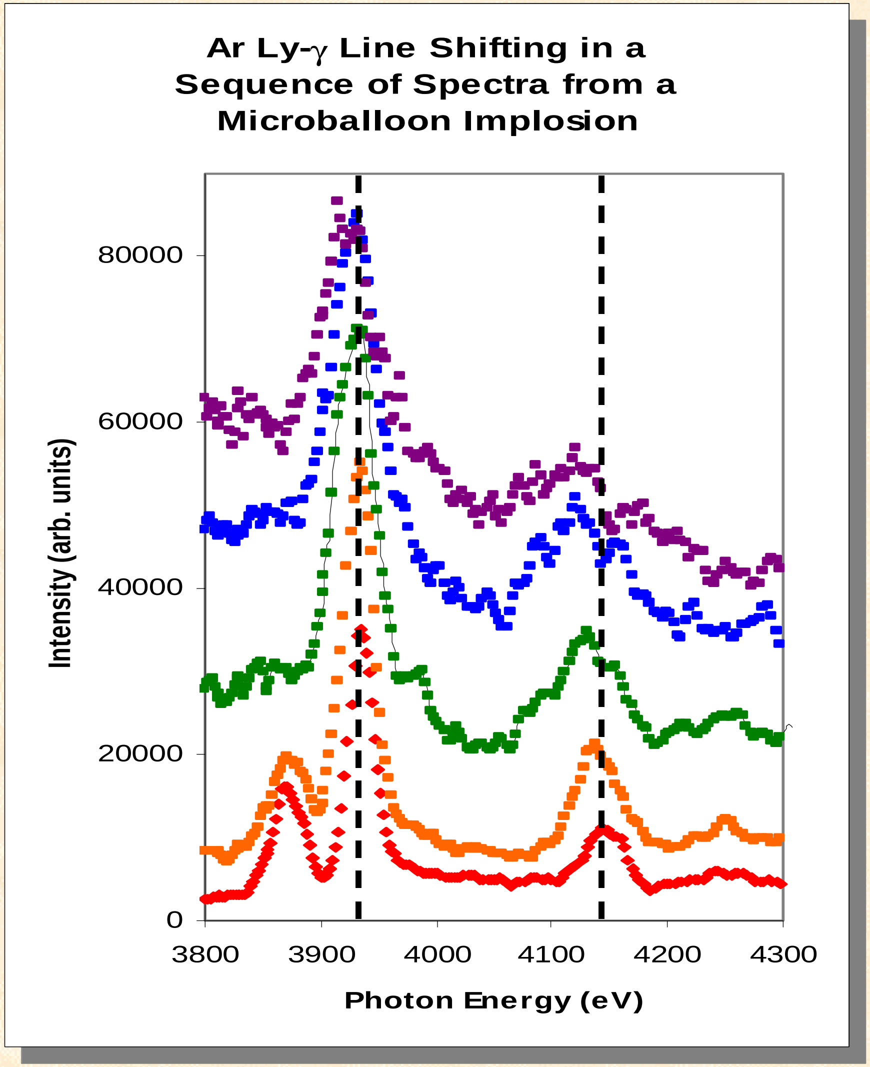
Plasma Induced Line Shifts:
Line Merging, Continuum Lowering and Population Kinetics



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Atomic Processes in Plasmas

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Summary and Outline

The observation of plasma-induced line shifts in the K-shell spectrum emitted by hot, dense plasmas necessitates an exploration of the implications of these shifts on line merging and population kinetics.

- Experimental observation of line shifts
- Line shift calculations
- Line merging and the Inglis-Teller Limit
- Population kinetics model to explore the effects of shifts on line ratios

Collaborators and Acknowledgements

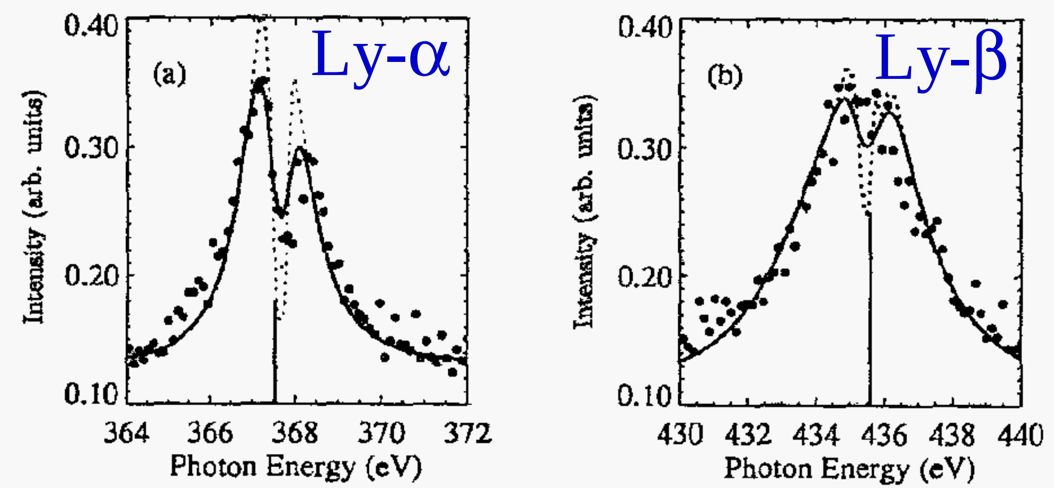
- University of Florida
    - C. F. Hooper, Jr.
    - M. A. Gunderson
    - G. C. Junkel-Vives
- National Laser Users Facility
    - D. K. Bradley (LLNL)
    - P. A. Jaanimagi
    - S. Regan

Experimental Observation of Plasma-induced Line Shifts

During the past 4 years, a number of groups have reported observing plasma-induced line shifts in a variety of systems. Though I will concentrate on our results, I will briefly review the published results of other groups.

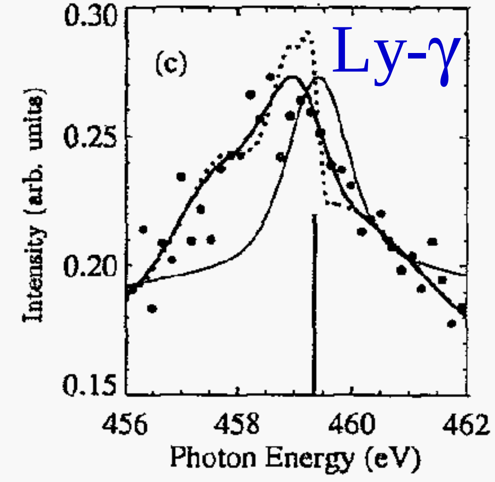
- Leng, *et al.* : Hydrogen-like C
- Eidmann, *et al.* : Hydrogen-like Al
- Woolsey, *et al.* : Ar He–β
- Hooper, *et al. :* Ar K-shell and satellites

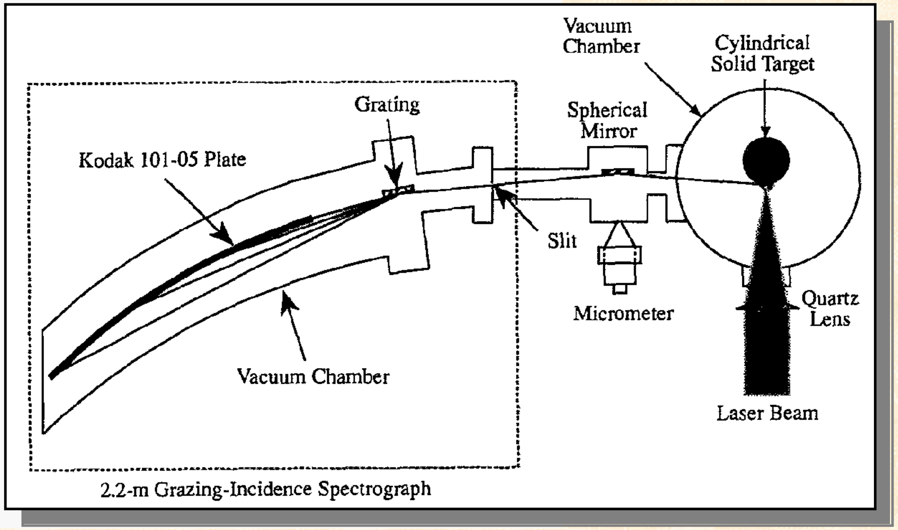
C VI Lyman line profiles from 10-ps KrF-laser-produced plasmas
Leng, Goldhar, Griem, and Lee, PRE **52** 4328 (1995), Figures 1 and 4



