High resolution spectroscopy of K-shell transitions in highly charged xenon ions.

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Overview

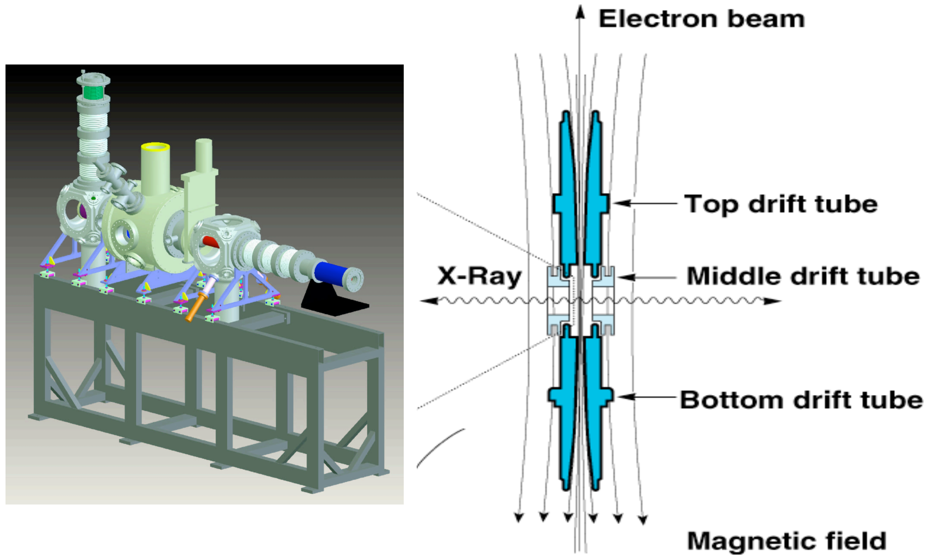
- Introduction
- Low Temperature Detectors in the Hard X-ray
- Precision Energy Measurements for Xe Ions
- EIE measurement for Xe ions

High-Z HCI spectroscopy

- Provide tests of QED and relativity in the strong field of a heavy nucleus.
  - Transition energies scale as Z^2 while QED and relativity scale as Z^4
- Few precision high-Z measurements then for lower-Z.
- Test dynamics of collisions for heavy systems
  - Of use for the next generation plasma devices

Production of HCI

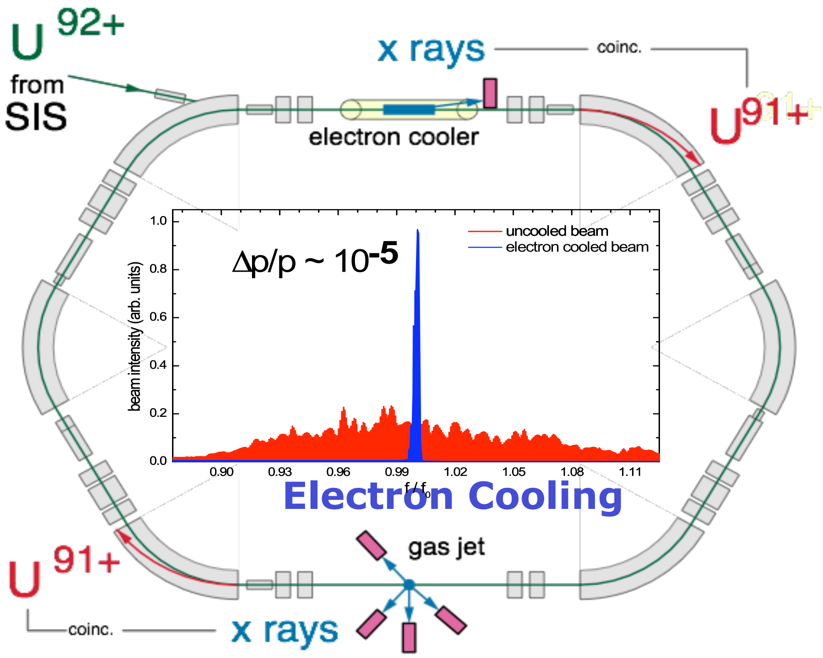
Electron Beam Ion Trap (EBIT)



Moving Electrons

Stationary Ions

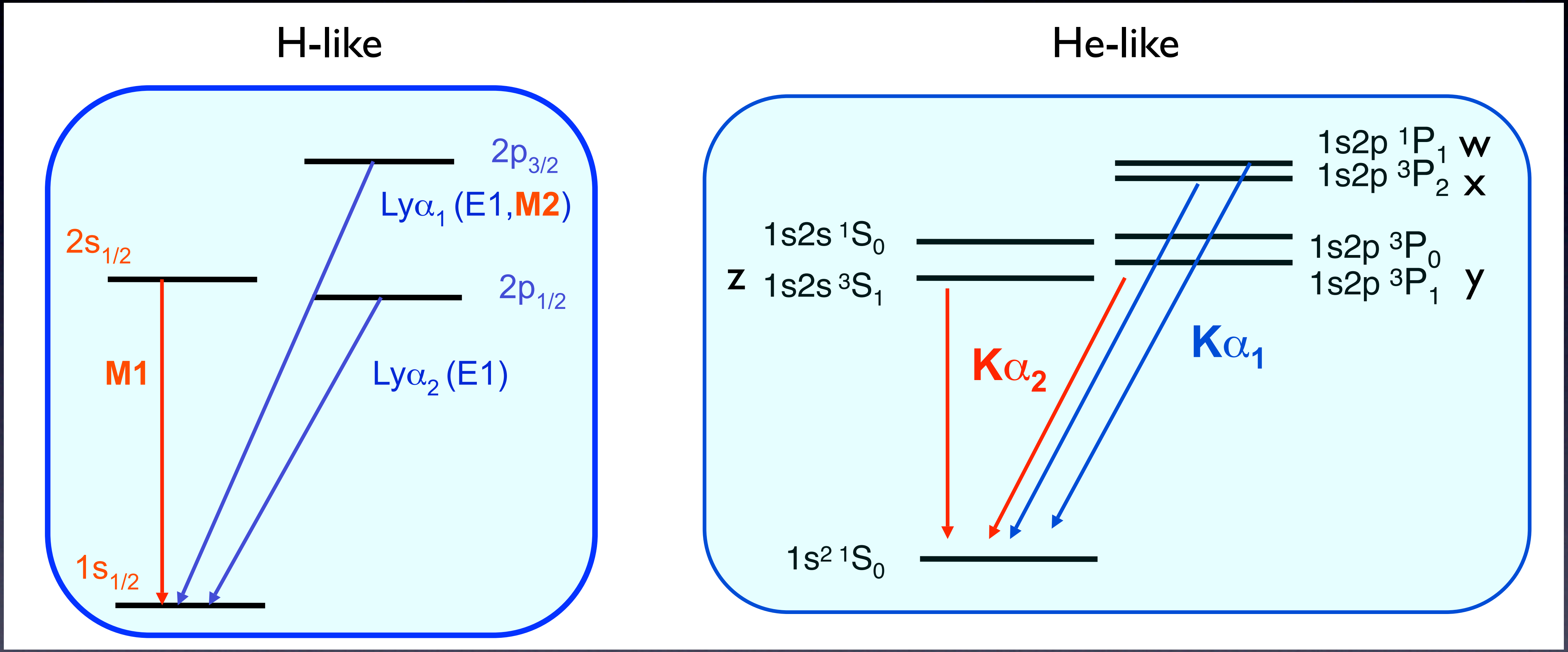
Storage Ring (ESR)



Stationary Electrons

Moving Ions

Level Diagrams for H-like and He-like transitions



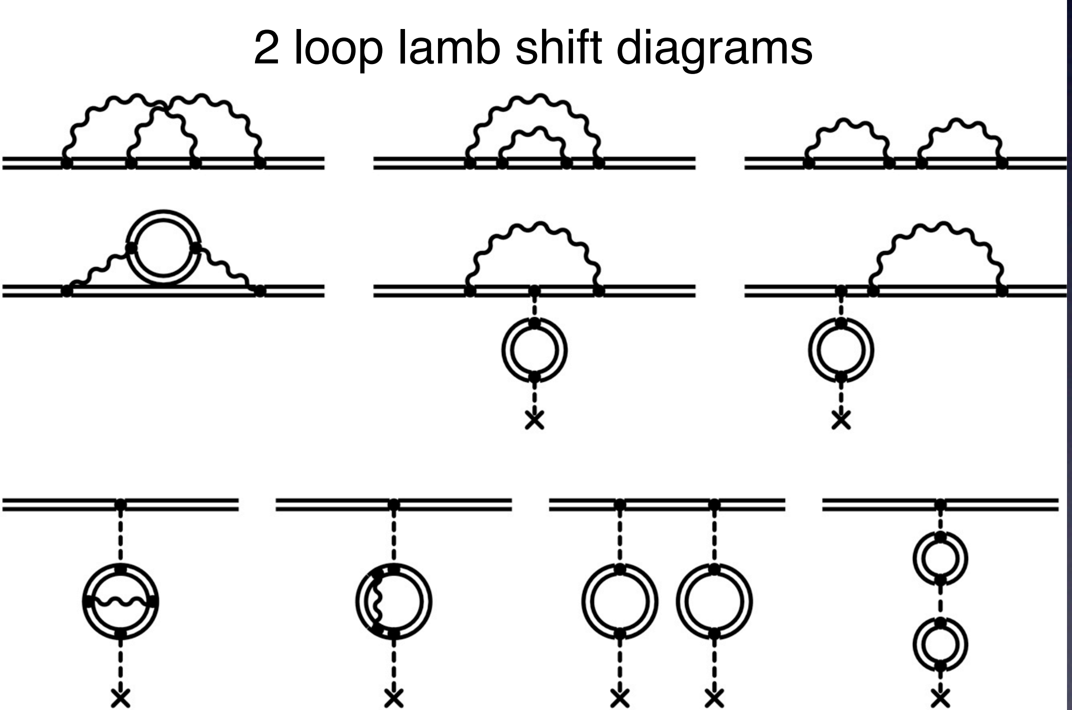
Because of relativity structure of He-like and H-like are similar. Operating in the J-J coupling regime

Some spectroscopic terms: Historical

- Resonance line = electric dipole transition
  - He-like = w
  - H-like = Lyman alpha 1 or 2
- Intercombination line = electric dipole transition that arises because of mixing of the LS states
  - He-like = y
- Forbidden line = completely E1 forbidden
  He-like = z

High Precision: Holy Grail?

- A 1 eV measurement of uranium allows for a direct test of QED at the "2 loop" level. The "Holy Grail" of high-Z spectroscopy.
- One of the limiting factors is due to the poor resolving power of solid state detectors which are the work horse of current detection schemes.
- To due that we need to push back from traditional solid state detector systems and look for higher resolution instruments.



What else can a 1 eV measurement bring?

- Measure helium-like transitions, which are of importance in a number of applications including hypothetical experiments for atomic parity violation*.
  - Differing ways of calculating He-like systems causes confusion as to which theory to use.
- Measure electron impact excitation cross-sections.
- Test QED scattering corrections: Generalized Breit Interaction (GBI) for electron impact excitation.
  - GBI is the first QED correction in scattering and modifies the line ratios of resonance/intercombination lines.

* ref: A. Schäfer and G. Soff et. al, PRA **40**, 7362 (1989), Labzowsky et. al, PRA 63 (2001)

Generalized Breit Interaction: Dynamical QED

- GBI is the first order QED correction to the process of an electron scattering off an ion/atom.
- Changes spectral line ratios
- In very high-Z ions the effect can be as great as a factor of 2
- an important effect to consider for high temperature fusion devices
- As of yet untested

Table of collision strengths for near threshold excitation*

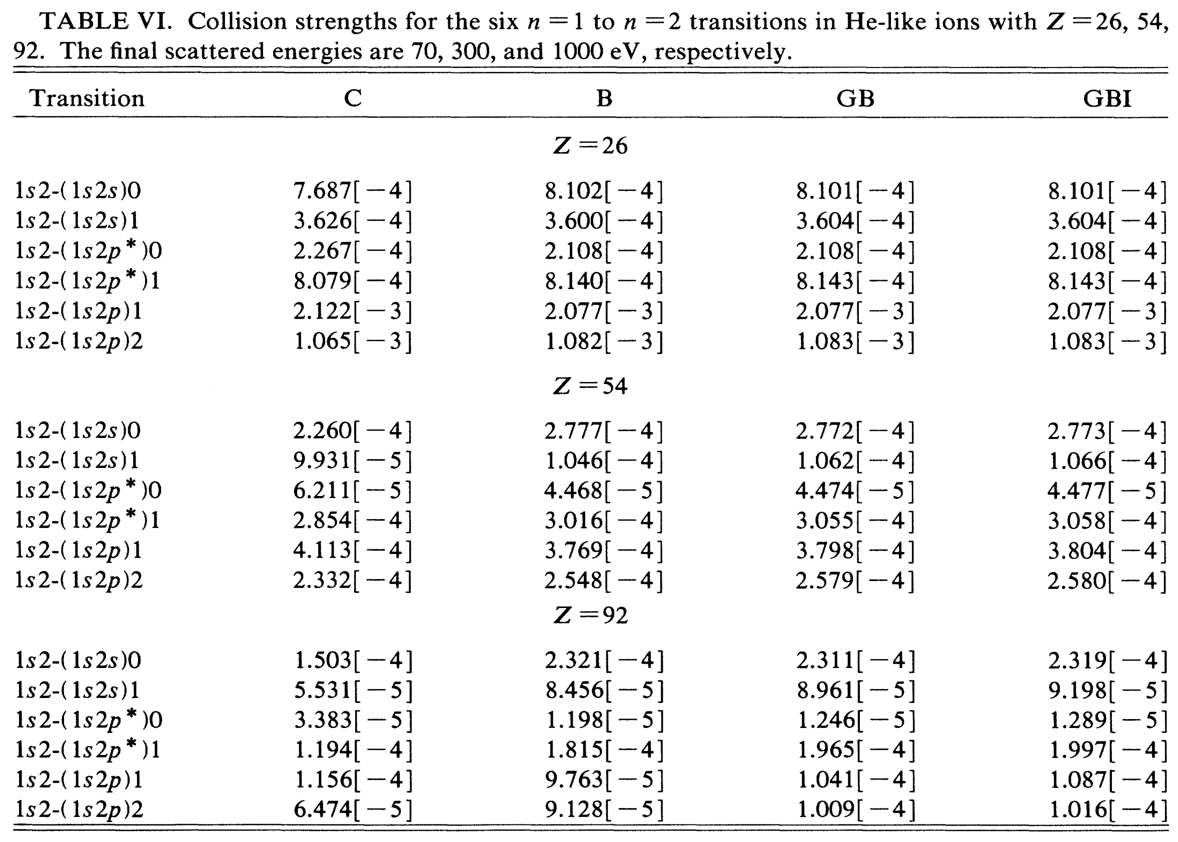


TABLE VI. Collision strengths for the six $n=1$ to $n=2$ transitions in He-like ions with $Z=26$, 54, 92. The final scattered energies are 70, 300, and 1000 eV, respectively.

