Hydrogenic Lamb Shift in Iron, Revisited, with Lessons for the future; and Current Status on the hydrogenic and helium-like investigations of titanium and vanadium at NIST and Oxford

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Hydrogenic Lamb Shift in Iron, Fe 25+ & fine structure Lamb shift 1s-2p Lyman α transitions in hydrogenic iron, Fe25+

Observed from beam-foil source in 4th order diffraction off ADP 101 and PET 002 crystals, simultaneously with n=2 - n=4 Balmer β transitions diffracted in 1st order [*].

Calibration of local dispersion relation of spectrometer provides measurements of Lyman wavelengths.

Novel approach of fitting full two-dimensional dispersion relation, using Balmer and Lyman series, limits random & systematic correlation.
Theory of X-ray diffraction from mosaic crystals.

[*] C. T. Chantler, J. M. Laming, D. D. Dietrich, W. A. Hallett, R. McDonald, J. D. Silver, ‘The Hydrogenic Lamb Shift in Iron, Fe^{25+} and fine structure,’ Phys. Rev. A76 (2007) 042116-1-19

Hydrogenic Lamb Shift in Iron, Fe 25+ & fine structure Lamb shift 1s-2p Lyman α transitions in hydrogenic iron, Fe25+

Several systematics:

2s-1s and 4f-2p satellites;
Variable location of spectral emission downstream of the beam-foil target; … [*]

Results agree with but lie higher than theory.
This represents a 5.7% measurement of the hydrogenic 1s-$2p_{1/2}$ Lamb shift in iron.
The technique also reports iron $2p_{3/2}$ -$2p_{1/2}$ fine structure as 171108 cm^{-1} ± 180 cm^{-1}, a 51% measurement of the hydrogenic iron fine-structure Lamb shift
Reports measurements of secondary lines

[*] C. T. Chantler, 'Charge and State Population in Dilute plasmas from Beam-Foil Spectroscopy,' Can. J. Phys. 86 (2008) 331-350

Hydrogenic Lamb Shift in Iron, Fe 25+ & fine structure Lamb shift 1s-2p Lyman α transitions in hydrogenic iron, Fe25+

Need for careful consideration of experimental systematics

Future for EBIT sources

Continuing investigations of hydrogenic & helium-like tests of QED in medium-Z systems: especially including titanium & vanadium

Precision QED tests: highly ionised atoms

Mark N Kinnane, Justin A Kimpton, Lucas F Smale

D. Paterson, C.-H. Su, G. Christodoulou, A. Payne

- *L. T. Hudson, B. Radints, R. D. Deslattes, J. Schweppe, A. Henins, NIST, Gaithersburg, Maryland*
- *D. Crosby, J. D. Silver, A. J. Varney, W. A. Hallett, S. N. Lea, Clarendon Laboratory, University of Oxford*
- *J. D. Gillaspy, J. Pomeroy, J. Tan, F. G. Serpa, E. Takacs, J. R. Roberts, + Atomic Physics Division, NIST*
- *J. M. Laming, C. Brown, Naval Research Laboratory, Washington DC*
- *D. D. Dietrich, Lawrence Livermore National Laboratory, California*
- *P. H. Mokler, GSI, Darmstadt*
- *C. Szabo, P. Indelicato, J.-P. Briand, Paris*
- *H. F. Beyer, D. Liesen, GSI, Darmstadt*
- *K. D. Finlayson, CSIRO Perth, Western Australia*

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Standards and Technology

What is Atomic Physics?

- Precise physics of simple atomic systems (Venice, 2006):
  - Hydrogen TESTING PROTON FORM FACTOR, dα /dt [Hansch]
  - Helium TESTING ELECTRON CORRELATION, QED
  - **Highly ionised atoms (hydrogenic V, Fe, …)** **TESTING QED [,new technology, detectors, standards]** ***-see poster***
  - High-Z systems (U) TESTING QED, NUCLEAR PHYSICS, COUPLING
  - Exotic Atoms (antihydrogen p-e+, positronium e+e-, muonium, muonic atoms, g-2) TESTING QED IN EXTREME REGIMES and COUPLING NEAR DIVERGENCE, RENORMALISATION
  - **Neutral Atoms (Cs, Rb)** TESTING ELECTRO-WEAK THEORY, PARITY VIOLATION [Wieman] [Solid State: Cold Traps, BECs, Phillips]
  - **Neutral Atoms (synchrotrons) TESTING RELATIVISTIC ATOMIC FORM FACTORS, SCATTERING THEORY, ATOMIC AND SOLID STATE PHYSICS, RADIAL ELECTRON DENSITIES OF ATOMS [XAFS, materials science, medicine, biology, chemistry]** ***-see poster***

QED Motivation

- QED theoretical uncertainties are comparable to experimental accuracy
- expansions in α/π & $Z\alpha$, from successive Feynman diagrams, are only asymptotically convergent

Karshenboim00: current progress on $\alpha(Z\alpha)^7 m$, $\alpha^2(Z\alpha)^6 m$ terms

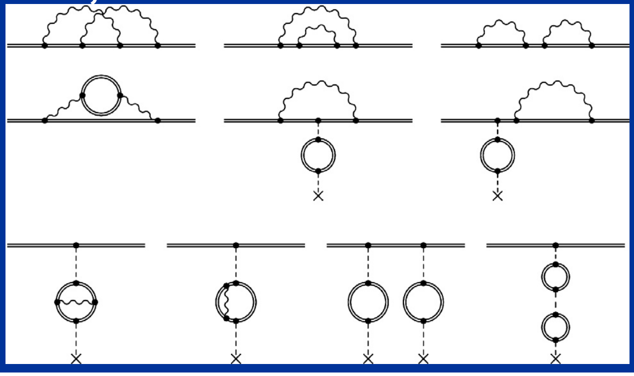
Eides 95, Pachucki96: Lowest order *two-loop term* of order ?%.

Sapirstein 98: asymptotic expansions - divergence in $Z\alpha$ & α possible

- higher order terms may yield corrections as large or larger than lower order terms [Jentschura, U.D., Phys. Rev. D62, 076001 (2000)]
- Alternative theoretical approaches are testable in medium-Z systems [F. Ruzzene, Aust. J. Phys. 53 (2000)]
- Tools required for fundamental investigations have yielded new state-of-the-art spectrometers & detectors designed & constructed in Australia (Melbourne)

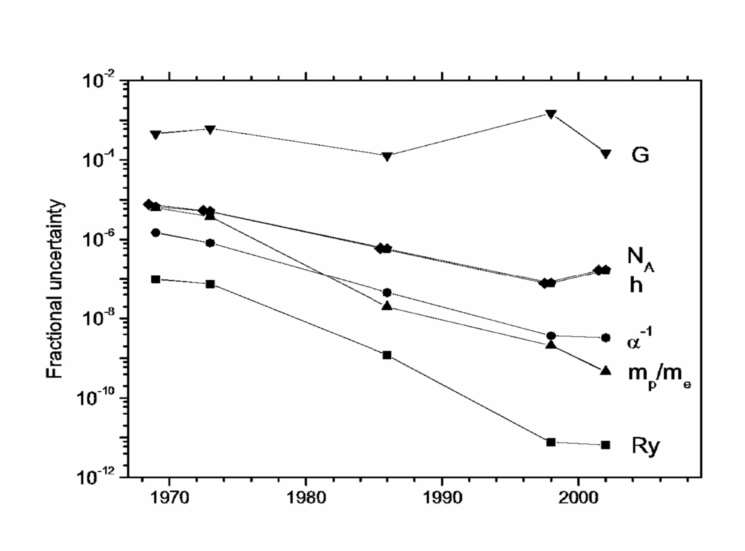
Recent QED Motivation

- Fundamental constants, CODATA results & inconsistencies, alternative interpretations [Karshenboim; Jentschura; PSAS 2006, CJP85 (2007) 531; 551]
- Numerical calculation of $G_{SE}(Z\alpha)$ for Z=1-5 differed by 13 kHz for hydrogen 1S. Perturbative high orders are really large! [Jentschura, Mohr (2004, 2005); Eides PSAS 2006]
- Two-loop $\alpha^2(Z\alpha)^6m$ terms dominated by single logarithm term (B_{61}). Estimates of uncalculated terms is an art, not science [Eides PSAS 2006]. Numerical error of B_{60} is 15% [Pachucki, Jentschura (2003), J (2004); major disagreement with Yerokhin, Indelicato, Shabaev (2005)]
- Radiative-recoil single loop $\alpha(Z\alpha)^6m/M$ known, but other terms of similar order not.
- Proton Radius
- Non-S state high order terms
- direct confirmation for higher-Z



QED & New Physics

- Measurements of Quantum Electrodynamics (QED) in atomic physics develop & push back frontiers of science in Cosmology, Diffraction Theory, Crystallography, Detector Characterisation, Atomic Form Factor Theory & the application & computation of QED theory itself
- X-ray spectroscopy
- Electron-Beam Ion Trap (EBIT)
- Systematics in general



DECEMBER 1997 PHYSICS TODAY 19 [PRL 79 (Oct. 1997) 2646]

At the Max Planck Institute for Quantum Optics in the Munich suburb of Garching, Theodor Hänsch and colleagues have measured the ultraviolet transition frequency between the 1S and 2S states of atomic hydrogen to be

2.466 061 413 187 34 (84) x 10^{15} Hz. It's so accurate that simply repeating the measurement a year from now would provide a better and more direct verification (or falsification) of the constancy of the fine-structure constant over cosmological time than any astrophysical data we have.

Dirac, among others, conjectured that the fundamental constants might be varying very slowly. "Of course, it's not why we developed this high-precision technique," Hänsch told us. "But if it lets us do the best test ever, we should."

Testing QED

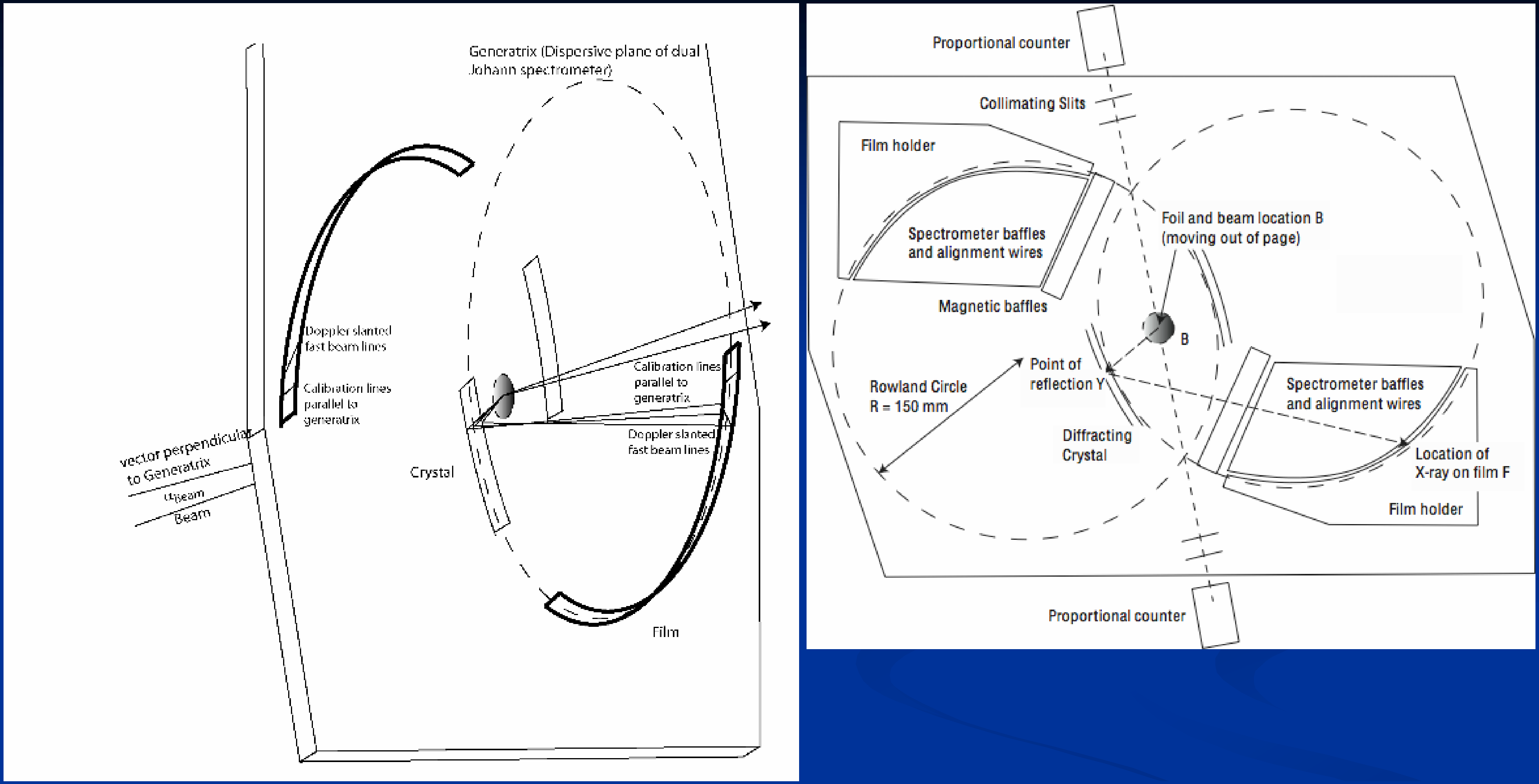
"Our high-precision measurements in the last few years seem to have stimulated a <u>renaissance of quantum electrodynamics calculations,</u>" Hänsch told us. "<u>Calculating small higher-order QED effects can yield surprises</u>…"

H,He: r, form factor of nucleus, polarizability, α, 2e-correlation, 2e-QED *but*

QED terms scale as $(Z\alpha)^4$ & $(Z\alpha)^6$, $(Z\alpha)^8$:

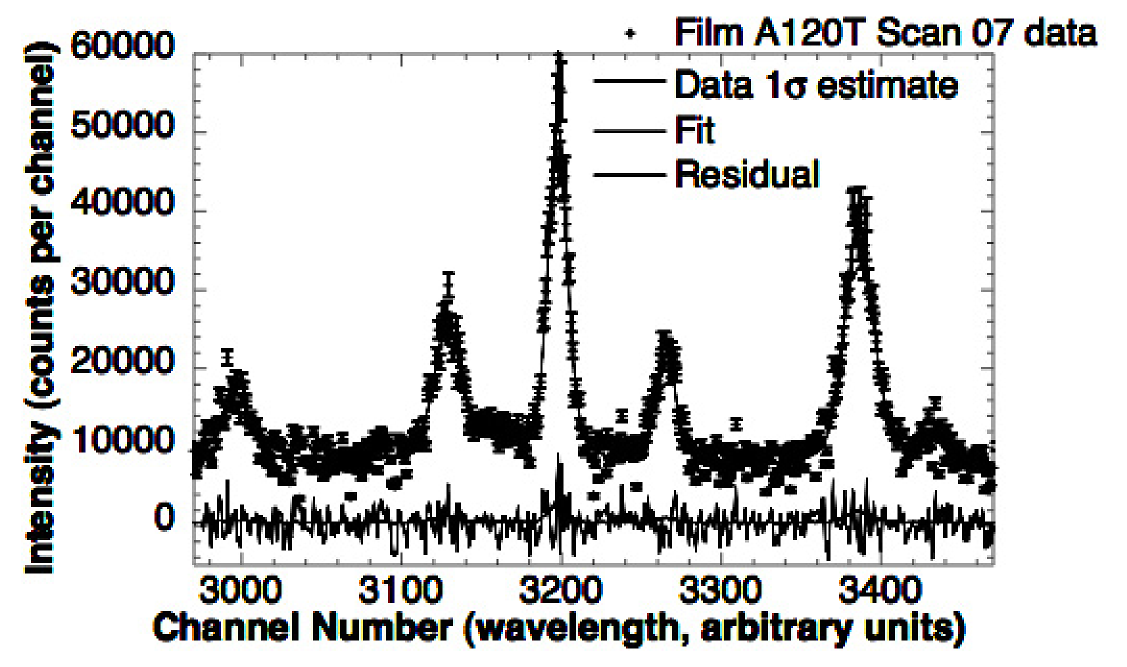
Contribution (1-e)	Lowest Order	Theory (H, MHz)
Self-energy	$\alpha(Z\alpha)^4$...	1085.812
Vacuum polarization	$\alpha(Z\alpha)^4$...	-26.896
Fourth order	$\alpha^2(Z\alpha)^4$...	0.101
Reduced mass	$(m/M)\alpha(Z\alpha)^4$...	-1.647
Relativistic recoil	$(m/M)(Z\alpha)^5$	0.359
Nuclear size	$(Z\alpha)^4$	0.145 or 0.1..
total		1057.873(20) or 1057.82(2)...