Temporal and Spatial Integration

▪▪▪▪▪▪▪▪▪ Data
- - - - - - - - Theory
━━━━ Theory (convolved)
──── Theory (no shift)

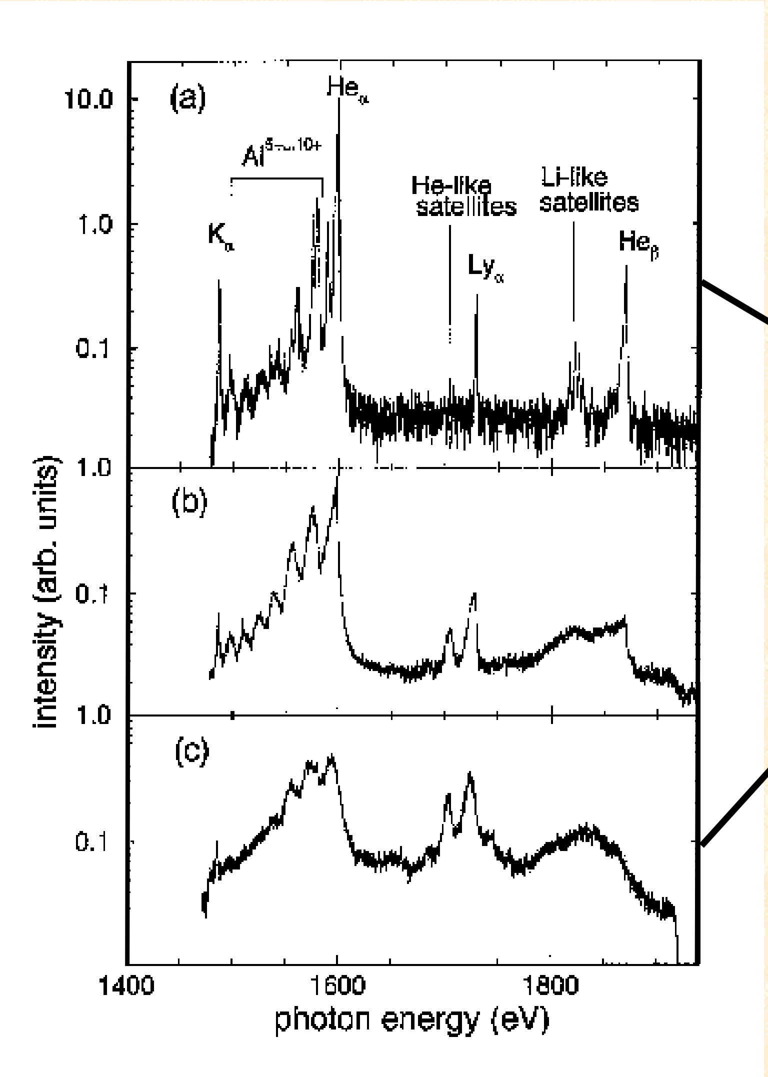


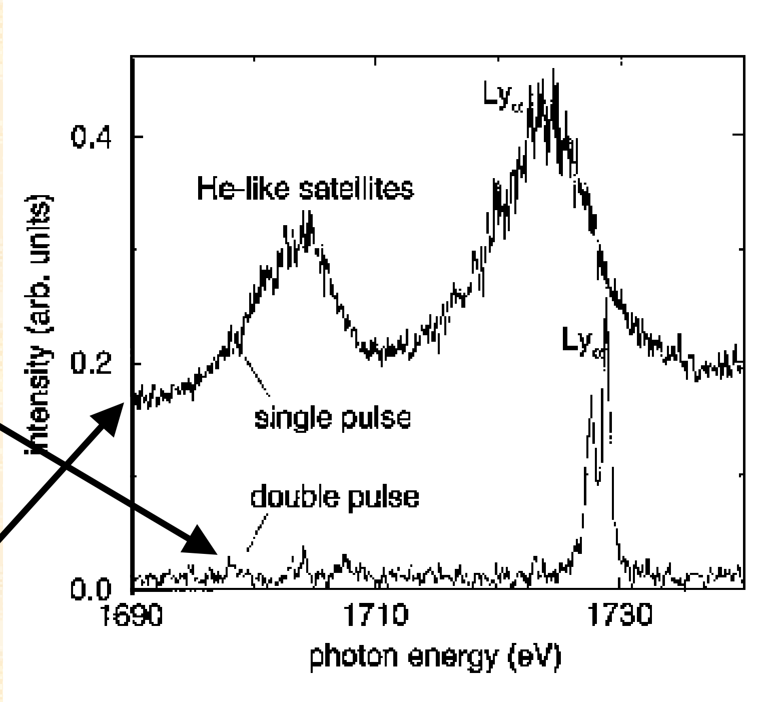


$n_e \leq$ 1e22/cc,

$kT_e \leq 200$eV

Isochoric heating of solid aluminum by ultrashort laser pulses focused on a tamped target Saemann, Eidmann, Golovkin, Mancini, Andersson, Foester, and Wine PRL **82** 4843 (1999)