Transition	C	B	GB	GBI
		$Z=26$		
1*s*2-(1*s*2*s*)0	7.687[−4]	8.102[−4]	8.101[−4]	8.101[−4]
1*s*2-(1*s*2*s*)1	3.626[−4]	3.600[−4]	3.604[−4]	3.604[−4]
1*s*2-(1*s*2*p**)0	2.267[−4]	2.108[−4]	2.108[−4]	2.108[−4]
1*s*2-(1*s*2*p**)1	8.079[−4]	8.140[−4]	8.143[−4]	8.143[−4]
1*s*2-(1*s*2*p*)1	2.122[−3]	2.077[−3]	2.077[−3]	2.077[−3]
1*s*2-(1*s*2*p*)2	1.065[−3]	1.082[−3]	1.083[−3]	1.083[−3]
		$Z=54$		
1*s*2-(1*s*2*s*)0	2.260[−4]	2.777[−4]	2.772[−4]	2.773[−4]
1*s*2-(1*s*2*s*)1	9.931[−5]	1.046[−4]	1.062[−4]	1.066[−4]
1*s*2-(1*s*2*p**)0	6.211[−5]	4.468[−5]	4.474[−5]	4.477[−5]
1*s*2-(1*s*2*p**)1	2.854[−4]	3.016[−4]	3.055[−4]	3.058[−4]
1*s*2-(1*s*2*p*)1	4.113[−4]	3.769[−4]	3.798[−4]	3.804[−4]
1*s*2-(1*s*2*p*)2	2.332[−4]	2.548[−4]	2.579[−4]	2.580[−4]
		$Z=92$		
1*s*2-(1*s*2*s*)0	1.503[−4]	2.321[−4]	2.311[−4]	2.319[−4]
1*s*2-(1*s*2*s*)1	5.531[−5]	8.456[−5]	8.961[−5]	9.198[−5]
1*s*2-(1*s*2*p**)0	3.383[−5]	1.198[−5]	1.246[−5]	1.289[−5]
1*s*2-(1*s*2*p**)1	1.194[−4]	1.815[−4]	1.965[−4]	1.997[−4]
1*s*2-(1*s*2*p*)1	1.156[−4]	9.763[−5]	1.041[−4]	1.087[−4]
1*s*2-(1*s*2*p*)2	6.474[−5]	9.128[−5]	1.009[−4]	1.016[−4]

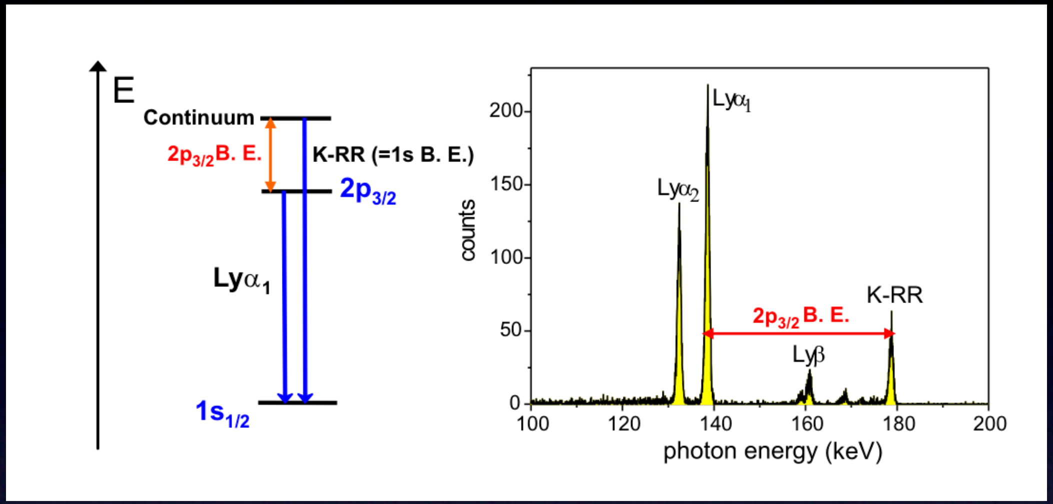
* Ref: Fontes et. al, PRA 47, 1009 (1993)

Current Detectors: Low count rate sources

- Use high QE detectors because x-ray flux very low.
- Solid state detectors, like high purity Ge detectors, have E/∂E resolving powers on the order of 100 for high-Z atomic transitions.
- Detectors for the under 10 keV x-ray band can have resolving powers well exceeding 3000.
- To fully resolve the high-Z spectra resolving powers exceeding 1000 are needed.

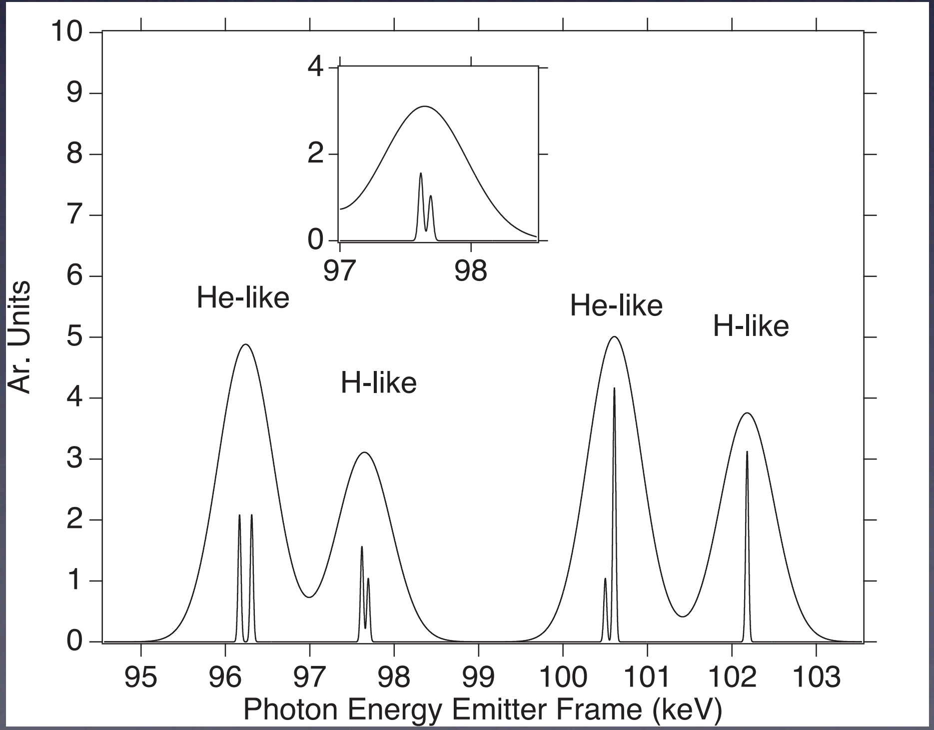
Need New Detectors!

- Current state of the art in a H-like measurement of U is Gumberidze 2005.
- Was able to obtain a 4.5 eV measurement of the Lamb shift.
- Confirms first order QED only
- To get to under 1 eV we need a factor of 5-10 improvement in detector FWHM.
- Thermal detectors might be able to directly determine the 2s lamb shift...



Gumberidze et al., PRL 94 (2005)

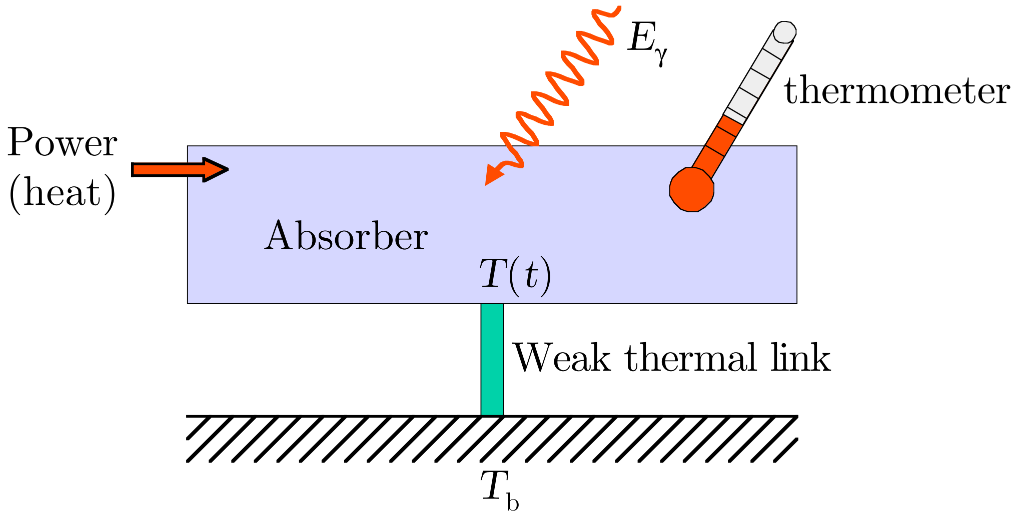
Simulated spectrum of He- and H-like U DE lines for Ge detector (750 eV) and x-ray calorimeter spectrometer (40 eV)



X-Ray Calorimeter Spectrometer (XCS)

Calorimeter Spectrometer: Basics

Schematic of Calorimeter Principle



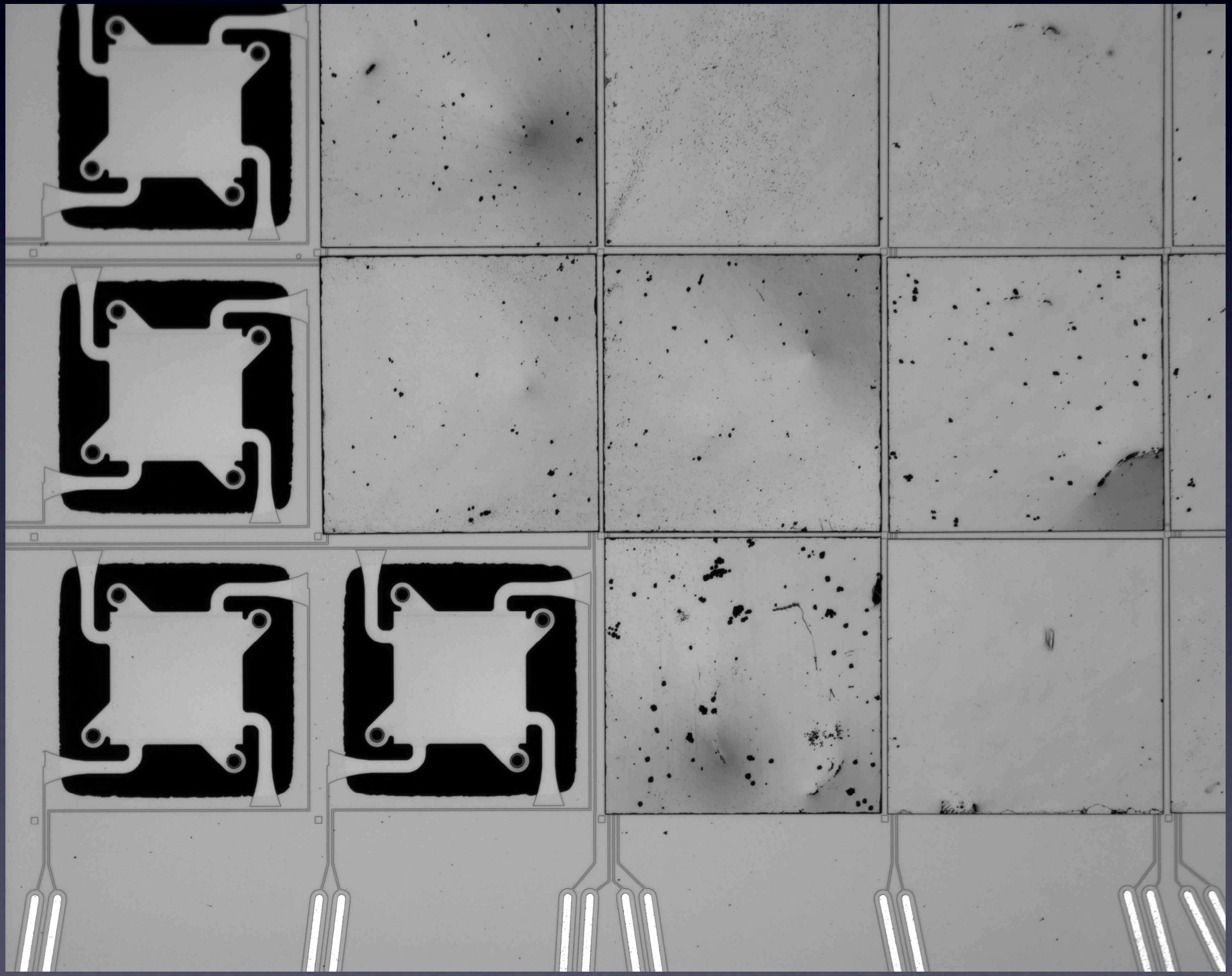
$$T(t) = \frac{E_\gamma}{C} e^{-t/\tau_o} + \left(\frac{P}{G} + T_\mathrm{b} \right)$$

$$\Delta U = \sqrt{k_B T^2 C},$$

- Measures the heat associated with a photon absorbed in a material.
- Uses a thermometer to measure the rise in temperature of the absorber material.
- The energy of the photon is proportional to the peak rise in temperature of the absorber.
- Broadband and high resolution. Has the advantages of crystal and solid state detectors in one package.

