Review of Polarization Measurements with EBIT

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Topics

- Motivation
- General considerations
  - Transition radiation properties
  - Measurement techniques
  - Apparatus effects
- Early measurements
- Current work and advances

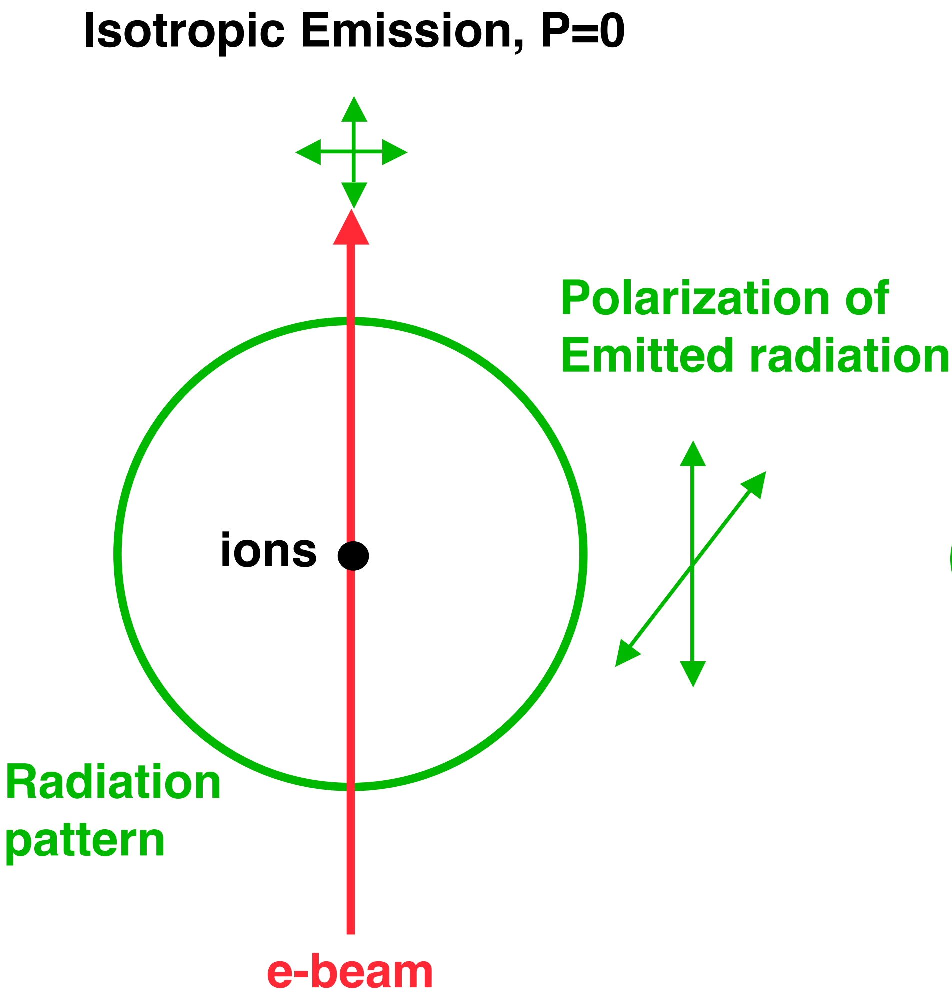
- Caveat – Much more interesting work than can be covered in one talk