- Higher-Order terms, divergences & $(Z\alpha)$ expansions?

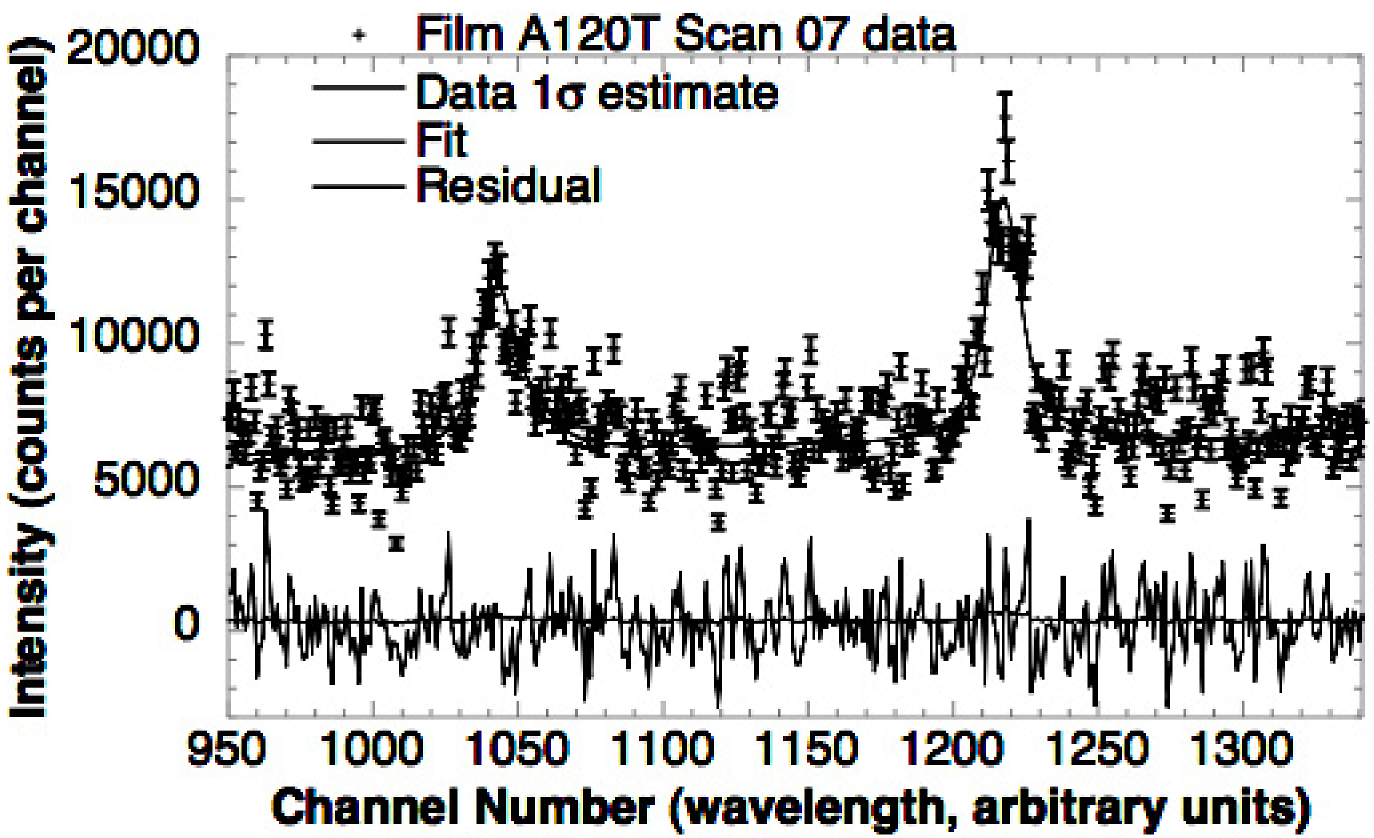


The Hydrogenic Lamb Shift in Iron, Fe^{25+} and fine structure. 1s-2p Lyman α observed from a beam-foil source in 4th order diffraction off ADP 101 and PET 002 crystals, simultaneously with n=2 to n=4 Balmer β transitions diffracted in first order.

An individual scan (number 7 of 18) of a particular emulsion (A120T) using a PET diffracting crystal, in the region of Lyman α & Balmer β overlap between the first and fourth orders of diffraction: [From left to right, Ba β $2p_{1/2}$ - $4d_{3/2}$, $2s_{1/2}$ - $4p_{3/2}$; Ba β $2p_{1/2}$ - $4s_{1/2}$, $2s_{1/2}$ - $4p_{1/2}$; Ly α $1s_{1/2}$ - $2p_{3/2}$; Ly α $1s_{1/2}$ - $2p_{1/2}$; Ba β $2p_{3/2}$ - $4d_{5/2}$, $2p_{3/2}$ - $4d_{3/2}$; Ba β $2p_{3/2}$ - $4s_{1/2}$]. Residuals dominated by noise.



Ba γ $2p_{1/2}$ - $5d_{3/2}$; Ba γ $2p_{3/2}$ - $5d_{5/2}$

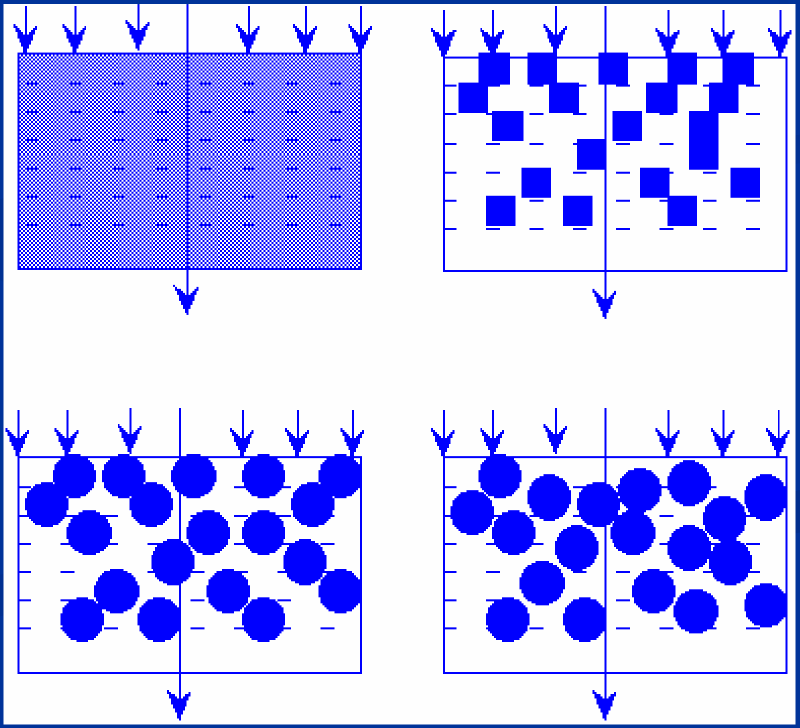


Curved Crystal Diffraction theory

- Model developed in 1990. A few simplifications & inconsistencies
- Two papers developed earlier model (1992). First to combine curvature & mosaicity in a dynamical diffraction theory
- Further development. A J Varney. Mammography & EBITs (1994 – 96)
- Invited Review with R D Deslattes (1995) - issues for experimentalists
- Development with D Paterson, M Kinnane - systematics of curved crystals & EBITs

(X-ray) photographic theory & linearisation

- Three papers, first to give physically meaningful variables (1993)
- Currently most accurate & valid available
- Experimental confirmation



Crystal-specific parameters	PET crystal	ADP crystal
RI: infinite flat perfect crystals	-63.80µm	-74µm
RI: (finite crystal with focusing)	+0.06µm	-
RI: Depth penetration	-97.18µm	-45µm
Geometry: finite source correction	-4.70µm	-
Densitometry: Emulsion penetration	+2.87µm	+4.74µm
PET Mosaic crystal, 0.7µm block T		
ADP perfect crystal, medium precision	-148.12µm	-112.20µm
Balmer wavelength ±1.77ppm	±0.79µm	±0.49µm
High-precision (0.6µm PET) shifts	-4.64µm	+2.90µm
Contributions to uncertainties due to input parameter uncertainties		
crystal T	±4.50µm	±0.02µm
α_{plane}	±3.93µm	±1.30µm
polarisation	-(0.26±.26)µm	±0E-4µm
other (α_{Beam})	±.36µm	±.77µm
Voigt fitting (h=1.00mm)	(+2.95±.65)µm	(+2.71±.51)µm
Voigt fitting (h=0.45mm or 0.40mm)	(+3.74±.61)µm	(+3.96±.47)µm
Densitometry	±0.26µm	±0.26µm

Balmer f.s. $2p_{1/2}$-$4d_{3/2}$ –> $2p_{3/2}$-$4d_{5/2}$	11630 ppm
Lyman fine structure	3042 ppm
Lamb shift (theory)	573.6 ppm
Instrumental resolution	550 ppm

Crystal-specific parameters	PET crystal	ADP crystal
20 µm densitometer step	45.4 ppm	72.8 ppm
RI: (flat crystal) 4th v 1st order shift	-145 ±13.7 ppm	-269 ±5.9 ppm
Curved crystal depth penetration	-221 ppm	-164 ppm
Total curved crystal shift	-346.8 ppm	-397.9 ppm
Voigt centroid - mean shift (h=1.00mm)	(6.7 ±1.5) ppm	
Voigt centroid - mean shift (h=0.45mm)	(8.5 ±1.4) ppm	
Correction for polarisation	-0.59±0.59ppm	0 ppm

Typical Hydrogenic iron results using the PET diffracting crystal: Film emulsion A120T:

C Target 9 μgcm^{-2}; h(f) 0.45mm; Observation Length: 2 mm; Scans: 12

Local Ly - Ba fit: Mean, medium precision shift, 1 std dev. uncertainty:

Lyman α_1 143.3±6.4 ppm   Lyman α_2 143.4 ±5.6 ppm

Weighted global fits of whole Lyman - Balmer series for all scans, medium precision:

Lyman 149.6 ±8.6ppm

Correction: high precision computations, with theoretical uncertainty:

Lyman α_1 2.65±13.8 ppm   Lyman α_2 2.62±13.6 ppm

Additional spectral features & transitions, corrections to above:

Dielectronic satellites: Lyman α_1 +.01±1.01 ppm   Lyman α_2 +1.93±1.01 ppm

Corrections for satellites based upon decay at the foil target exit:

2s-1s+Ly   Lyman α_2 -0.91±2.4ppm

4f-2p decays   Lyman α_1 -3.39±2.ppm   Lyman α_2 -3.00±2.ppm

Fitting Errors, corrections: Lyman -19±19 ppm

Upper limit C2 or thickness-independent source, with 25% increase for nmax >14:

Correction   Lyman α_1 -29.3 ±22 ppm   Lyman α_2 -28.9 ±21 ppm

Upper limit for fits of each film, PET exposures ‡: statistical uncertainty only:

Upper limit   Lyman α_1 94.27±6.4 ‡ ppm   Lyman α_2 96.12±5.6 ‡ ppm

Upper limit, global fits   Lyman 101.46±8.6 ‡ ppm

Total Uncertainty   Lyman α_1 ±32.9 ppm   Lyman α_2 ±32.1 ppm

Lower (Yrast) limit for C2 decay source (instead of C2 decay estimate): Yrast shift/2mm -79±22 ppm

Lower (Yrast) limit   Lyman α_1 44.57 ppm   Lyman α_2 46.02 ppm

Typical Hydrogenic iron results: ADP diffracting crystal: Film emulsion A322S:

C Target 5 μgcm^{-2}; h(f) 0.45mm; Observation Length: 1 mm; Scans: 14

Local Ly – Ba fit: Mean, medium precision shift:

Lyman α_1 189.4 ±13.7 ppm Lyman α_2 170.6 ±12.4 ppm

Weighted global fits of whole Lyman - Balmer series for all scans, medium precision :

Lyman 154.4 ±14.7 ppm

Correction: high precision computations, with theoretical uncertainty:

Lyman α_1 -24.6 ±5.9 ppm Lyman α_2 -24.5 ±5.8 ppm

Additional spectral features & transitions, corrections to above:

Dielectronic satellites: Lyman α_1 -1.09±0.61 ppm Lyman α_2 -1.01±0.83 ppm

Corrections for satellites based upon decay at the foil target exit:

2s-1s+Ly Lyman α_2 -3.0±4.5 ppm

4f-2p decays Lyman α_1 -3.2±2. ppm Lyman α_2 -2.8±2. ppm

Fitting Errors, corrections: Lyman -19 ±19 ppm

Upper limit C2 or thickness-independent source, with 25% increase for nmax >14:

Correction Lyman α_1 -35 ±35 ppm Lyman α_2 -34 ±35 ppm

Upper limit for fits of each film, ADP exposures ‡: statistical uncertainty only:

Upper limit Lyman α_1 106.4±13.7 ‡ ppm Lyman α_2 85.6±12.4 ‡ ppm

Upper limit, global fits Lyman 70.4±14.7 ‡ ppm

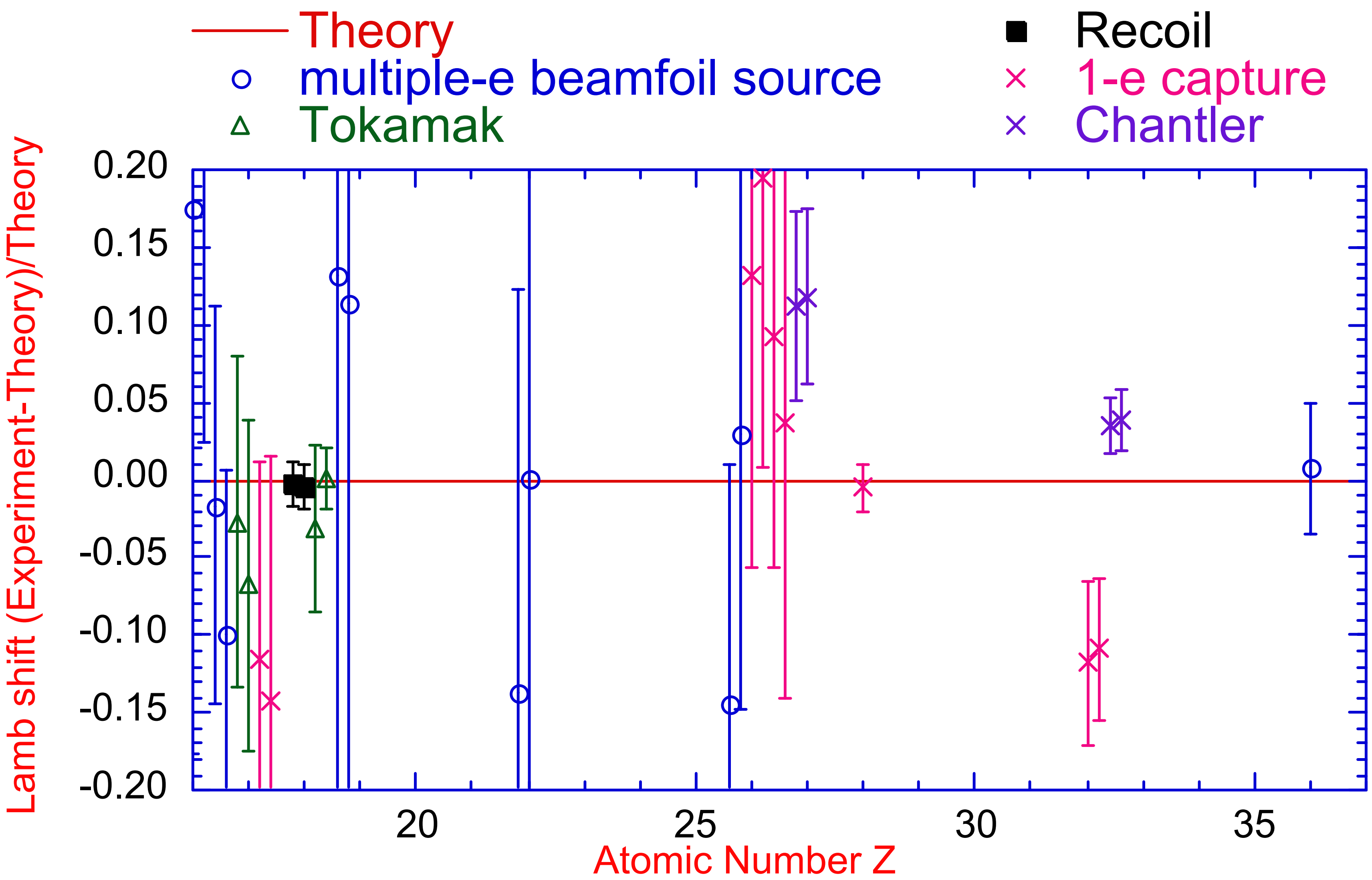
Total Uncertainty Lyman α_1 ±42.6 ppm Lyman α_2 ±42.4 ppm