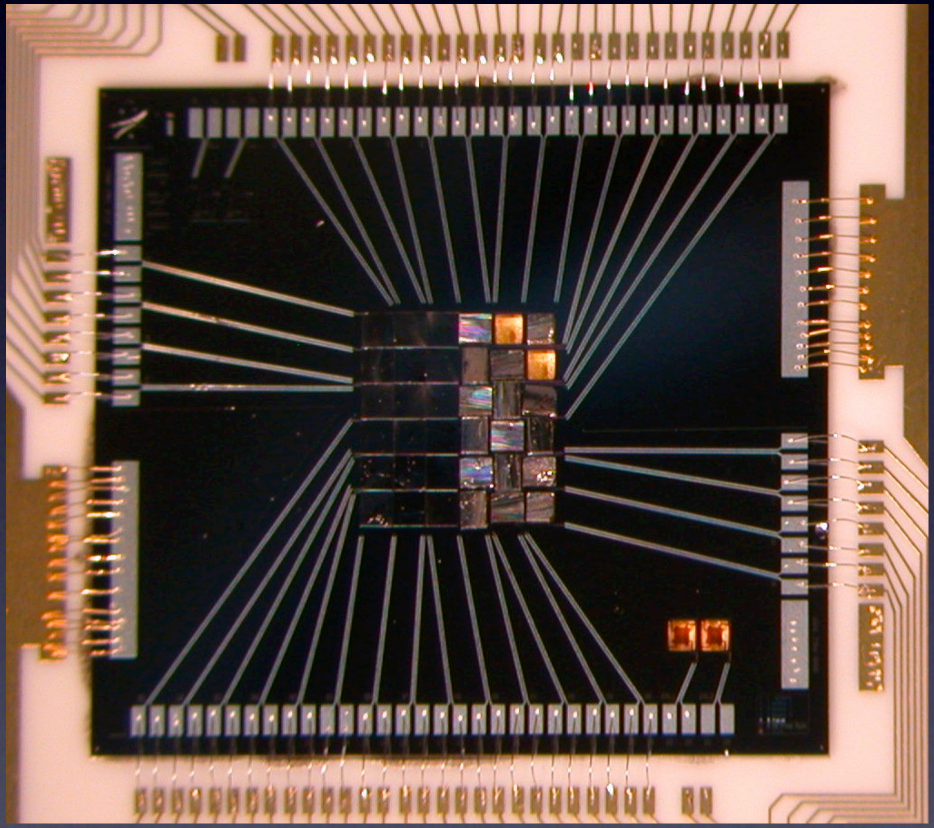
Thermistor Type

- State of the art detector that uses a doped silicon thermistor.
- Thermistor is operated in current biased mode.
- Thermistor has a known resistance vs temperature curve.
- Can only handle low (astrophysical or EBIT type rates)



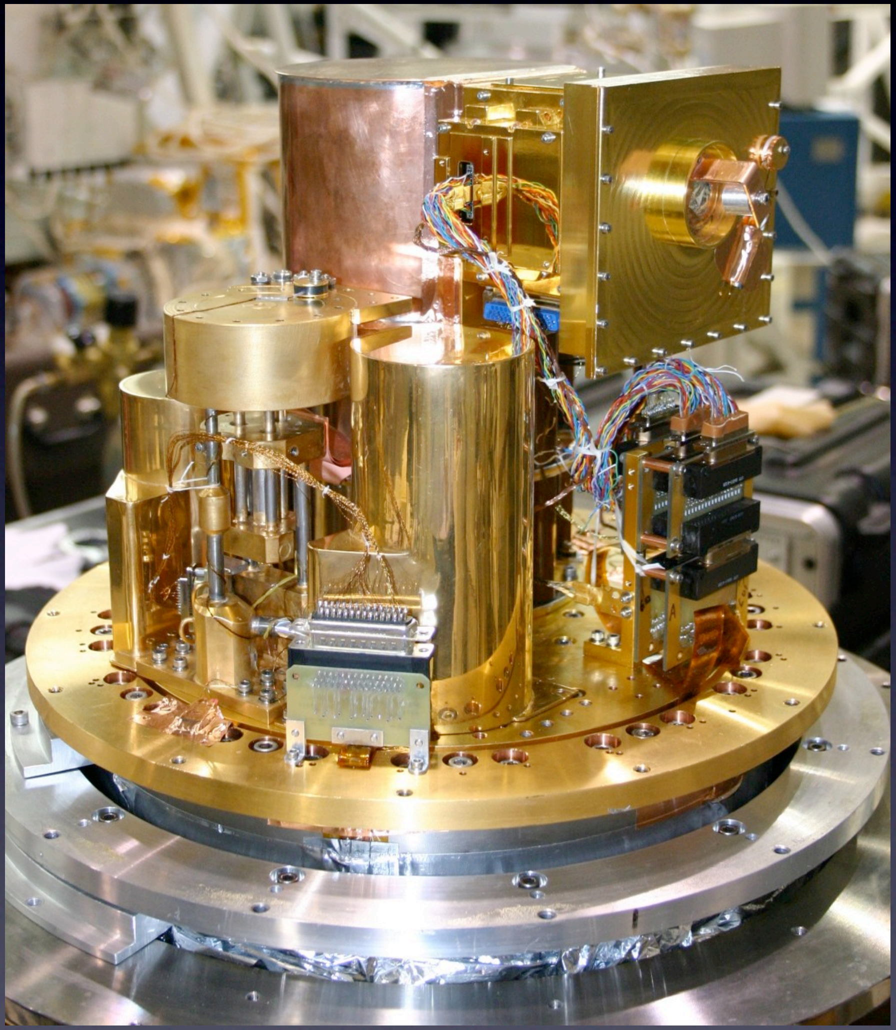
EBIT Calorimeter Spectrometer (ECS)

- Design based on NASA/GSFC suzaku x-ray calorimeter planned for X-ray work under 10 keV.
- Hybrid of thirty-two pixels, comprised of: fifteen 624 µm x 624 µm x 8 µm HgTe absorbers and twelve 624 µm x 624 µm x 100 µm and one 500 µm x 500 µm x 100 µm HgTe absorbers attached to doped silicon thermistors.
- Thin pixels are used for low energy detection while thick pixels are used for high energy work.



NASA/GSFC Team: Rich Kelley, Scott Porter, Caroline Kilbourne

Operating parameters



- Detector is run at 50 mK via an adiabatic demagnetization refrigerator (ADR).
- a He3/He4 sorption cooler keeps heat load on 50 mK stage low by maintaining 350 mK. Liquid He and liquid nitrogen protect sorption pump.
- Hold time for ADR and thus detection is 60 + hours vs a 3 hour recycle time.

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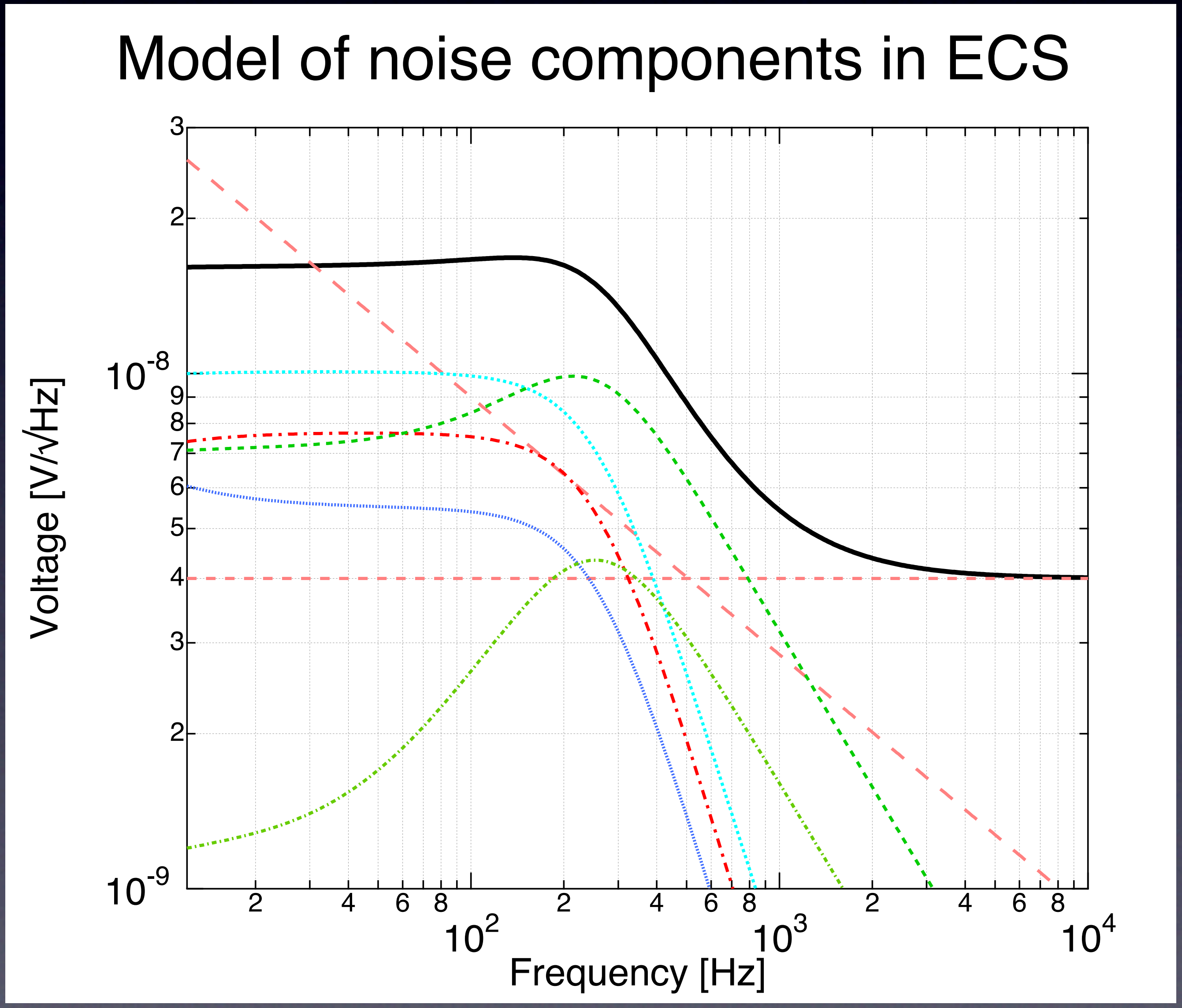
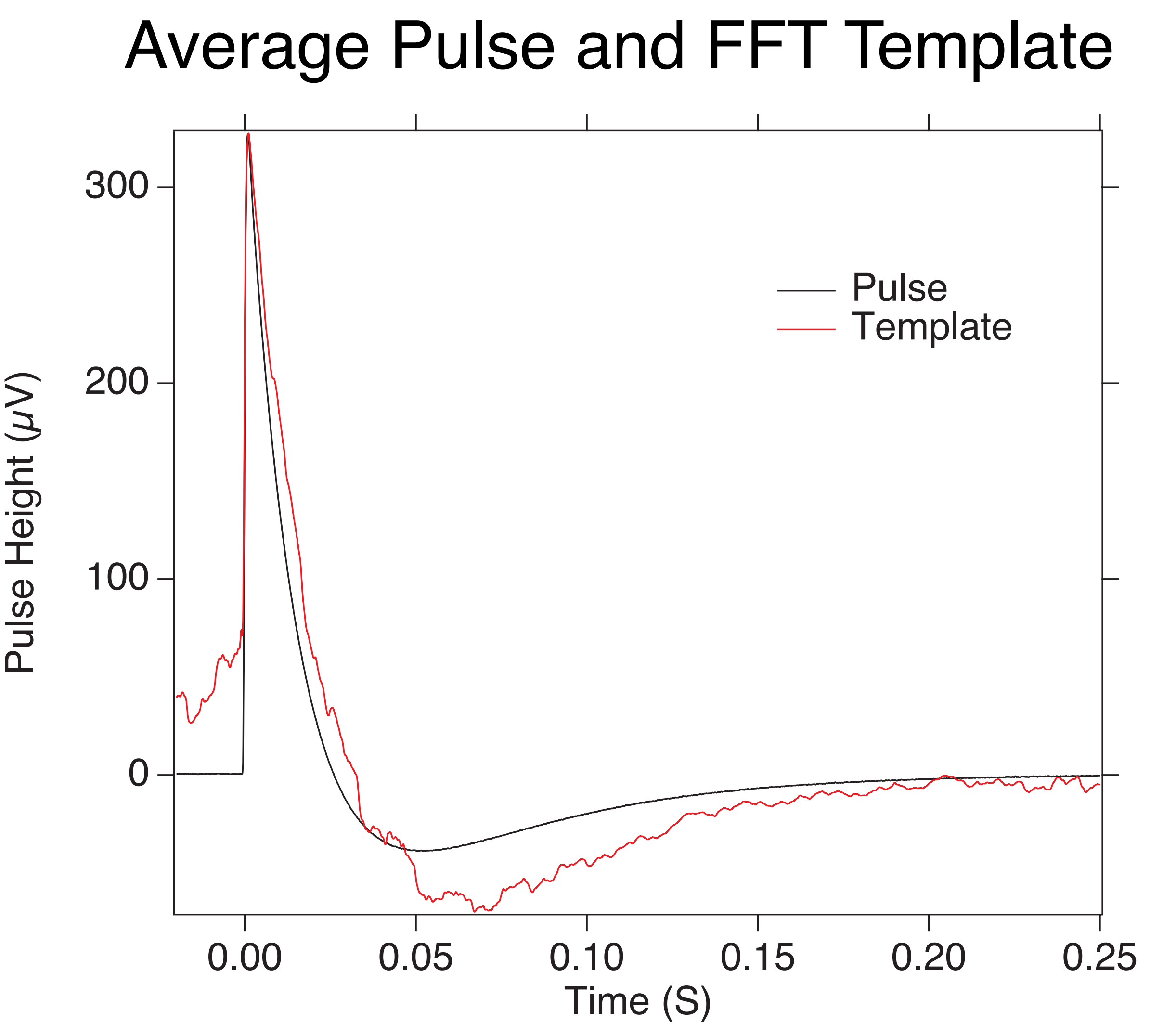
Assigning Pulse Height

- Pulse detection is done in the frequency domain.
- Noise is the limiting factor in determining resolution.
- Slower pulses have more power at lower frequency.