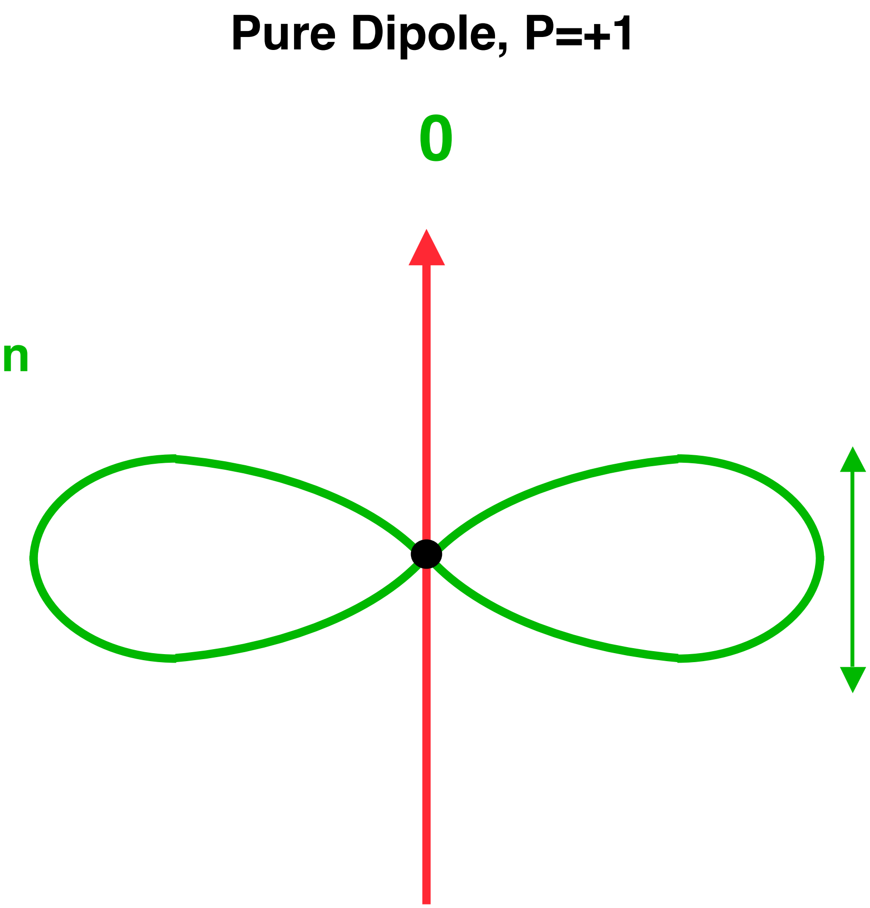
Motivation

- Test theory, access to hyperfine interaction
  - Measure polarization, angular emission pattern
- Compare EBIT to other experiments and theory
  - Angular dependence
  - Line ratios
  - Measure TOTAL cross sections
- EBIT/EBIS beam diagnostics
  - Use measurements to determine instrument parameters

- Applies to non-thermal sources
  - Solar flares
  - Neutron stars
  - Current drive in tokamaks

Transition Radiation Pattern





Measurement Techniques

- Measure angular emission
- Rotatable spectrometer
- 2 crystal technique

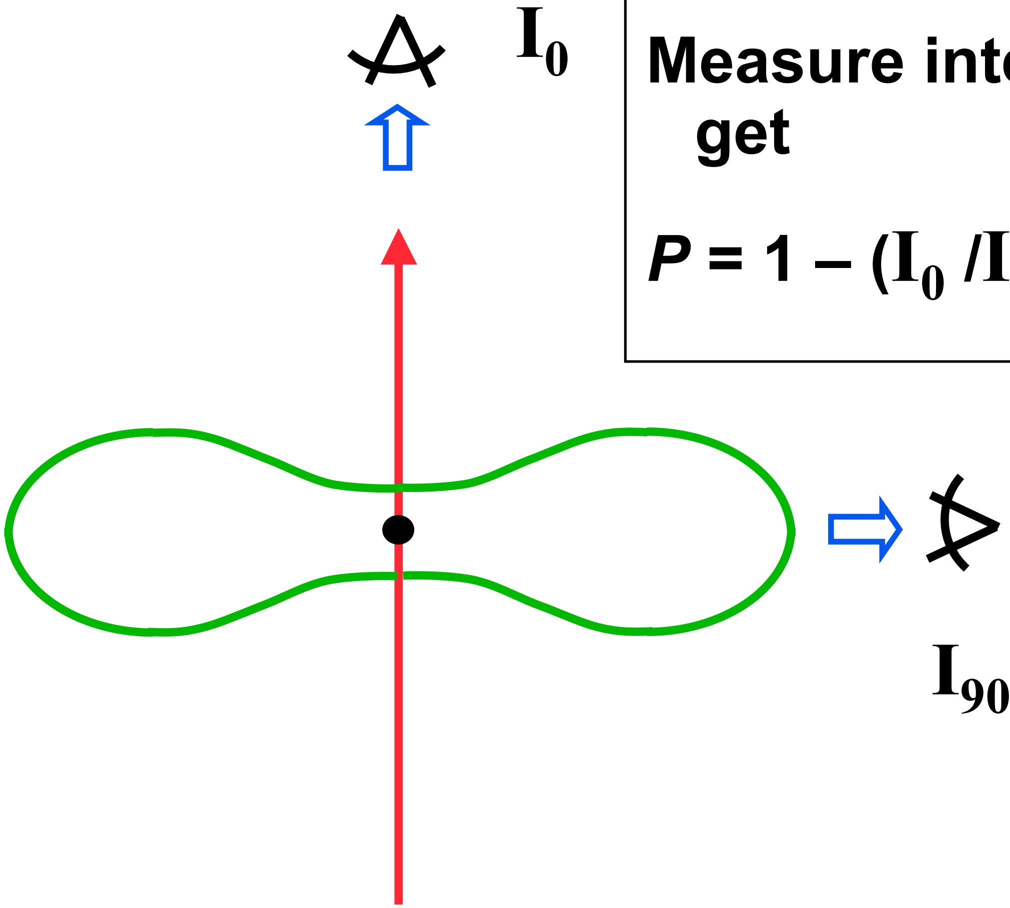
- Variants that exploit known polarization of one line and line ratios