Lower (Yrast) limit for C2 decay source (instead of C2 decay estimate): Yrast shift/1mm -75±35 ppm

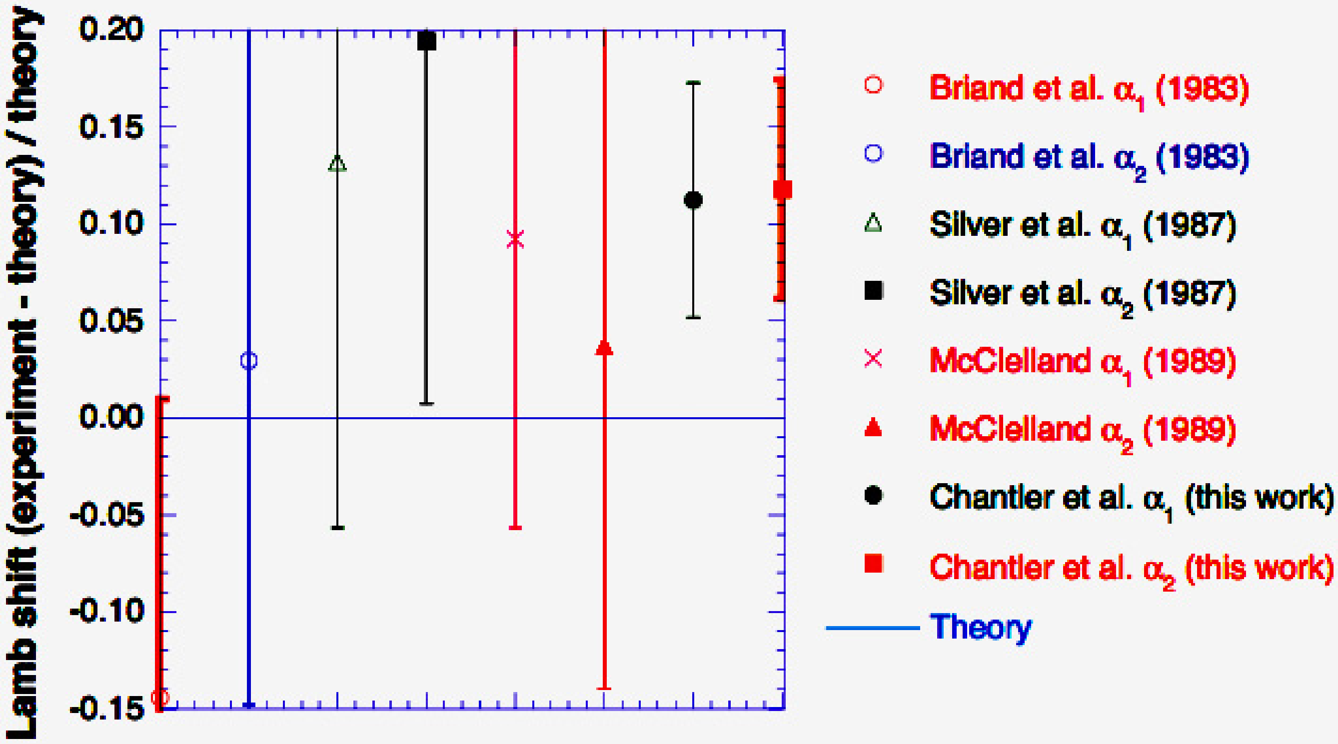
Lower (Yrast) limit Lyman α_1 66.5 ppm Lyman α_2 45.0 ppm

Mean Hydrogenic iron results using the PET & ADP diffracting crystals: All Film emulsions:

	PET average	ADP average	Pooled Average
Upper limit C2 or thickness-independent source, with 25% increase for nmax >14:			
‡: statistical uncertainty:			
Upper limit, Lyman α_1	92.4 ±7.9 ‡ ppm	88.9 ±19.9 ‡ ppm	91.7 ±11.4 ‡ ppm
Upper limit, Lyman α_2	97.9 ±3.2 ‡ ppm	88.9 ±11.2 ‡ ppm	95.4 ±7.7 ‡ ppm
Upper limit, global fits	99.3 ±4.8 ‡ ppm	84.6 ±9.6 ‡ ppm	98.2 ±6.5 ‡ ppm
Total Uncertainty, Lyman α_1	±33.2 ppm	±45.0 ppm	±34.2 ppm
Total Uncertainty, Lyman α_2	±31.7 ppm	±42.1 ppm	±32.5 ppm
Lower (Yrast) limit for C2 decay source (instead of C2 decay estimate):			
Lower limit, Lyman α_1	42.7 ppm	48.9 ppm	
Lower limit, Lyman α_2	47.8 ppm	48.3 ppm	
Yrast estimate from Lyman β:	-29.4 ± 23.8 ppm	-23.5 ± 19.0 ppm	
Final estimate, local fits, Lyman α_1	63.0 ppm	65.3 ppm	63.5 ±11.4±32.3 ppm
Final estimate, local fits, Lyman α_2	68.5 ppm	65.4 ppm	67.6 ±7.7±31.5 ppm
Derived Wavelengths	1.7781293[203][574] Å	1.7835626[137][562] Å	
Theory, Johnson, Soff (1985)	1.7780163[6] Å	1.7834420[6] Å	
Theory, Erickson (1977)	1.7780439[55] Å	1.7834690[59] Å	
Experimental Lamb shift	35376[641][1817] cm^{-1}	35953[432][1766] cm^{-1}	
Silver et al. PRA36(1987)1515:	36000[6000] cm^{-1}	38400[6000] cm^{-1}	
Briand et al. PRL50(1983)832:	27400[4800] cm^{-1}	33300[5600] cm^{-1}	
Theory, Johnson, Soff (1985):	31802[20] cm^{-1}	32160[20] cm^{-1}	



Comparison of theory and experiment for the 1s-2p Lamb shift.
Results are paired with Lyman α_1 (1s-2p$_{3/2}$) followed by Lyman α_2 (1s-2p$_{1/2}$)



Comparison of theory and experiment for the 1s-2p Lamb shift.
Results are paired with Lyman α_1 (1s-2$p_{3/2}$) followed by Lyman α_2 (1s-2$p_{1/2}$)

Measurement of iron $2p_{3/2}$ - $2p_{1/2}$ fine structure

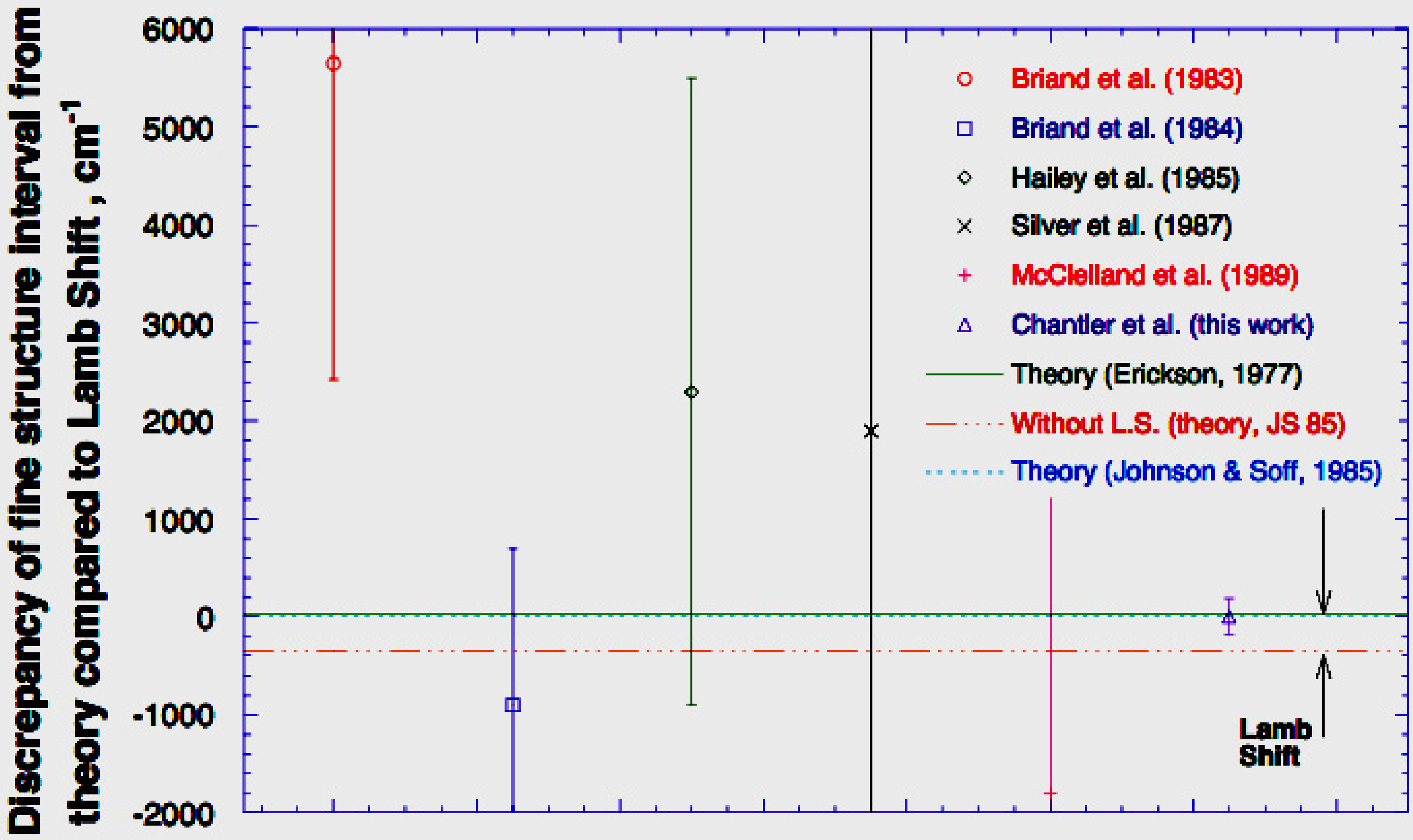
	PET average	ADP average	Pooled Average
From earlier summary:	5.48 ±8.1ppm	0.29 ±35. ppm	4.44 ±20. ppm
Direct measurement:	0.174 ± 3.4 ppm	-0.281 ± 6.0 ppm	-.089 ± 3.0 ppm
Weighted mean:			0.0654 ± .194 ppm
Residual systematics (ppm of Lyman α wavelength):			
Diffraction uncertainty:	± 0.20ppm	± 0.20ppm	
Dielectronic satellites	± 1.01ppm	± 1.49ppm	
2s-1s+Ly γ:	± 2.4ppm	± 4.5ppm	
4f-2p decays:	± 0.40ppm	± 0.40ppm	
Fitting error:	± 1.82ppm	± 1.82ppm	
Decay source:	± 0.4ppm	± 0.7ppm	
Fine structure wrt theory	0.174 ± 4.66ppm	-0.281 ± 7.90ppm	0.0654 ± 3.2ppm
ppm of f.s. interval	57.0[1101][1058]	-92.1[1966][1684]	21.4[63.6][1058]
Δ cm^{-1} wrt Johnson, Soff	9.76 ± 261 cm^{-1}	-15.76 ± 442 cm^{-1}	+3.67 ± 181 cm^{-1}

McClelland+ NIMB9(1989)706: -1804 ±7400 cm^{-1} Silver+ PRA36(1987)1515: +1896 ±5300 cm^{-1}

Briand+ PRA28(1983)1413: +5650 ±3228 cm^{-1} Briand+ PRA29(1984)3143: -904 ±1600 cm^{-1}

Hailey+ JPhysB18(1985)1443: +2296 ±3200 cm^{-1}

f.s. Theory, Johnson, Soff	171104 ±1 cm^{-1} = ±5.8ppm f.s.
f.s. Theory, Erickson (1977)	171080 ±30 cm^{-1} = ±175ppm f.s.
Lamb shift contribution	358 ±.99 cm^{-1} = 2092 ±5.8ppm f.s.
Lamb shift, w.r.t. Johnson, Soff	1% ± 51%


Discrepancy of fine structure interval from theory compared to Lamb Shift , cm^{-1}
6000
5000
4000
3000
2000
1000
0
-1000
-2000
○ Briand et al. (1983)
□ Briand et al. (1984)
◇ Hailey et al. (1985)
× Silver et al. (1987)
+ McClelland et al. (1989)
△ Chantler et al. (this work)
Theory (Erickson, 1977)
Without L.S. (theory, JS 85)
Theory (Johnson & Soff, 1985)
Lamb Shift

- Fitting the full two-dimensional dispersion relation, including other members of Balmer and Lyman series, limits random and systematic correlation of parameters, and reveals a major systematic due to dynamical diffraction depth penetration into a curved crystal.
- Circa 34 ppm