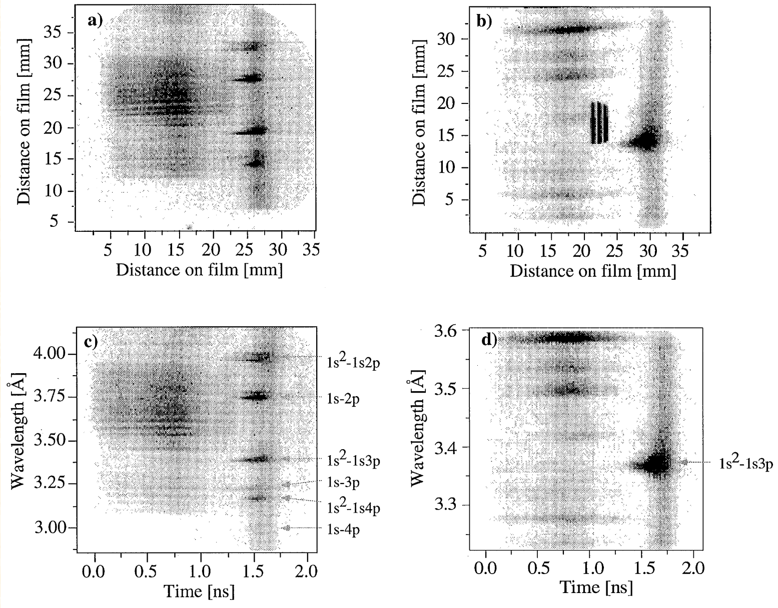


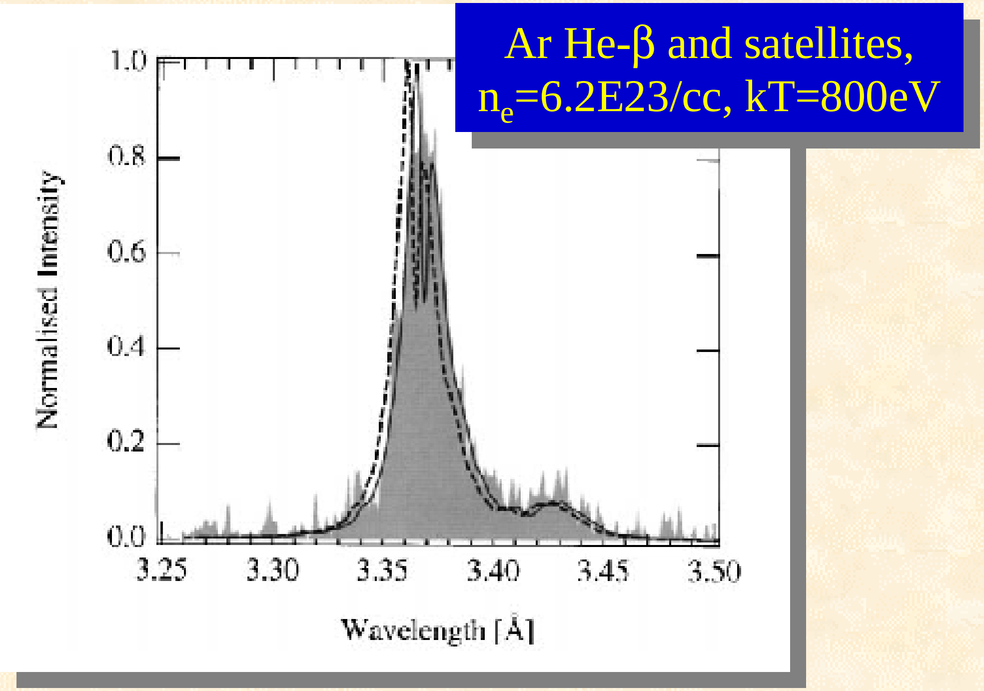


The presence of the 1.4eV (FWHM) cold Kα line in both spectra established the uncertainty in the reported 3.7eV±0.7eV shift for n_e=8e23/cc and kT_e=300eV.

Experimental results on line shifts from dense plasmas Woolsey, Back, Lee, Calisti, Mosse, Stamm, Talin, Asfaw, Klein JQSRT **65** 573 (2000)

In their painstaking analysis of time-resolved data from an indirectly-driven microballoon implosion, Woolsey, *et al.* measured the +4mÅ shift of the composite Ar He-β line and its satellites with an accuracy of ± 2mÅ.

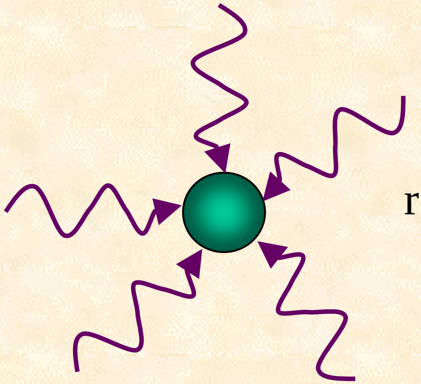




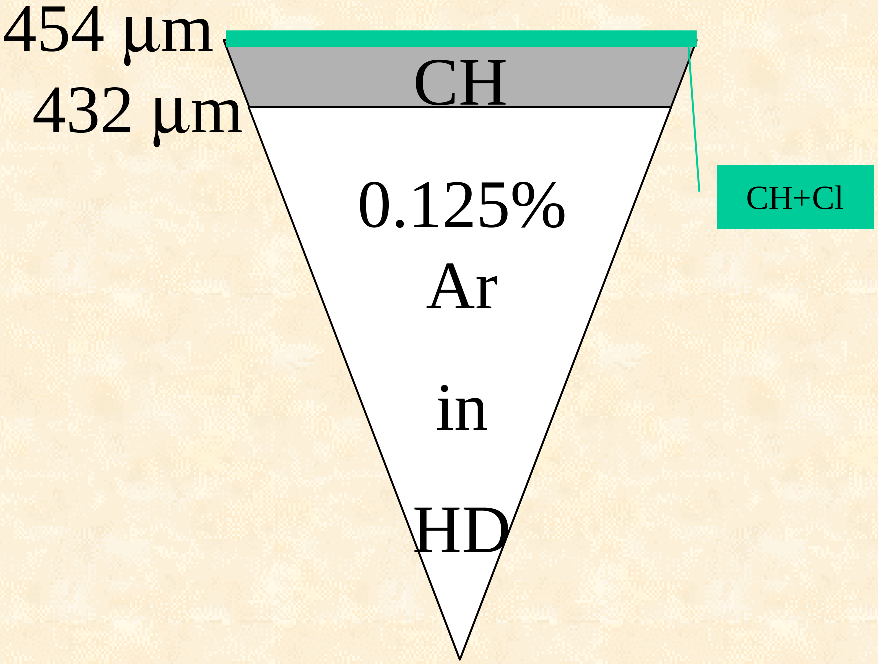
Ar He-β and satellites, n_e=6.2E23/cc, kT=800eV

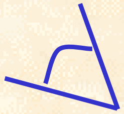
In a series of campaigns using the Omega Laser System at the University of Rochester’s Laboratory for Laser Energetics, Prof. Hooper’s group at UF has observed plasma-induced line shifts in directly-driven spherical implosions

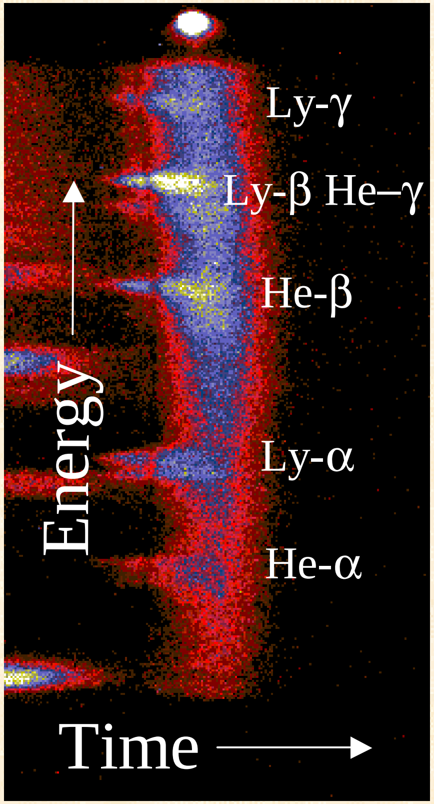
28.2 kJ
in a
1ns square pulse



During the implosion, the time-dependent **Ar K-shell** spectrum was recorded by a flat crystal spectrometer attached to an x-ray streak camera