Angular Distribution Technique

$I(\theta) = [1 - P*\cos^2(\theta)\ ] \ / \ [1 - {}^{1}/_{3}*P]$

Measure intensity at 0° and 90°, get

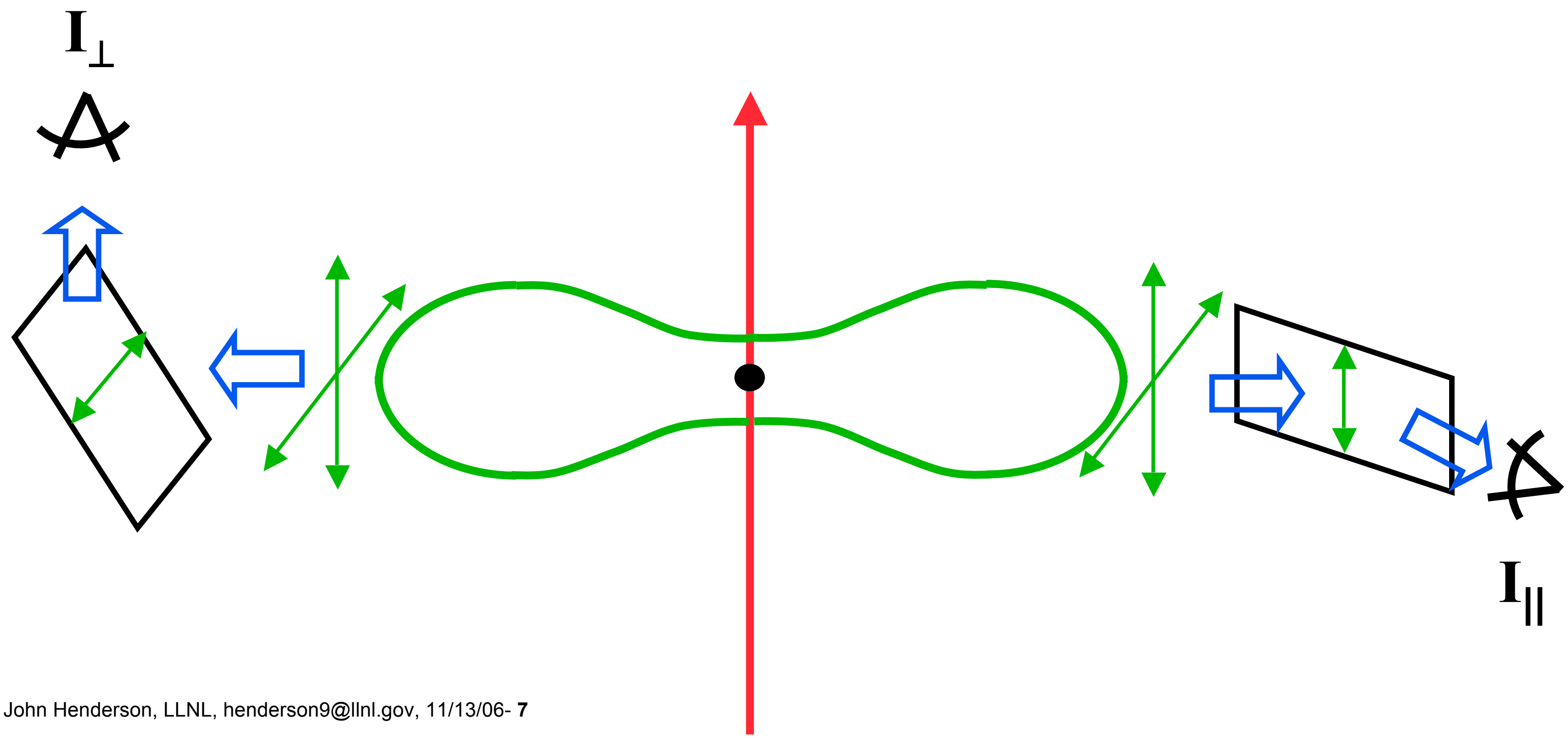
$P = 1 - (I_0 / I_{90})$



Rotatable Spectrometer Technique

$P = (I_{||} - I_{\perp}) / (I_{||} + I_{\perp})$ at 90°

- Flat crystal spectrometers shown with $\theta_{Bragg} = 45°$