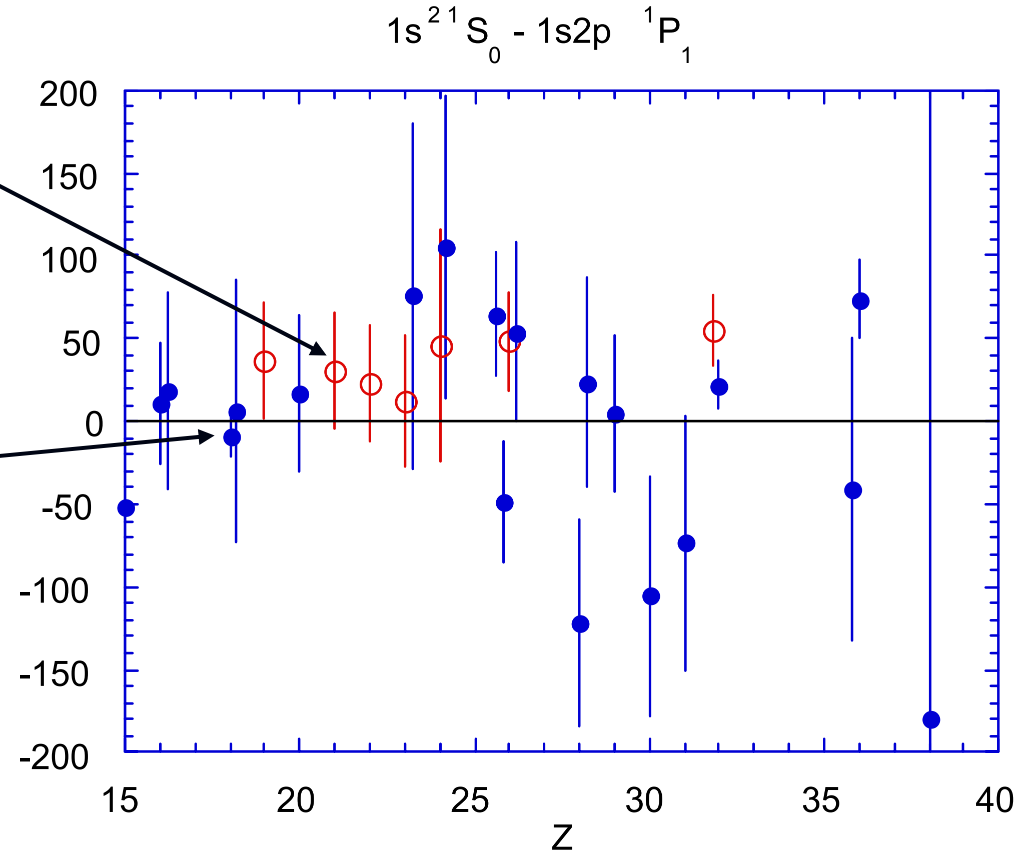
- Developing a theory of X-ray diffraction from mosaic crystals
- New Photographic theory
- 2s-1s & 4f-2p satellites explicitly investigated

- dominant systematic is due to variable location of spectral emission downstream of beam-foil target [>3x statistical uncertainty] 30 ppm vs 11 (or 8) ppm
- fitting systematics [partly due to use of photographic emulsion] 19 ppm
- diffraction theory & testing 14 ppm

- 1s-2p$_{3/2}$, 1s-2p$_{1/2}$ iron Lamb shifts are 35376 ± 1900cm^{-1} and 35953 ± 1800cm^{-1}
- These agree with but lie higher than theory (2σ)
- 5.7% measurement of the hydrogenic 1s-2p$_{1/2}$ Lamb shift in iron
- Iron 2p$_{3/2}$ - 2p$_{1/2}$ fine structure 171108 cm^{-1} ± 180 cm^{-1}: [3.2 ppm]
- 51% measurement of the hydrogenic iron fine structure Lamb shift

Measurements of the w transition in medium Z ions

- Reported trend above theoretical energies
    - Tokamak plasma
    - Satellite contamination
- Best measurement
    - Argon: 12 ppm
    - Recoil ion method
- Compared with theory of Drake



Helium-like resonance lines

General expression

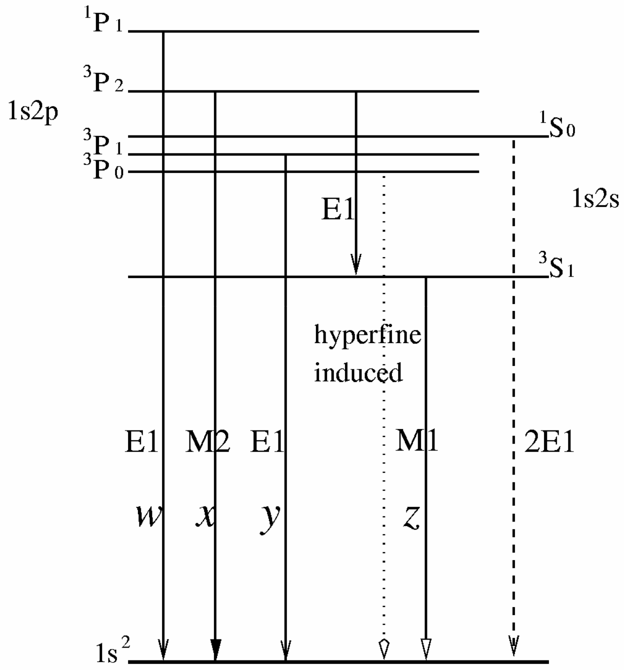
$1s2l \rightarrow 1s^2 + h\nu$

Notation (Gabriel 1972)

w	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$
x	$1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$
y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$
z	$1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$

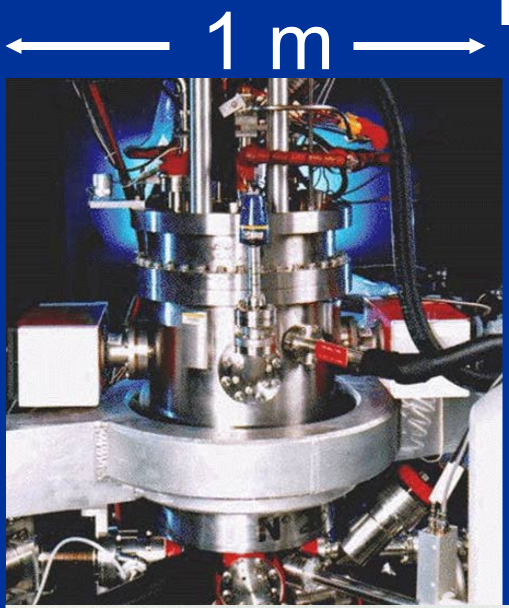
Hyperfine induced decay

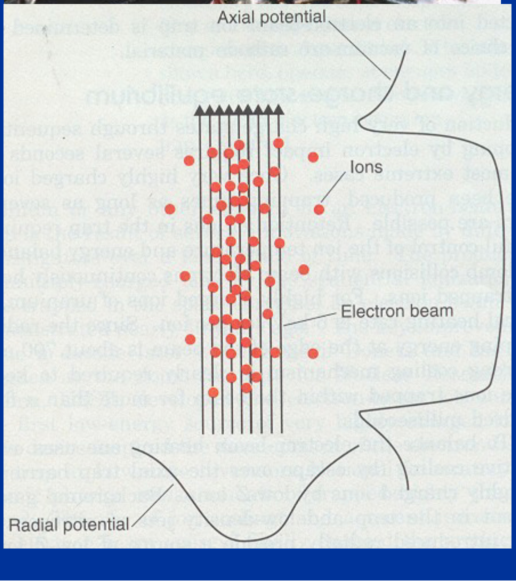
$1s2s\ ^3P_o \rightarrow 1s^2\ ^1S_0$



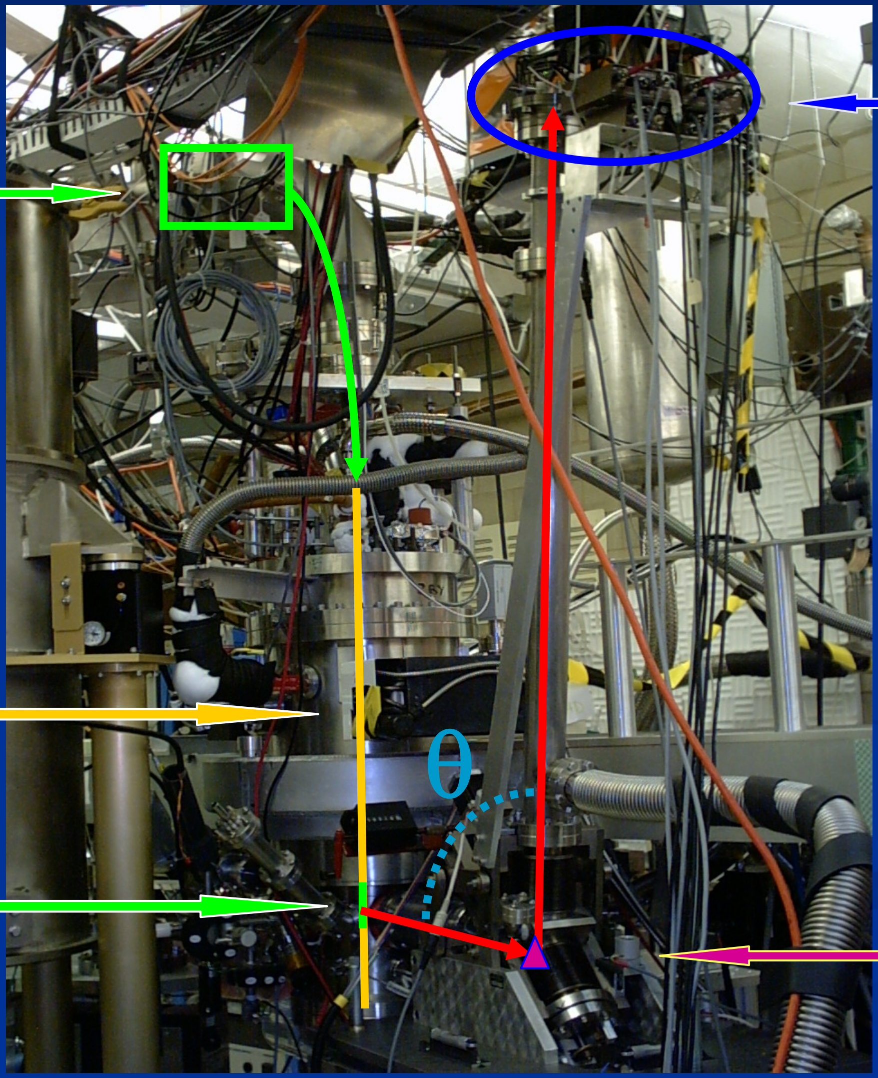
Source of highly charged ions

- Electron beam ion trap (EBIT)
- Table-top device, modest cost
- Magnetically confined electron beam ionises and traps ions
  - Highly charged => Bare uranium (92+)
  - Novel source for spectroscopy
  - Tune electron beam to transition energy, reduce satellite contamination
  - Ions at thermal velocities, negligible Doppler shifts





NIST Experiment



MEVVA

Detector System

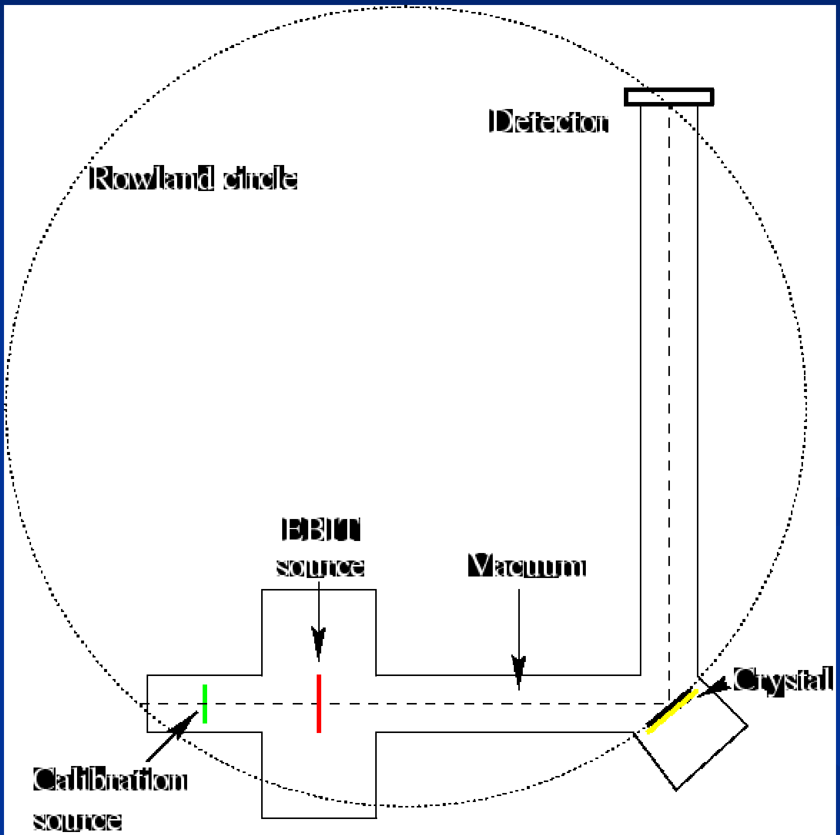
Electron Beam

Ion Trap

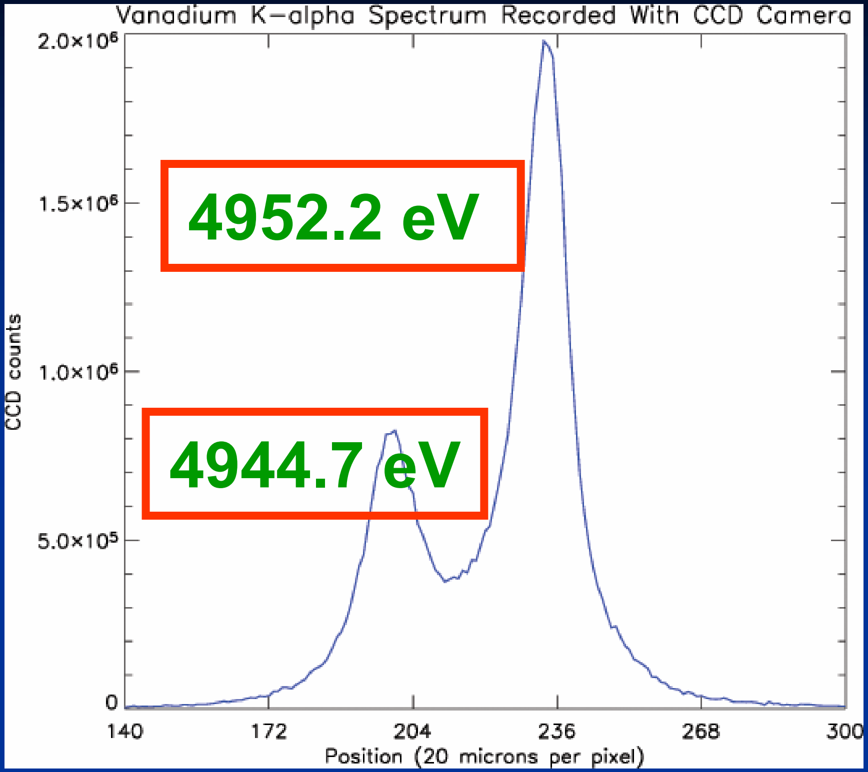
Diffracting Crystal

Calibration source arrangement

- Features:
  - Calibration source located inside Rowland circle
  - Measure range of wavelengths clustered around region of interest *(calibration spectra)*
  - Spectra and dispersion function linked by angle measurement *(clinometry)*
  - Investigate systematics, e.g. source size
- D. J. Paterson, C. T. Chantler, C. Tran, L. T. Hudson, F. G. Serpa, and R. D. Deslattes, Phys. Scr. **T73**, 400 (1997).