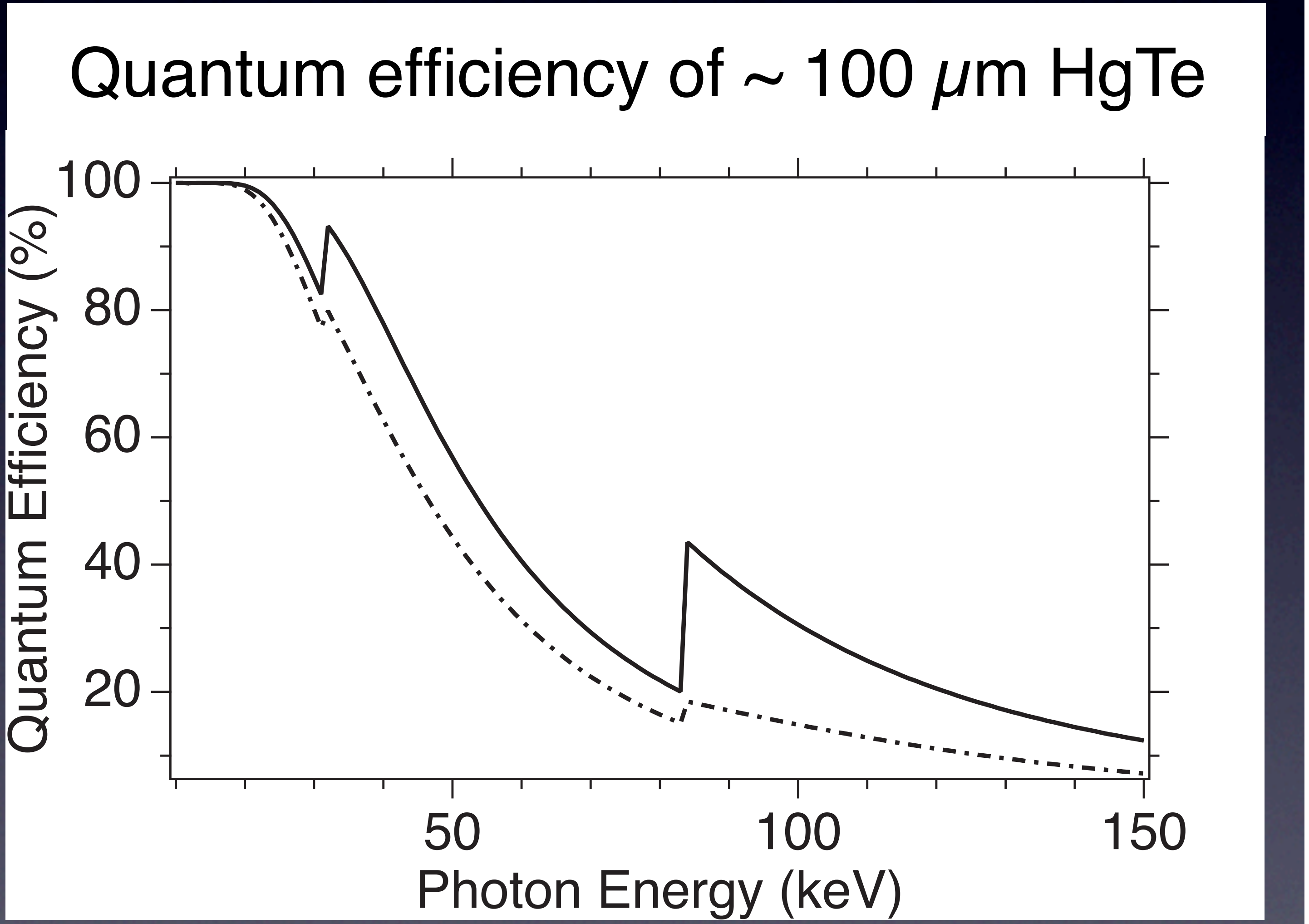
Resolution



- A template is generated in the frequency domain and is then used to compare other pulses and assign a pulse height value to them.
- A FWHM resolution of ~ 30 eV is obtained with the ECS detector under ideal noise conditions at a photon energy of 60 keV.
- This it only the first attempt newer versions should produce much better FWHM resolutions for higher energy photons.

Quantum Efficiency

- Need a high quantum efficiency for high-Z ions.
- Quantum Efficiency for 100 μm of HgTe is around 80 % at the Xe K-shell photon energy of ~ 30 keV.
- QE is ~ 20 % at U K-shell energies.



Xenon Spectral Measurements with a Low Temperature Detector

Previous attempts at high precision of H and He -like xenon.

- Xe has been studied with both a Ge detector and a hybrid crystal/Ge detector setup.

Xe K-shell with Ge detector^

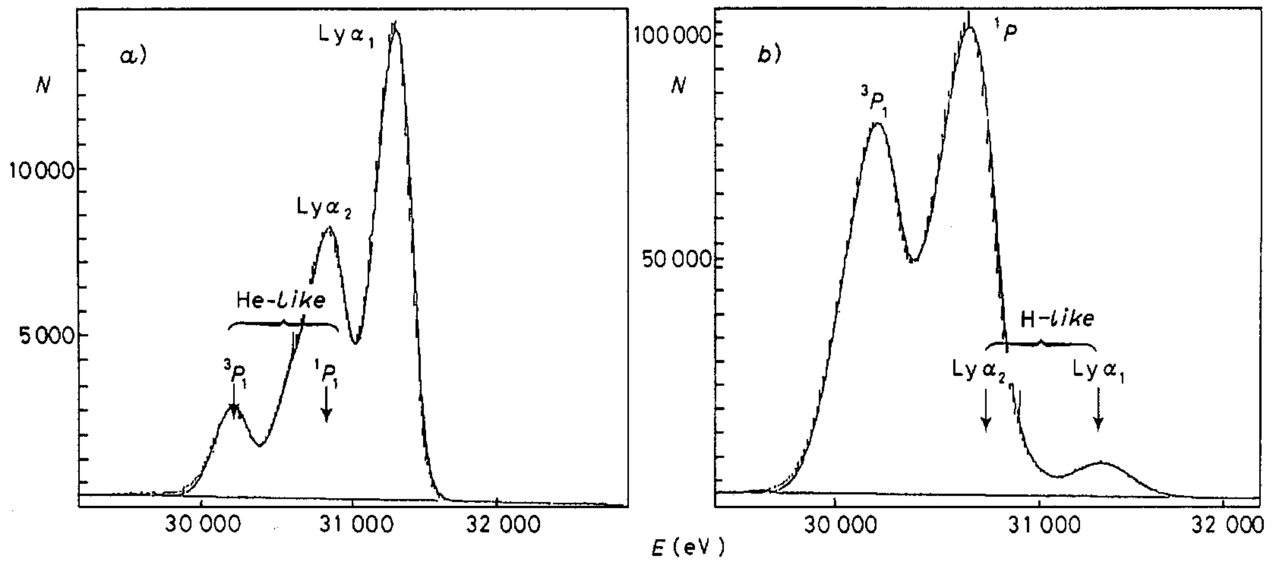
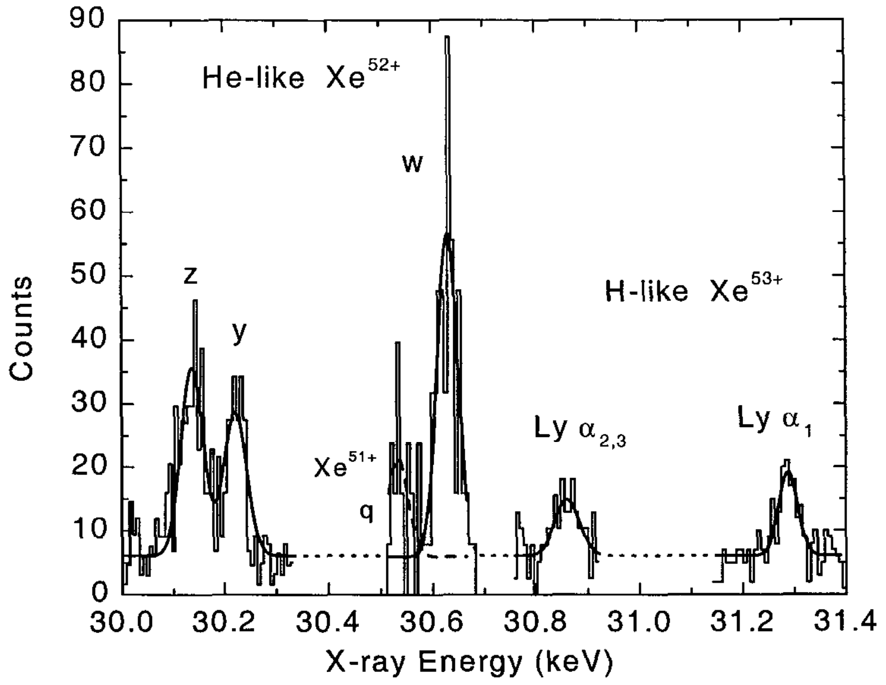


Fig. 3. – Lyman α spectra observed with Xe^{54+} (hydrogenlike) (a)), and Xe^{53+} (heliumlike) (b)) beams.

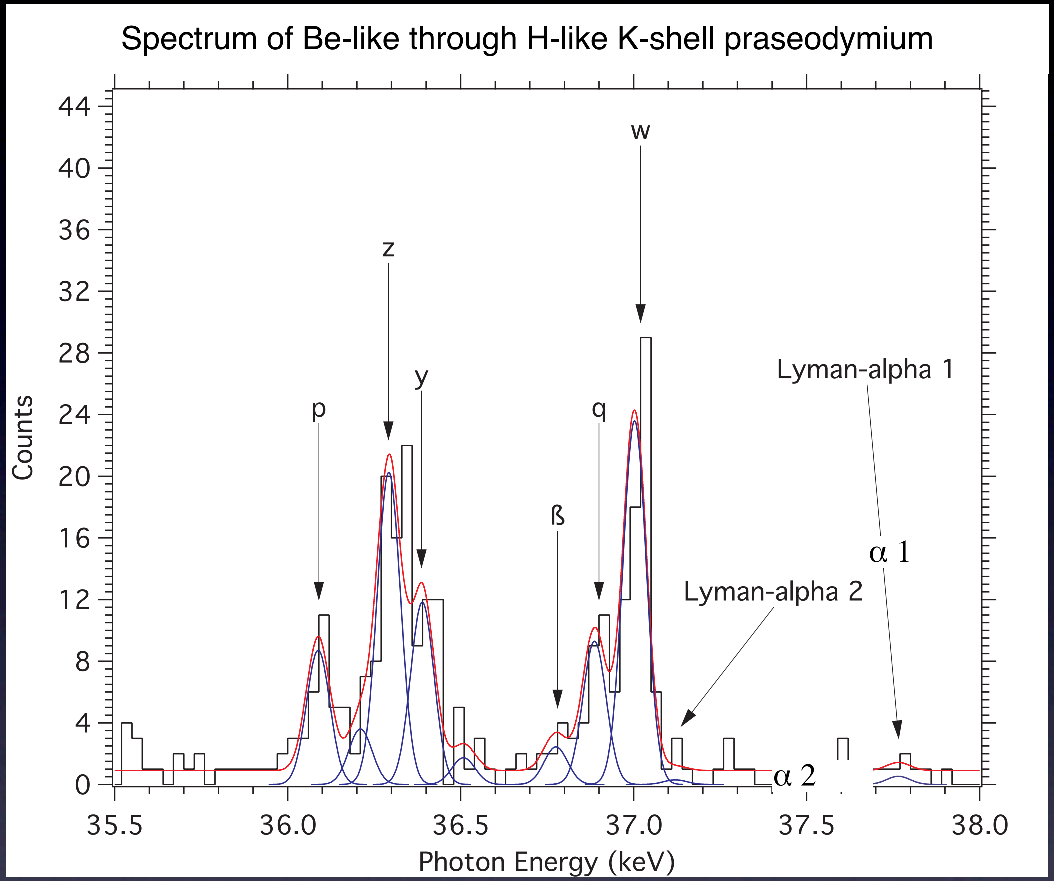
^ Ref: Briand et. al, Europhys. Lett. 9, 225 (1989)

Xe K-shell with Hybrid Detector*

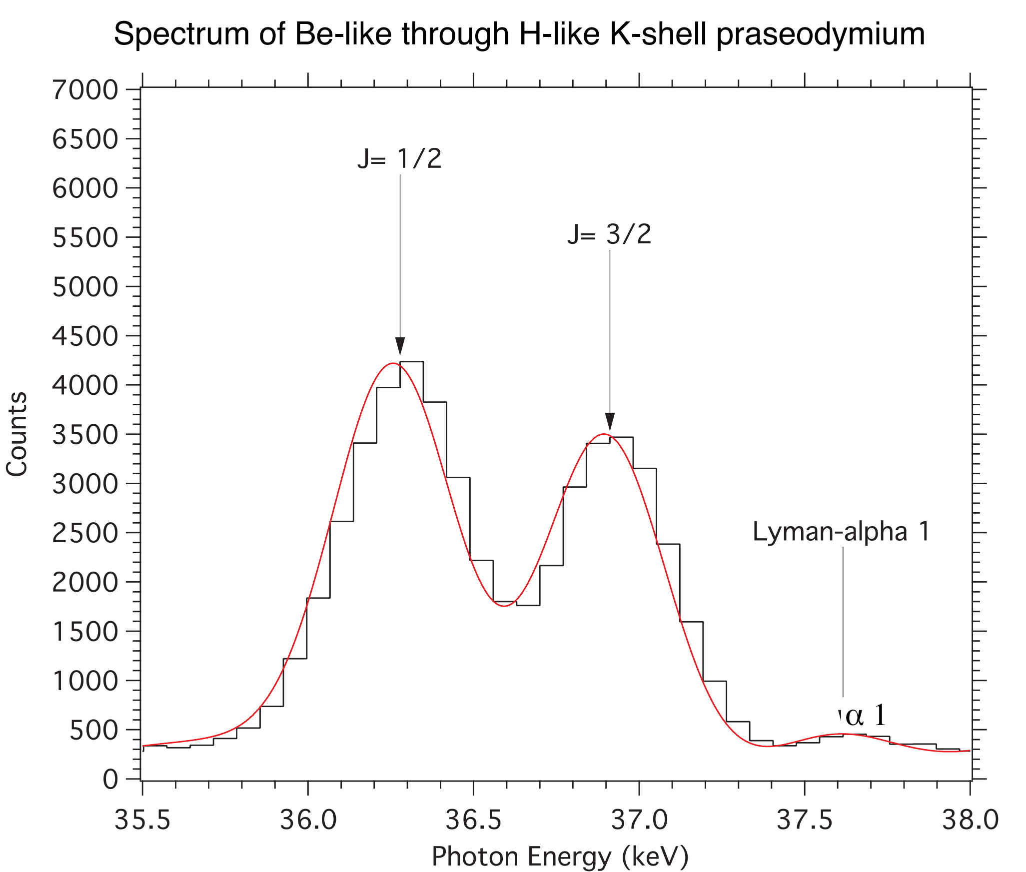


* Ref: Widmann et. al, AIP Conf. Proc. 506, 444 (2000)