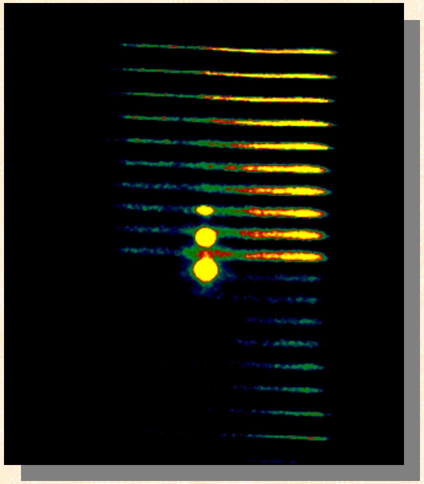






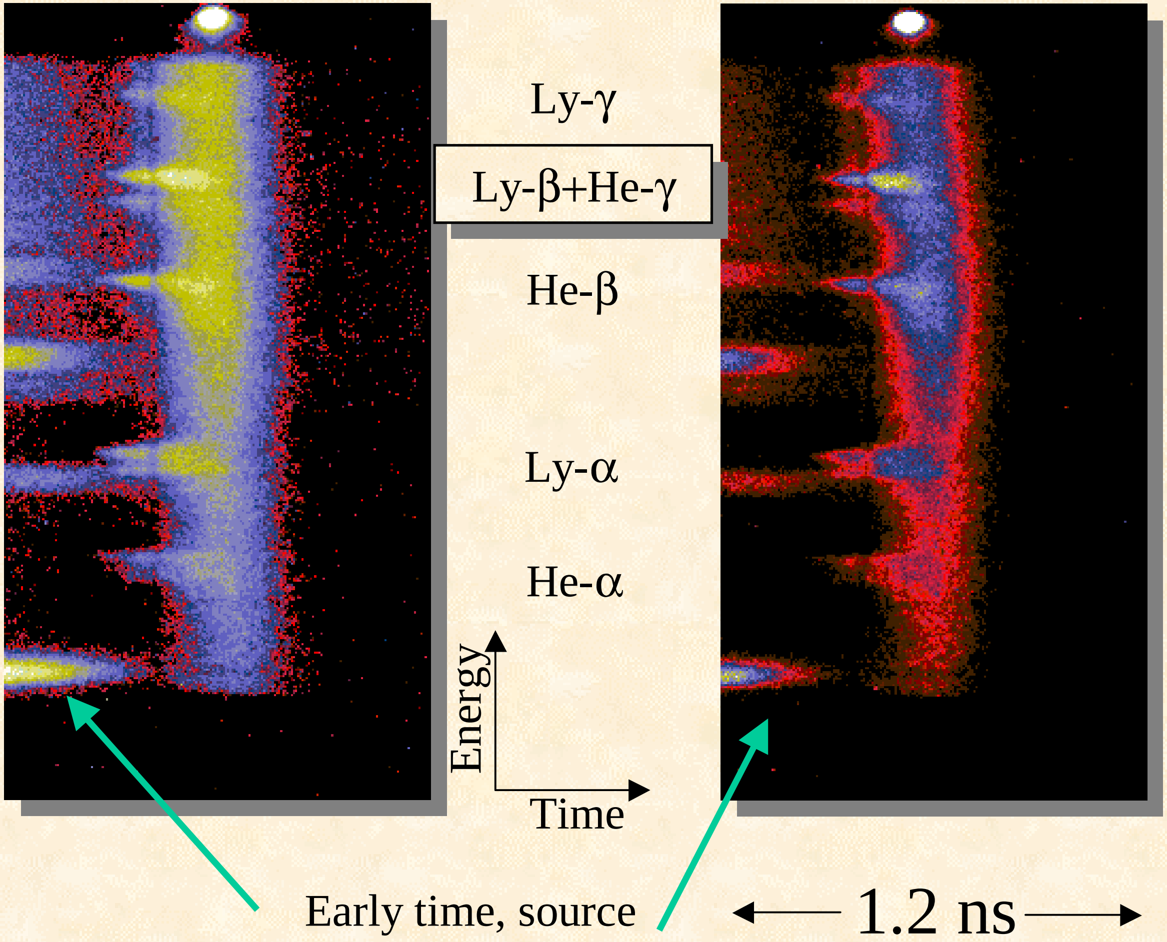
In situ characterization of the streak camera helped in the process of data reduction

The use of a ramped pulse with the spectrometer replaced by an array of slits assisted in the characterization of streak camera distortions



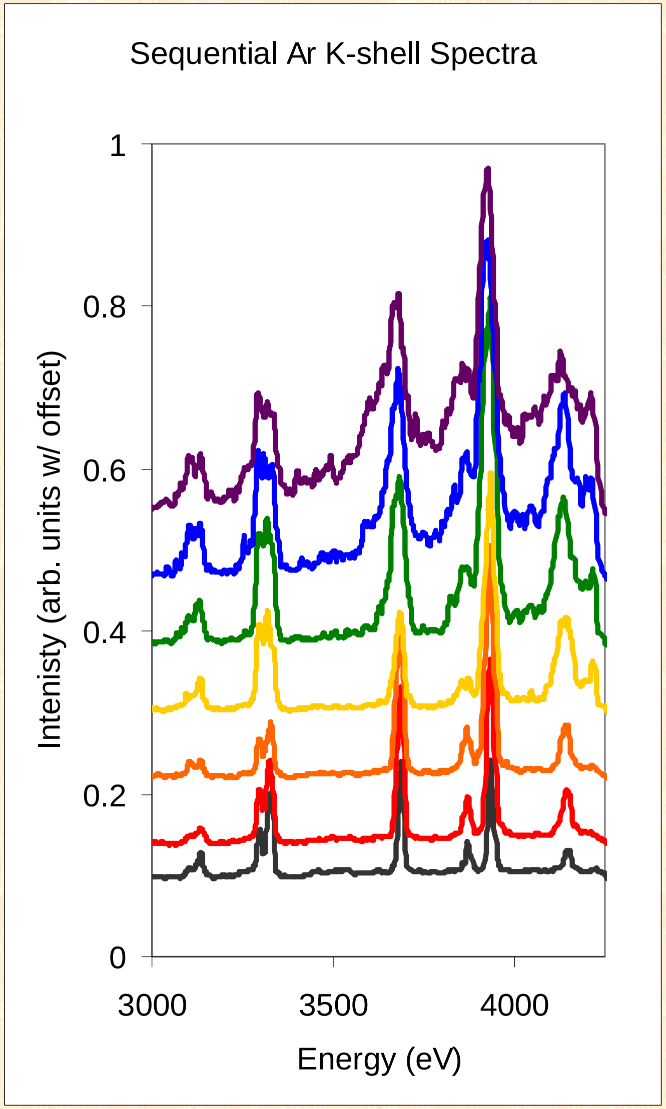
Raw Data

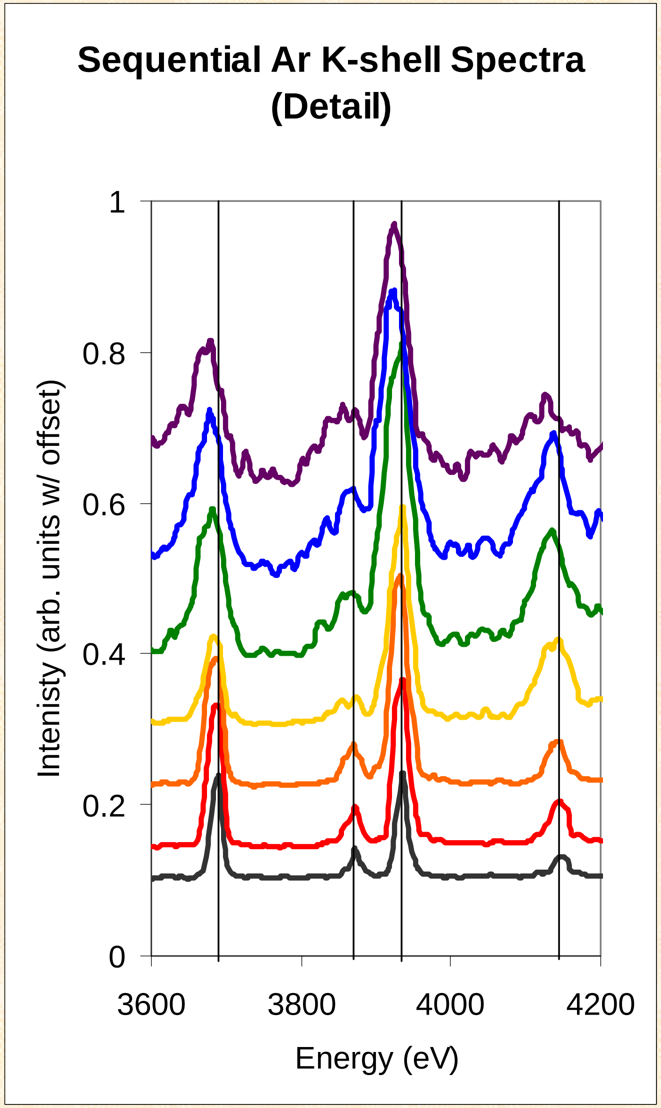
Corrected Data



Early time, source broadened Cl emission from ablator

Two facts make the Ar Ly-β + He-γ composite feature useful for shift studies: proximity and different upper level pqns.