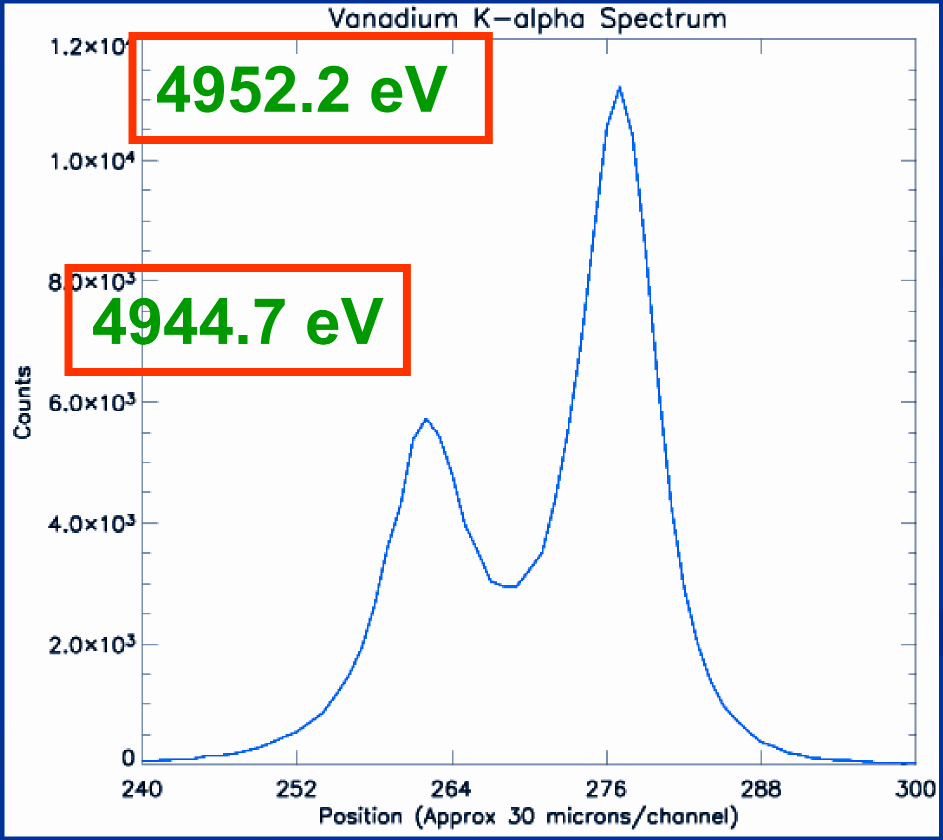
CCD camera
(20 microns/pixel)

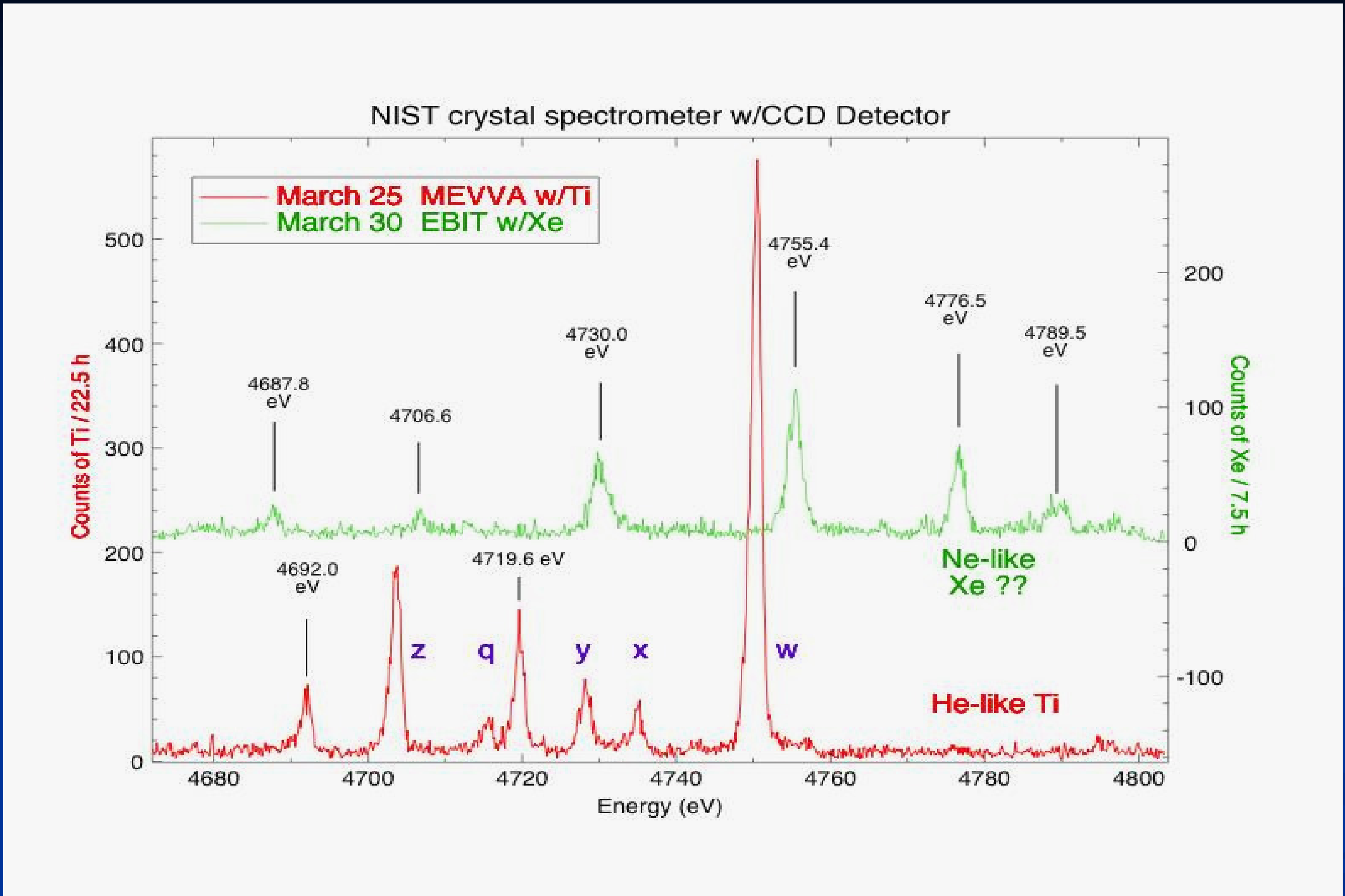


- *K*α doublets well resolved
- Doublets are used to calibrate detector scale
- Asymmetry of diffraction profiles?

New detector

Backgammon Detector
(circa 30 microns/channel)





w :He-like Ti ($^1S_0$-$^1P_1$) **x** :He-like Ti ($^1S_0$-$^3P_2$) **y** :He-like Ti ($^1S_0$-$^3P_1$)

q :Li-like Ti($^2P^0_{1/2}$-$^2D_{3/2}$) **z** :He-like Ti ($^1S_0$-$^3S_1$)

Issues for accurate determinations in the X-ray regime:

- **Calibration Issues (crystal or other spectrometry):**
- Sc, Ti, V, Cr and Mn, E = 4 - 6.5 keV
- Z = 21, 22, 23, 24 and 25
- X-ray reference spectra: Bearden, Deslattes, Indelicato?
- Cu Kα: 0.3 ppm; Mn Kα: 1.4 ppm
- More generally: Indelicato (theory) 100-200 ppm
- Sc Kα: 49 ppm (Bearden)
- Sc Kα 5 ppm (Deslattes, Anagnostopoulos - not tied to metre)
- V Kα 12 ppm, V Kβ 13 ppm (Deslattes, Bearden)?
- Ti Kβ 12 ppm (Deslattes, Bearden)?
- a calibrated array:???
- But what *experimentally* are these reference energies?

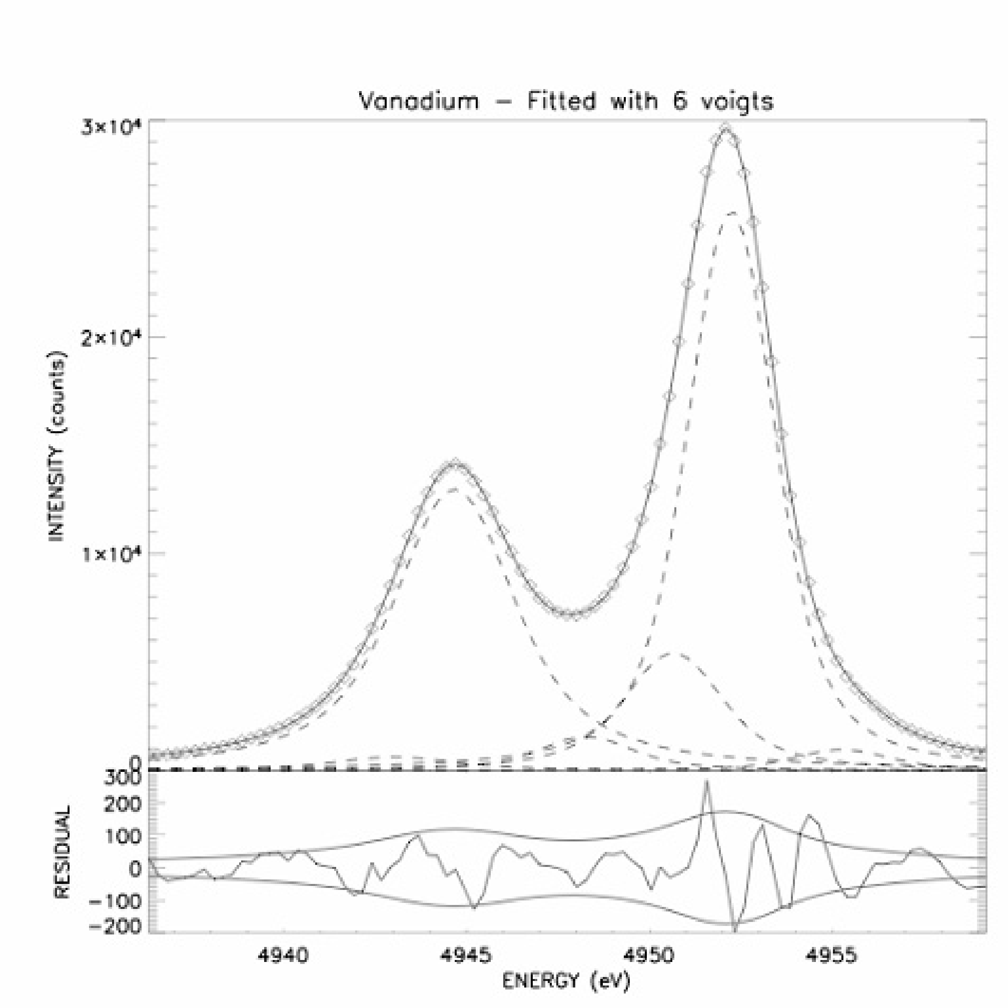
Issues for accurate determinations in the X-ray regime:

Calibration Issues (crystal or other spectrometry):

- Profiles, resolution and consistent component fitting:
- The characterisation of energy must be by *profile*
- *Any use of a nominal Kα_1 energy without profile registration will amplify errors*
- *The resolution affects the peak locations and fitted component locations and intensities*
- Sc Kα 5 ppm profile available; Ti - no profile analysis done
- V Kα 12 ppm, V Kβ 13 ppm (Deslattes, Bearden)? No profiles previously available
- Chantler, Kinnane, Su, Kimpton PRA73 (2006) 012508

Experiment: calibration

- V Kα 12 ppm, profile, Voigt components, χ^2_r=0.91



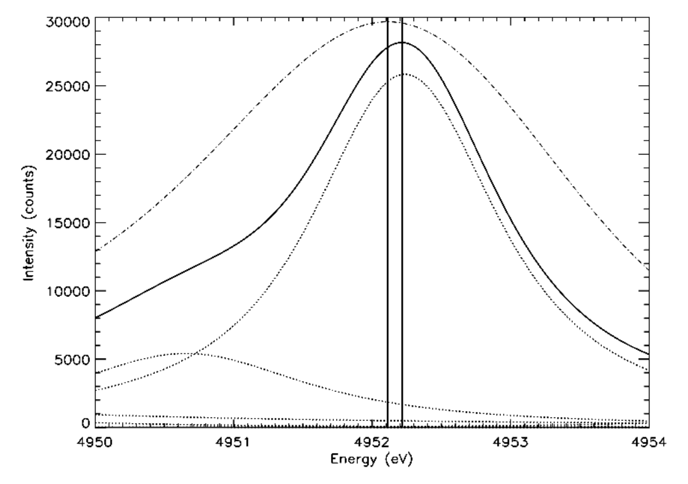
Issues for accurate determinations in the X-ray regime:

Calibration Issues (crystal or other spectrometry):

- Resolution: *The resolution affects the peak locations and fitted component locations and intensities*: a 15 ppm shift, calibrated to 1 ppm

Centroid Shifts ΔC for the peak values $K\alpha_1^0$, $K\alpha_2^0$ for vanadium and σ(ΔC) in eV, including the resolution correction. Widths of Lorentzian L = (1.39 ± 0.03) eV, and Gaussian (or Slit) G or S = (0.6 ± 0.1) eV follow the consistency of double-flat crystal measurements for Sc, Ti, Cr and Mn

	ΔC, eV	σ(ΔC), eV	ΔC, eV	σ(ΔC), eV
Resolution Mismatch	$K\alpha_1^0$	$K\alpha_1^0$	$K\alpha_2^0$	$K\alpha_2^0$
V, Voigt fit	-0.085	0.006	-0.020	0.011
V, L-S fit	-0.1025	0.011	-0.003	0.0235
Precision of		$K\alpha_1^0$		$K\alpha_2^0$
Single (backgammon) image:		0.0034		0.0068
Indicative statistical precision:		$K\alpha_1^0$		$K\alpha_2^0$
fwhm/ $\sqrt{N}$		0.005		0.009



Shifts of V $K\alpha_1^0$ (vertical solid line) of the deconvolved (Voigt) spectrum (solid curve and dotted sub-component amplitudes) compared to the experimental profile and width (dot-dash curve and vertical line). The scale is expanded in order to demonstrate the shift between the two results for $K\ \alpha_1^0$ as a consequence of the additional broadening.

Issues for accurate determinations in the X-ray regime:

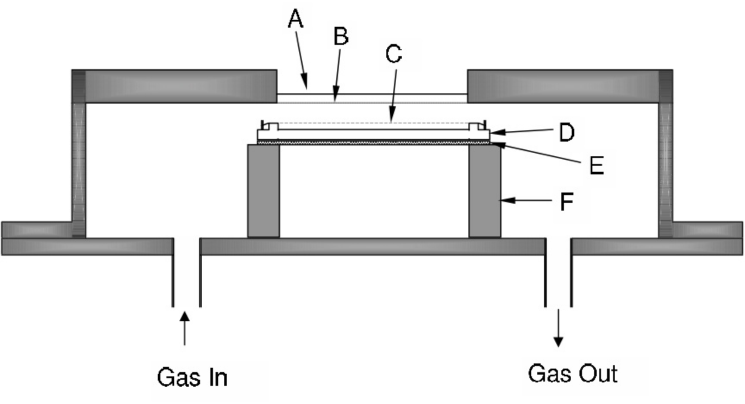
- ***Dynamical diffraction theory is essential in precision X-ray spectroscopy***
- Systematic shifts [C.T.Chantler, R.D.Deslattes, Rev. Sci. Instrum. **66**, 5123 (1995)]

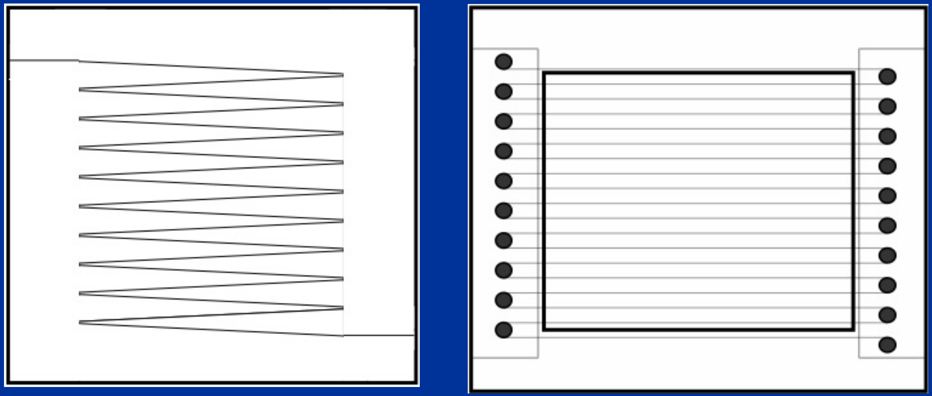
	(ppm)
Refractive Index correction	100-300, ± <1 ppm
Depth penetration	100
Lateral shifts	10-100
Geometrical effects	100-200

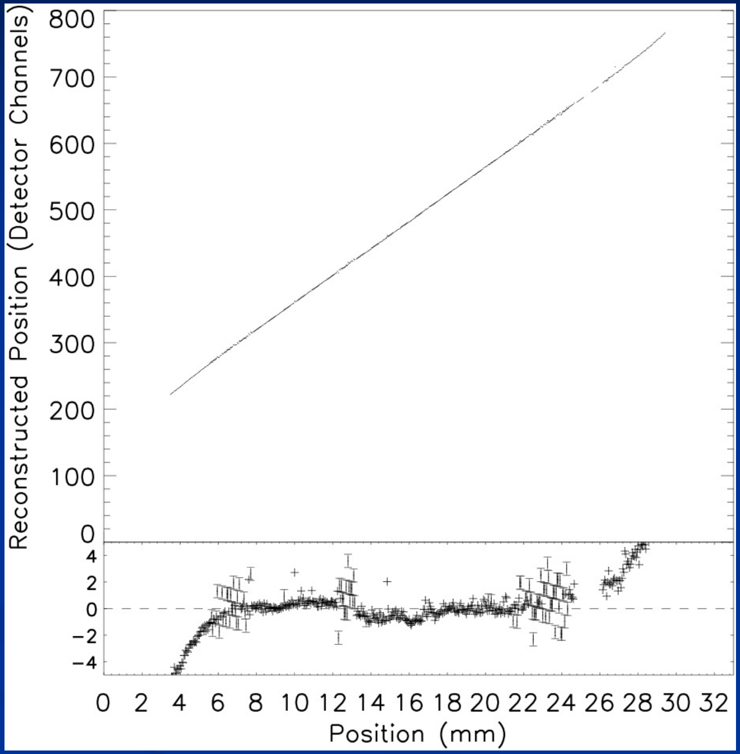
C. T. Chantler, D. Paterson, L. T. Hudson, *et al.*, Phys. Scripta **T80** (1999)

- ***Recent success:*** prediction of off-axis asymmetric centroid shifts. Shape & magnitude predicted.