- $I_{||}$ and $I_{\perp}$ are mixed for angles other than 45°



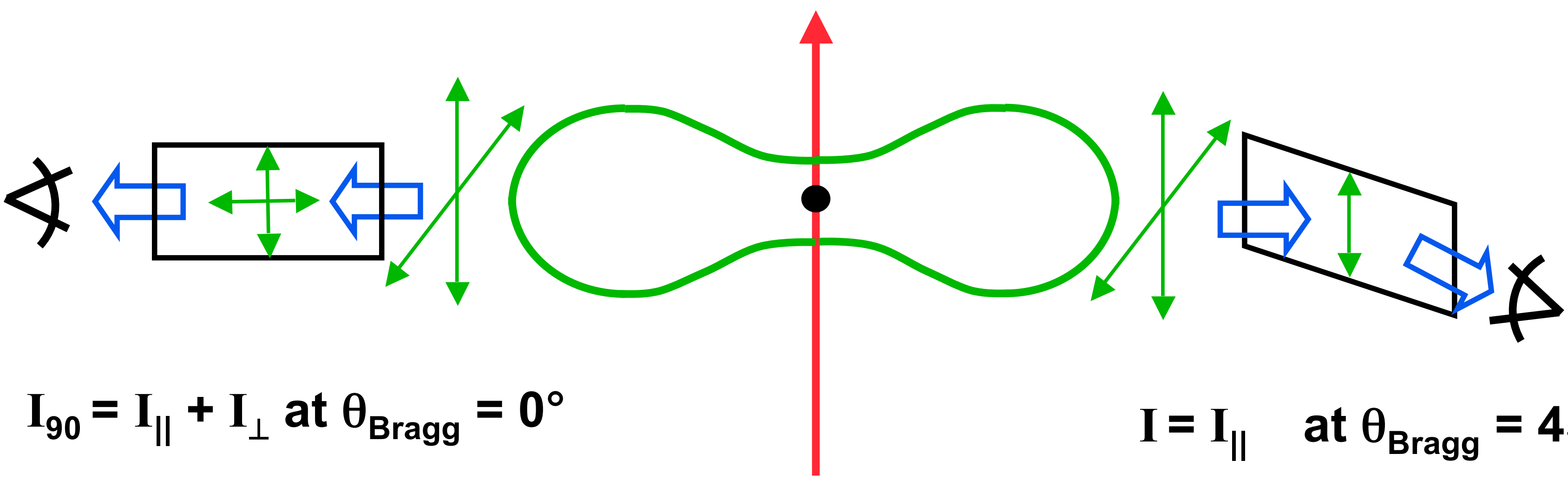
Two Crystal Technique

$P = (I_{||} - I_{\perp}) / (I_{||} + I_{\perp})$ at 90°

$I_{90} = I_{||} + I_{\perp}$

$P = 2*(I_{||} / I_{90}) - 1$

I_{90} can also be measured with any non-polarization sensitive technique, and the technique can be generalized for Bragg angles other than 0° and 45°.