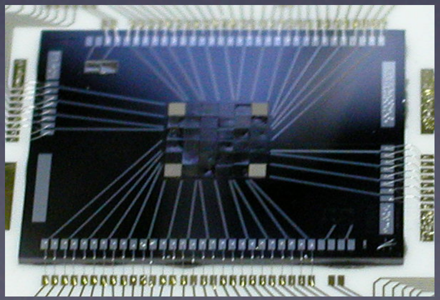
XRS Measurement of Be-like through H-like Pr



Single 30 µm Bi pixel
40 hr measurement



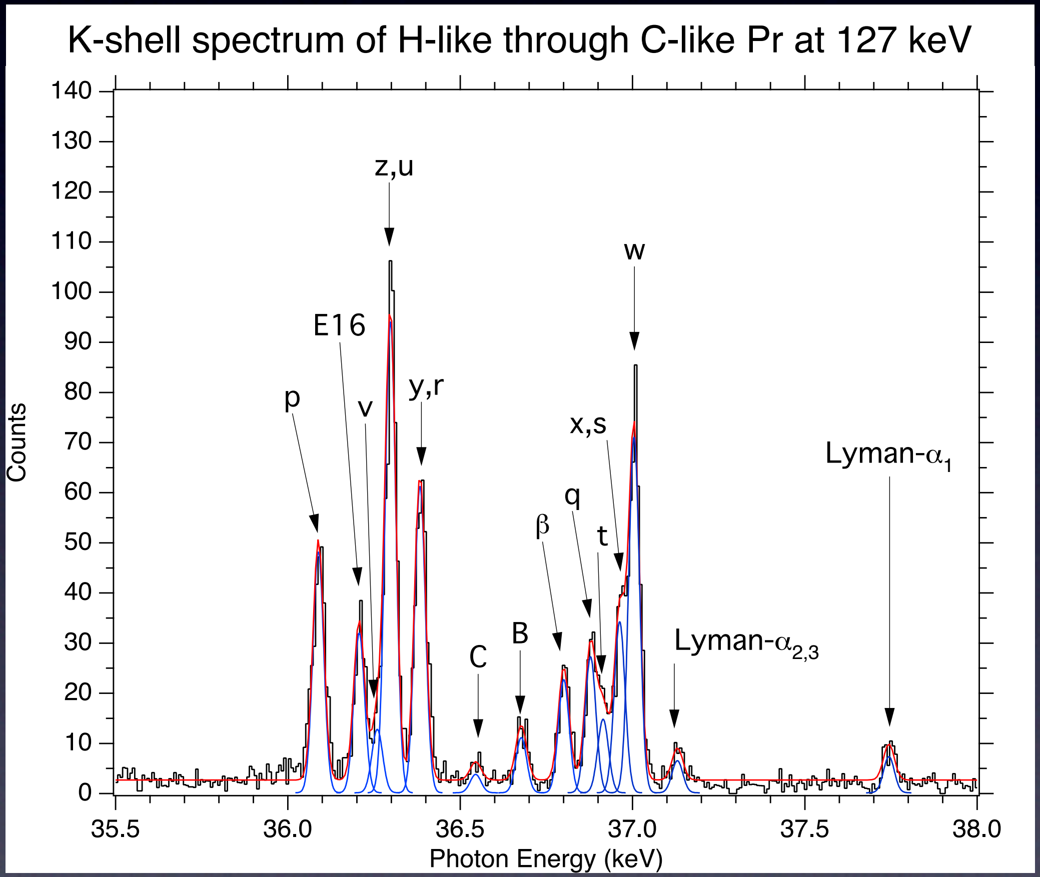
6mm Ge detector
16 hr measurement



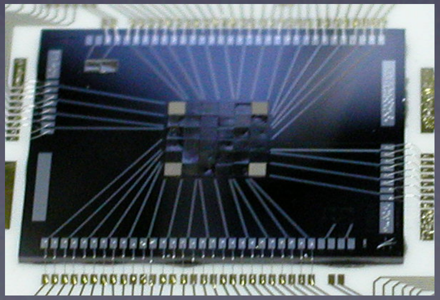
D. B. Thorn et al., Can. J. Phys., 86, 241 (2008)

Improvement in Technique

- Use twenty 8 μm thick HgTe pixels.
- Addition of all pixels over 8 measurement days.
- Resolving power of 1000.
- Drifts were seen and technique proved proof of concept that XCS detectors are useable for a QED measurement.

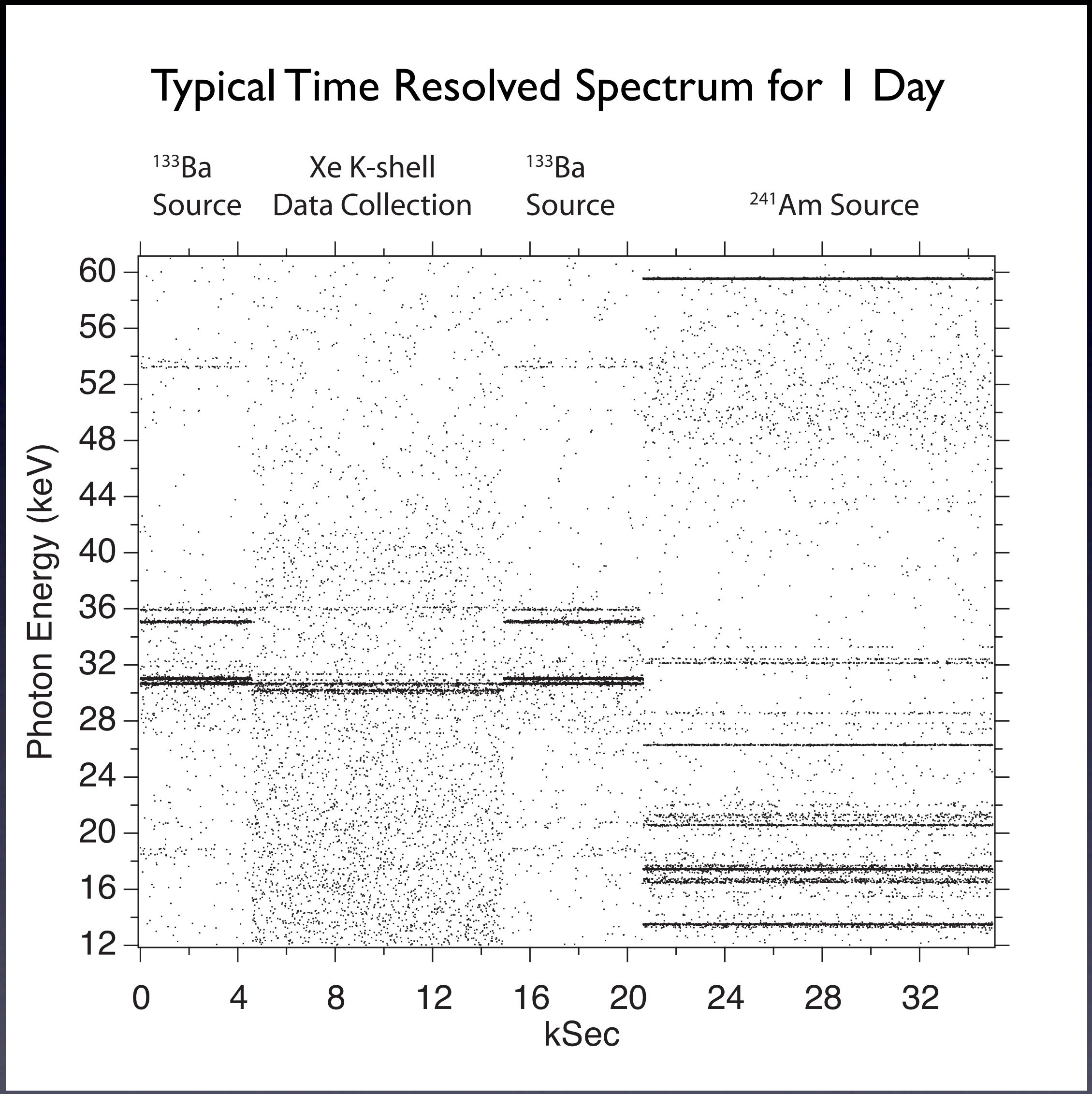


D. B. Thorn et al., RSI, 79 (2008)



Stability and Calibration of ECS

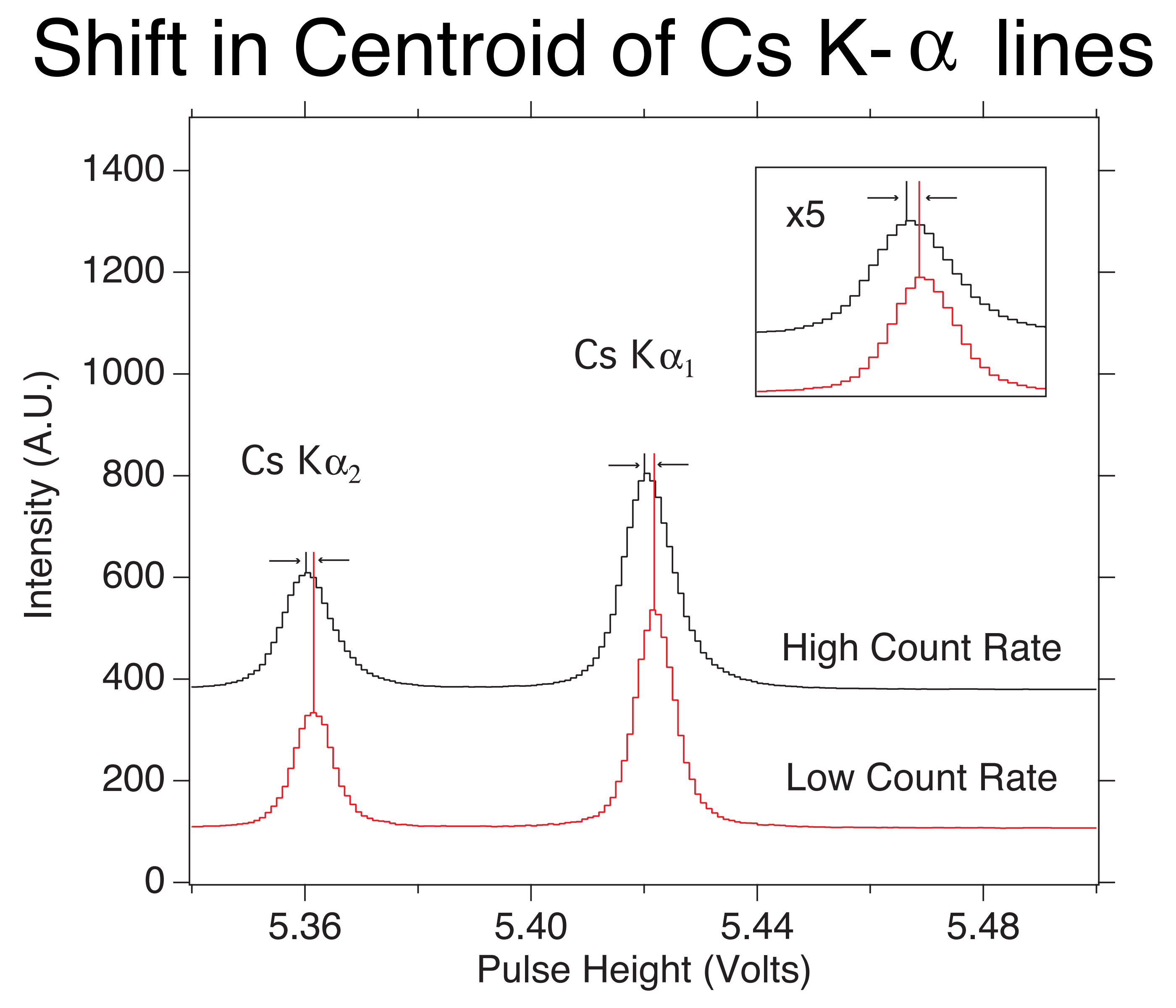
- Calibration was performed with radioactive Ba-133 and Am-241 sources.
- Good resolution and no gain shifts seen in one day.
- Broadband and high-resolution nature of calorimeter can be seen.