Backgammon Detector

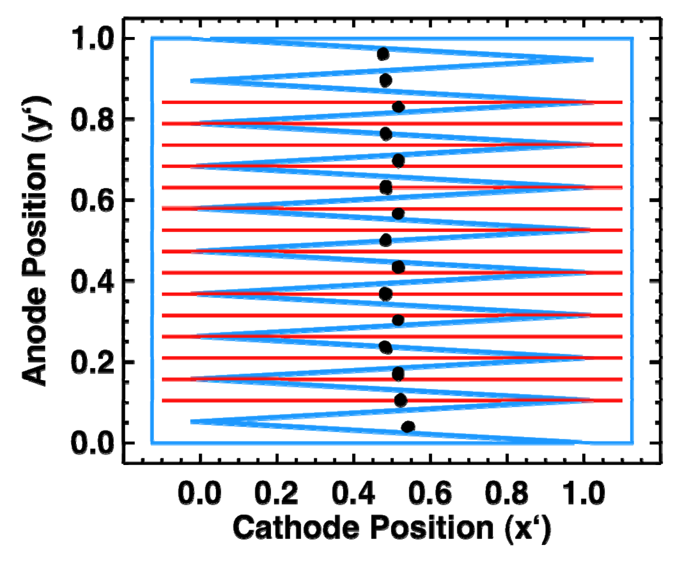


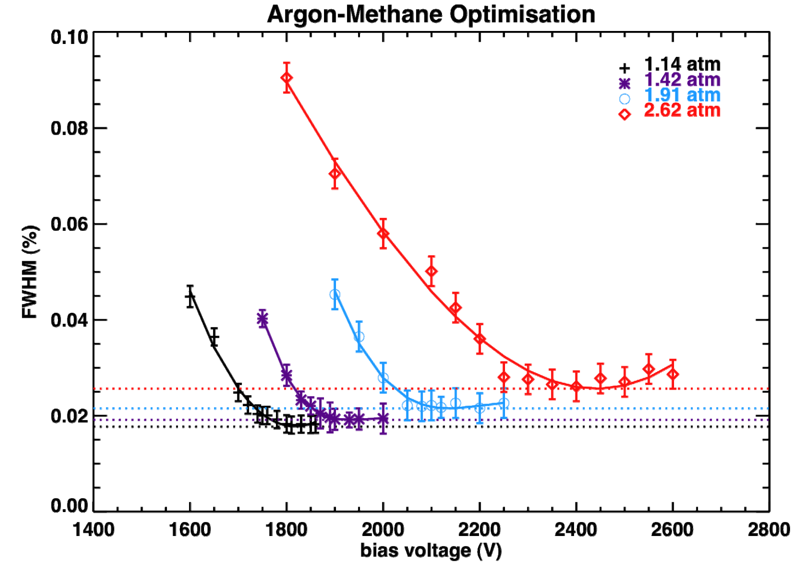


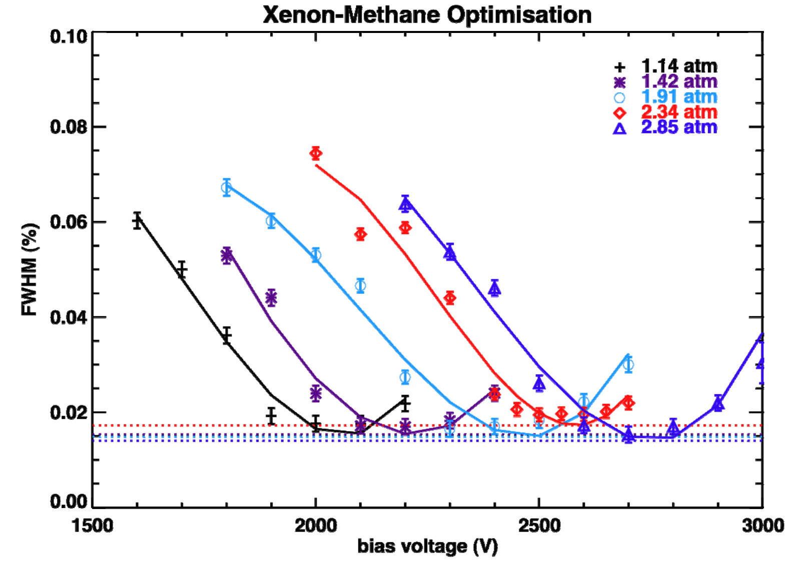


- Highly linear
- Flexible
- Suitable for relatively high flux

Backgammon Detector







Optimisation & characterisation of residual systematics & non-linearities

Error sources (ppm)	*He-V(PRA2000)*	*He-Ti*
	ppm	ppm
Statistical uncertainty of *w* line	10	3-7
Temperature and Doppler broadening	5	<1-2
Clinometry & related contributions		1-5
Statistical contributions to dispersion function		3-5
Reference wavelengths	12	6-11
Diffraction theory (& vignetting)	6	1-12?
Dispersion function determination	20	
Total dispersion function determination		10-20?
Total for the *w* line	27	6-15?
Other resonance lines:	*x*=40, *y*=33, *z*=28	9-43

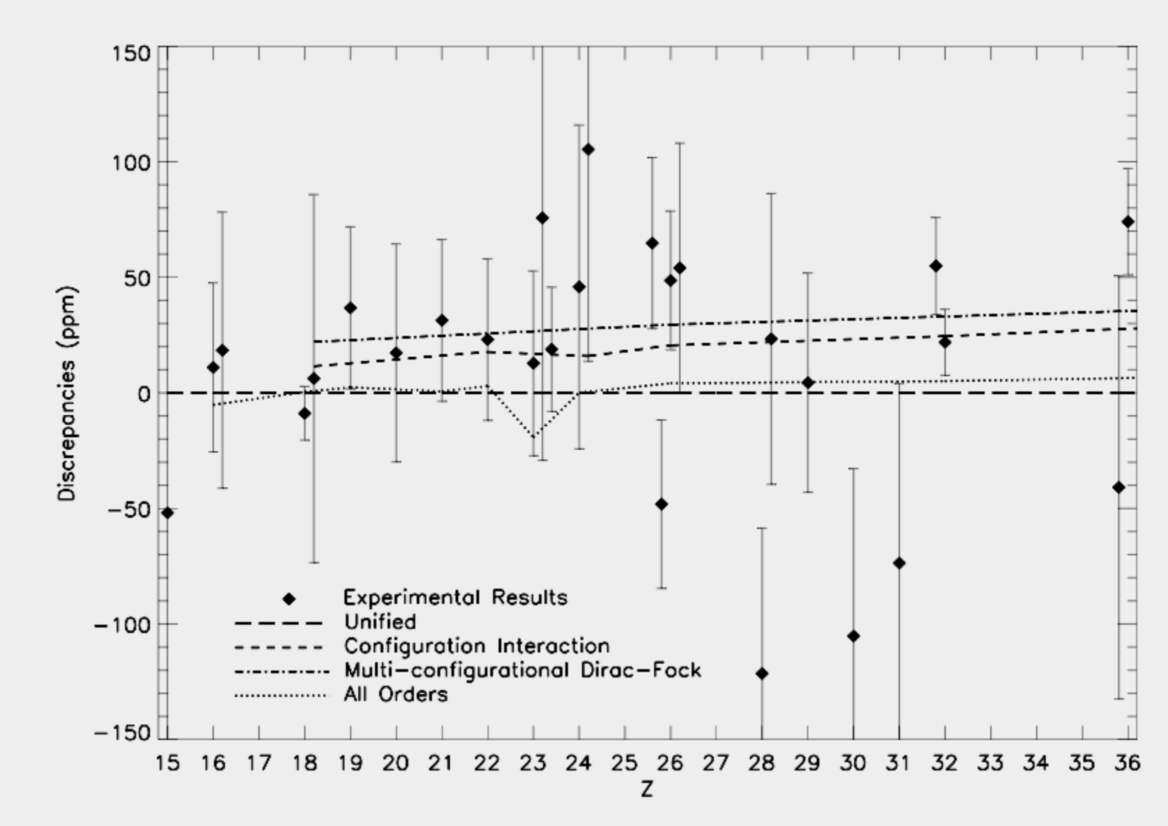
New systematics isolated for the first time

Shifts:	10-50
Uncertainty after calibration:	1-12

Near future? An approach to a few ppm for general X-ray spectroscopy
Remeasurement of standard reference lines will be needed

w ($1s2p\ {}^1P_1 \rightarrow 1s^2\ {}^1S_0$) transition energies, experiment & theory for medium *Z* ions

Kinnane et al, Rad. Phys. Chem. 75 (2006) 1744



Theoretical discrepancies relative to Drake (1988) in the medium Z regime for transition energies in helium-like systems Chen (1993), Indelicato (1988), Plante (1994). The experimental uncertainties cover the variation between calculations.

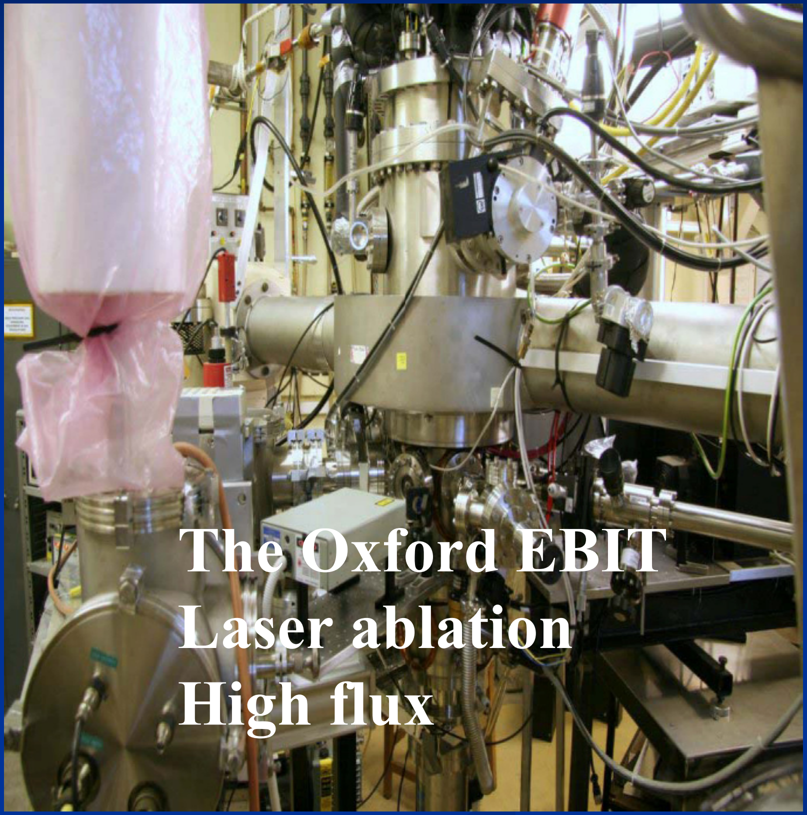
n=1 Lamb shift in (e.g) Ar17+ is 1.141 eV, two loop contribution is of order 0.4 meV, total 1s1/2–2p1/2,3/2 transitions are at ~3320 eV

For *two-loop* sensitivity, measurement target accuracy: 1 ppm

Diffraction Theory, Statistics & Doppler effects
All controllable down to this level

How to deal with Absolute Calibration??
In part: replace Bearden / Deslattes
•not just for Kα but also Kβ
•not just a number but a replaceable profile

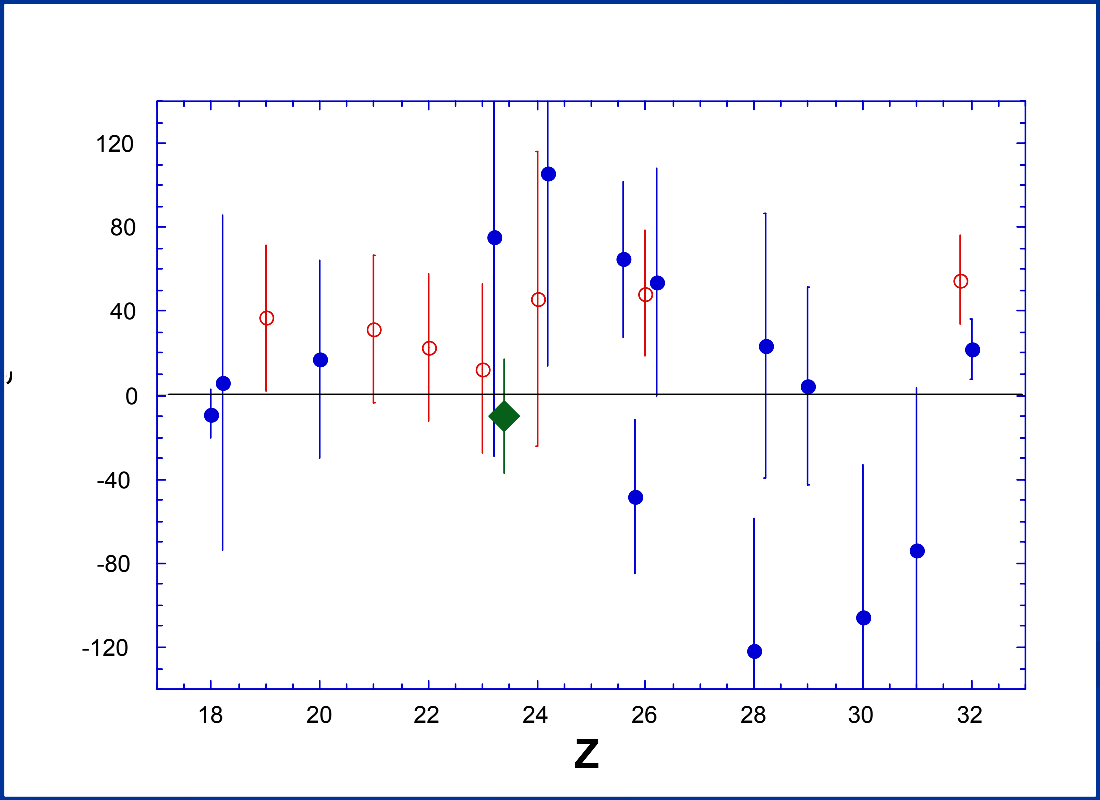
Then: dominated by Dispersion Function.
Stay tuned for Kinnane et al. & Smale et al.