$I_{90} = I_{||} + I_{\perp}$ at $\theta_{Bragg} = 0°$

$I = I_{||}$ at $\theta_{Bragg} = 45°$

Apparatus Effects

- Transverse electron temperature
- Electron cyclotron motion (e^- in *B* field)
- Charge exchange from neutral atoms
- Emission region is line source of finite width and length

- Solid angle of viewing (typically negligible)
- Imperfect polarimeter
  - XL's not at exactly 45° or 90°
  - Mix π and σ components
    - modeling req'd for mixing ratio
  - XL inhomogeneities
    - get focus/defocus intensity variations if crystal is not flat

Early Measurements

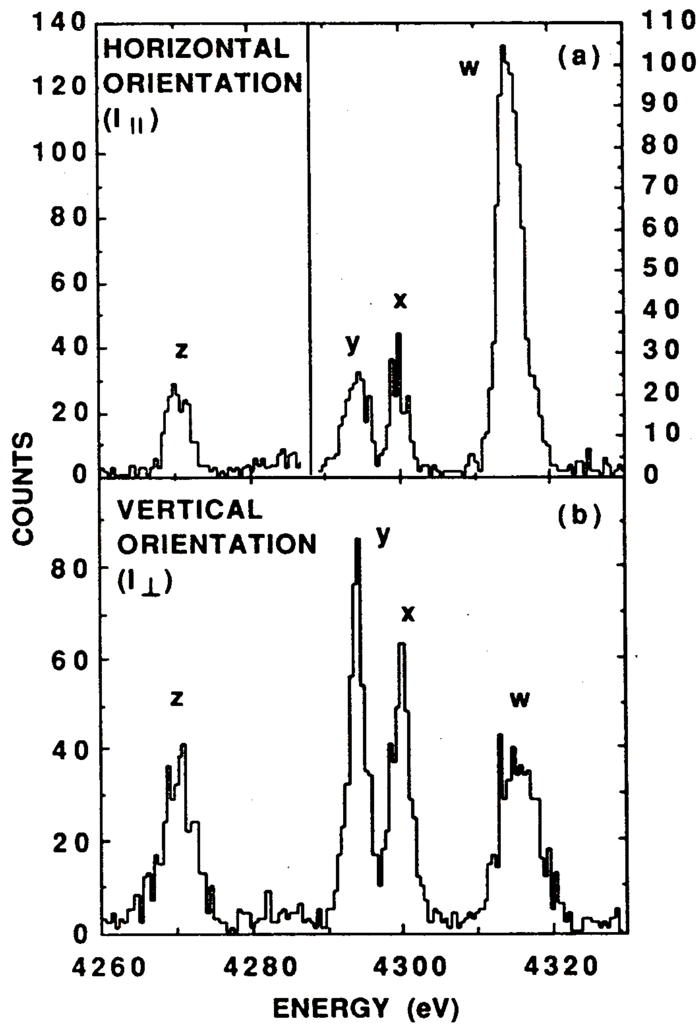
- **Polarization measurements started because**
  - **Absence of relevant measurements**
  - **Possibility to resolve relative line strength puzzles**

- **Tried all 3 techniques**
  - **Angular – fast, limited spectral resolution**
  - **Rotatable – cleanest, need XL with θ_B ~ 45 °**
  - **2 XL – flexible, systematics with cross-XL calibration**

- **Following example from PRL, 65 (1990), p 705**

Polarization of X-Ray Emission Lines from Heliumlike Scandium as a Probe of the Hyperfine Interaction, J. R. Henderson et al

Early Measurements of Polarization of He-like Sc (Rotatable Spectrometer)



- Note that resolution varies between the two orientations and that the upper data is a composite of two measurements

Measurements Showed Need for Hyperfine Interaction in Theory

Polarization of x-ray emission lines of SC19+

Line	Theory at 4.4 keV: No Hyperfine	Theory at 4.4 keV: With hyperfine	Experiment: 4.36 keV	Experiment: 5.62 keV
w (4315.24 eV)	0.60	0.60	0.70 ± 0.06	0.65 ± 0.05
x (4300.04 eV)	- 0.52	- 0.068	- 0.05 ± 0.09	- 0.08 ± 0.10
y (4294.51 eV)	- 0.37	- 0.054 [a]	0.00 ± 0.09 [b]	- 0.04 ± 0.10 [b]
z (4270.96 eV)	0.00	0.00	- 0.02 ± 0.10	- 0.03 ± 0.10

[a] To facilitate comparison with experiment, this value is for the blend of line *y* (*P* = - 0.072) and the 3*P* o decay (*P* = 0.0), assuming the 3 *P* o decay has one-third the intensity of line *y*.