Thus, a wide variety of recent experimental work has led us to the conclusion that we must account for this effect in our multi-electron radiator lineshape (MERL) calculations.

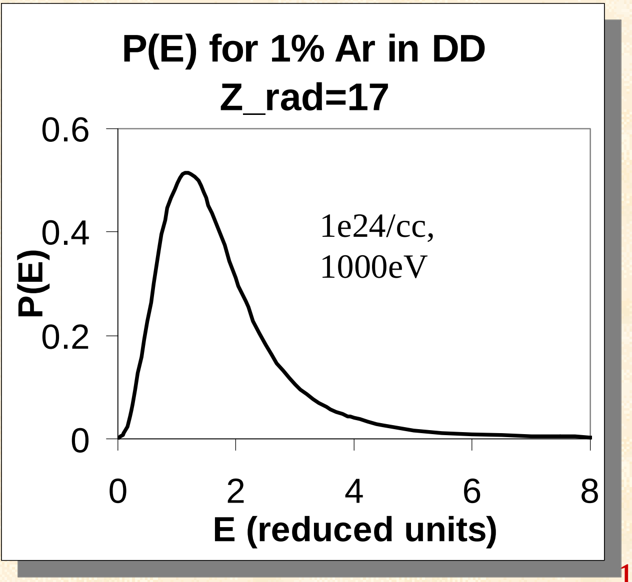
$$I(\omega) = \frac{4\omega^4}{3c^3}\int_0^\infty \underbrace{dE\;P(E)}\;J(\omega;E)$$

Lineshape

- APEX microfield
- BID Ion Dynamics
- Two full-coulomb formulations of electron broadening: all-order semi-classical, 2nd order quantum mechanical

Average weighted by ion microfield distribution function

Electron-broadened lineshape emitted by a radiator experiencing a static ion microfield *E*


P(E) for 1% Ar in DD Z_rad=17

The plasma-induced lineshift arises naturally if all n-pole moments of the Coulomb interaction of the radiator with the plasma electrons are retained.

$$J\left(\omega;E\right)=-\frac{1}{\pi}\operatorname{Re}\underset{\mathrm{r}}{\operatorname{Tr}}\left[\vec{d}\bullet R\left(\omega;E\right)\rho_{\mathrm{r}}\vec{d}\right]$$

$$R\left(\omega;E\right)=\frac{1}{\Delta\omega-\underset{\substack{\nearrow\\ \text{Ion microfield}\\ \text{splitting}}}{L_{i,r}}\left(E\right)\underbrace{-B-M\left(\Delta\omega\right)}_{\substack{\text{Plasma electron-radiator}\\ \text{interaction}}}}$$

Details of this formalism were given by Gwyn Junkel-Vives during her Monday poster.

The separation of the electron-radiator interaction into 2 terms is a matter of convenience, and **not** indicative of an *ad hoc* addition to the theory.

- The quantum mechanical formulation proceeds by expanding the lineshape in powers of V_{er} and retaining all terms to 2nd order.

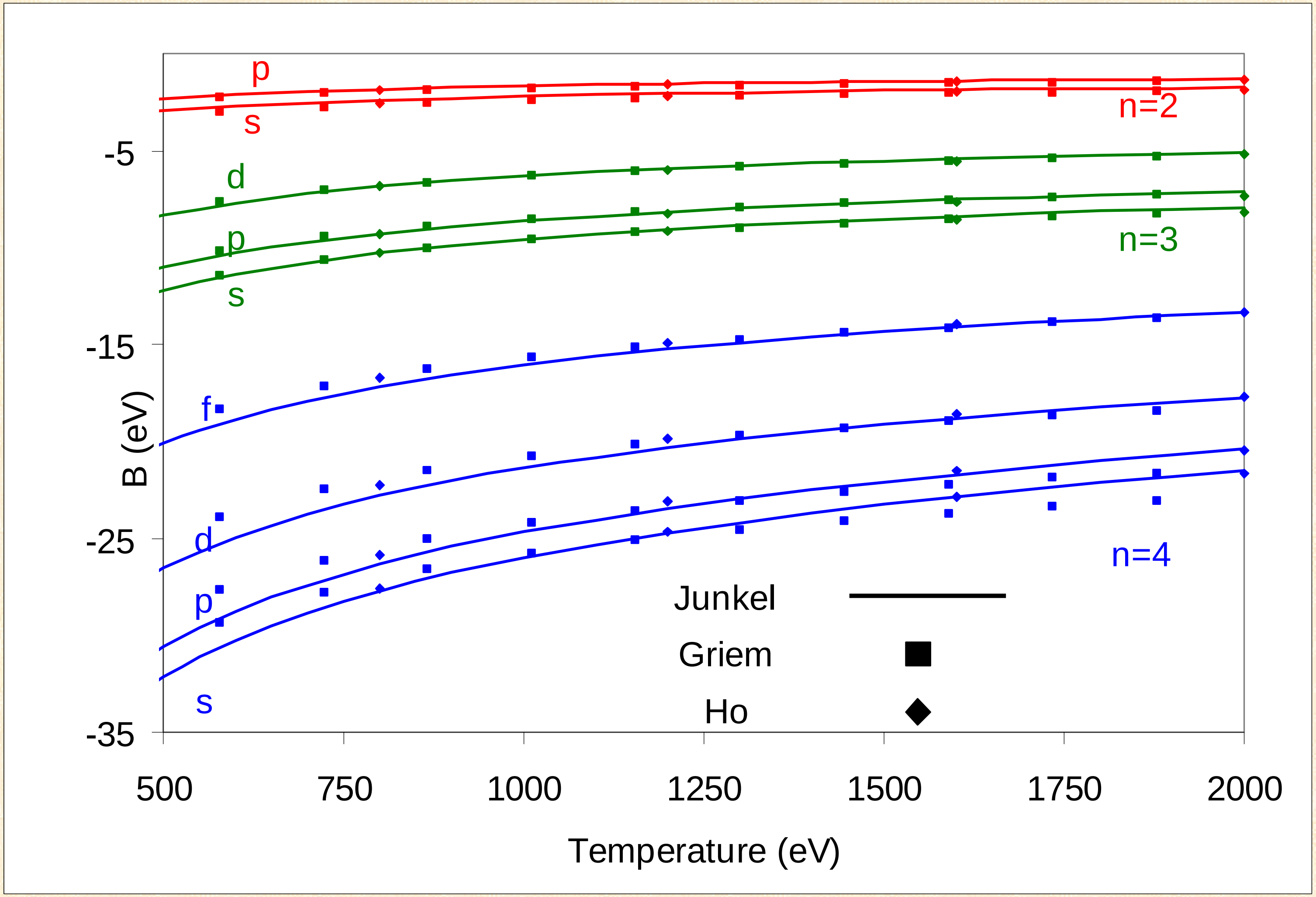
- This truncation has been shown (Cooper, Kelleher, and Lee) to be appropriate **provided that** the penetrating collisions which dominate B are small, in the sense that the perturber electron experiences a small change in its momentum.

