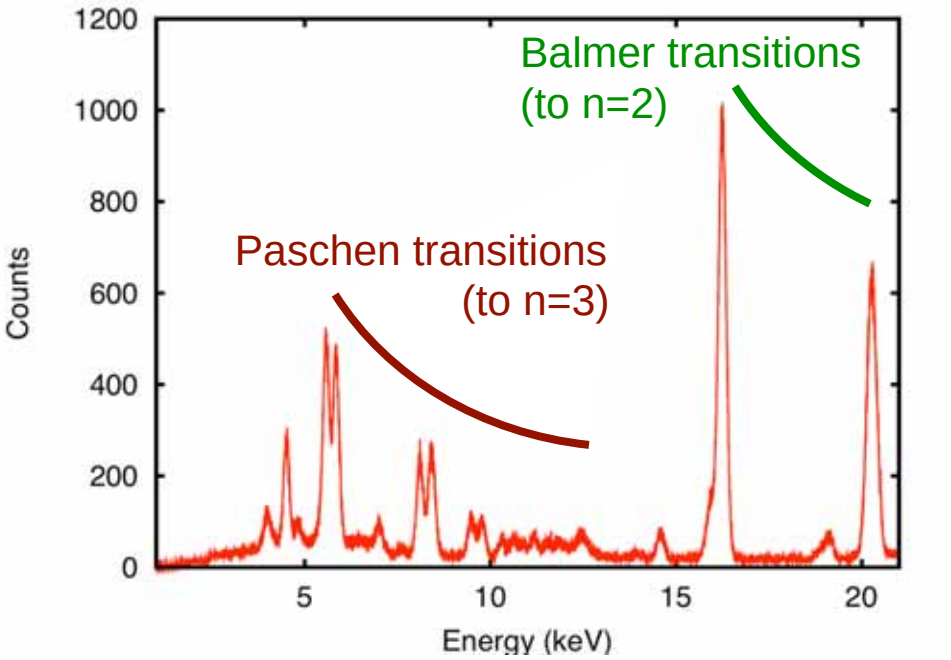
Relativistic Doppler effect

$$E_{\mathrm{Lab}} = \frac{E_{\mathrm{Proj}}}{\gamma(1 - \beta \cos\theta_{\mathrm{Lab}})}$$

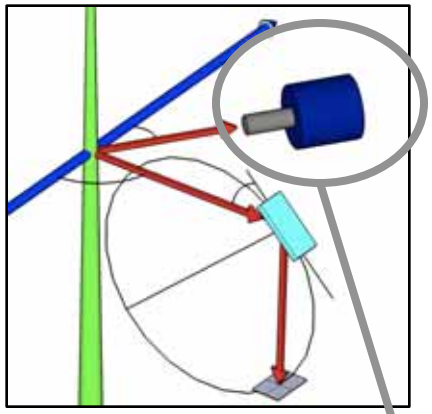
Spectrum of the solid state detector

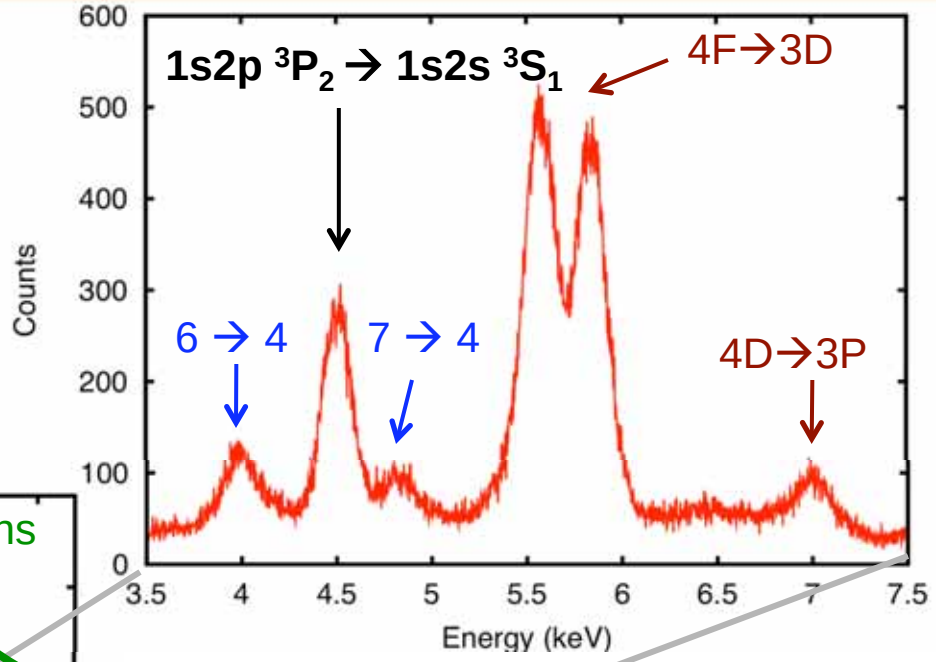


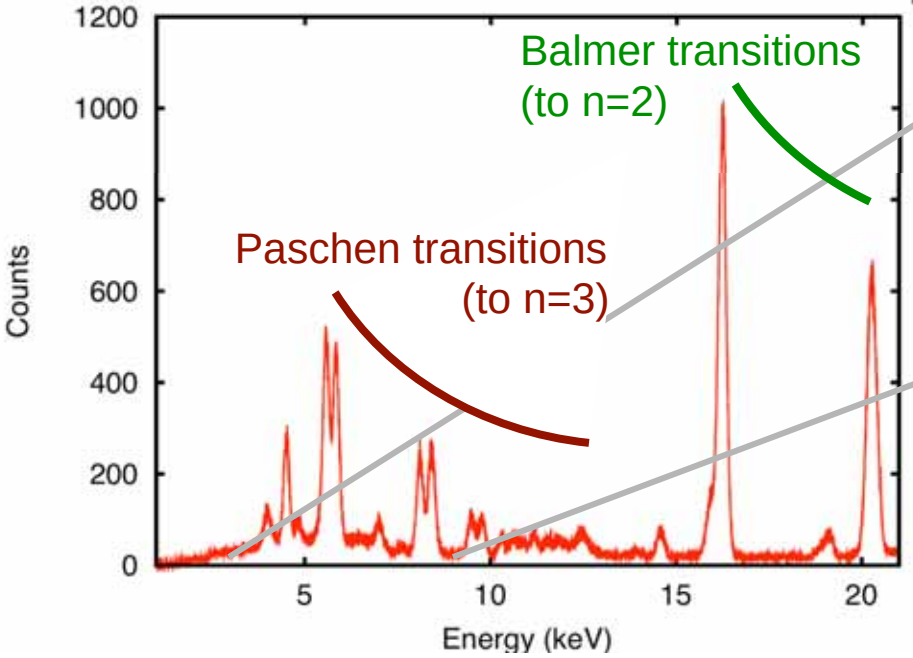
Ge(i) detector



Spectrum of the solid state detector

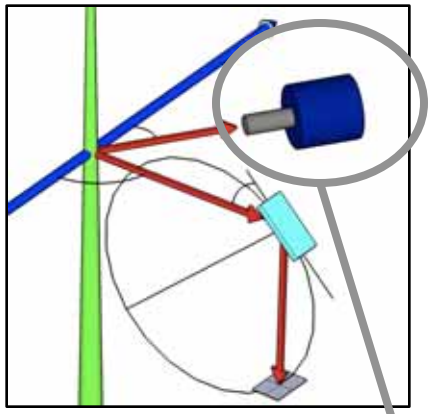


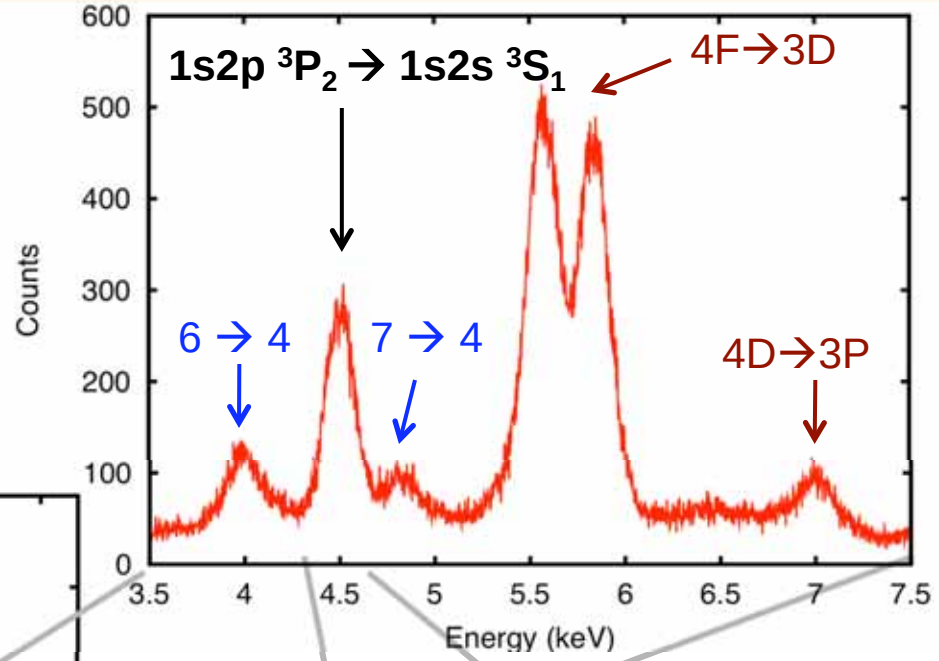


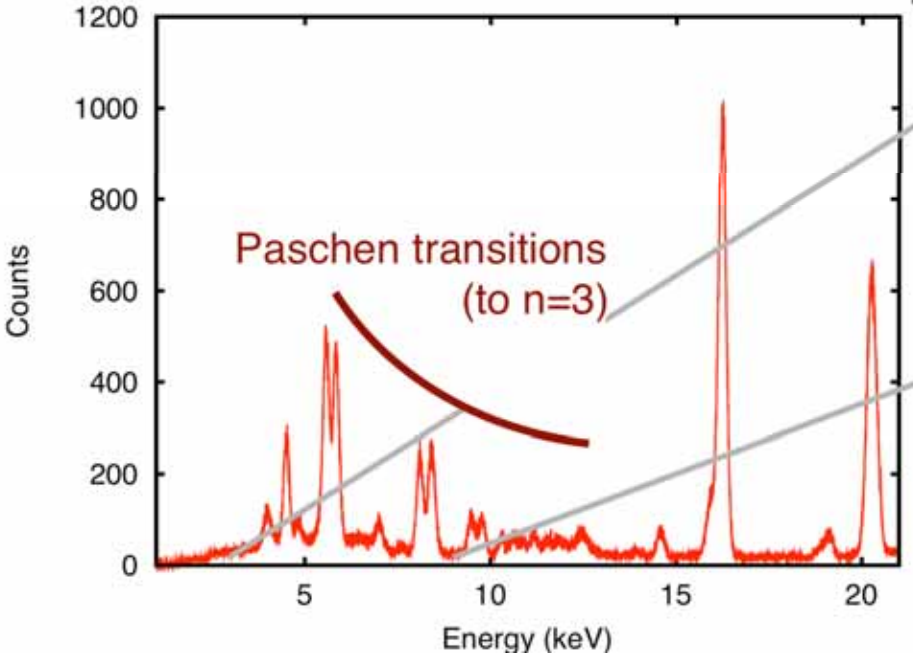


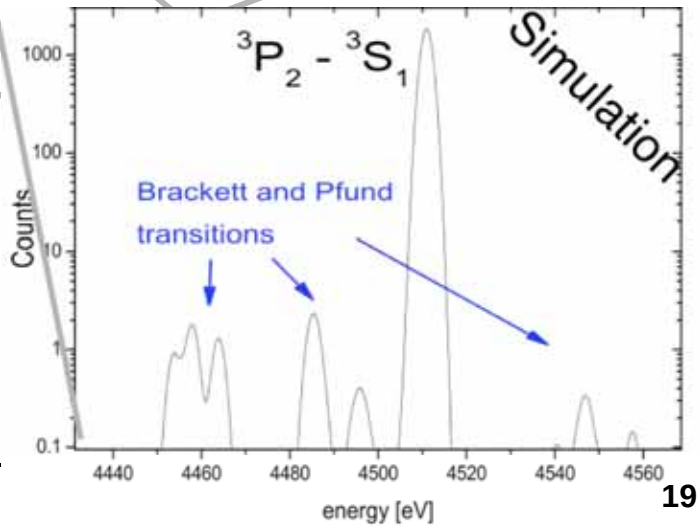
He-like intra-shell transition identified!!