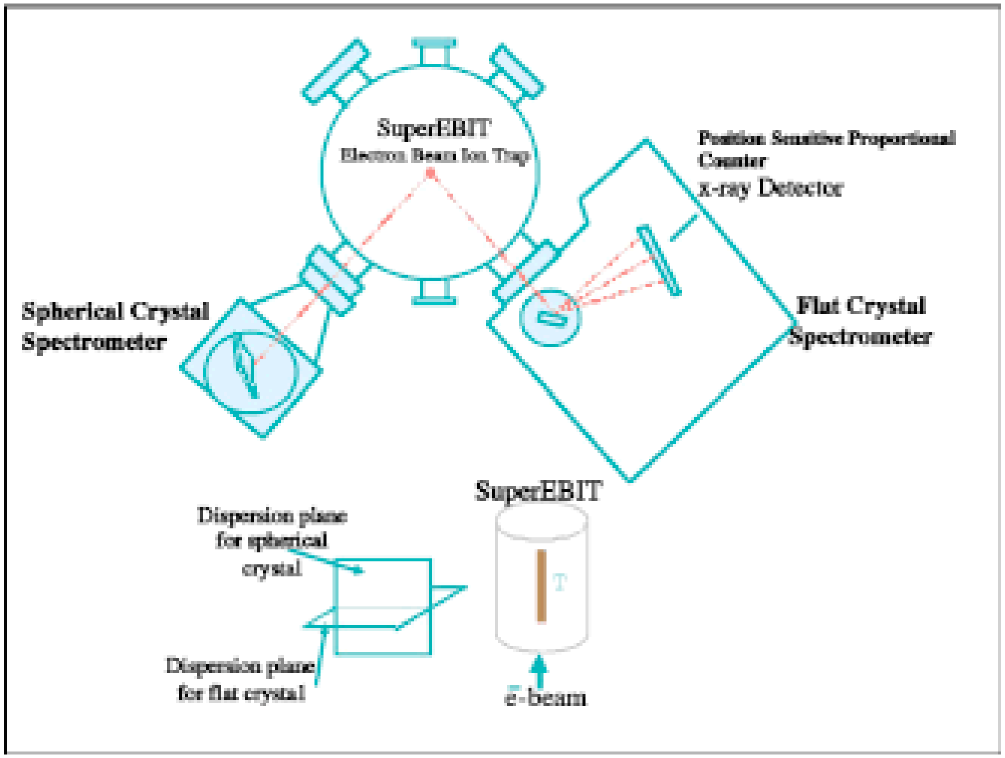
[b] This includes the unresolved blend of the 3 *P* o-to-1 *S* o transition with line *y* .

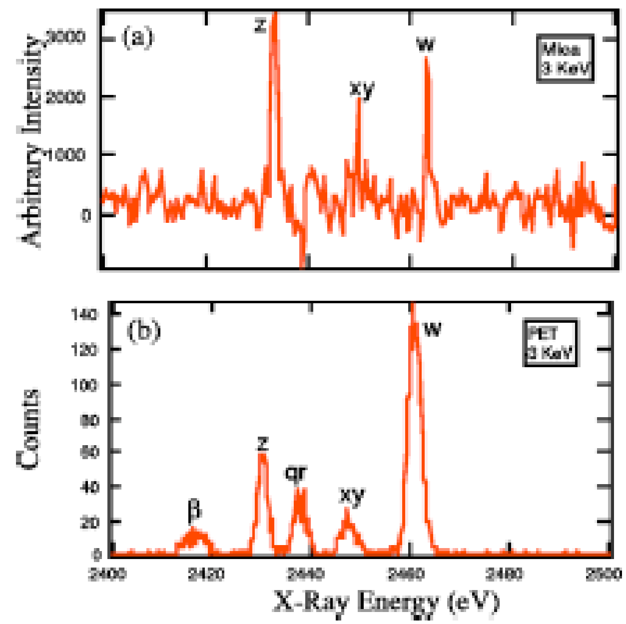
- **At 4.4 keV, lines are mostly from direct excitation and the theory is straightforward**
- **At 5.6 keV, there is a significant cascade contribution to consider also**
- Table from Henderson et al, Phys Rev Lett, 65, 705 (1990)
- Theory calculations from Inal and Dubau, J Phys± B, 20, 4221 (1987)