$$kT > \frac{Z(Z-1)}{n^2}\ \mathrm{Ry}$$

Ar Line	**kT (min)**
Ly-a	1040eV
Ly-b	340eV
Ly-g	260eV

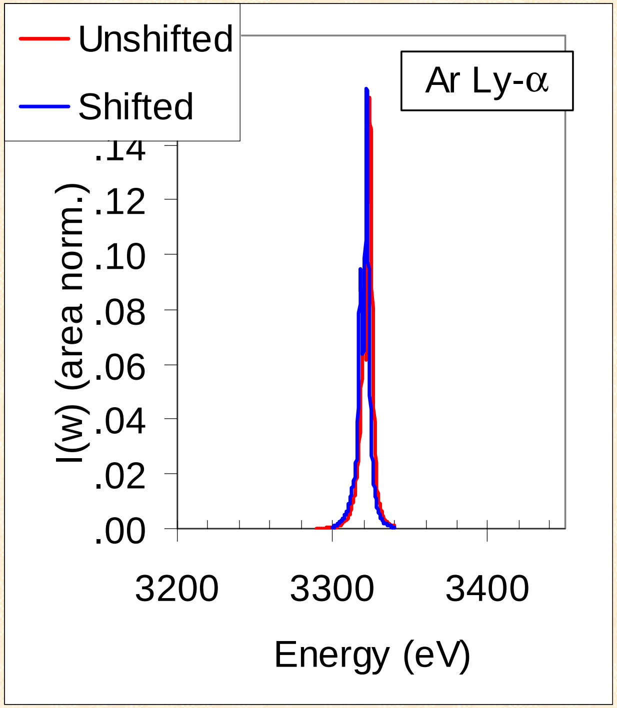
- Mark Gunderson has implemented an all-order semi-classical formulation whose results we use to compare with the 2nd order QM results to check the appropriateness of this truncation

The shifts also depends on angular momentum introducing an asymmetry as well as an overall shift to the lines

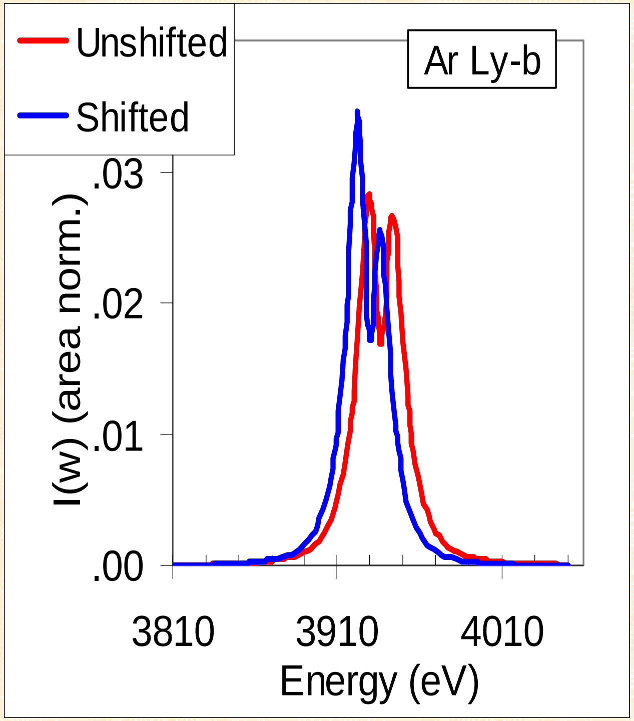


For non-neutral radiators and temperatures such that the 2nd order theory is adequate, the shift is nearly **<u>linear in density</u>**, and strongly dependent on **<u>pqn of the upper state</u>**.

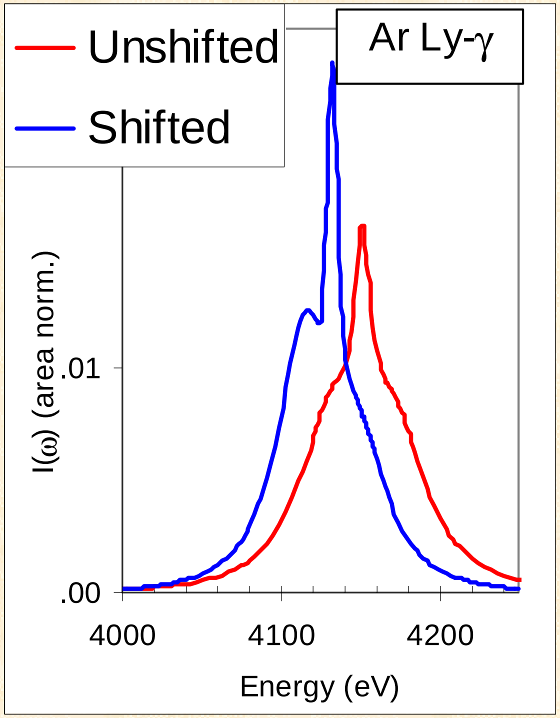
N_e=1e24/cc, kT_e=1keV



C.o.G Shift = -1.78eV



C.o.G. Shift = -9.01eV

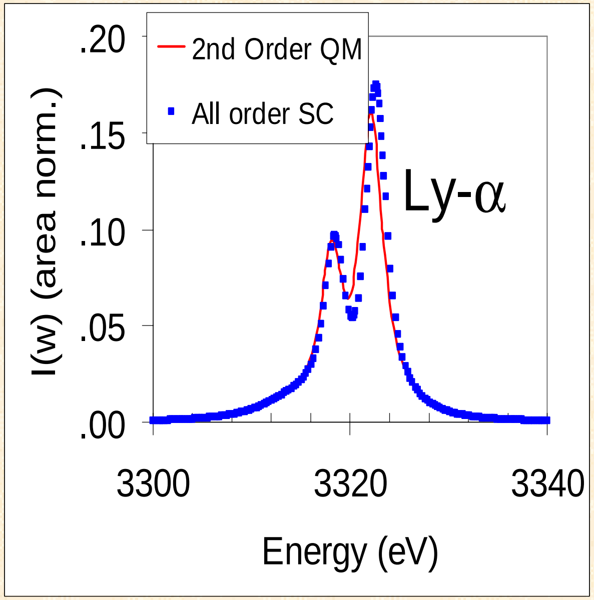


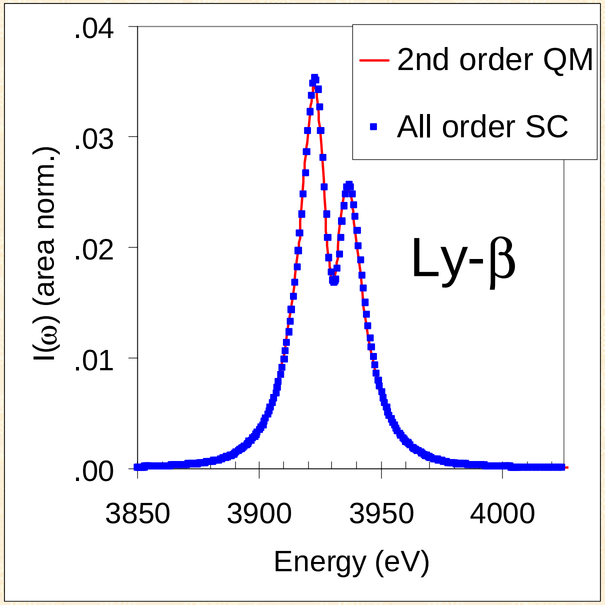
C.o.G. Shift = -22.87eV

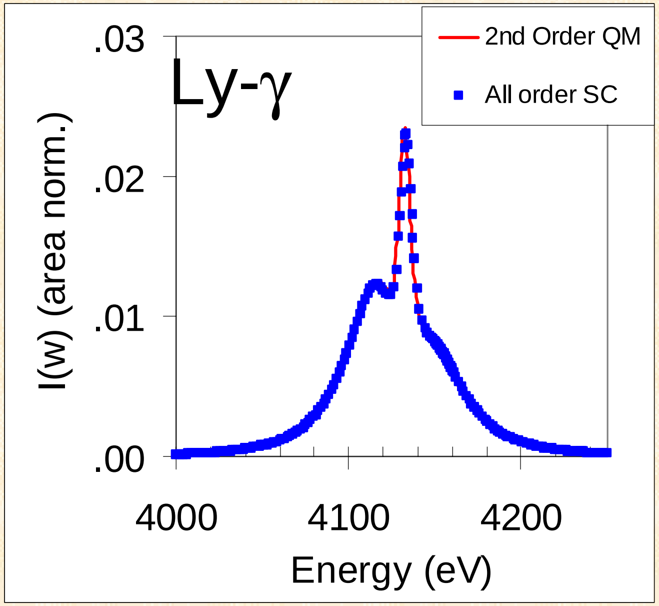
$$\text{Center of Gravity} = \frac{\int d\hbar\omega\ \hbar\omega\,\mathrm{I}(\hbar\omega)}{\int d\hbar\omega\ \mathrm{I}(\hbar\omega)}$$

For conditions relevant to the analysis of emission lines from the hot core of directly-driven microballoon implosions, the SC and QM results are substantially similar.