Spectrum of the solid state detector

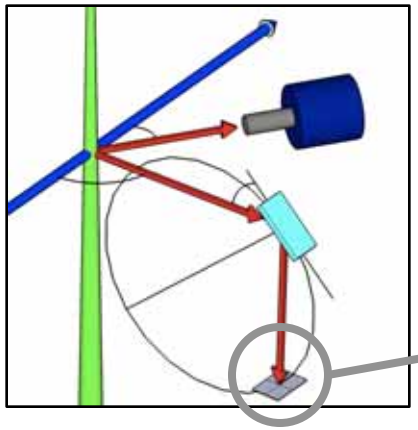




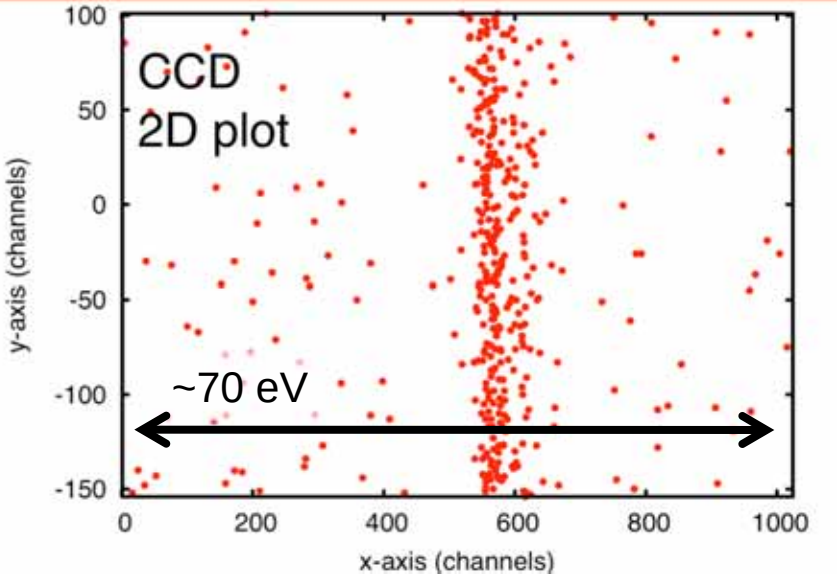




High resolution He-like U spectrum



Crystal spectrometer



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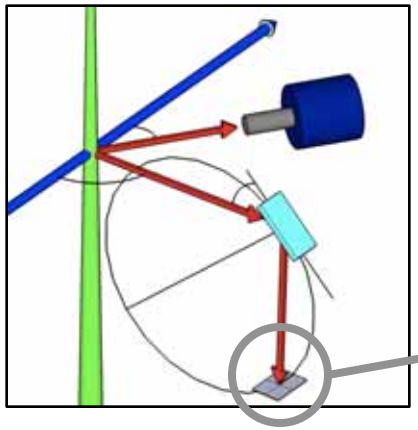

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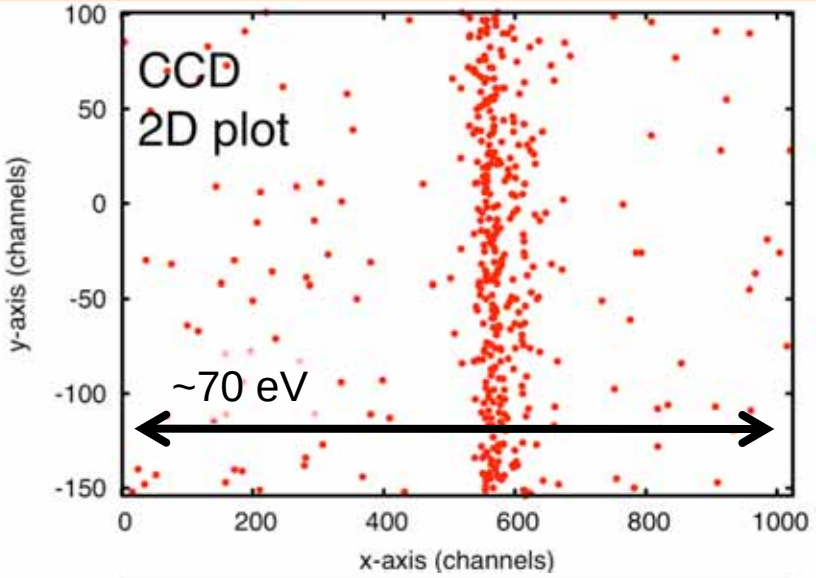
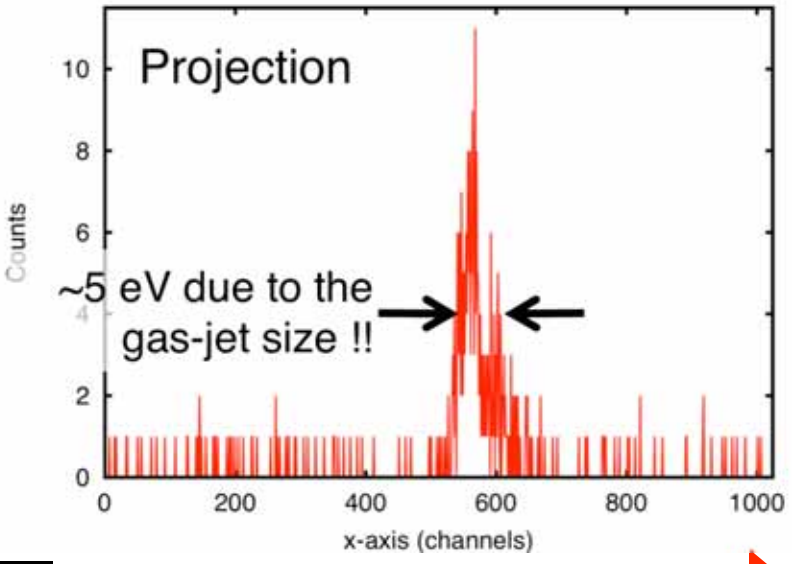
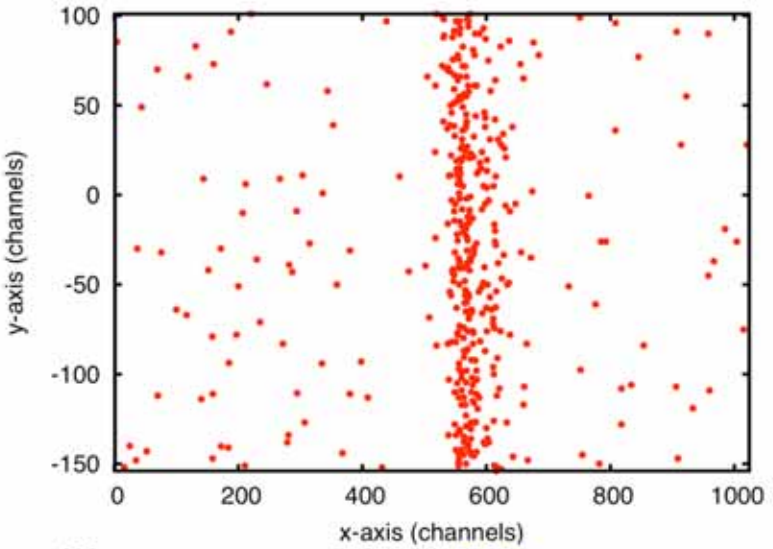




High resolution He- and Li-like U spectra

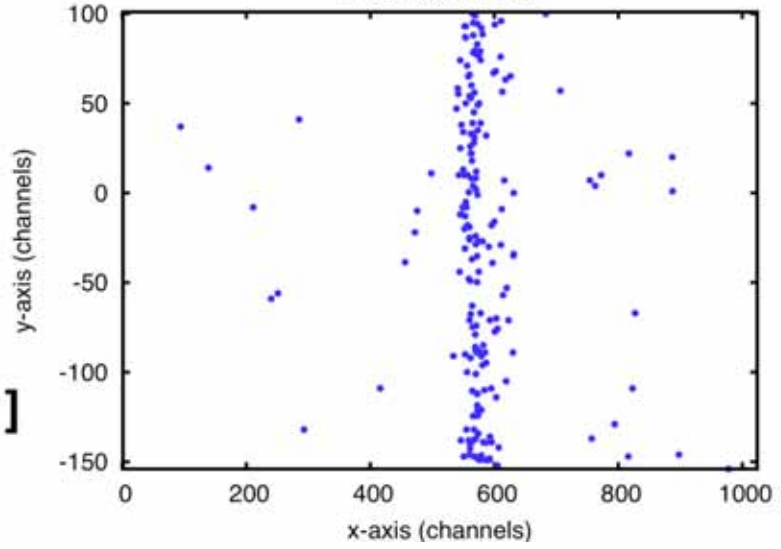
He-like uranium $1s2p\ ^3P_2$ - $1s2s\ ^3S_1$

- Counts: ~ 328
- Acquisition time: 24.6 hours
- Ion cin. energy: 43.55 Mev/u
- γ: 1.046771 ± 0.000020
- Transition energy: around 4510 eV



Li-like uranium $1s^22p\ ^2P_{3/2}$ - $1s^22s\ ^2S_{1/2}$

- Counts: ~167
- Acquisition time: 4.6 hours
- Ion energy: 32.60 Mev/u
- γ: 1.035025 ± 0.000020
- Transition energy **(Ref.): 4459.37 ± 0.21 eV [1]**



[1] P. Beiersdorfer et al., Phys. Rev. Lett. **71**, 3939 (1993), P. Beiersdorfer, Nucl. Instrum. Meth. B **99**, 114 (1995)

Energy

High resolution He- and Li-like U spectra

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Same transition energy in the laboratory frame (E= 4308 eV) ⇨ Systematic errors reduction!!

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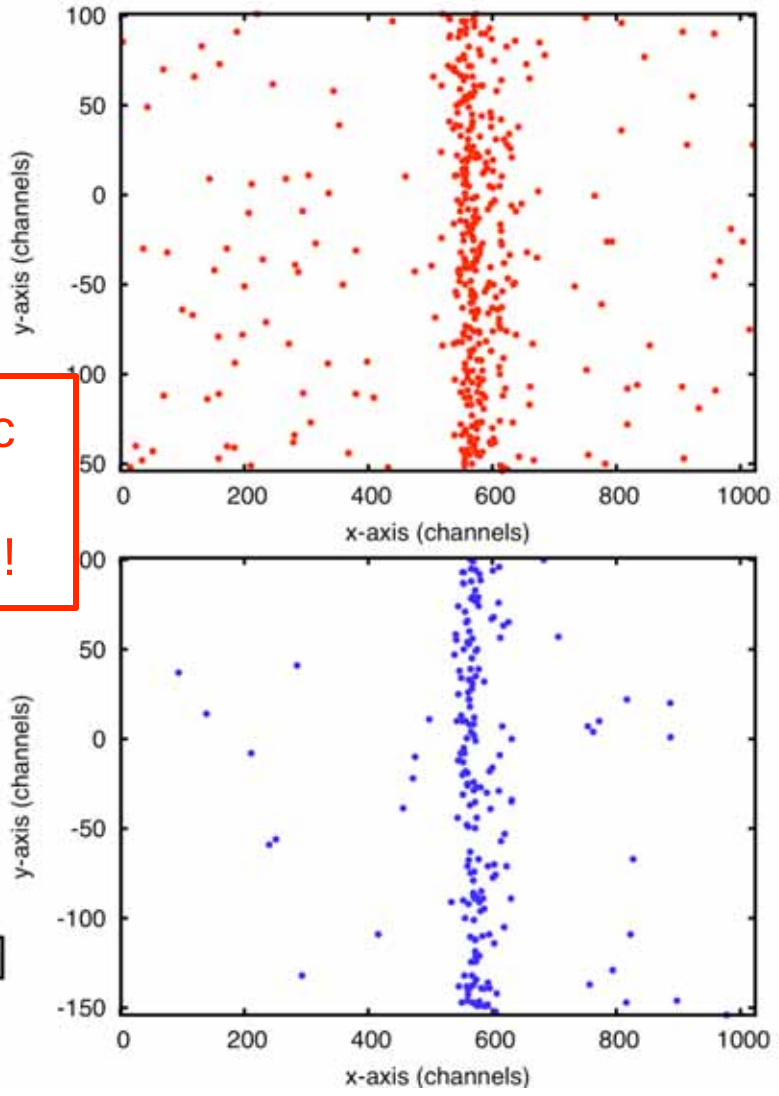

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High resolution He- and Li-like U spectra

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- Counts: ~ 328
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D = 575 mm

$$E_{\mathrm{He}} = E_{\mathrm{Li}} \frac{\gamma_{\mathrm{He}}}{\gamma_{\mathrm{Li}}} \left(1 + \frac{\Delta x}{\tan \Theta_B \ D} \right)$$