Thorn et al. PRL 103 (2009)

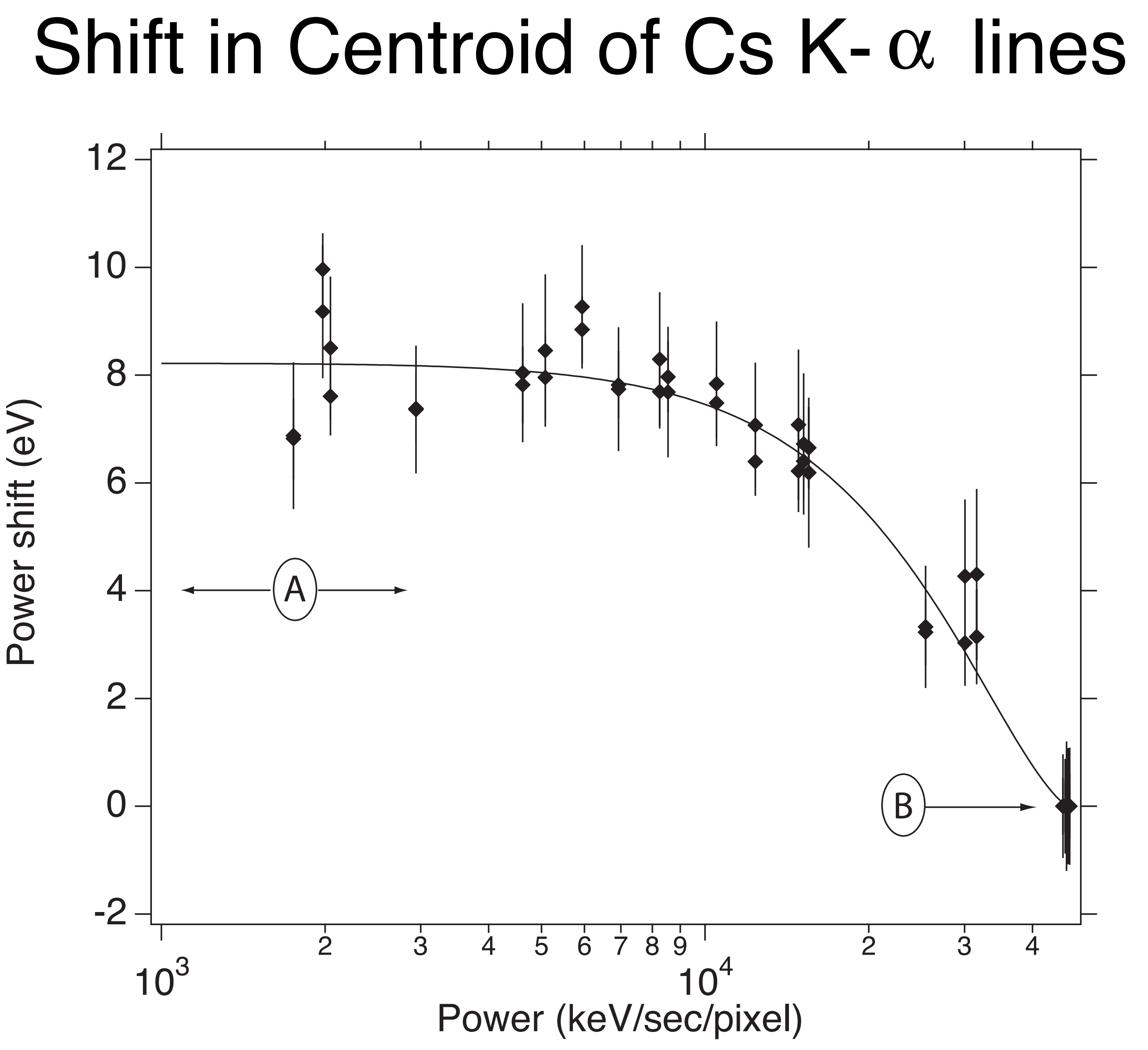
LLNL Team: Peter Beiersdorfer, Greg Brown, Ming Feng Gu, Ed Magee

Power Shift



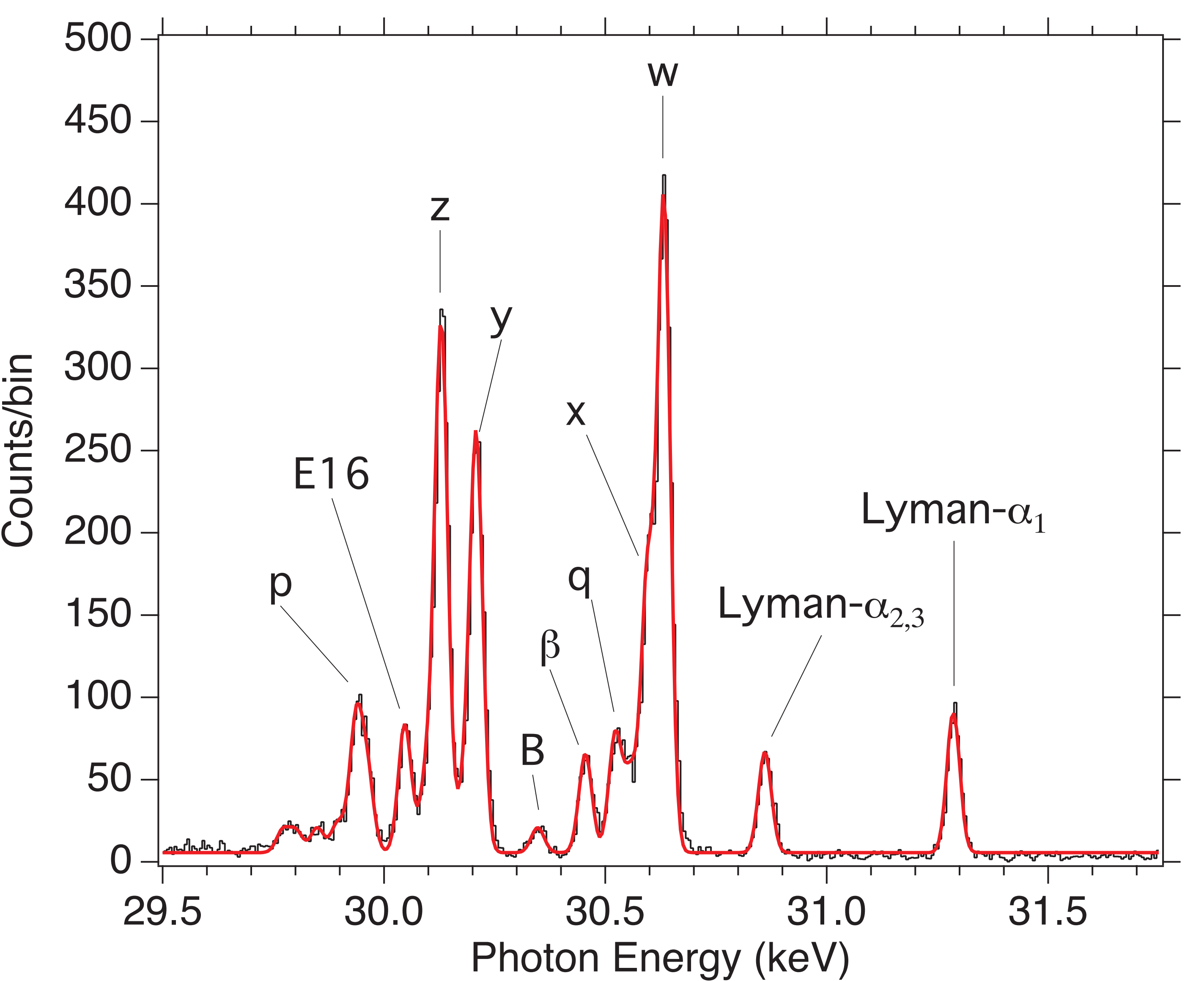
- To obtain enough statistics during calibration, a higher count rate was needed then was seen for data collection.
- Higher count rate = more power on detector than durning data collection times.
- At higher powers the pulse height of the calibration peaks are shifted lower in voltage

Power Shift



- Used a filtered Ba133 source.
- Calibration done at 50 keV/s/pixel. Xe K-shell data taken at under 3 keV/s/pixel
- Reduced the power incident on detector from roughly 50 keV/s/pixel to under 2 keV/s/pixel
- For powers under 9keV/s/pixel the shift in the centroid relative to the 50 keV/s/pixel power is 8.12 ± 0.76 eV.

Spectrum of H-like through B-like Xe recorded at the SuperEBIT facility.



Thorn et al. PRL 103 (2009)

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Table of H-like values

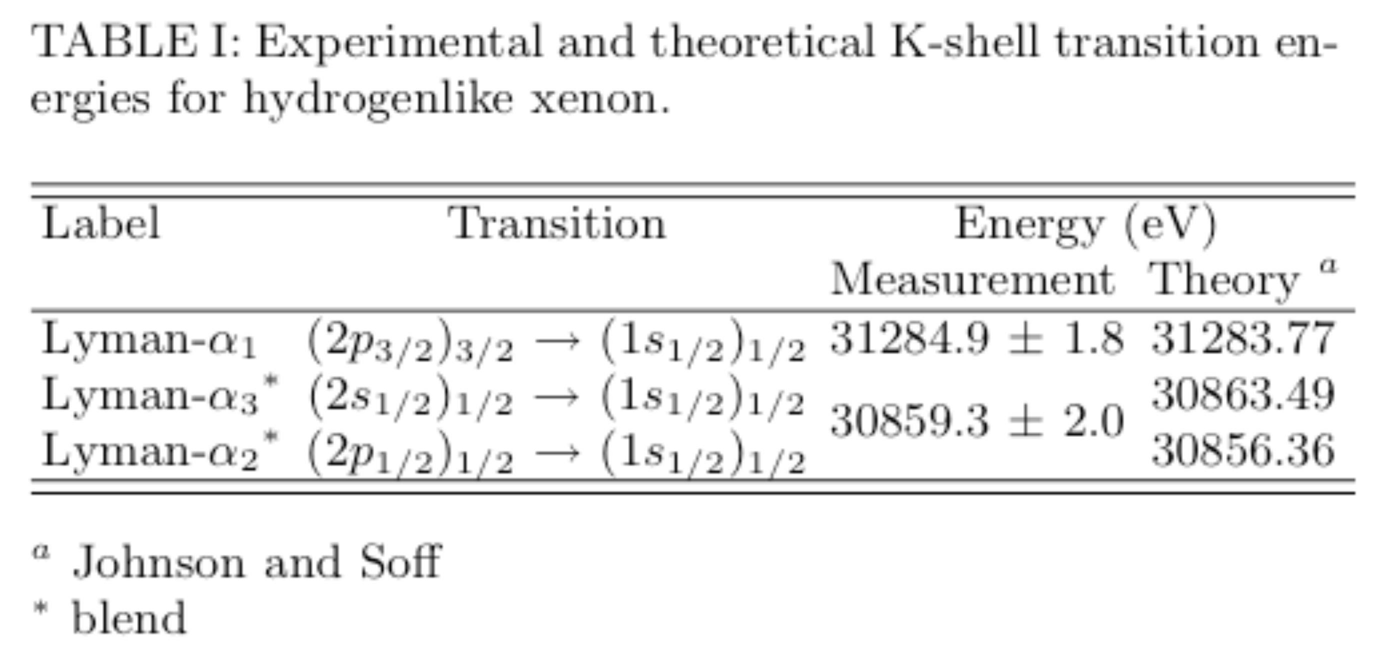


TABLE I: Experimental and theoretical K-shell transition energies for hydrogenlike xenon.

Label	Transition	Energy (eV)	
		Measurement	Theory [a]
Lyman-α_1	$(2p_{3/2})_{3/2} \rightarrow (1s_{1/2})_{1/2}$	31284.9 ± 1.8	31283.77
Lyman-α_3*	$(2s_{1/2})_{1/2} \rightarrow (1s_{1/2})_{1/2}$	30859.3 ± 2.0	30863.49
Lyman-α_2*	$(2p_{1/2})_{1/2} \rightarrow (1s_{1/2})_{1/2}$		30856.36

[a] Johnson and Soff

* blend

Thorn et al. PRL 103 (2009)

- Calculations taken from Johnson and Soff * agree within experimental error bars.
- Theoretical prediction (FAC ^ intensities) for the location of the Lyman-2,3 blend is 30857.73. Which is with in experimental error bars.

A roughly 40 ppm measurement precision is obtained which is an order of magnitude better then previously reported

* ref: W. Johnson and G. Soff, Atom. Data Nuc. Data Tables **33**, 405 (1985) ^ ref: M. F. Gu, Can. J. Phys. **86**, 675 (2008)

Table of He-like values

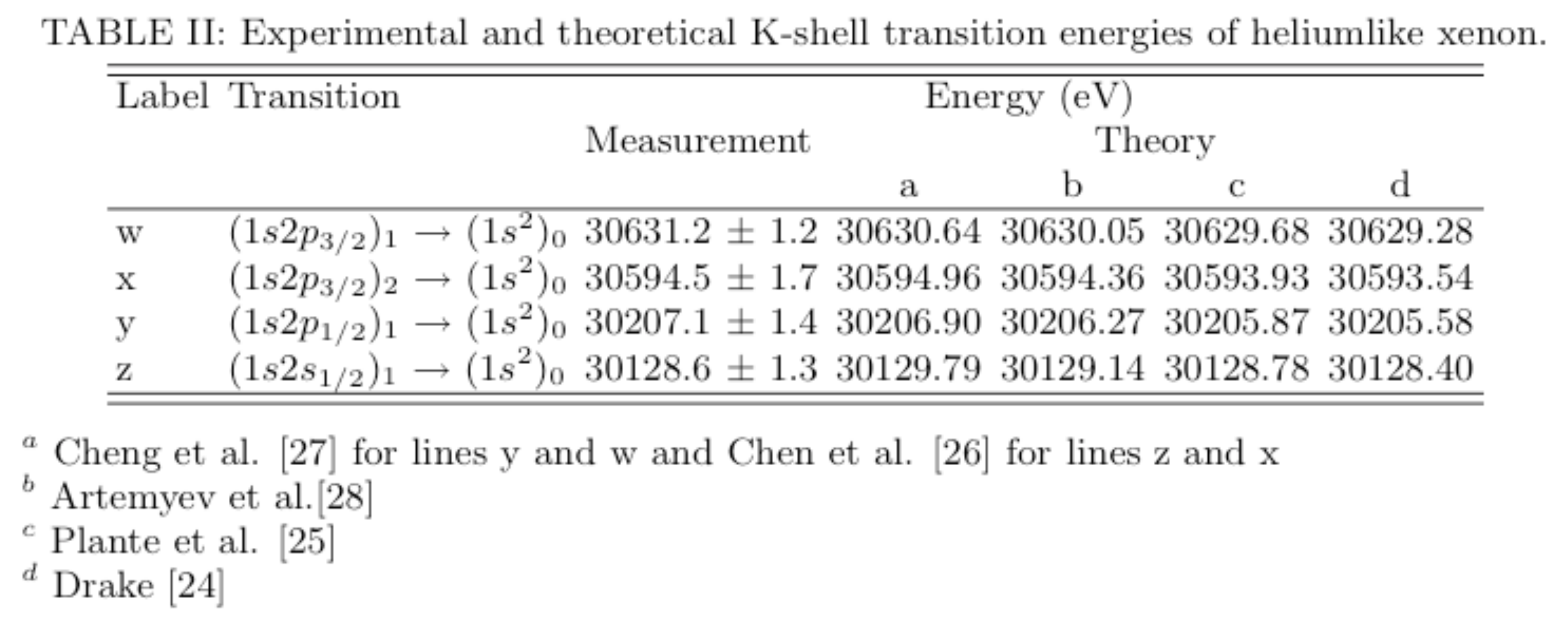


TABLE II: Experimental and theoretical K-shell transition energies of heliumlike xenon.