Earlier Results:QED contributions to transition energies of helium-like vanadium:

Transition	QED† (ppm)	Expt test (%){*}	Expt (eV)	Theory (eV)	QED (eV)	2e QED† (eV)
w	*471.1*	*5.7%*	5205.10(14)	5205.15	2.474	0.15
x	*478.1*	*8.4%*				
y	*482.5*	*6.9%*				
z	*415.5*	*6.7%*				
$2s\ ^3S_1$ level	*64.6*	*43.3%*				

† QED contribution to transition, **[Drake 1988]** {*} C.T. Chantler, et al., PRA62 (2000) 042501:1-13.



Total QED and two-electron QED (eV)

Z	Experiment (eV)	Ref.	Theory [1]	QED [1]	2eQED† [1]&[9]	2eQED‡ [10]
18	3139.553(38)	[5]	3139.577	1.055	0.09	0.09
23	5205.10(14)	{*}	5205.15	2.474	0.15	0.16
32	10280.70(22)	[8]	10280.14	7.674	0.31	0.40

† **Difference between total QED for 2 electron ion and QED contribution to hydrogenic ion** [1] Drake 1988, [9] Johnson and Soff 1985

‡ Extrapolated from values for **Z=32-92**, [10] Persson *et al.* 1996

{*} **Chantler Phys. Rev. A 2000**

[5] R. D. Deslattes, H. F. Beyer, and F. Folkmann, J. Phys. B 17 1984

[6] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, Phys. Rev. A 40, 1989.

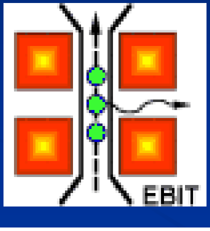
[7] C. T. Chantler, et al. PRA76 (2007) 042116

[8] S. MacLaren, et al, Phys. Rev. A 45 1992.

- Several ***new systematics*** observed for the first time & quantified
- Robust spectrometry & detection method
- Improved understanding of spectral lines & accuracy of reference calibration
- Clinometry accuracy approaching 1ppm

Conclusions

These systematics are present generally in all X-ray calibration: *must be understood*

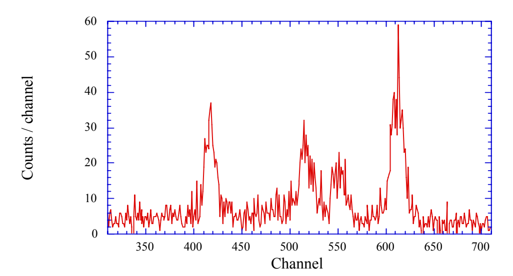


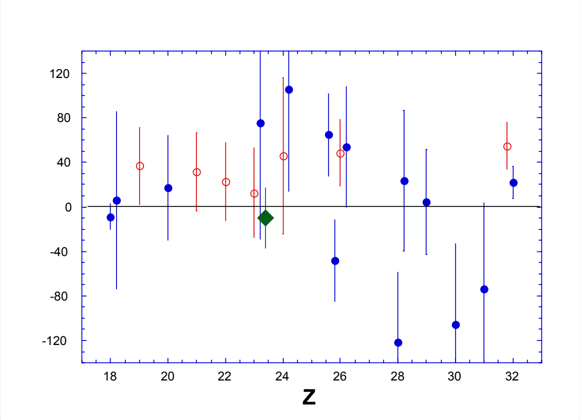
- EBIT: clean, Doppler free spectra
- Earlier result: 27 ppm, most precise for Z=19–31; agreed with current theory,

with comparable uncertainty, 2e QED

Anomalies remain; new tests needed

- New result soon
- ***developments could reach 1 ppm***





International Conference on Photon & Neutron Science:

11th International Symposium on Radiation Physics (ISRP-11)

21st - 27th September 2009, Melbourne

Organized by the International Radiation Physics Society (IRPS); supported by DEST, the Australian Synchrotron & the Victorian Govt. Devoted to current trends in radiation research. The latest in a series of triennial symposia. A 2 day Workshop will also be held. Oral and poster sessions. Presentations will include fundamental physics and applied topics, X-ray, UV & Neutron sources :

A. Processes in radiation physics B. Quantitative X-ray & particle analytical techniques

C. Absorption & fluorescence spectroscopy (XAFS, XANES, Raman …)

D. Sources and detectors and simulation of radiation transport

E. Materials Science & applications to minerals, mining & processing

F. Medical therapeutics & biology G. Application to space, earth & environmental sciences

H. Cultural heritage & art   I. New technologies and industrial applications

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w (1*s*2*p* $^1P_1 \rightarrow 1s^2\ ^1S_0$) transition energies, experiment & theory for medium *Z* ions

Z	Experiment	Ref.	Theoretical transition energies					ΔTheory
			Unified	AO	New RCI	RCI	MCDF	(ppm)
18	**3139.553(38)**	**[5]**	**3139.577**	**3139.582**		**3139.617**	**3139.65**	**23**
22	4749.74(17)	[6]	4749.63	4749.64	4749.65	4749.71		17
23	**5205.10(14)**	**{*}**	**5205.15**	**5205.16**	**5205.18**			
24	5682.32(40)	[6]	5682.05	5682.06	5682.08	5682.15		18
26	**6700.08(24)**	**[7]**	**6700.40**	**6700.43**	**6700.45**	**6700.54**	**6700.60**	**30**
32	10280.70(22)	[8]	10280.14	10280.19	10280.25	10280.39		24

{*} Chantler+, Phys. Rev. A 2000 ΔTheory: Maximum discrepancy between theories

Unified: Variational technique with relativistic corrections, G. W. Drake, Can. J. Phys. **66**, (1988).

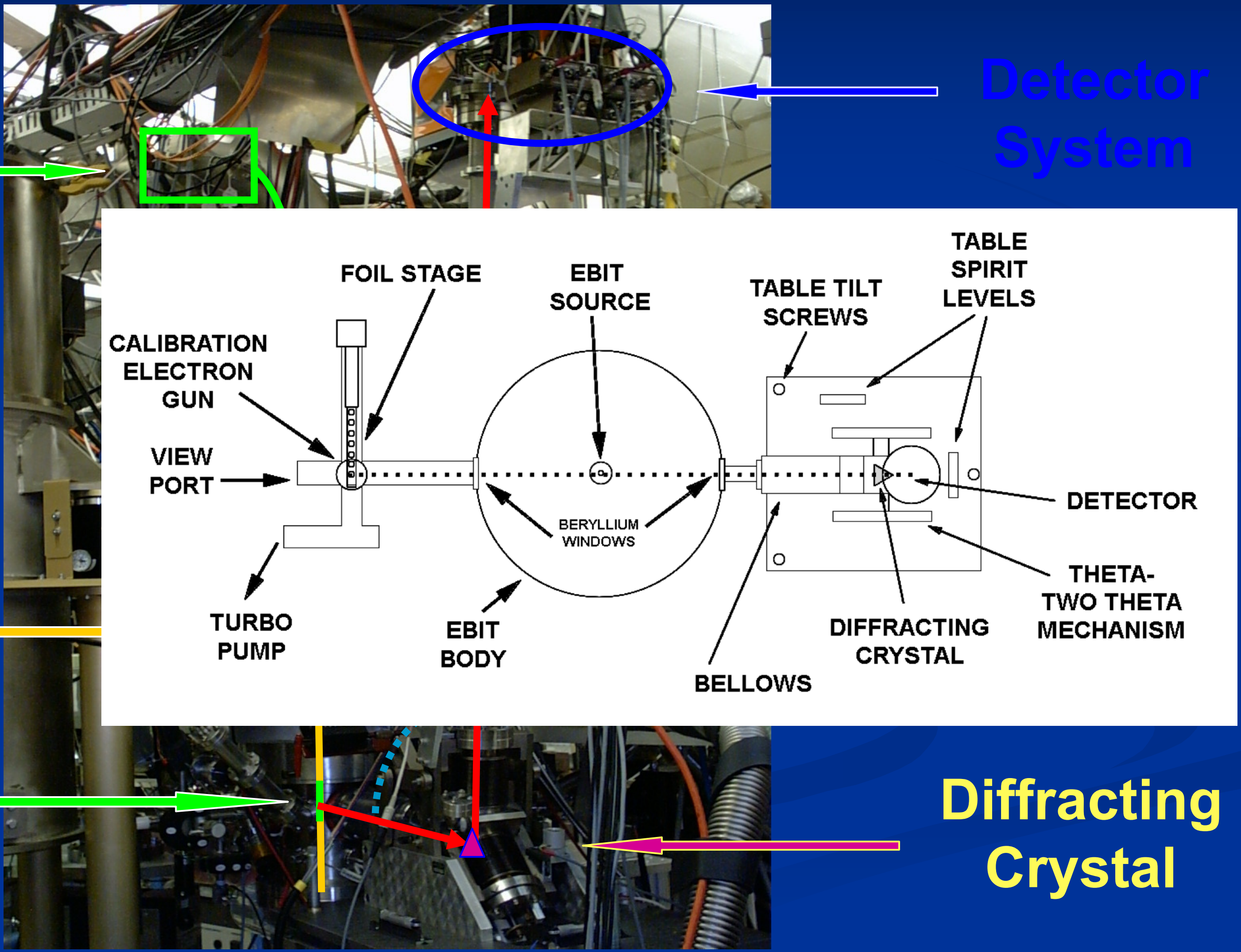
AO: All-Orders calculation, D. R. Plante, W. R. Johnson, and J. Sapirstein, Phys. Rev. A **49**, (1994).

New RCI: Relativistic Configuration Interaction, K. T. Cheng and M. H. Chen, Phys. Rev. A **61**, (2000).

RCI: Relativistic Configuration Interaction calculation K. T. Cheng, *et al*., Phys. Rev. A **50**, (1994);

MCDF: Multi-Configuration Dirac-Fock, P. Indelicato, F. Parente, and R. Marrus, Phys. Rev. A **40**,

NIST Experiment



MEVVA

Detector System

Electron Beam

Ion Trap

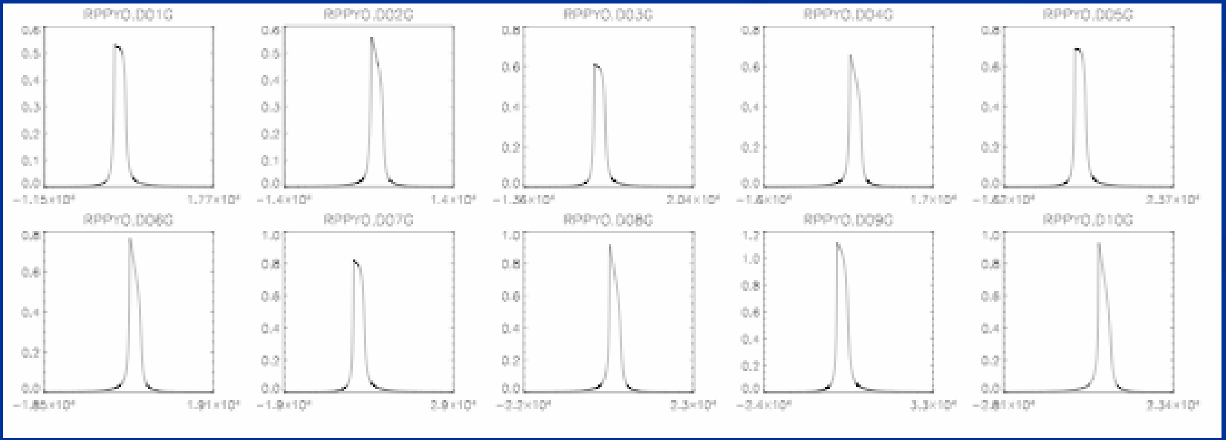
Diffracting Crystal

Issues for accurate determinations with X-rays

- We have measured the resonance lines for the two-electron titanium ion at the NIST Electron-Beam Ion Trap
- Results show a statistical precision of 6 ppm, well in advance of earlier work
- This allows a critical test of QED in a new regime
- Detailed investigations have evaluated *several (new) systematic and statistical issues* to be addressed for high accuracy results.
- *What are these problems? How can they be addressed? What limiting accuracy can they yield?*

Issues for accurate determinations in the X-ray regime:

- ***Dynamical diffraction theory is essential in precision X-ray spectroscopy***
- prediction of off-axis asymmetric centroid shifts. Shape and magnitude predicted
- Estimated accuracy of computations limited by accuracy of measured geometrical source positions … circa 1-12 ppm

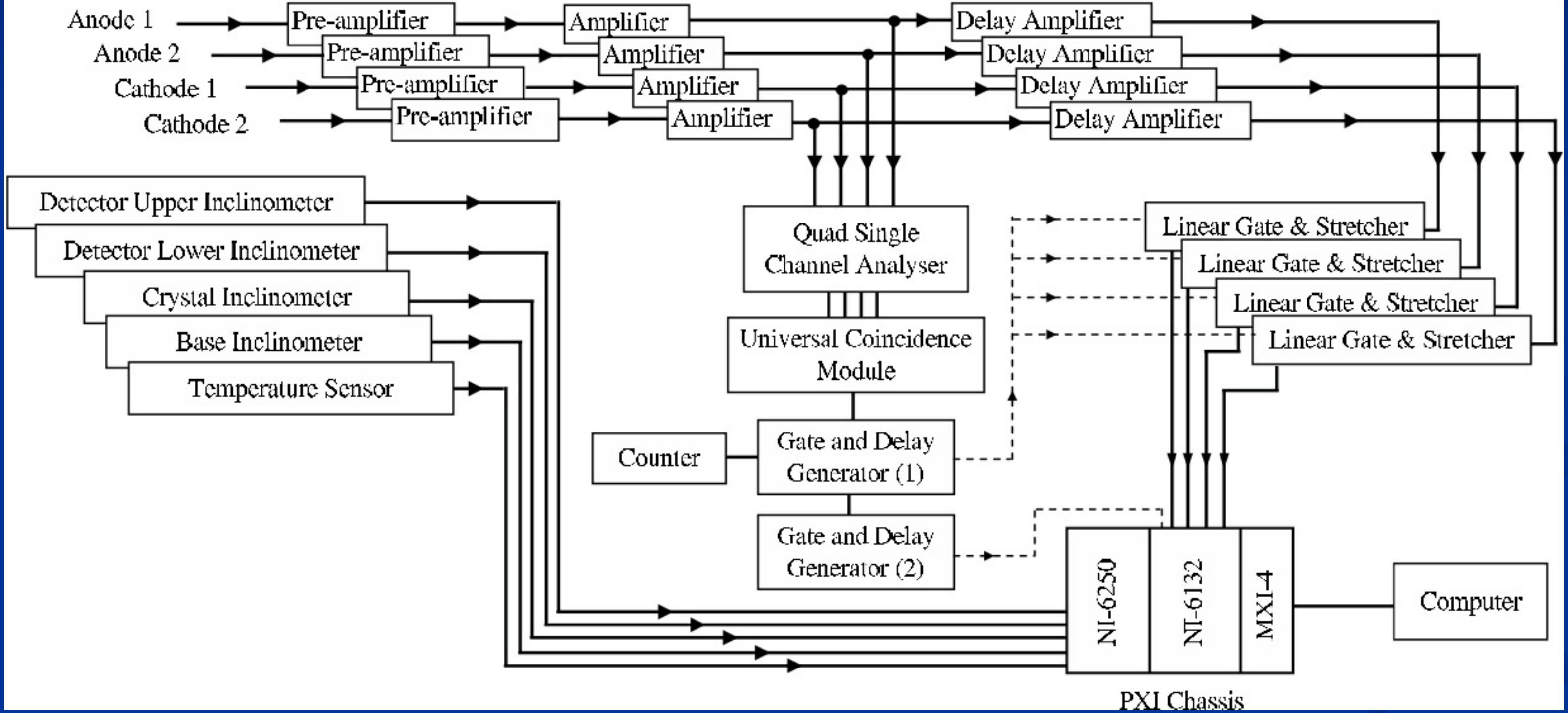


Preliminary conclusions for hydrogenic vanadium

- First absolute measurement of the **1*s*** Lamb shift in hydrogenic vanadium
- Curved crystal diffraction theory **=>** reduction of systematic uncertainties
- **45 ppm** uncertainty **=> 9% test of QED**
- Results are within 1.5σ of theory
- Systematic uncertainties can be reduced further

Status of QED measurements in atomic systems

Hydrogen 1s 97- M Weitz,TW Hansch [Garching] ⌛✍
Helium 98- M Inguscio... [Florence] 🗐
H98,He+91,2000 2s-van Wijngaarden, Drake[Windsor] 🗐⌛?
He 1s 98- S D Bergeson, K Baldwin,+ [NIST, ANU] ♈
g-2 muonium 1999,2000 - F Farley,VW Hughes[Yale] 🗐
He-like ions 98 2s - E.G. Myers+ [Florida, Oxford] ⌛⌛
He-,H-like ions 95-99 1s - P.Beiersdorfer [LLNL] ⌛? 🗐
H-, He-like ions 99 1s- C.T. Chantler+[Melbourne/NIST] ?🗐?