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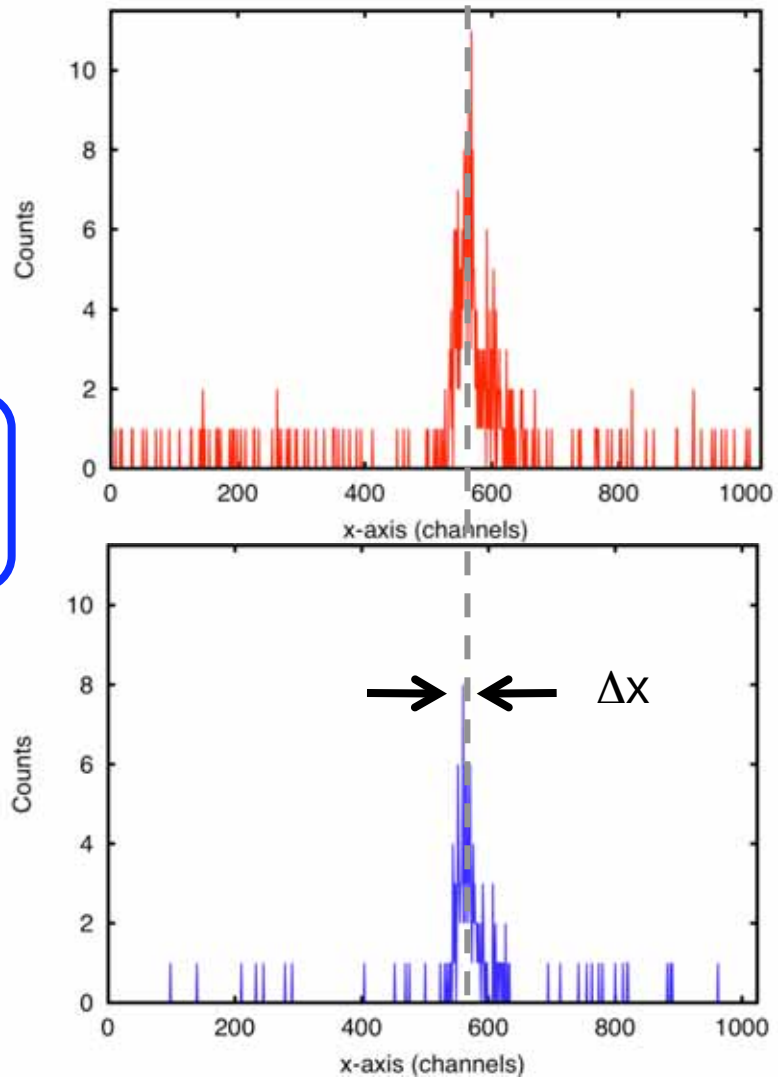
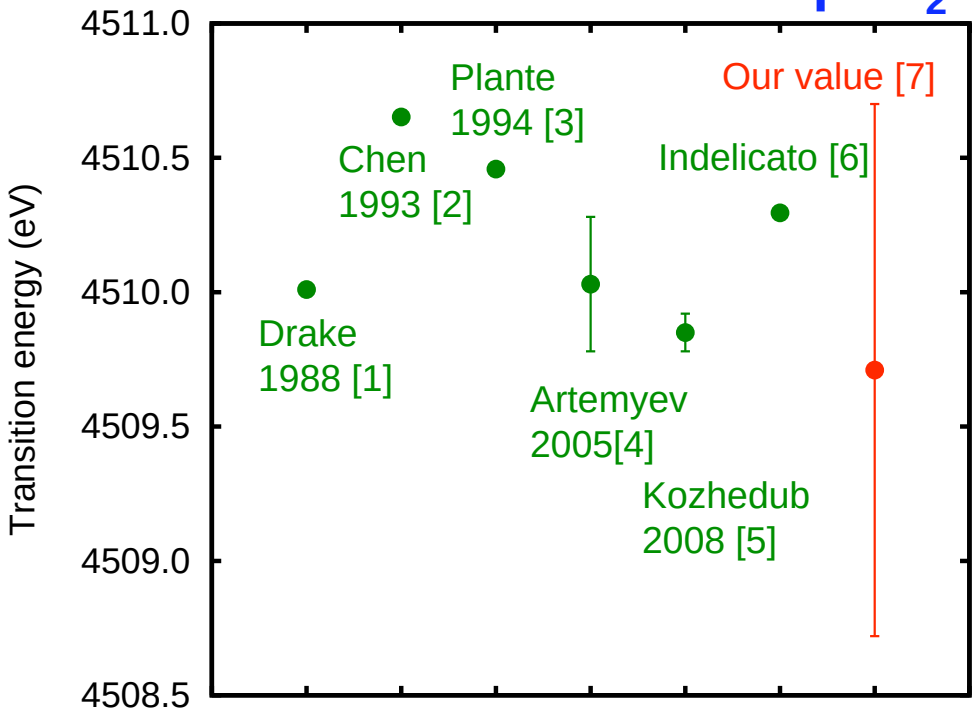


Comparison with theory He-like U

He-like uranium $1s2p\ ^3P_2$ - $1s2s\ ^3S_1$ transition energy



Our value: **4509.71 ± 0.99 eV**

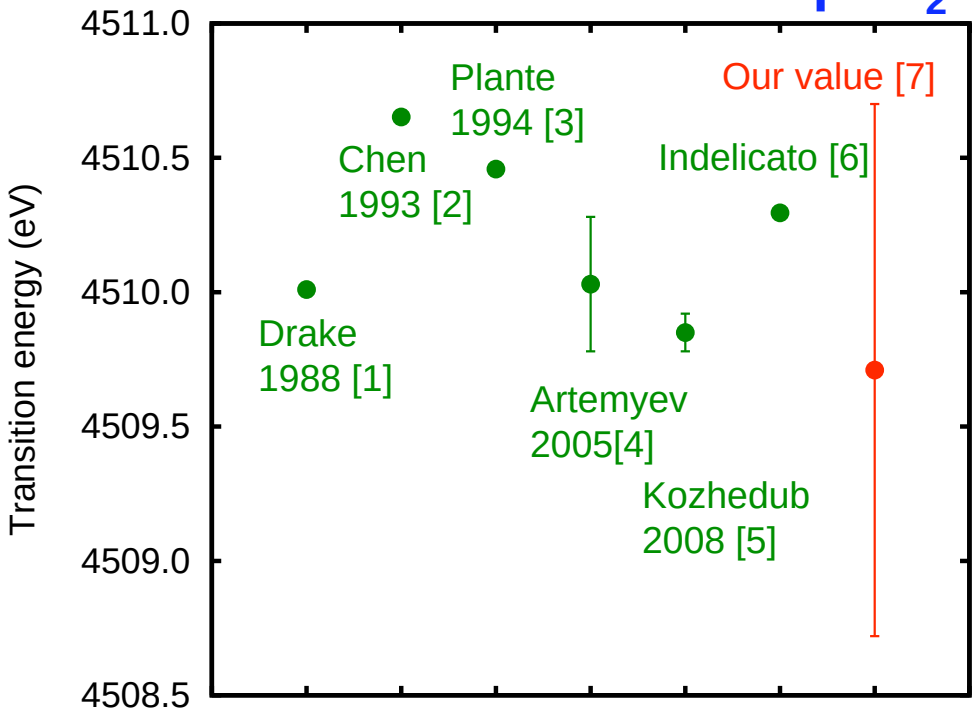
Theory: **4509.86 ± 0.07 eV [5]**

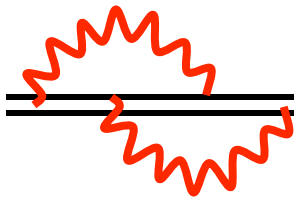
4510.03 eV [6]

[1] Drake, Can. J. Phys. **66**, 586 (1988), [2] Chen et al., Phys. Rev. A **47**, 3692 (1993),
[3] Plante et al., Phys. Rev. A **49**, 3519 (1994), [4] Artemyev et al., Phys. Rev. A **71**, 062104 (2005),
[5] Kozhedub and Shabaev, unpubblished (2008), [6] Indelicato, unpublished (2008),
[7] Trassinelli et al., Eur. Phys. Lett. 87, 63001 (2009).

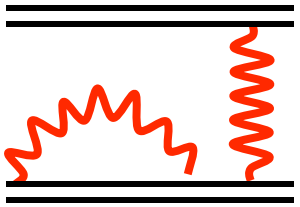
Comparison with theory He-like U

He-like uranium 1s2p $^3P_2$ - 1s2s $^3S_1$ transition energy





Two loop QED = 0.20 eV [4,5]



Two electron QED = 0.76 eV [4,5]

Our value: **4509.71 ± 0.99 eV**

Theory: **4509.86 ± 0.07 eV [5]**

4510.03 eV [6]

[1] Drake, Can. J. Phys. **66**, 586 (1988), [2] Chen et al., Phys. Rev. A **47**, 3692 (1993),
[3] Plante et al., Phys. Rev. A **49**, 3519 (1994), [4] Artemyev et al., Phys. Rev. A **71**, 062104 (2005),
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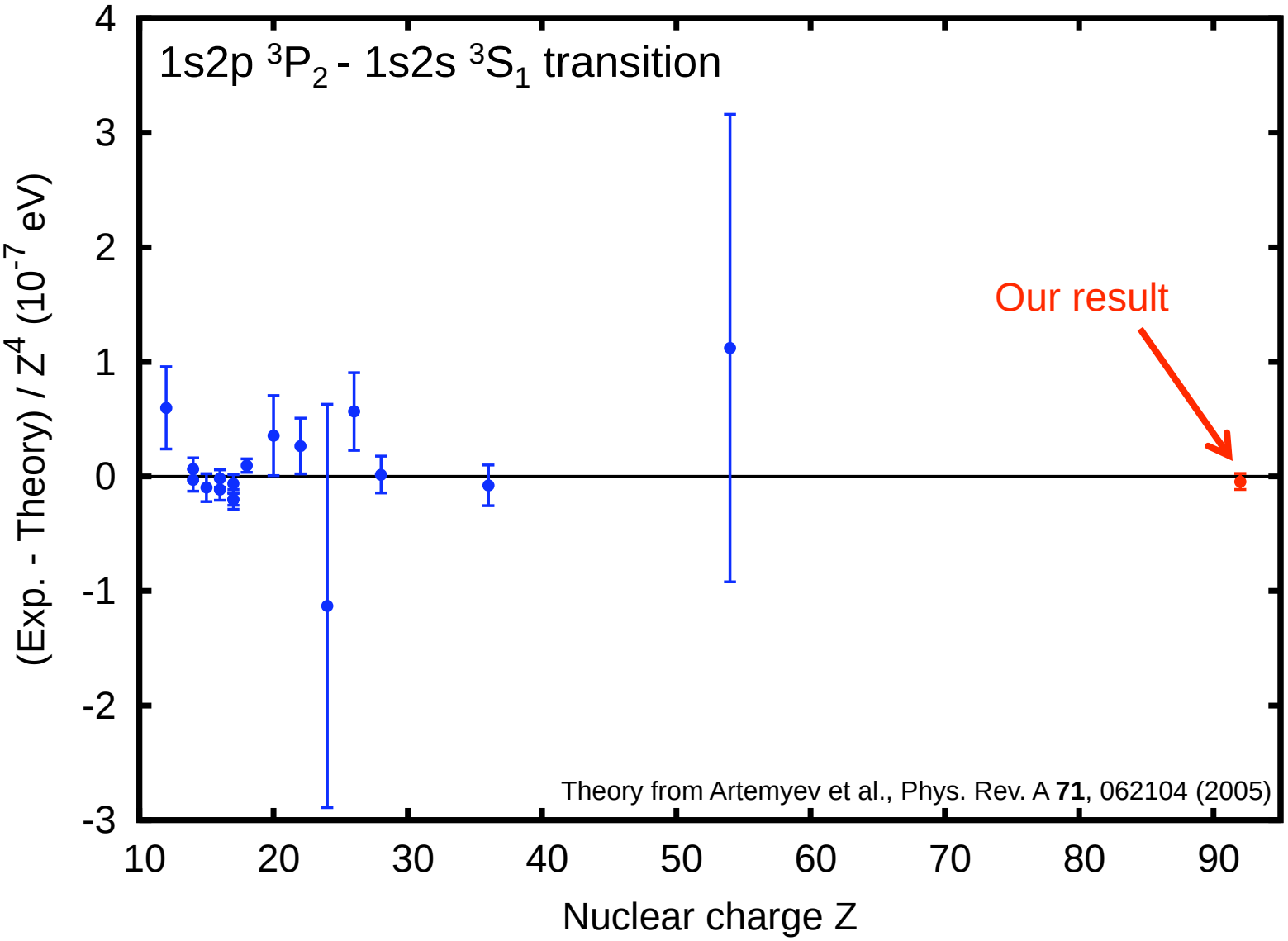
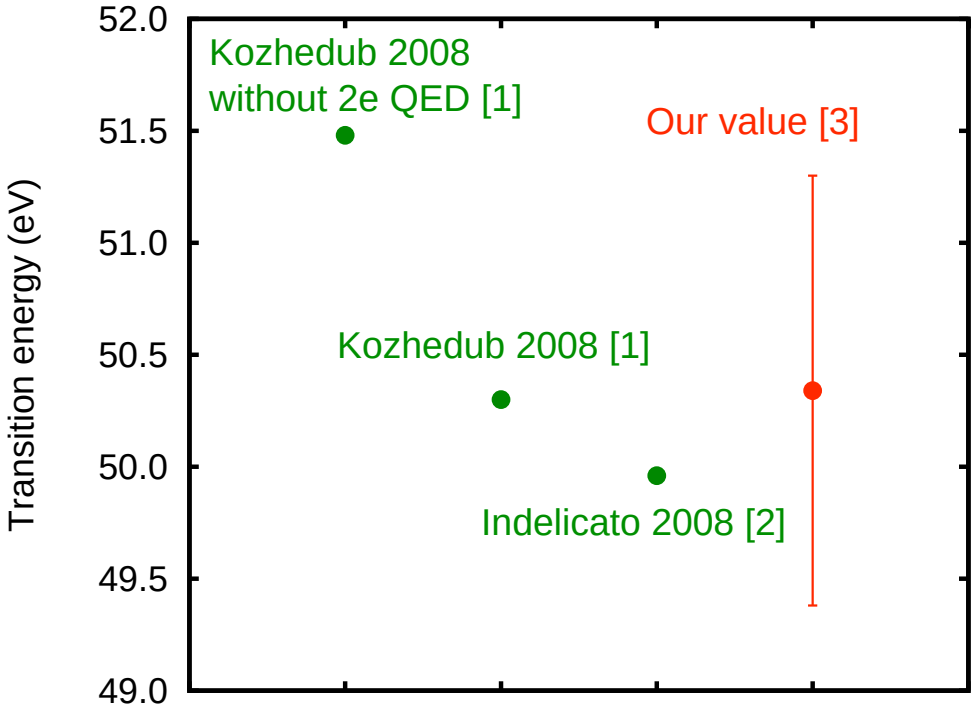
[7] Trassinelli et al., Eur. Phys. Lett. 87, 63001 (2009).