Label	Transition	Energy (eV)				
		Measurement	Theory			
			a	b	c	d
w	$(1s2p_{3/2})_1 \rightarrow (1s^2)_0$	30631.2 ± 1.2	30630.64	30630.05	30629.68	30629.28
x	$(1s2p_{3/2})_2 \rightarrow (1s^2)_0$	30594.5 ± 1.7	30594.96	30594.36	30593.93	30593.54
y	$(1s2p_{1/2})_1 \rightarrow (1s^2)_0$	30207.1 ± 1.4	30206.90	30206.27	30205.87	30205.58
z	$(1s2s_{1/2})_1 \rightarrow (1s^2)_0$	30128.6 ± 1.3	30129.79	30129.14	30128.78	30128.40

[a] Cheng et al. [27] for lines y and w and Chen et al. [26] for lines z and x

[b] Artemyev et al.[28]

[c] Plante et al. [25]

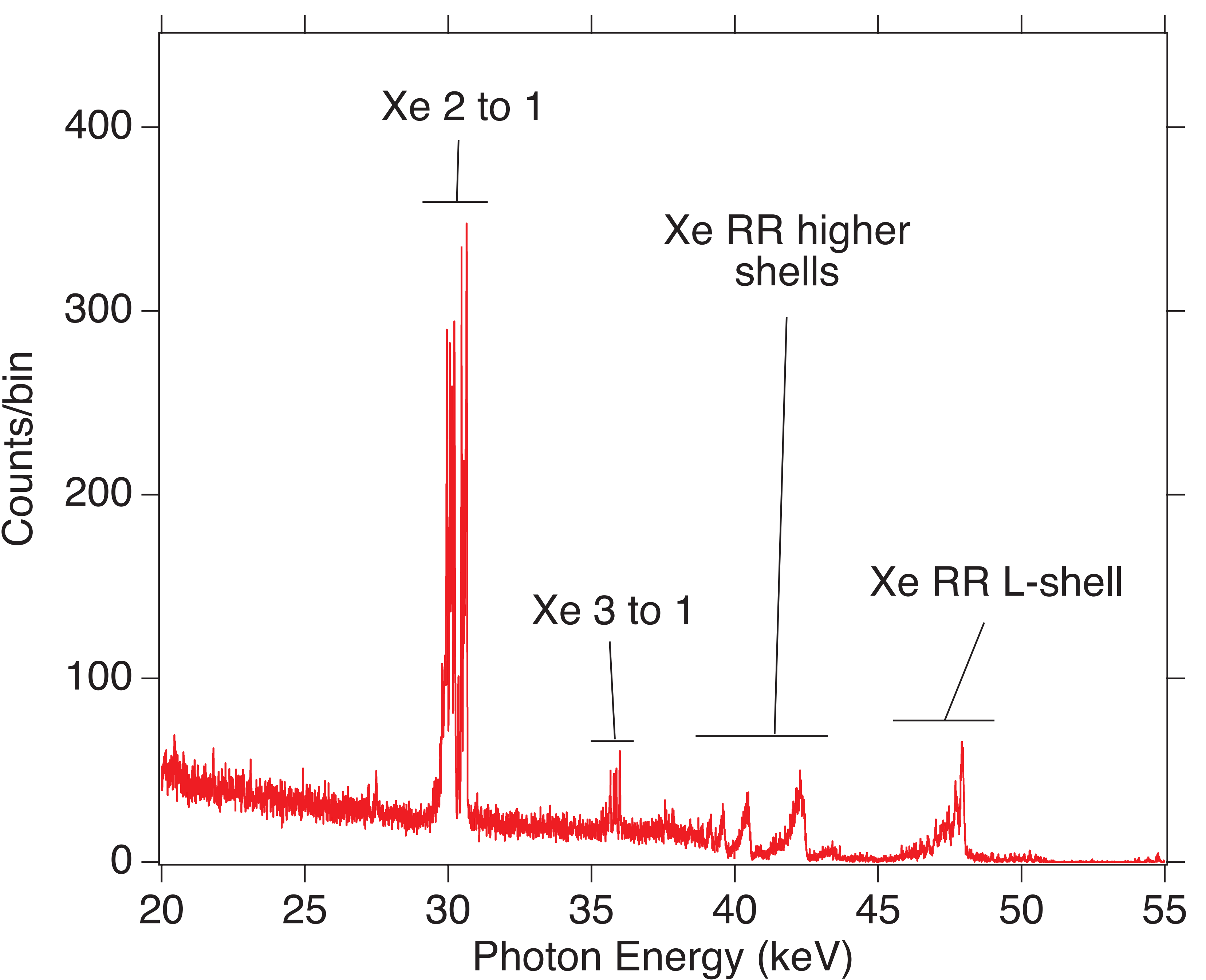
[d] Drake [24]

Thorn et al. PRL 103 (2009)

Singlet and triplet in He-like system are not blended allowing for a true measurement of the He-like resonance line in a high-Z system for the first time.

Dynamics: Excitation Measurements

Spectrum of He-like through C-like Xe at an electron beam energy of 39 keV.



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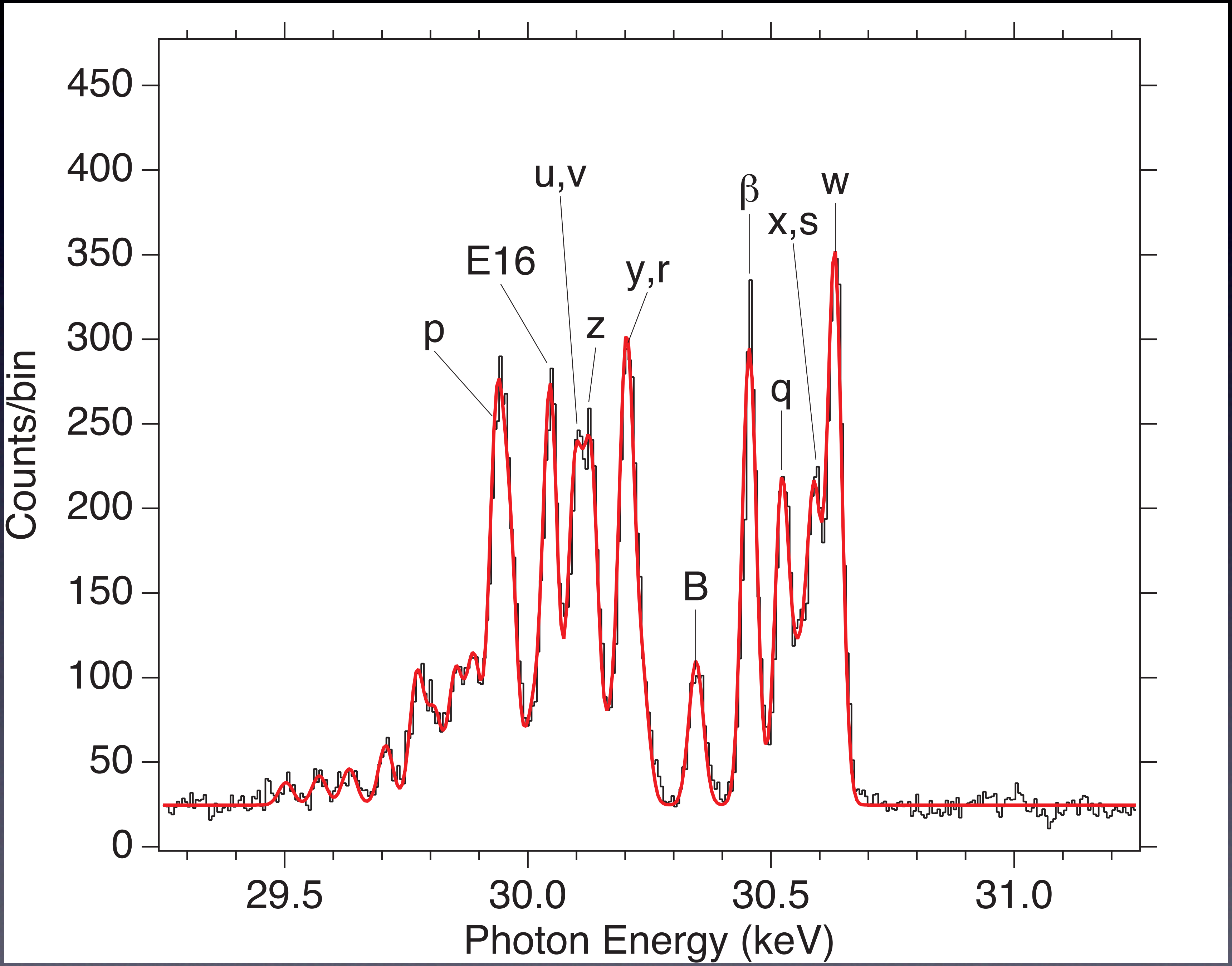

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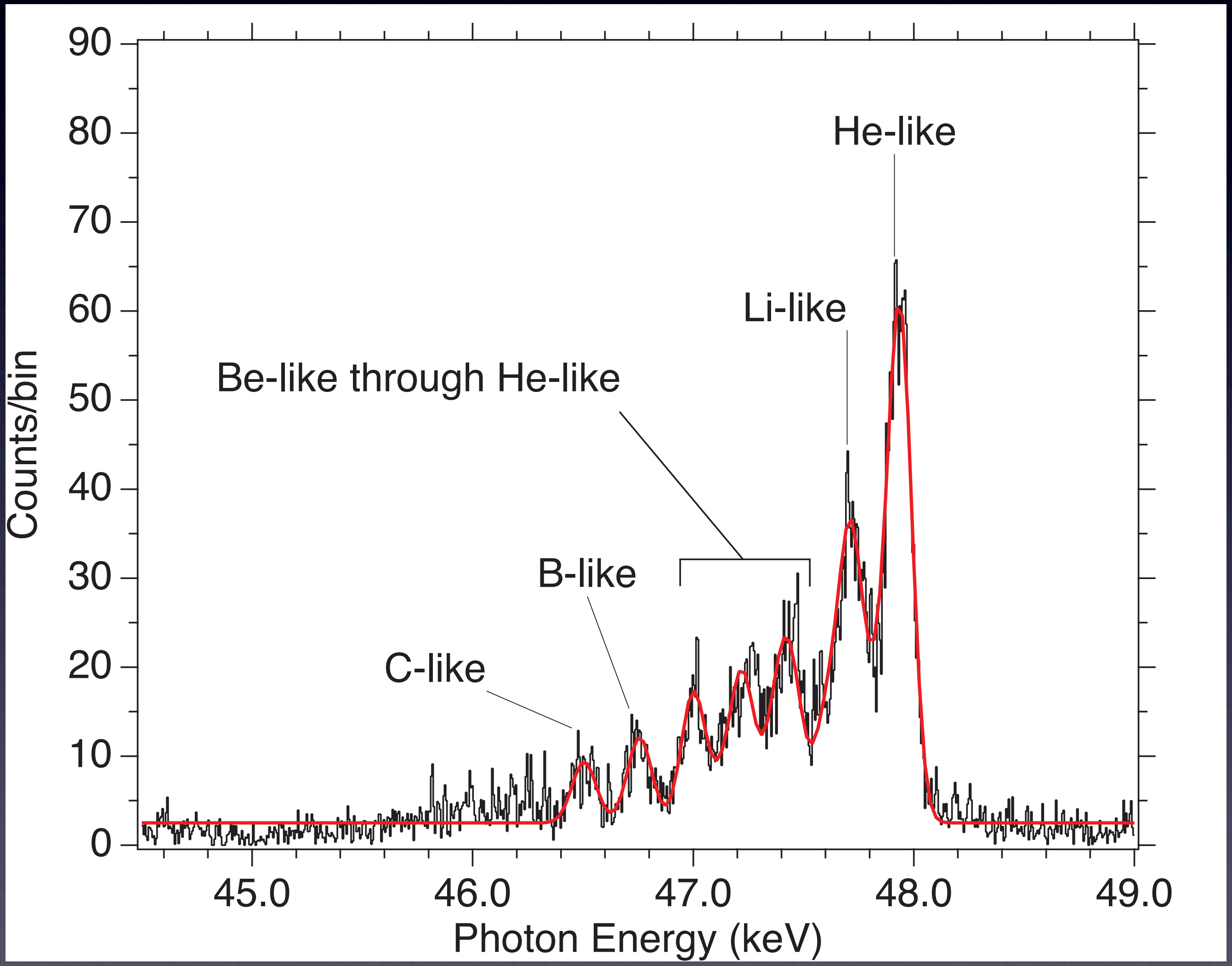
Radiative Recombination

- Fitting the radiative recombination yields charge balance information as well as a way to normalize direct excitation to obtain absolute electron impact excitation cross-sections.