N_e=1e24/cc, kT_e=1keV

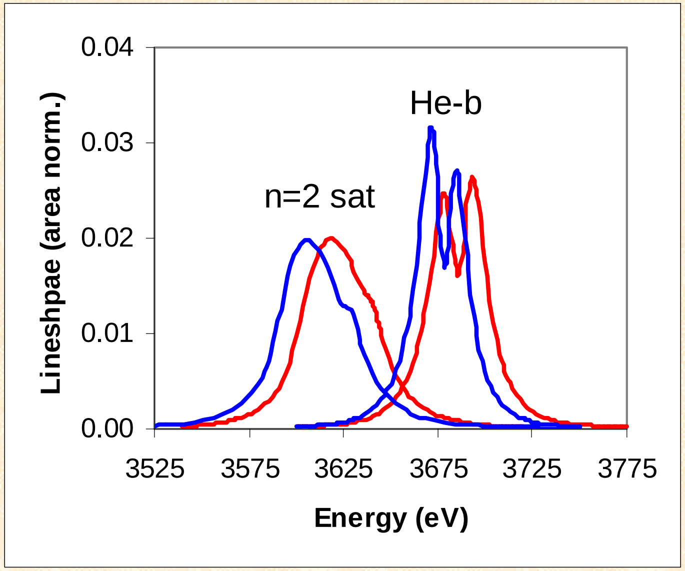


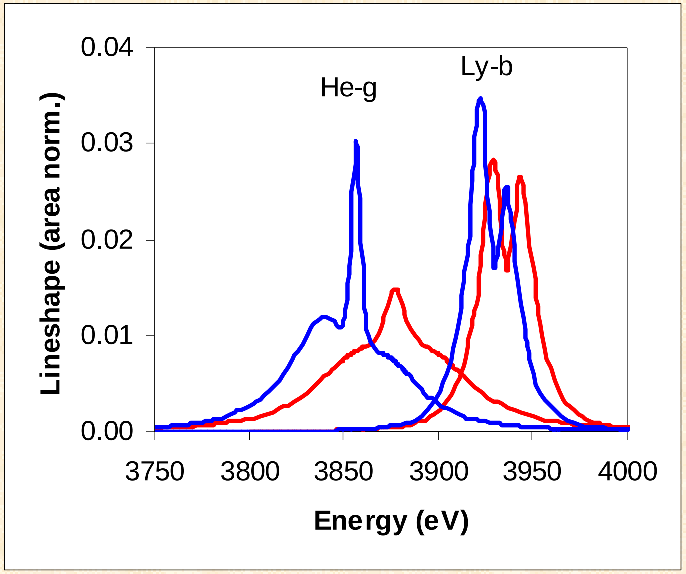




The differential shift of the [Ar Ly-β – Ar He-γ] is easier to observe than that of the [Ar He-β - Li-like satellites]

N_e=1e24/cc, kT_e=1keV





Differential Shift: 2.6eV

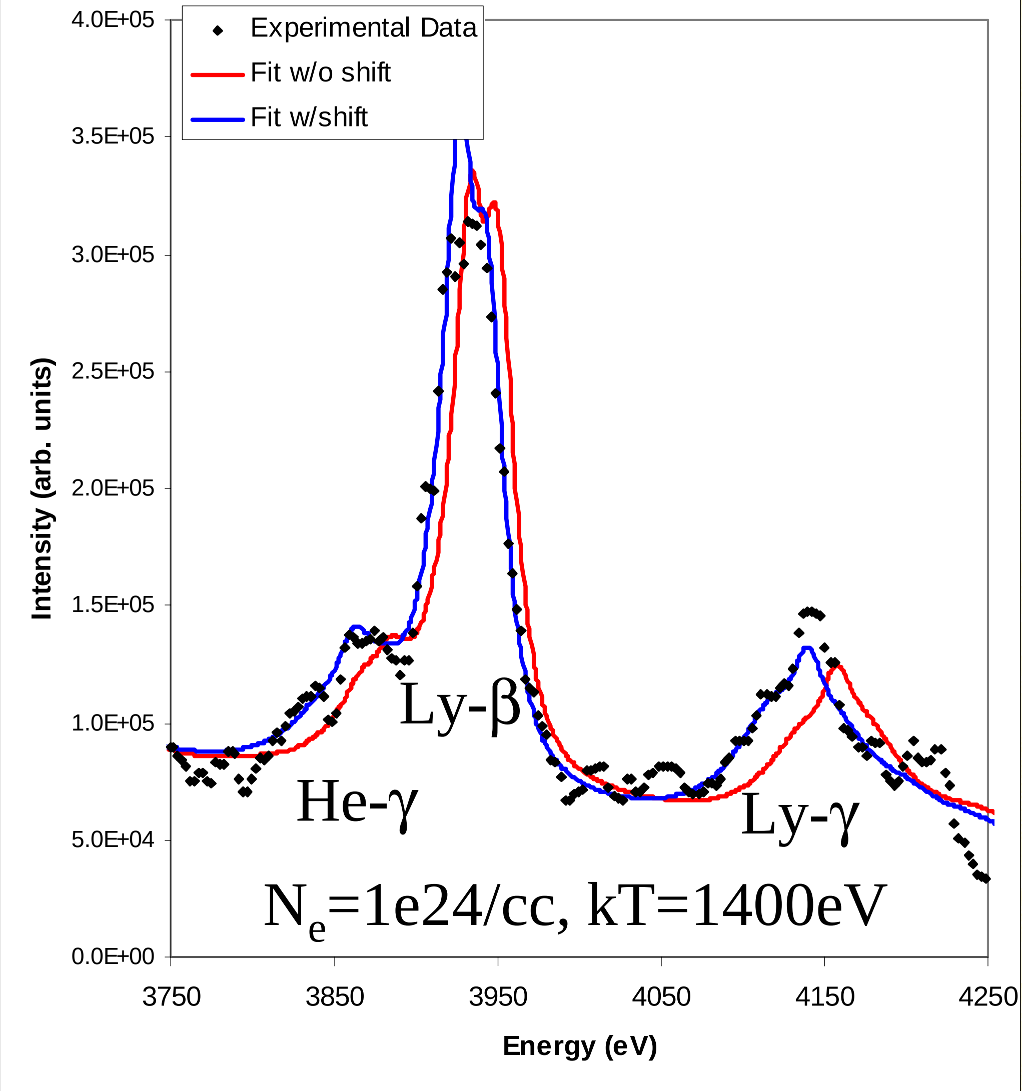
Differential Shift: 16.2eV

$$\text{Center of Gravity} = \frac{\int d\hbar\omega\ \hbar\omega\, \mathrm{I}(\hbar\omega)}{\int d\hbar\omega\ \mathrm{I}(\hbar\omega)}$$

The Ar spectrum from 3750eV-4250eV (He-γ+Ly–β+Ly-γ) provides a robust testing ground for shift formalisms.