Theory v.s. experiments in He-like ion intra-shell transitions



Comparison with theory He- and Li-like U

$E_{\text{He-like U}}(1s2p\ ^3P_2 - 1s2s\ ^3S_1) - E_{\text{Li-like U}}(1s^22p\ ^2P_{3/2} - 1s^22s\ ^2S_{1/2})$



Experiment
No uncertainty due to the calibration line

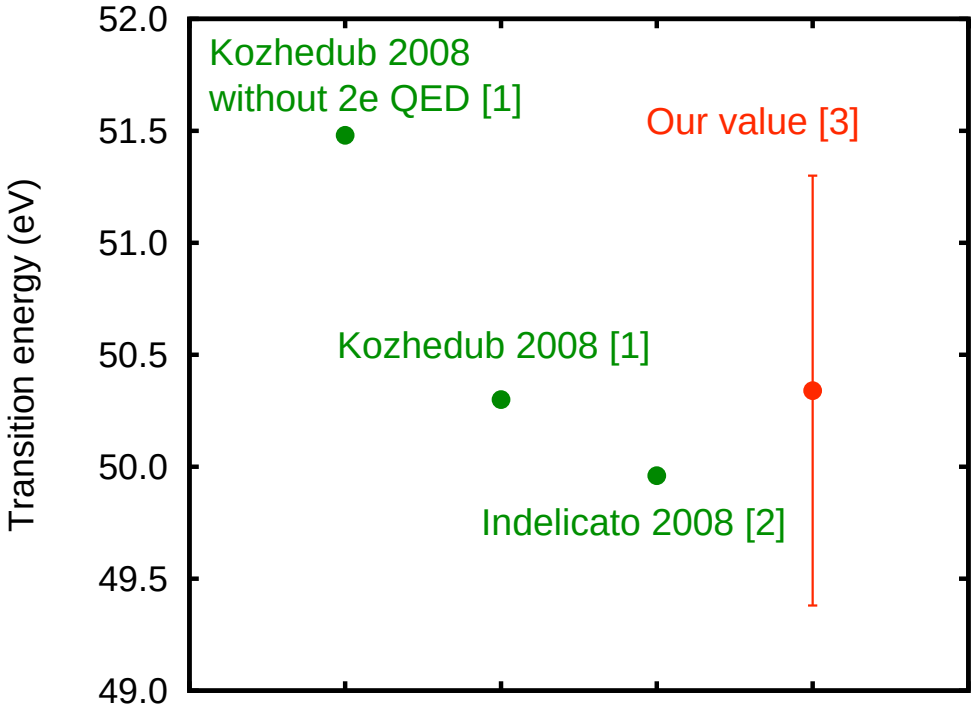
Theory
No uncertainty due to the nuclear radius and 1e QED

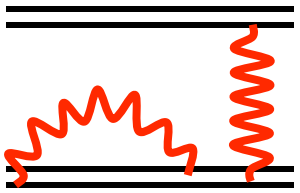
Our value: **50.34 ± 0.96 eV**
Theory: **50.30 ± 0.03 eV [1]**
49.96 eV [2]

[1] Kozhedub and Shabaev, unpublished (2008), [2] Indelicato, unpublished (2008),
[3] Trassinelli et al., Eur. Phys. Lett. 87, 63001 (2009).

Comparison with theory He- and Li-like U

$E_{\text{He-like U}}(1s2p\ ^3P_2 - 1s2s\ ^3S_1) - E_{\text{Li-like U}}(1s^2 2p\ ^2P_{3/2} - 1s^2 2s\ ^2S_{1/2})$





Two electron QED
= -1.18 eV [1]

Starting to be sensitive to
the 2e QED!!

Our value: **50.34 ± 0.96 eV**

Theory: **50.30 ± 0.03 eV [1]**

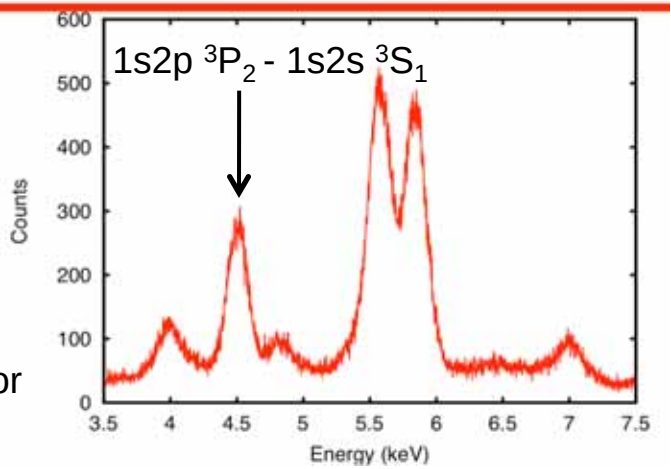
49.96 eV [2]

[1] Kozhedub and Shabaev, unpublished (2008), [2] Indelicato, unpublished (2008),
[3] Trassinelli et al., Eur. Phys. Lett. 87, 63001 (2009).

Conclusions

- First clear identification of the 1s2p $^3P_2$ - 1s2s $^3S_1$ transition in He-like uranium

Ge(i) detector



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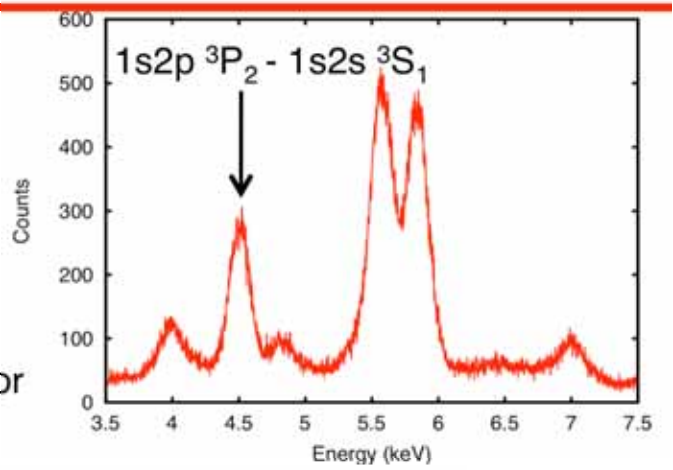
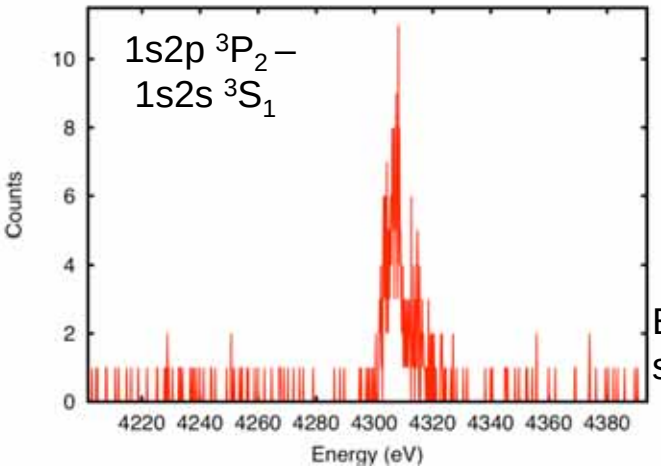


Ge(i) detector

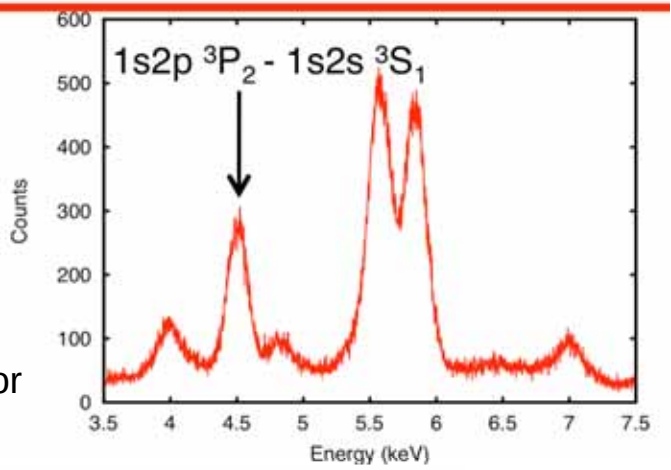
- Precise measurement of the transition using Doppler tuned Bragg spectroscopy: **$\delta E/E = 10^{-4}$**



Bragg spectrometer

Conclusions

- First clear identification of the 1s2p $^3P_2$ - 1s2s $^3S_1$ transition in He-like uranium



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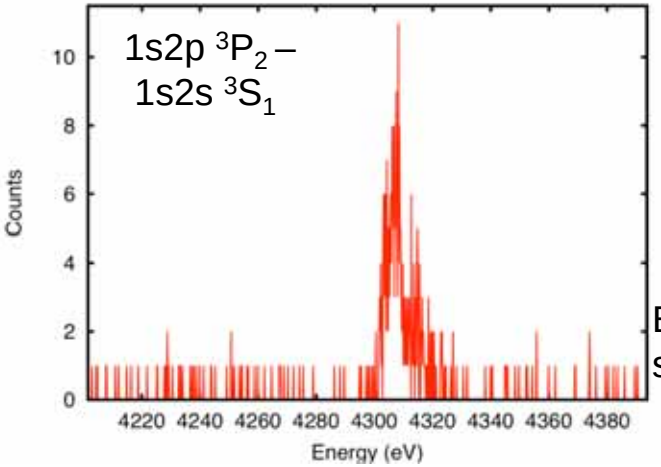
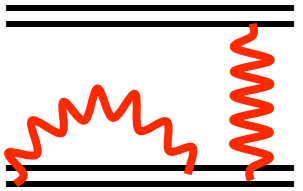


Bragg spectrometer

- First test of two-electron QED in excited levels of heavy He-like ions:

δE = 1.0 eV, $\Delta E_{2e\ QED}$ ~ 0.8 eV (He-like U)

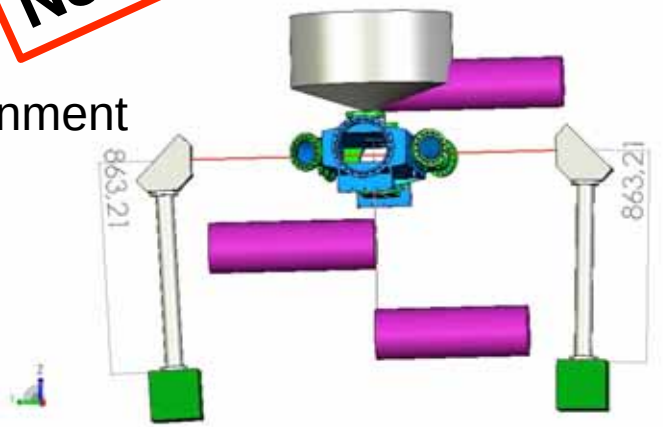
δE = 0.9 eV, $\Delta E_{2e\ QED}$ ~ -1.2 eV (He- and Li-like U)



Outlooks

- **Repeat the experiment for a better accuracy**
  - More beam time (now only 3-4 days)!!
  - Larger dispersion for the crystal spectrometer
  - Better spectrometer crystal (Ge (220) with R=2000)
  - Twin pair of spectrometer at ± 90° for gas jet misalignment compensation

New proposal!!