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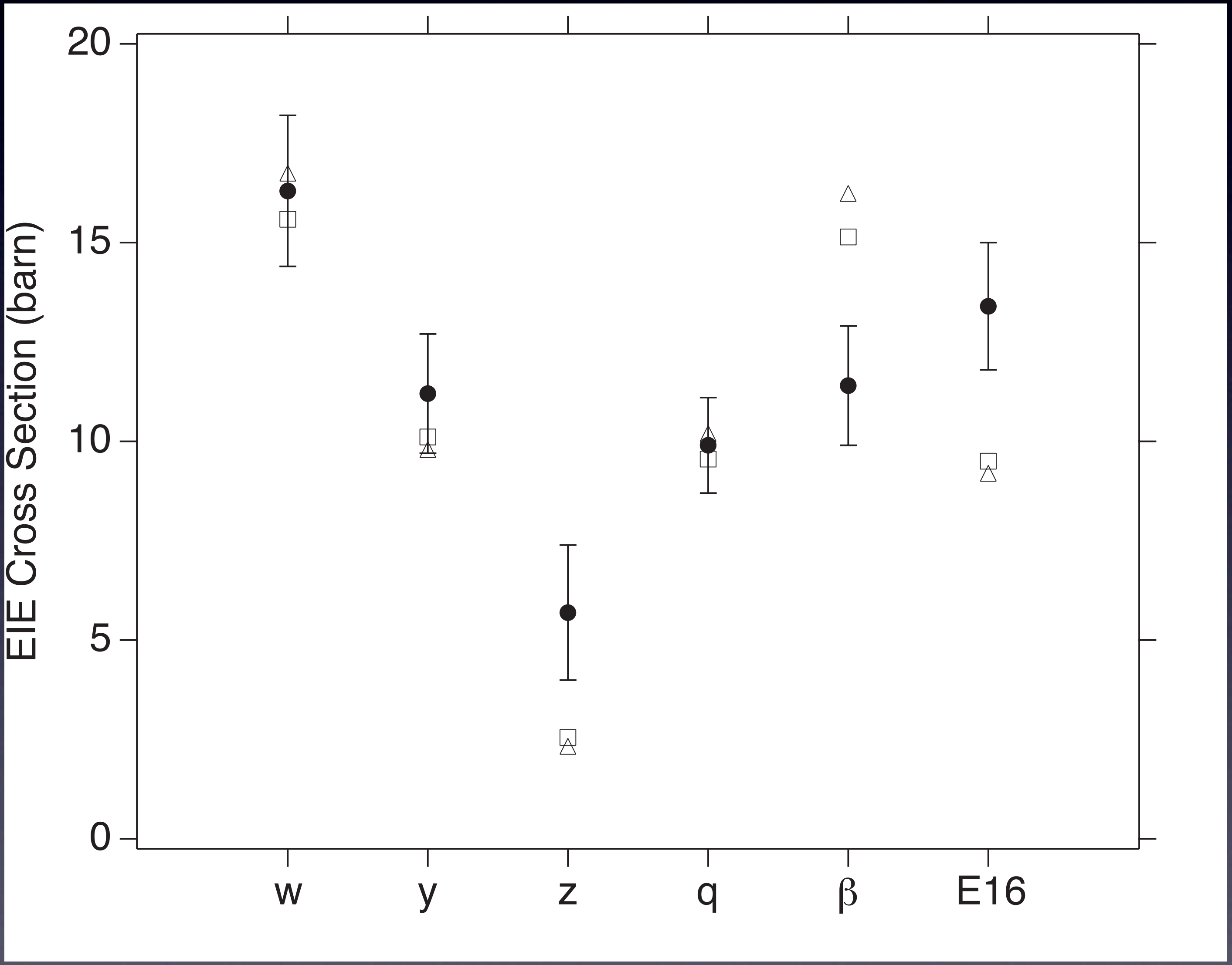
Total Cross Sections

- Theory works well for E1 lines but E1 forbidden lines need work as does the Be-like system.
- Experimental precision is not good enough to test dynamical QED.



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Generalized Breit Interaction: Dynamical QED

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- In very high-Z ions the effect can be as great as a factor of 2
- an important effect to consider for high temperature fusion devices
- As of yet untested

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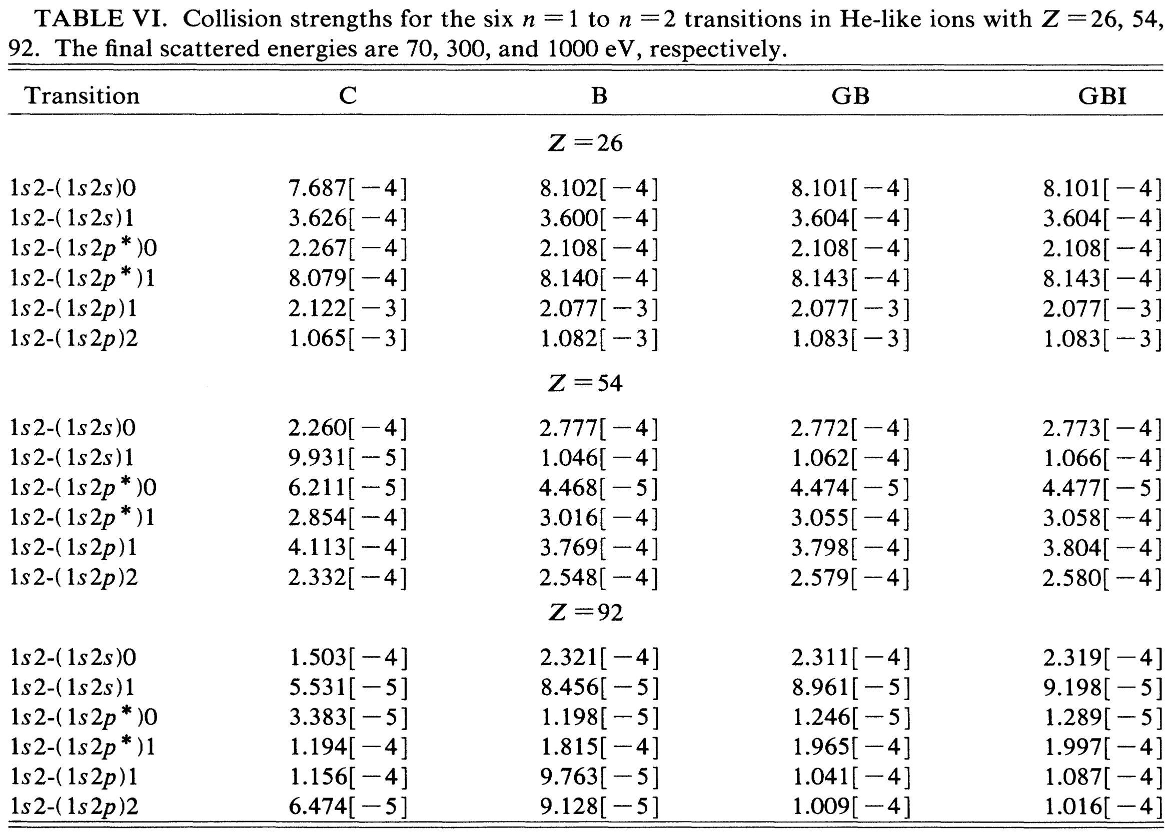

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1s2-(1s2s)0	2.260[−4]	2.777[−4]	2.772[−4]	2.773[−4]
1s2-(1s2s)1	9.931[−5]	1.046[−4]	1.062[−4]	1.066[−4]
1s2-(1s2p*)0	6.211[−5]	4.468[−5]	4.474[−5]	4.477[−5]
1s2-(1s2p*)1	2.854[−4]	3.016[−4]	3.055[−4]	3.058[−4]
1s2-(1s2p)1	4.113[−4]	3.769[−4]	3.798[−4]	3.804[−4]
1s2-(1s2p)2	2.332[−4]	2.548[−4]	2.579[−4]	2.580[−4]
		$Z=92$		
1s2-(1s2s)0	1.503[−4]	2.321[−4]	2.311[−4]	2.319[−4]
1s2-(1s2s)1	5.531[−5]	8.456[−5]	8.961[−5]	9.198[−5]
1s2-(1s2p*)0	3.383[−5]	1.198[−5]	1.246[−5]	1.289[−5]
1s2-(1s2p*)1	1.194[−4]	1.815[−4]	1.965[−4]	1.997[−4]
1s2-(1s2p)1	1.156[−4]	9.763[−5]	1.041[−4]	1.087[−4]
1s2-(1s2p)2	6.474[−5]	9.128[−5]	1.009[−4]	1.016[−4]

* Ref: Fontes et. al, PRA 47, 1009 (1993)

Line Ratios and GBI

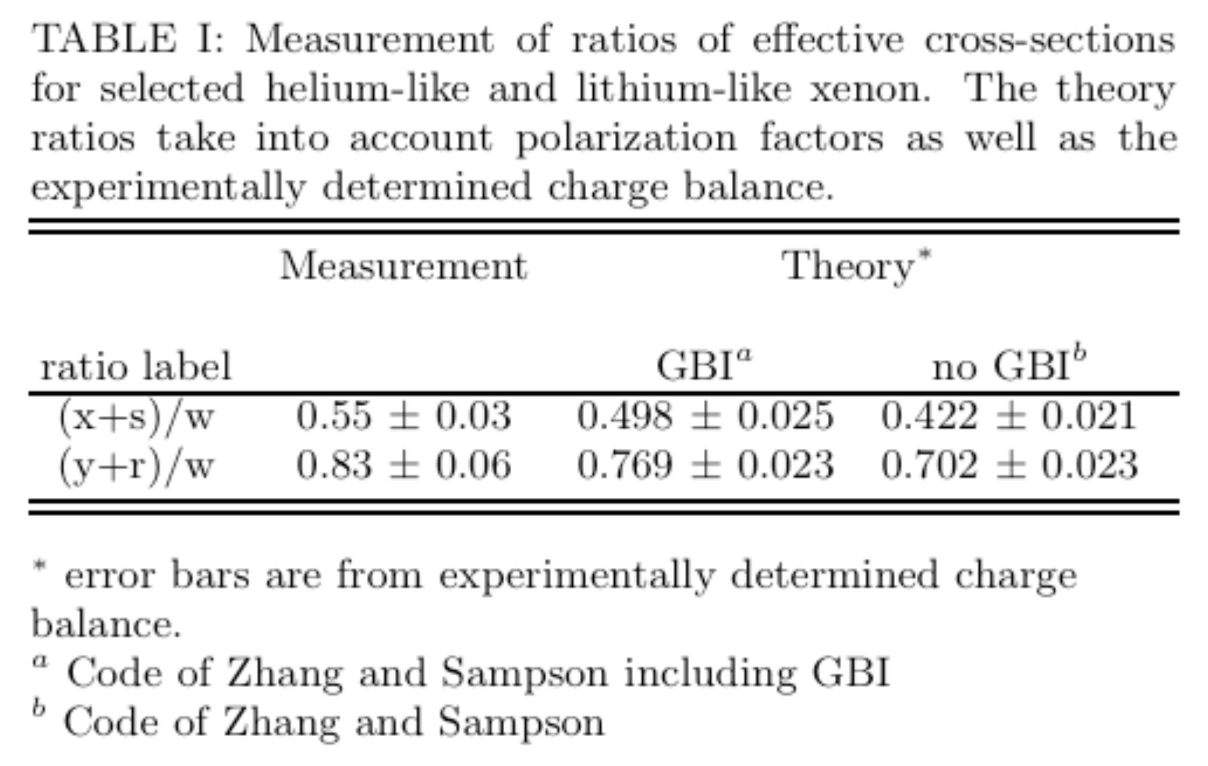


TABLE I: Measurement of ratios of effective cross-sections for selected helium-like and lithium-like xenon. The theory ratios take into account polarization factors as well as the experimentally determined charge balance.

	Measurement	Theory*	
ratio label		GBI[a]	no GBI[b]
(x+s)/w	0.55 ± 0.03	0.498 ± 0.025	0.422 ± 0.021
(y+r)/w	0.83 ± 0.06	0.769 ± 0.023	0.702 ± 0.023

* error bars are from experimentally determined charge balance.

[a] Code of Zhang and Sampson including GBI

[b] Code of Zhang and Sampson

Submitted to PRL

- Data shows inclusion of the GBI effect into the calculations for electron impact excitation cross-sections is important at Xe. GBI will be even more important for higher-Z ions.
- Need dynamical QED to make theory fit with experiment.

Summary and Outlook

- First prototype calorimeter is precise enough to resolve the K-shell of few electron high-Z ions.
- Precision increase from previous measurements is an order of magnitude.
- Current ECS type calorimeter can be used *as is* to measure H-like U at heavy ions storage ring facilities and obtain similar improvement in precision as the Xe measurement did.
- Precision QED measurements on high-Z ions can take the next leap forward.

Improvements in XCS technology!

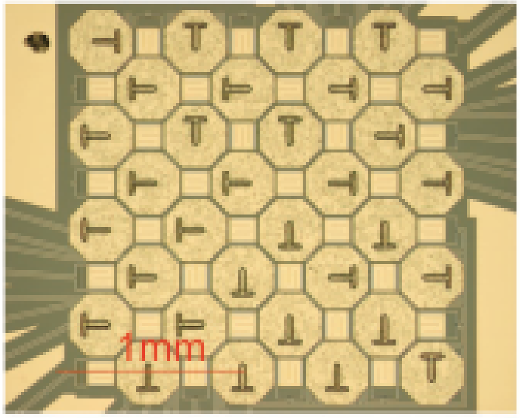
- To be installed 2010
- Cryogen free
- > 100 hours continuous operation,
- 3 hour recycle

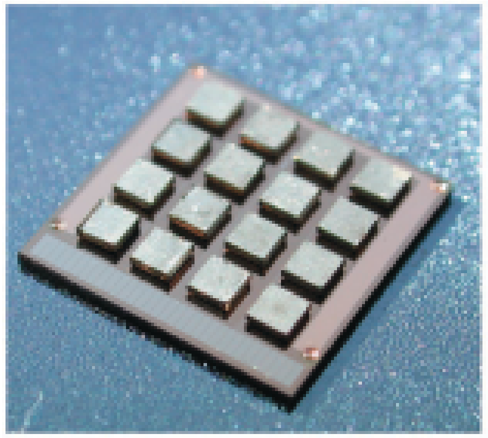
Low/Midband array:

- 256 pixels
- 0.8 eV at 1 keV
- bandpass 0.1 – 1 keV
- 2 eV at 6 keV
- bandpass 0.1 – 10 keV
- 10 x higher count rate

High energy detectors:

- 64 pixels
- 30 eV at 60 keV
- 60% QE at 60 kev
- bandpass 0.5-200 keV
- 10 x higher count rate





Courtesy of P. Beiersdorfer (LLNL) and F. S. Porter, C. A. Kilbourne, and R. Kelley (NASA/GSFC X-ray Calorimeter Spectrometer Group)

References

Thank You For Your Attention!

- Theory
  - W. Johnson and G. Soff, Atom. Data Nuc. Data Tables 33, 405 (1985)
    G. W. F. Drake, Can. J. Phys. 66, 586, (1988)
    K. T. Cheng et. al, PRA 50, 247 (1994)
    D. R. Plante et al, PRA 49, 3219 (1994)
    A. Schäfer et. al, PRA 40, 7362 (1989)
    L. N. Labzowsky et. al, PRA 63, 054105 (2001)
    A. N. Artemyev et. al, PRA 71, 062104 (2005)
    M. F. Gu, Can. J. Phys. 86, 675 (2008)
- Measurements
  - J. P. Briand et. al, Europhys. Lett. 9, 225 (1989)
    K. Widmann et. al, AIP Conf. Proc. 506, 444 (2000)
    D. B. Thorn et al., RSI, 79 (2008)
    D. B. Thorn et al., Can. J. Phys., 86, 241 (2008)
    D. B. Thorn et al., PRL 103 (2009)
    Beiersdorfer et. al, PRA 40, 150 (1989)
    Gumberidze et al., PRL 94 (2005)