Current Work

- **Measurement equipment significantly improved**
  - **Faster, more accurate measurements**
- **Measurements thus challenging theory again**
- **Diagnostic measurements more sophisticated**

Fast Spherical XL Spectrometer Facilitates Polarization Measurements





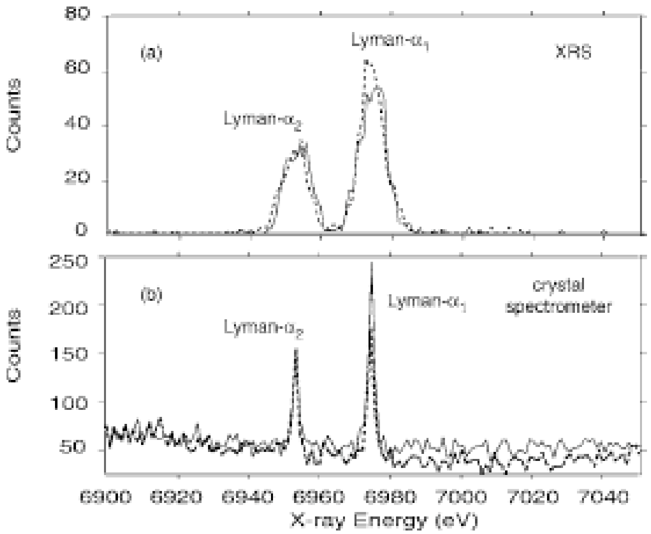
RSI 75, 3717 (2004)

High-resolution compact Johann crystal spectrometer with the Livermore electron beam ion trap

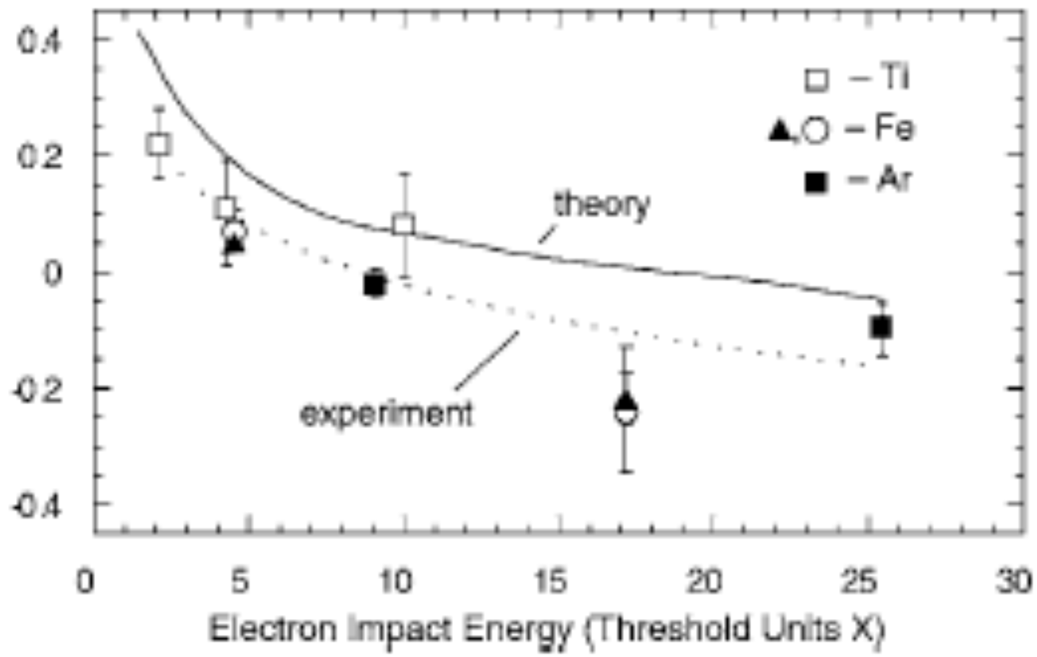
D. L. Robbins et al

Theory vs Measurement

Discrepancies have returned!