$\delta E = 1$ eV → 0.1 eV

$\Delta E_{2e\ QED} \sim 0.8$ eV in He-like uranium

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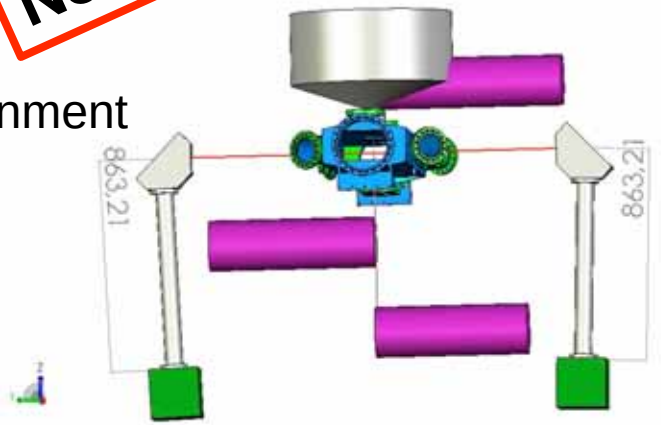

- **Extension to other atomic systems**
  - Intra-shell transitions in Li-, Be-, B-like, …. heavy ions

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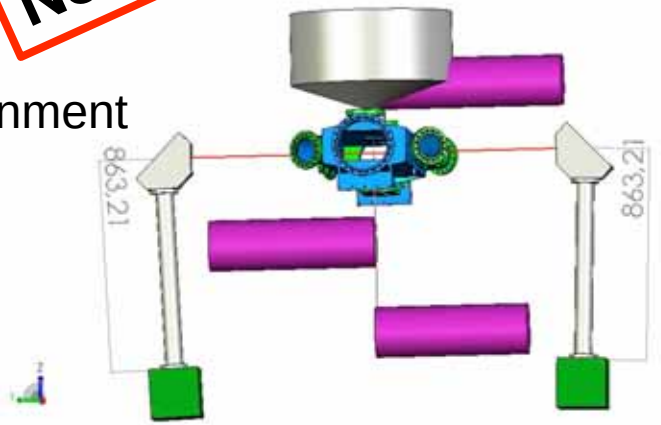

$\delta E = 1$ eV → 0.1 eV

- **Extension to other atomic systems**
  - Intra-shell transitions in Li-, Be-, B-like, …. heavy ions

- **More upgrades**
  - Smaller gas-jet target → **possible gain of a factor 5!!**
  - Microcalorimeter detector

Our team

M.T.[1]
A. Kumar[2]
H.F. Beyer[3]
P. Indelicato[4]
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R. Reuschl[1]
Y.S. Kozhedub[6]
C. Brandau[3]
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S. Geyer[3]
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S. Hess[3]
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C. Kozhuharov[3]
S. Trotsenko[9]
G. Weber[3,5]
D.F.A. Winters[3,5]
and Th. Stöhlker[3,5,9]

(1) Institut des NanoSciences de Pari, Paris, France
(2) Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, India
(3) GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
(4) Laboratoire Kastler Brossel, Paris, France
(5) Physikalisches Institut, Univ. Heidelberg, Heidelberg, Germany
(6) Department of Physics, St. Petersburg State Univ., St. Petersburg, Russia
(7) ExtreMe Matter Institue, Darmstadt, Germany
(8) Institute of Physics, Jan Kochanowski Univ., Kielce, Poland
(9) Helmholtz-Institut Jena, Jena, Germany

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THE END

Thank you!

Other material

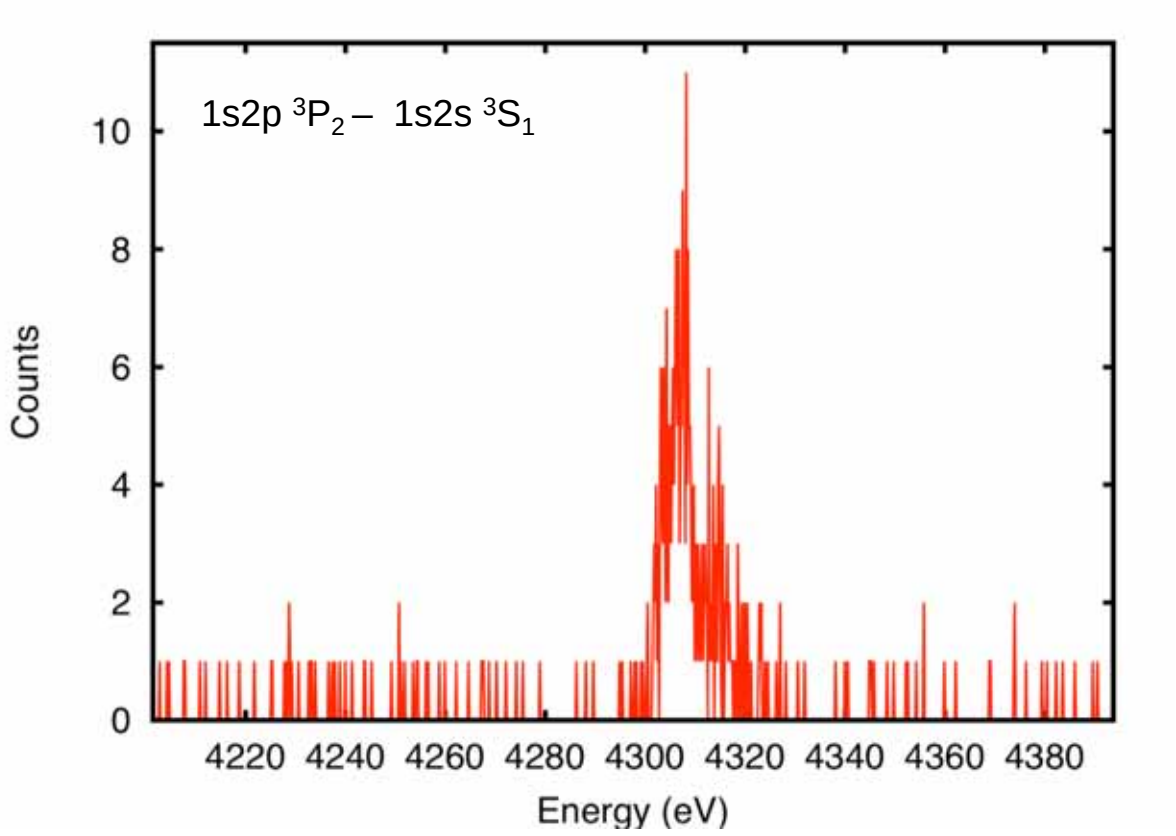
The speaker's attendance at this conference was sponsored by the Alexander von Humboldt Foundation.

- http://www.humboldt-foundation.de

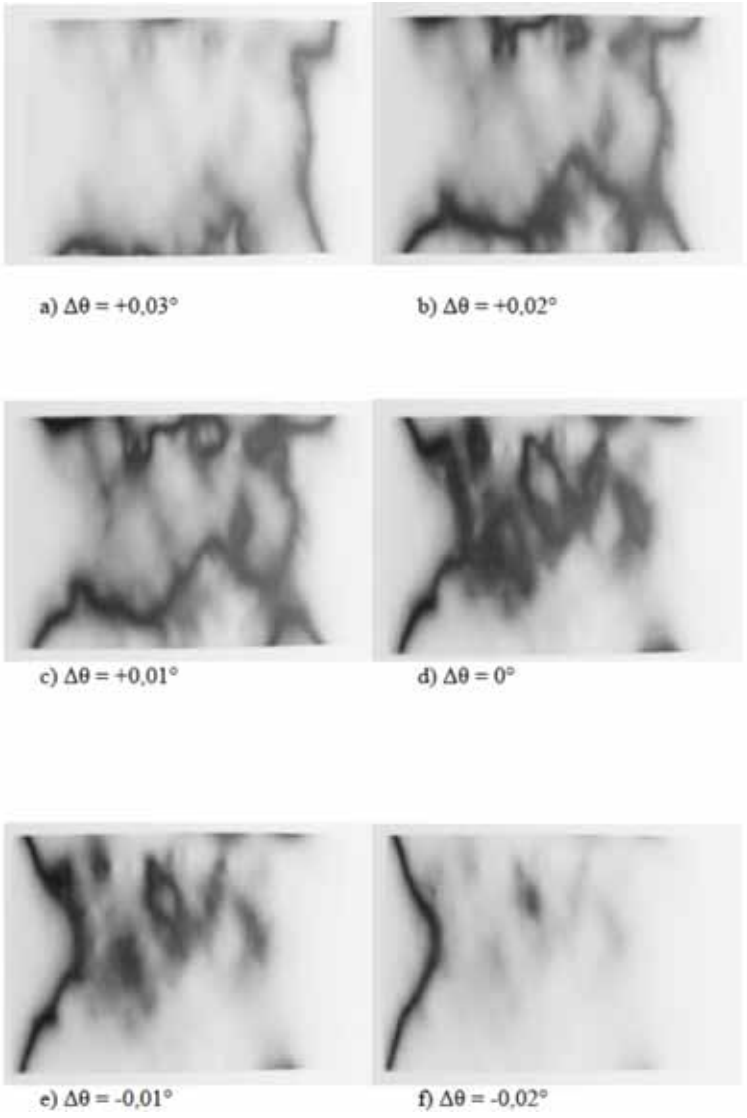
Detailed values

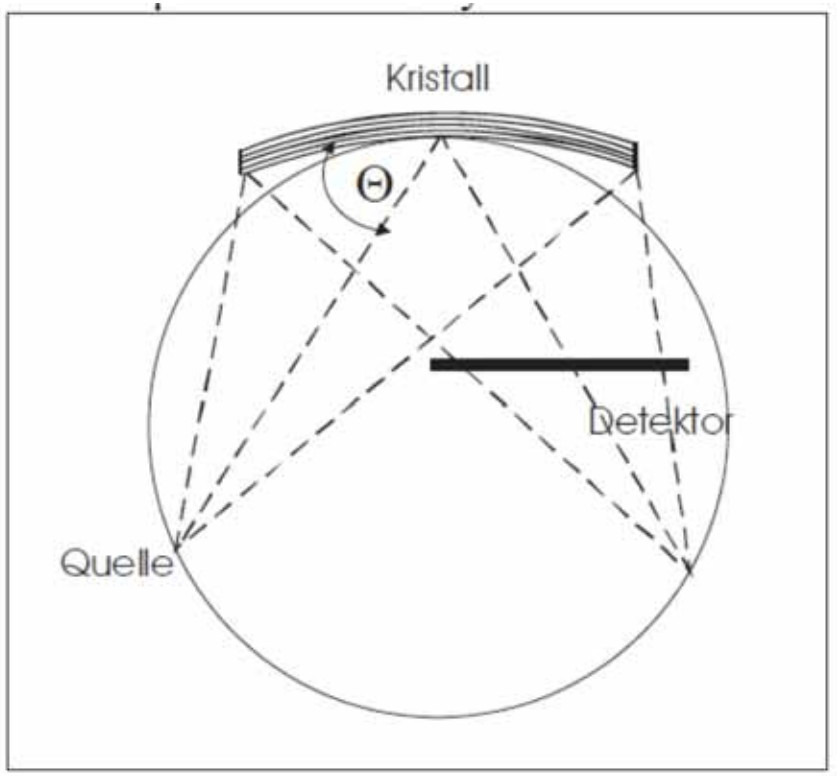
He-like U: $4509.71 \pm 0.48_{stat} \pm 0.83_{asym} \pm 0.24_{syst}$ eV