Anode 1
Anode 2
Cathode 1
Cathode 2
Pre-amplifier
Pre-amplifier
Pre-amplifier
Pre-amplifier
Amplifier
Amplifier
Amplifier
Amplifier
Delay Amplifier
Delay Amplifier
Delay Amplifier
Delay Amplifier
Detector Upper Inclinometer
Detector Lower Inclinometer
Crystal Inclinometer
Base Inclinometer
Temperature Sensor
Quad Single Channel Analyser
Universal Coincidence Module
Counter
Gate and Delay Generator (1)
Gate and Delay Generator (2)
Linear Gate & Stretcher
Linear Gate & Stretcher
Linear Gate & Stretcher
Linear Gate & Stretcher
NI-6250
NI-6132
MXI-4
Computer
PXI Chassis

Profile Analysis

- V $K\alpha$ 12 ppm, profile, Voigt components; Ti profile analysis completed
- individual components obtained from fitting 6 Voigts to $K\alpha_{1,2}$ emission profiles of elemental targets of Sc through Mn

Element	Peak i	Centroid C_i	Width W_i	Amplitude A_i	Integrated Intensity I_i	Source
		eV	eV	Counts	Counts	
Sc	$K\alpha_{11}$	4090.745(7)	1.17(5)	8175(166)	106068(5362)	Refit of
	$K\alpha_{12}$	4089.452(192)	2.65(44)	878(128)	22424(4948)	Anagnostopoulos et al. (1999)
	$K\alpha_{13}$	4087.782(104)	1.41(95)	232(101)	3474(2781)	Gaussian Width = 0.52(6) eV
	$K\alpha_{15}$	4093.547(61)	2.09(20)	387(21)	7993(867)	
	$K\alpha_{21}$	4085.941(9)	1.53(7)	4290(60)	68142(3238)	
	$K\alpha_{22}$	4083.976(541)	3.49(70)	119(45)	3585(1546)	χ^2_r=0.44
Ti	$K\alpha_{11}$	4510.926(14)	1.32(11)	579(12)	28582(2527)	Refit of
	$K\alpha_{12}$	4509.467(141)	1.54(47)	73(28)	4064(1976)	Anagnostopoulos et al. (2003)
	$K\alpha_{13}$	4507.735(217)	2.77(93)	42(9)	3717(1498)	Gaussian Width = 0.68(14) eV
	$K\alpha_{15}$	4513.848(109)	1.75(28)	30(3)	1793(352)	
	$K\alpha_{21}$	4504.914(20)	1.73(16)	272(8)	16280(1614)	
	$K\alpha_{22}$	4502.611(566)	3.30(106)	15(5)	1345(637)	χ^2_r=1.01
V	$K\alpha_{11}$	4952.237(12)	1.45(2)	25832(473)	363716(7705)	Chantler PRA 2005
	$K\alpha_{12}$	4950.656(184)	2.00(3)	5410(53)	88933(1451)	
	$K\alpha_{13}$	4948.266(261)	1.81(70)	1536(316)	24142(4972)	Gaussian Width = 1.99(12) eV
	$K\alpha_{15}$	4955.269(141)	1.76(30)	956(92)	14216(1370)	
	$K\alpha_{21}$	4944.672(21)	2.94(4)	12971(101)	264892(3901)	
	$K\alpha_{22}$	4943.014(303)	3.09(26)	603(48)	12721(1466)	χ^2_r= 0.91

Issues for accurate determinations in the X-ray regime 1:

- **Flux & Statistics (especially EBIT sources):**
  - weak source, 300 000 ions, 60 μm x 2 cm
  - neon-like, helium-like, hydrogenic spectra
- i. 2004: statistical determination of centroids from fwhm/$N^{1/2}$ and/or fitting to circa 6 ppm
- ii. 2005: better, estimated 3-4 ppm
- iii. Limitation from counting time and collection efficiency - circa 1-3 ppm
- iv. Temporal variation or drift?
- v. statistics on *calibration lines* or *clinometry* (angle or dispersion)?:

Issues for accurate determinations in the X-ray regime 2:

- **Flux & Statistics (especially EBIT sources):**
- v. statistics on *calibration lines* or *clinometry* (angle or dispersion)?
- *ARRAY* of characteristic *K*α and *K*β X-rays
- Calibration spectra statistics (2004): <2 ppm
- EBIT Line (He-Ti) clinometry statistics (2004): < 5ppm (per point)
- Calibration Line clinometry statistics (2004): <**15** ppm (per point)
- Statistical limit assuming consistent observations (2004): <3-4 ppm
- Expected (2004): 5-8 ppm

Issues for accurate determinations in the X-ray regime 3:

- **Calibration Issues (crystal or other spectrometry):**
- vi. Temperature / vibration (our case, 2004): < 1ppm
- vii. Mechanical stability of spectrometer (our case, 2004): < 1ppm *- see detector poster*
- viii. Doppler corrections, satellite contamination eliminated or reduced (EBITs): <1-2ppm

Issues for accurate determinations in the X-ray regime 4:

- **Calibration Issues (crystal or other spectrometry):**
- ix. One calibration line, or one calibration spectrum: (linear interpolation fraught; no extrapolation; unstable, but easier)
- *Absolute measurements require calibration to well determined reference lines*
- Versus a calibration array?: requires high level of mechanical stability, careful and reproducible calibration across a full spectral range, but in principle controls or quantifies any systematic
- x. final accuracy *depends upon* the accuracy of calibration line energies

Issues for accurate determinations in the X-ray regime 10:

- xiv. ***A problem of bandpass - vignetting***
- ideal profiles: large source, uniform illumination of Bragg angles across whole ($K\alpha_1$, $K\alpha_2$) profile region
- Real profiles have non-uniform illumination in general geometry (calibration lines primarily) causing “truncation” & calibration energy shifts qv. *Deutsch* “instrumental function is generally not a convolution”
- modelled by matching distortions experimentally and theoretically, and modelling effect of calibrated vignetting
- Primarily applies to non-optimised calibration profiles
- estimated accuracy of computations limited by accuracy of measured geometrical source positions … circa 1-12 ppm

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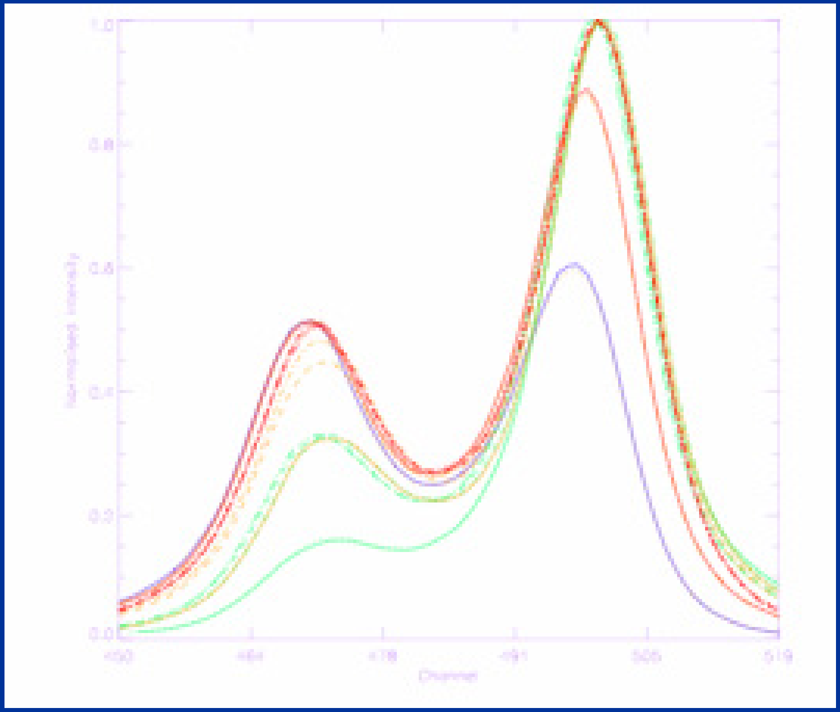


New spectrometer

- Thermal control to 1ppm
- Mechanical stability to 1-2ppm (vacuum tubing)
- Spectrometer controlled with kinematic mounts but automatically monitored by clinometry to circa 1-5 ppm
- Multiple clinometers monitor strain on mechanical angle, and monitor true central angle to same accuracy
- Pseudo-event mode operation to analyse and coordinate systematics of all types, especially including those previously considered to be random or statistical error contributions
- Faster processing, for higher statistics on monitoring processes and any temporal fluctuations
- Larger area detector to increase throughput, efficiency & statistics
- Development of resolution and efficiency of detector& technology
- Clean discrimination against cosmic rays in light of low fluxes
- Closer approach of spectrometer crystal to source
- Stronger, more flexible calibration source target and arrangement
- Optimisation of Rowland Circle positioning for minimisation of effects of dispersion function (limitations of dynamical diffraction theory circa 1-5 ppm depending upon geometry and statistics)

DECEMBER 1997 PHYSICS TODAY 19 *[PRL 79 (Oct. 1997) 2646]*

At the Max Planck Institute for Quantum Optics in the Munich suburb of Garching, Theodor Hänsch and colleagues have measured the ultraviolet transition frequency between the 1S and 2S states of atomic hydrogen to be

2.466 061 413 187 34 (84) x 10^{15} Hz.

Hydrogen II conference, June 2000; PRL (2000):

2.466 061 413 187 103 (46) x 10^{15} Hz *15 significant figures!*

It's so accurate that simply repeating the measurement a year from now would provide a better and more direct verification (or falsification) of the constancy of the fine-structure constant over cosmological time than any astrophysical data we have.

Dirac, among others, conjectured that the fundamental constants might be varying very slowly. "Of course, it's not why we developed this high-precision technique," Hänsch told us. "But if it lets us do the best test ever, we should."

Testing QED

"Our high-precision measurements in the last few years seem to have stimulated a renaissance of quantum electrodynamics calculations," Hänsch told us. "Calculating small higher-order QED effects can yield

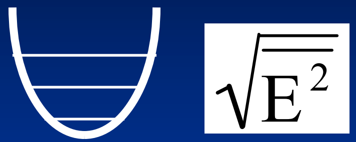
What is Atomic Physics?

- Major goals of recent PRL and conference presentations:
  - Proton radius, dα /dt, dc/dt, inconsistencies of the fundamental constants of nature
  - Are electron correlations and QED formalisms understood?
  - Is QED valid for atoms? Do the Z^6 terms fail to converge? If so, why?
  - How do photons interact with matter? What physics and inner structure do energy and angular dependencies of these interactions reveal?
  - Exotic Atoms (antihydrogen p-e+, positronium e+e-, muonium and muonic atoms) TESTING QED IN EXTREME REGIMES and COUPLING NEAR DIVERGENCE, RENORMALISATION

Quantum Electro-Dynamics: a *Quantum Field Theory*

Feynman, quantized radiation field

zero-point energy (Welton 1948)



Even in a *vacuum*, fluctuations δE of the field cause the electron to oscillate, smearing out the charge


ELECTRON SELF-ENERGY


VACUUM POLARISATION

A *bound electron* in a non-uniform field sees a different binding potential & energy shifts

Effect largest for s states (finite at nucleus)

- g-2 experiments
- Lamb Shift $2s_{1/2}$ - $2p_{1/2}$


n=2 j=3/2

n=2 j=1/2

$2p_{3/2}$

$2s_{1/2}$

$2p_{1/2}$

Dirac theory

QED

Bethe & Salpeter, 'Quantum Mechanics of one- and two-electron atoms',Springer-Verlag, 1957, p106:

"The Lamb shift is thus an excellent confirmation of present day quantum electrodynamics and of the relativistic theory of the electron"

1953: S (theory) = $\Delta\nu\ (2s_{1/2} - 2p_{1/2})$ =1057.13(13) MHz
S (experiment) =1057.77(10) MHz
Lamb shift = 0.0359 cm^{-1} *vs total Coulombic energy 30000* cm^{-1}

1988: S (theory) =1057.873(20) MHz (Mohr)
S (experiment)=1057.845(9) MHz (Lundeen, Pipkin)*(10 figures)*

1987 g-2 experiment: $g_e=2x(1+1.159652188(4)x10^{-3})$ (Van Dyck, Dehmelt)
1995 theory: $g_e=2x(1+1.159652272(52)x10^{-3})$ (Kinoshita) *(11 figures)*

... the most precise and sensitive way to test quantum electrodynamics at high field strength is to compare theory and measurements of the classic Lamb shift ... in [High Z] hydrogenic ions.

S. J. Brodsky, P. J. Mohr, in Structure and Collisions of Ions and Atoms, Topics in Current Physics Volume 5, I.A. Sellin, ed. (Springer, New York, 1978)

Hydrogen - M. Weitz,…,T.W.Hansch [Munich/Garching]
Helium - M. Inguscio+ [Florence]
H,He Polarizability/Anisotropy-W. van Wijngaarden+[York]
He - S. D. Bergeson+ [NIST, ANU]
g-2 experiment - F. Farley+ [Yale]
He-like ions - E.G. Myers+ [Florida, Oxford]

DISCREPANCIES IN QED

- Experimental tests of QED have developed dramatically for simple systems of hydrogen, proving accurate to one part in 10^{14} & confirming QED as the best tested theory ever devised by man. This & General Relativity are incompatible, leading to questions of where one or the other breaks down.
- *A range of anomalies has been discovered recently*, but the patterns involved elude current theoretical prediction.

- There has been significant progress for medium-Z hydrogenic and helium-like atoms over the last few years.
- Tests are often based on X-ray spectroscopic measurements.
- New types of test of two-electron QED and of np subshell and excited state QED have recently been made.

Status of QED measurements in atomic systems

Hydrogen 1s 97- M Weitz,TW Hansch [Garching] ⌛
Helium 98- M Inguscio... [Florence] 🗐
H98,He+91,2000 2s-van Wijngaarden, Drake[Windsor] 🗐⌛?
He 1s 98- S D Bergeson, K Baldwin,+ [NIST, ANU] ♈
g-2 muonium 1999,2000 - F Farley,VW Hughes[Yale]
🗐
He-like ions 98 2s - E.G. Myers+ [Florida, Oxford] ⌛⌛
He-,H-like ions 95-99 1s - P.Beiersdorfer [LLNL] ⌛? 🗐
H-, He-like ions 99 1s- C.T. Chantler+[Melbourne/NIST] ?🗐?