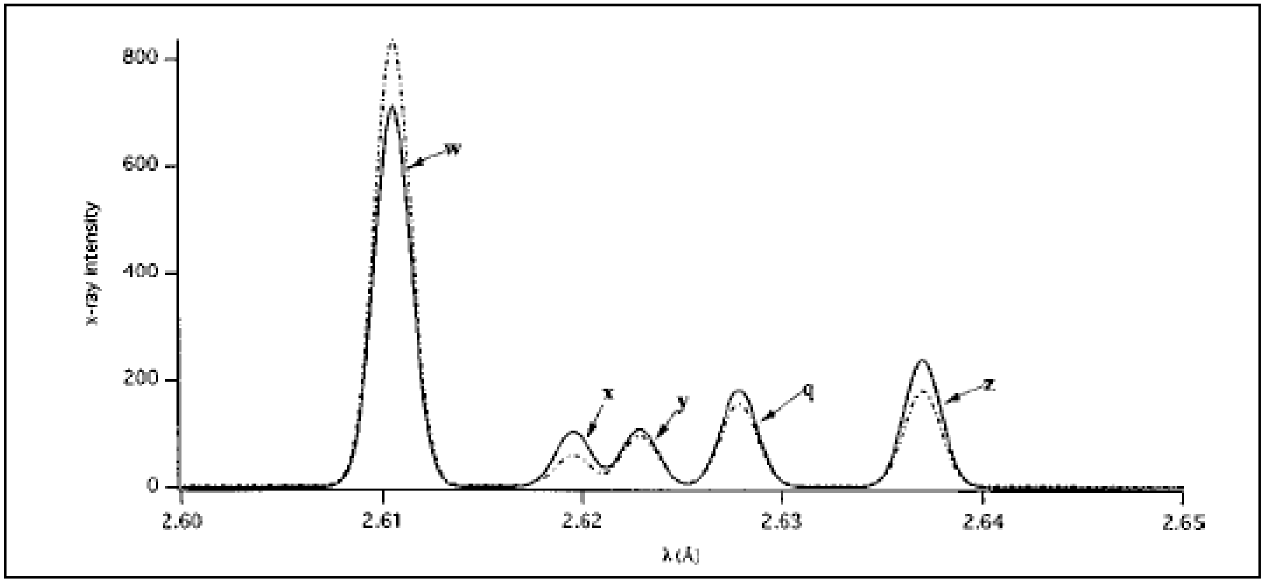
XRS Calorimeter data (top) and XL spectrometer data (bottom)



PRA 74, 022713 (2006)
Polarization Measurements of the Lyman-a1 x-ray emission lines of hydrogen-like Ar17+ and Fe25+ at high electron impact energies, D.L. Robbins et al

Spectropolarimetry to Measure Quasi-Maxwellian Beams in Plasmas

- **Experimental spectra show polarization effects, providing information on plasma properties**
  - **Si 220 (near pure polarization state) dotted**
  - **Ge 111 (mixed polarization state) solid**



- RSI 73, 1948 (2003)
  X-ray spectroscopy and spectropolarimetry of high energy density plasma complemented by LLNL electron beam ion trap measurements
  A. S. Shlyaptseva, et al

Advances

- Sophistication of measurements
  - ± 0.01 to 0.05 now vs ± 0.05 to 0.10+ initially
  - SuperEBIT for higher energies
- Theory
  - Z dependence of polarization
  - Relativistic mixing of singlet and triplet states
  - Energy dependence of polarization for DR
- Diagnostics
  - XL spectrometer improvements
    - 2 XL technique with focusing spectrometer to deal with line source
  - X-ray spectrometer microcalorimeter
  - ~8 eV vs 180 eV for Ge detector
  - Spectropolarimetry of non-thermal plasmas