He- Li-like U difference: $54.34 \pm 0.48_{stat} \pm 0.83_{asym} \pm 0.11_{syst}$ eV



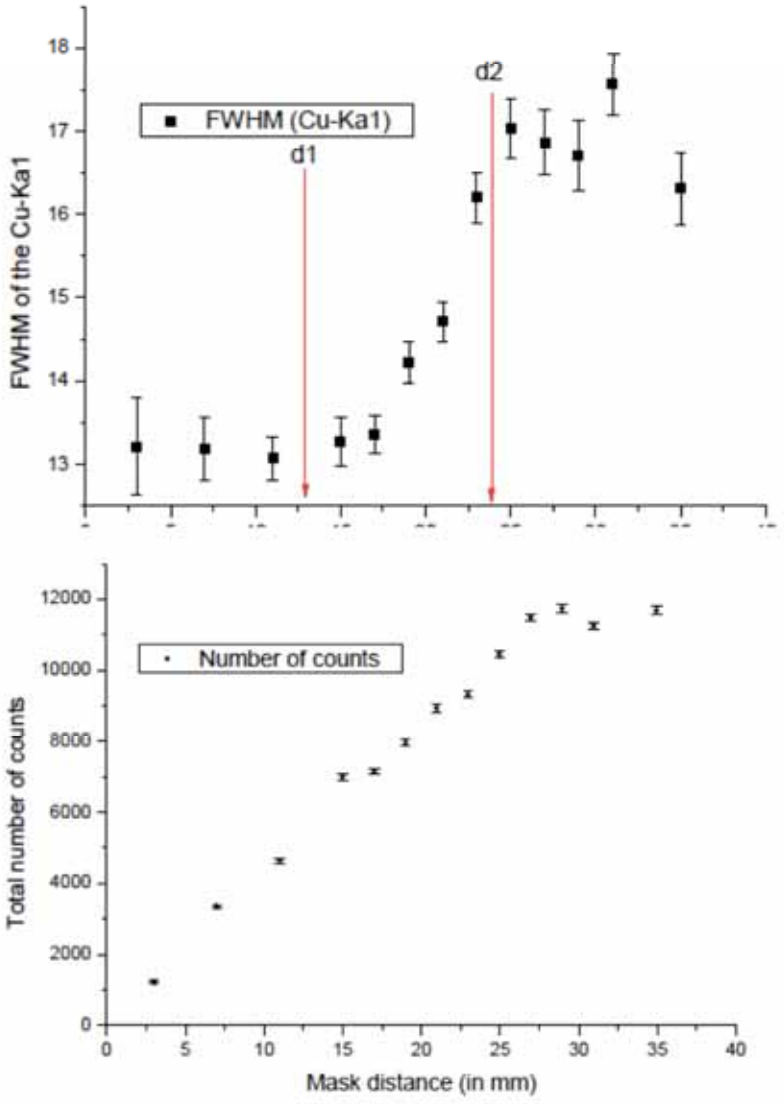
Crystal characterization

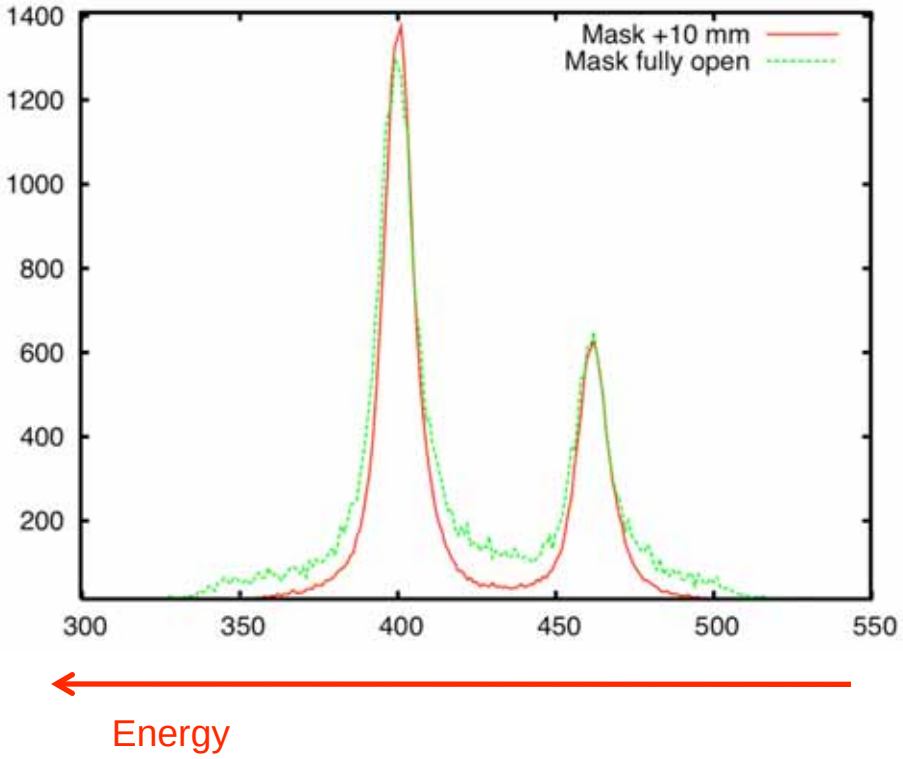




Characterization made by
O. Wehrhan, H. Marschner and E. Förster
from Jena X-ray Optics group

Crystal characterization





New proposal

Beam-Time Budget		
	previous	new
crystal	Ge (220)	Ge (220)
R (mm)	800	2000
Efficiency	7×10^{-7}	3×10^{-7}
FWHM	5 eV	2.8 eV
ΔE (stat)	0.5 eV	0.1 eV
# cts [He]	300 cts / 24 h	1100 cts / 8.5 d
# cts [Li]	160 cts / 5h	1100 cts / 3.5 d
Net Beam Time	29 h	12 d
Overhead (switching beams)	3.5 d	4 d
Total Beam Time	4.5 d	**16 d**

Outlooks

- **Repeat the experiment for a better accuracy**
  - **Statistics**
    - More beam time (now only 3-4 days)!!
    - Larger dispersion for the crystal spectrometer

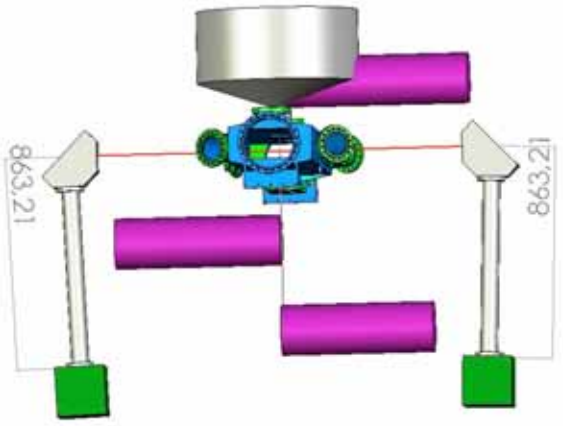
$$\delta E_{stat} = 0.5 \text{ eV} \rightarrow 0.1 \text{ eV}$$

    - Smaller gas-jet target → **possible gain of a factor 5!!**
  - **Systematic effects**
    - Better crystal for the spectrometer

$$\delta E_{peak\ asym} = 0.83 \text{ eV} \rightarrow 0.0 \text{ eV}$$

    - Twin pair of spectrometer at 90° for gas jet misalignment compensation

$$\delta E_{align} = 0.11 \text{ eV} \rightarrow 0.03 \text{ eV (?)}$$



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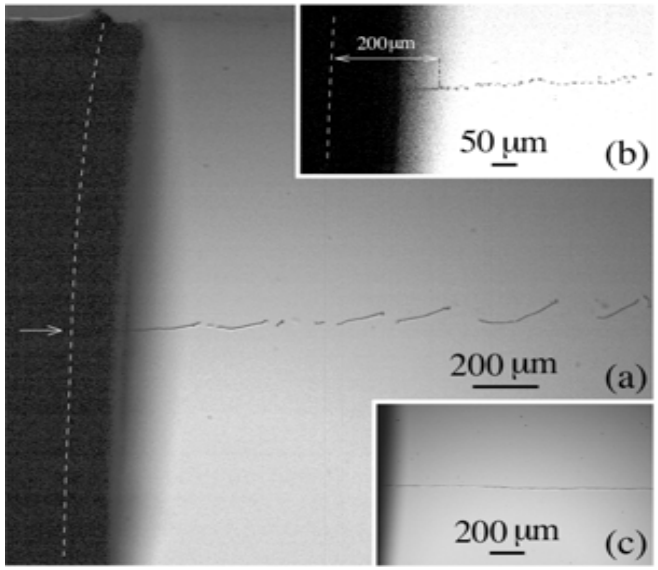
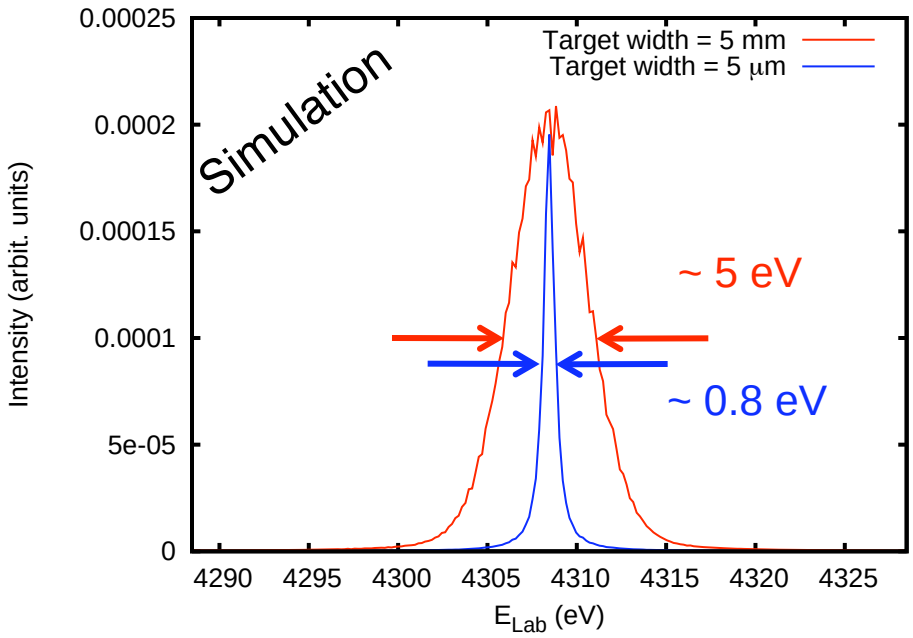


Micro-droplet target
(R. Grisenti)



A crystal spectrometer for fast ions

Bragg crystal spectrometer in Johann configuration

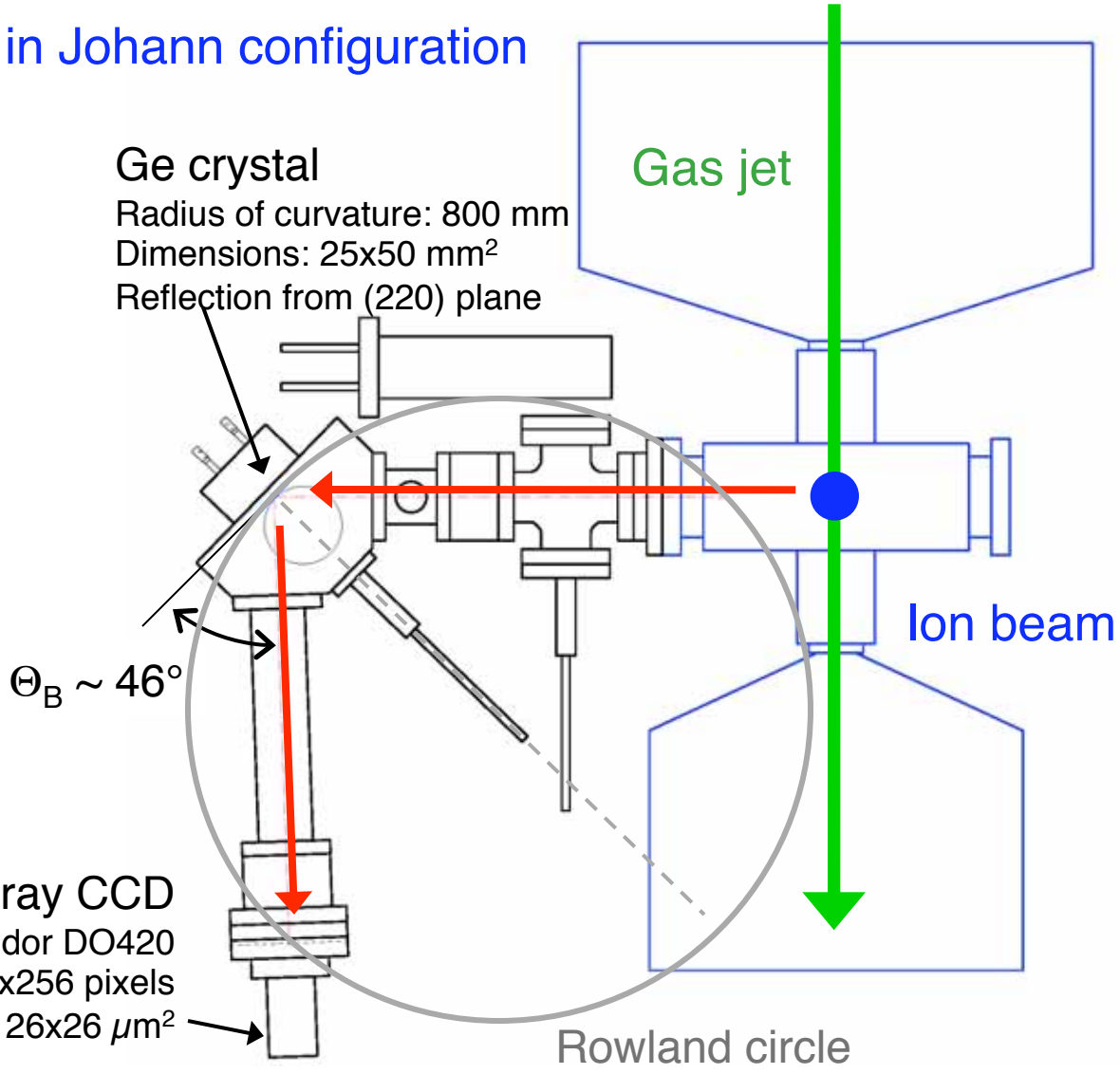
- Cylindrically bent crystal
➔ x-ray foussing

- Reflection plane perpendicular to the ions
➔ minimization of the Doppler effect

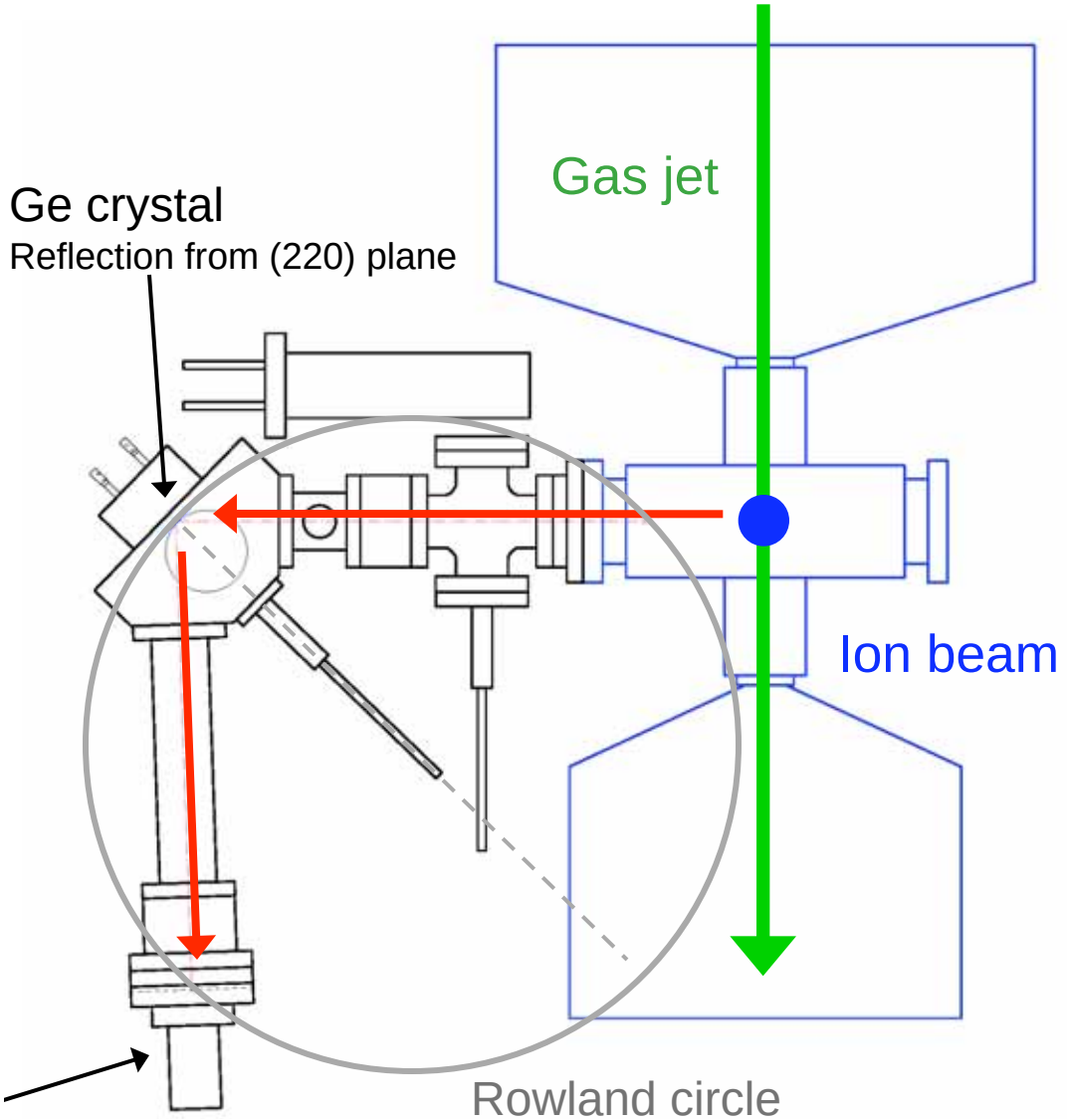
- Position of the reflected line
➔ measurement of the energy transition

$$\frac{hc}{E} = 2d \sin\Theta_{\mathrm{Bragg}}$$

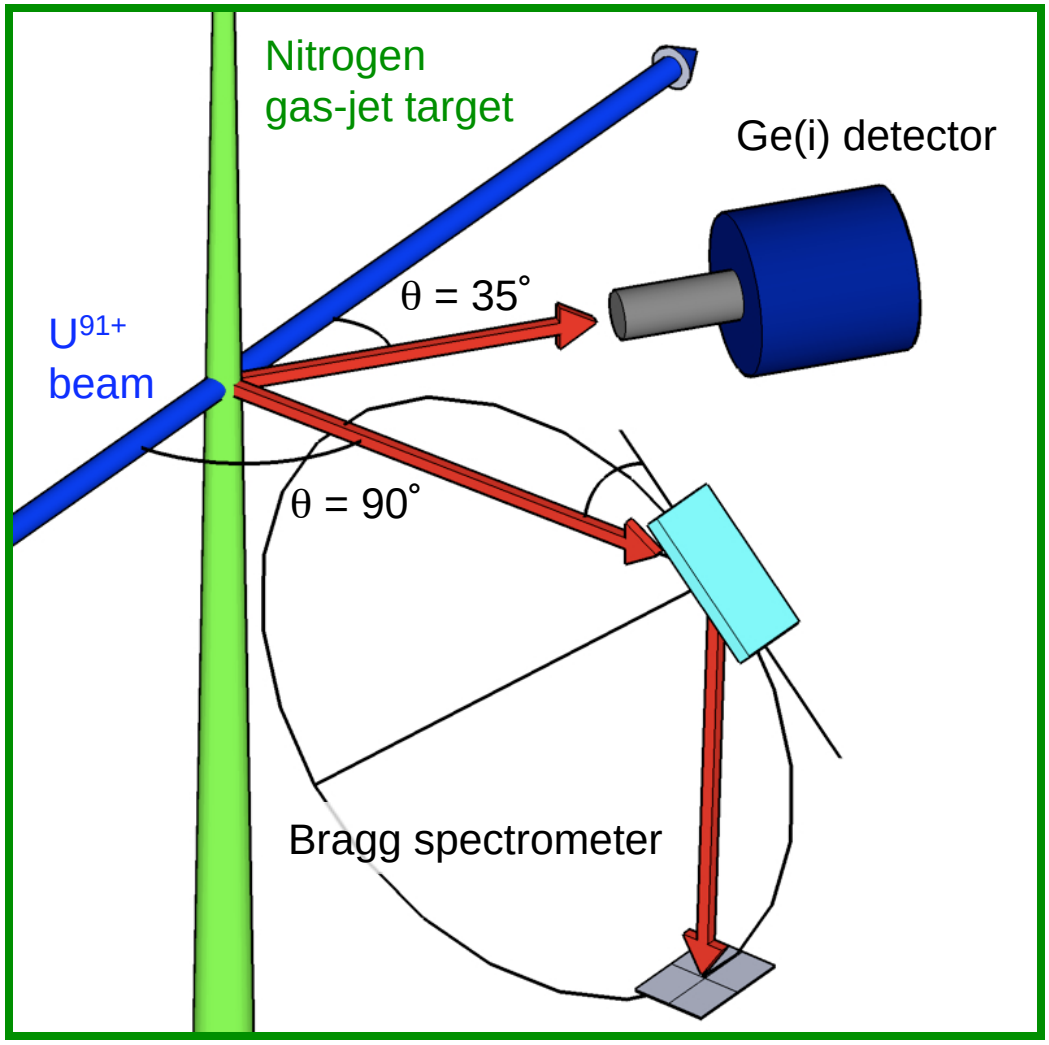
Θ_{Bragg} : Bragg angle
h : Planck constant
c : speed of light
d : crystal plane spacing



The crystal spectrometer at the ESR



Data acquisition of He-like U transitions



Important data:

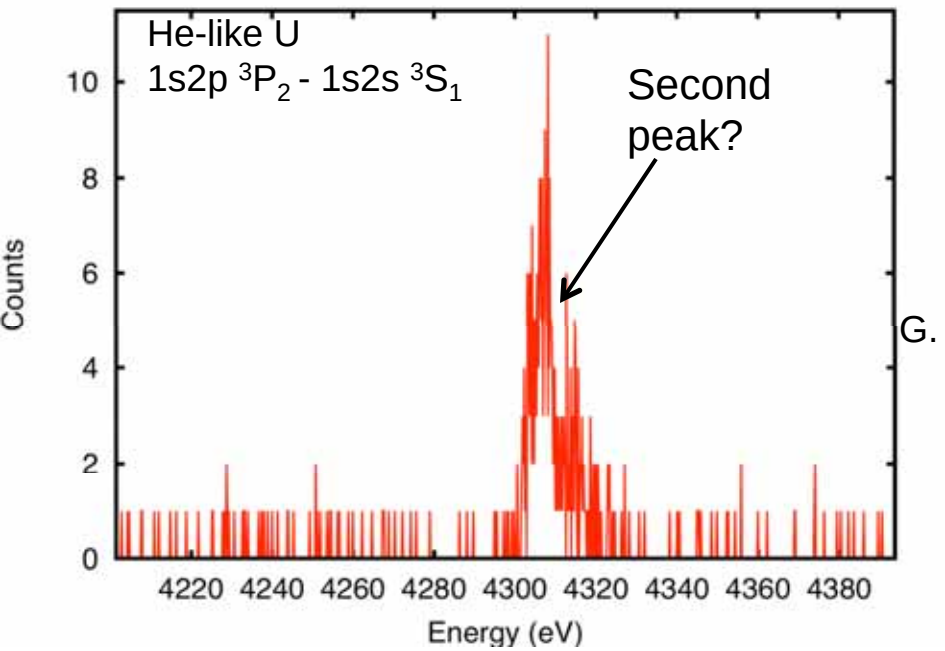
- Ion energy: 43.55 Mev/u
- β: 0.29558 ± 0.00019
- γ: 1.046771 ± 0.000020

- Gas-target density: 10^{12} part./cm^3

- H-like stored ions: ~ 10^8
- Ion current in ESR: ~ 1.7 mA

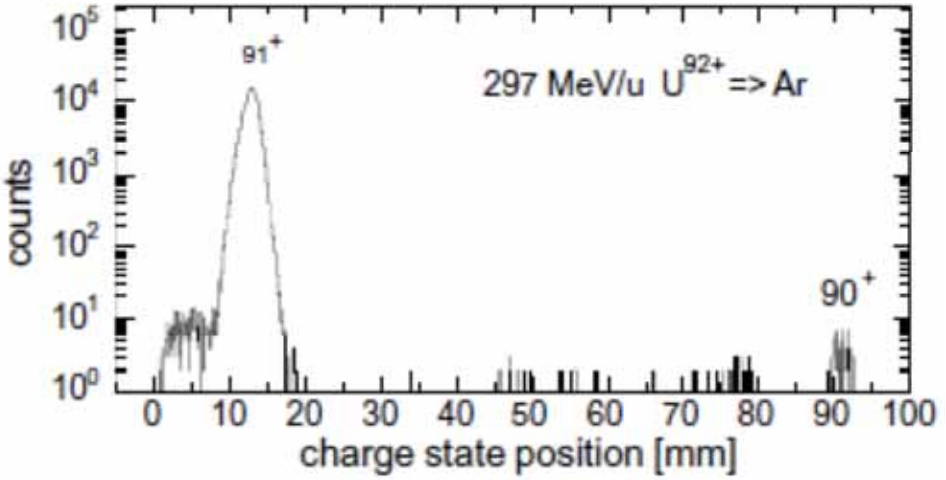
- **Acquisition time: 24.6 hours**

Peak asymmetry



In the laboratory frame

Double capture at the ESR gas jet



G. Bednarz et al., Nucl. Instrum. Meth. B **205**, 573-576 (2003)

Transitions between 4300 and 4320 eV

Element	Transition	Theoretical Energy (eV)	Direct Exp. Energy (eV)	Ref.
Te	L_3N_4	4 300.31(91)	4 301.70(18)	1d
Te	L_3N_5	4 301.89(91)	4 301.70(18)	1d
Xe	L_1M_1	4 303.2(19)		
I	L_1M_3	4 312.8(19)	4 313.49(20)	1d

Back to Search

NIST National Institute of Standards and Technology Physics Laboratory

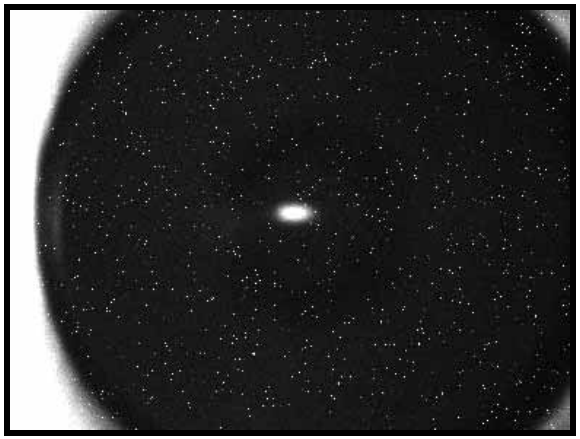
Outlooks

- **Repeat the experiment for a better accuracy**
  - **Statistics**
    - More beam time (now 3-4 days)!! → gain of a factor ~2 in the accuracy
    - Smaller gas-jet target → **possible gain of a factor 5!!**

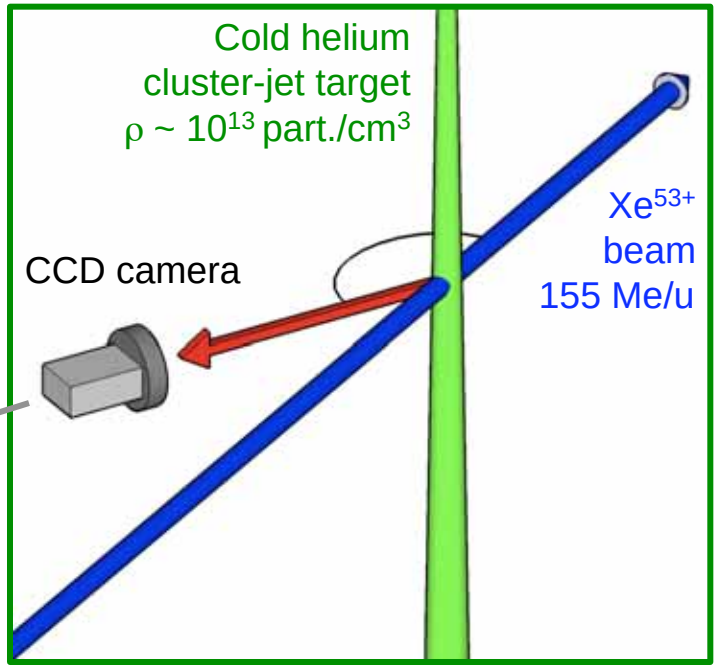
$$\delta E_{stat} = 0.43 \text{ eV} \rightarrow 0.04 \text{ eV}$$

  - **Systematic effects**
    - Better diagnostic on the gas-jet position → more accurate observation angle

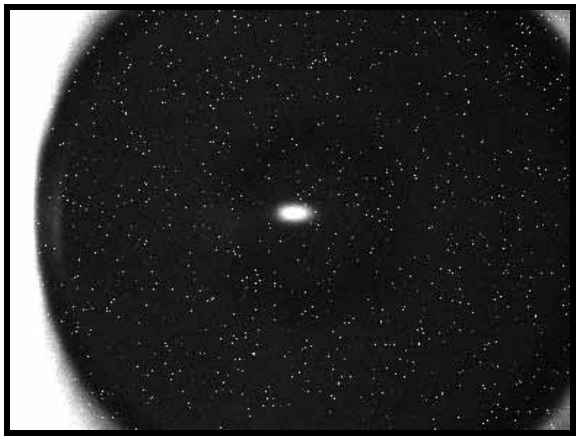
March 2008 experiment

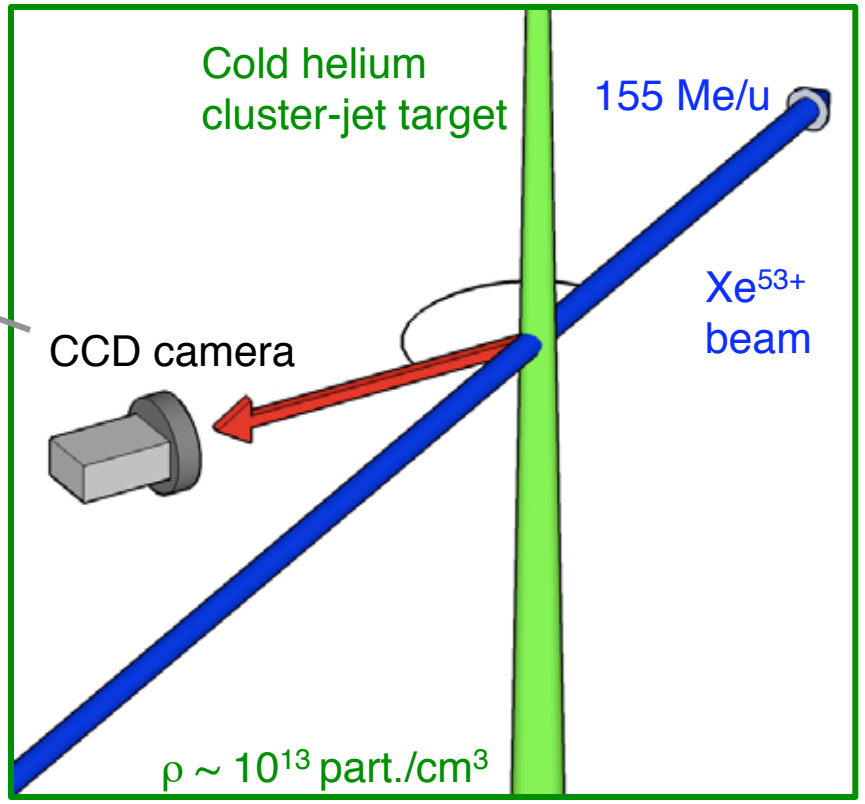


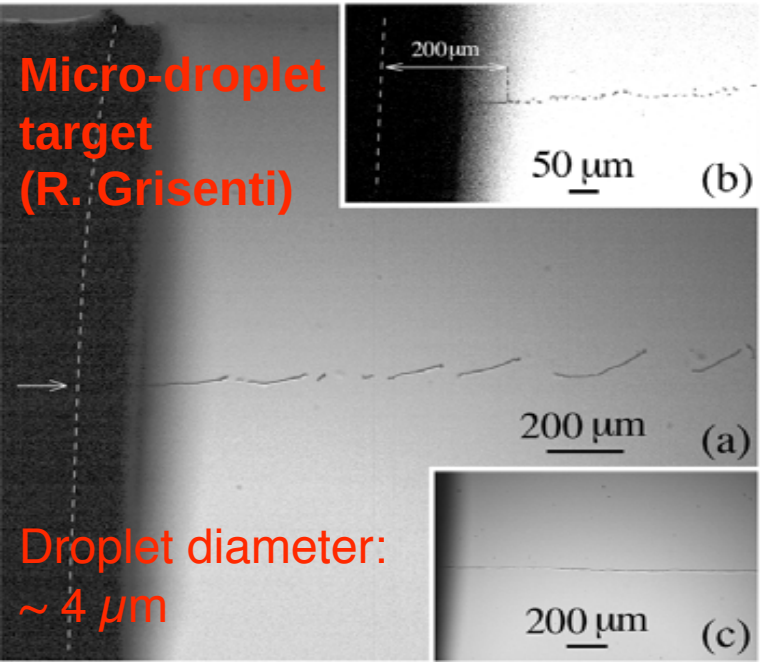
See next talk from N. Petridis



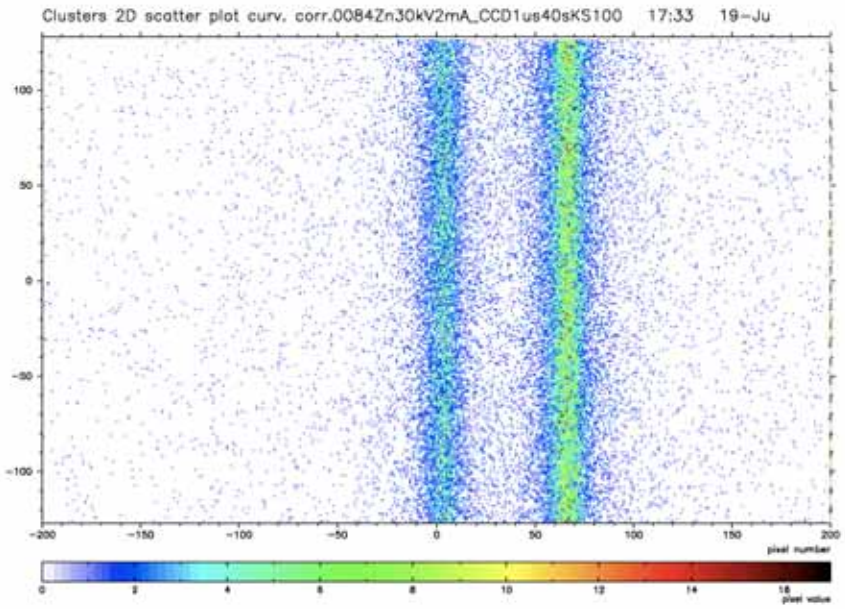
New target and new diagnostic

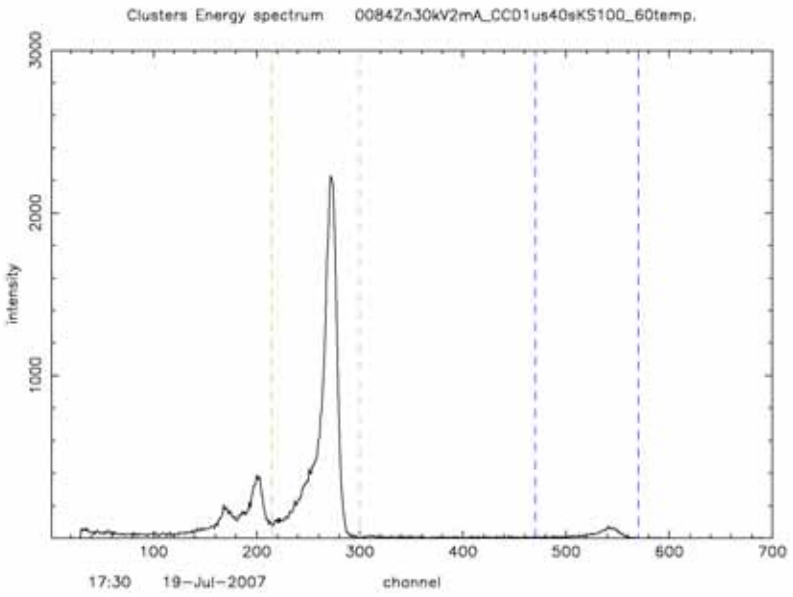






CCD energy spectra for Zn Kα lines





CCD energy spectra for He-like U