Theoretical spectrum:

- Stark broadened Ar K-shell resonance lines and satellites.
- 1380 level CRE population distributions.
- Population effect of the transfer of the thick (τ_ν~30) He-α approximated using Mancini's escape factors.
- Uniform core approximation

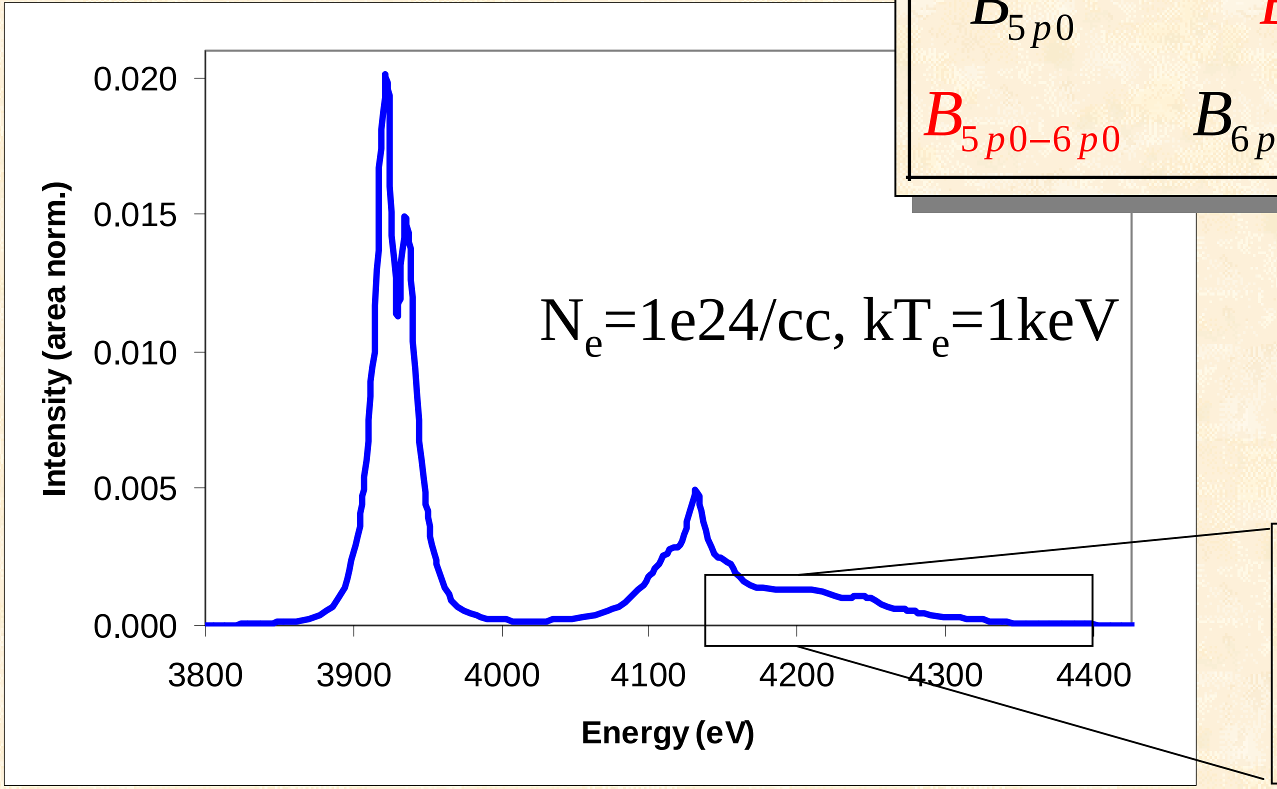


N_e=1e24/cc, kT=1400eV

Line merging and the Inglis-Teller limit

To first order in the radiator-electron interaction the shift of an isolated line is linear in density and strongly increases with pqn. Successive lines in a Rydberg series do not ‘cross’ because of the interaction between adjacent upper manifolds.

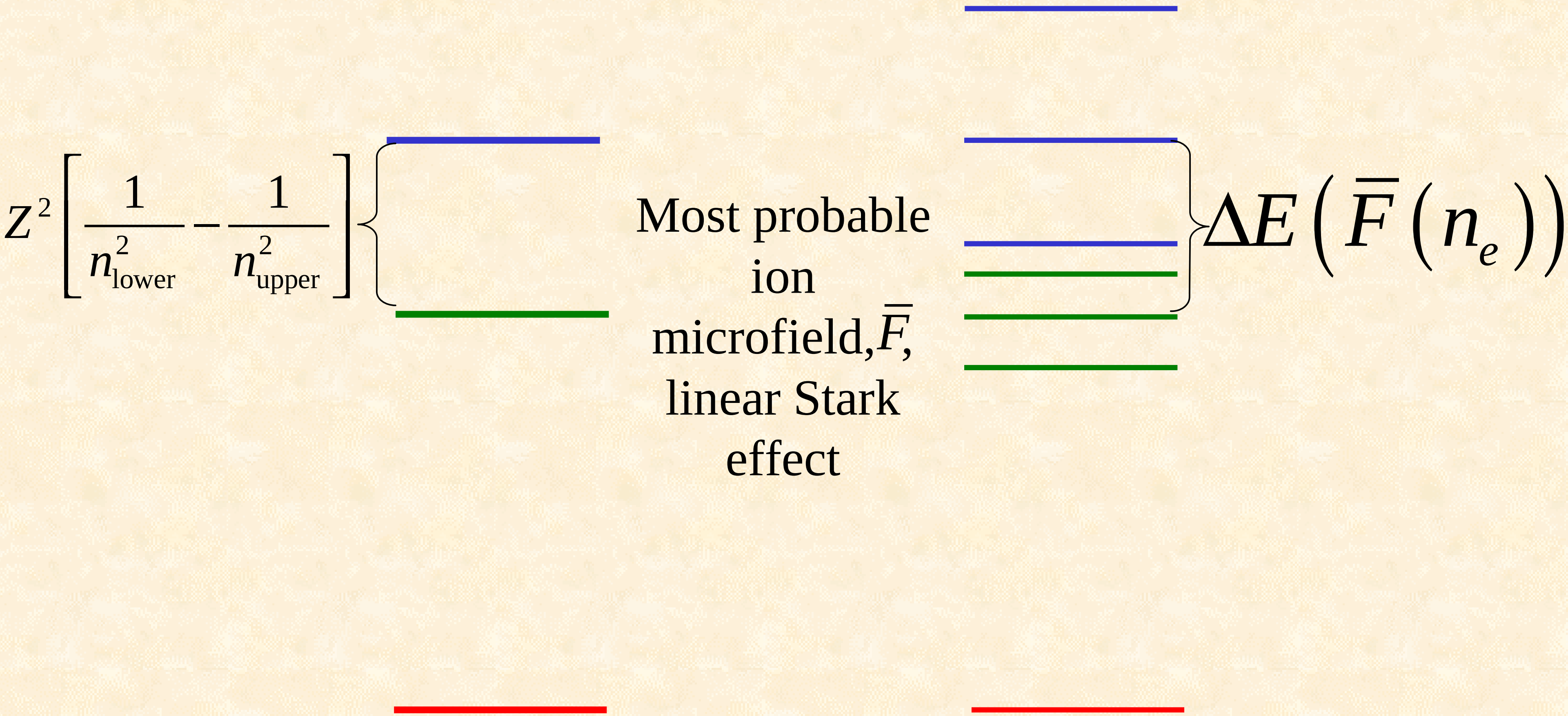
$$\begin{vmatrix} B_{5p0} & B_{5p0-6p0} \\ B_{5p0-6p0} & B_{6p0}\left(> B_{5p0}\right) \end{vmatrix}$$



merged δ, ε, … lines

Possible modification of Inglis-Teller limit based inferences of density due to line shifts should be considered.

Inglis and Teller, Astrosphys. J. **90** (1939), derived a limit, $n_{max,}$, for the highest pqn which must be retained as bound states in accurate calculations, also providing an upper bound on density based on the last two distinct lines observed in a Rydberg series.



$$Z^2\left[\frac{1}{n_{\text{lower}}^2}-\frac{1}{n_{\text{upper}}^2}\right]$$

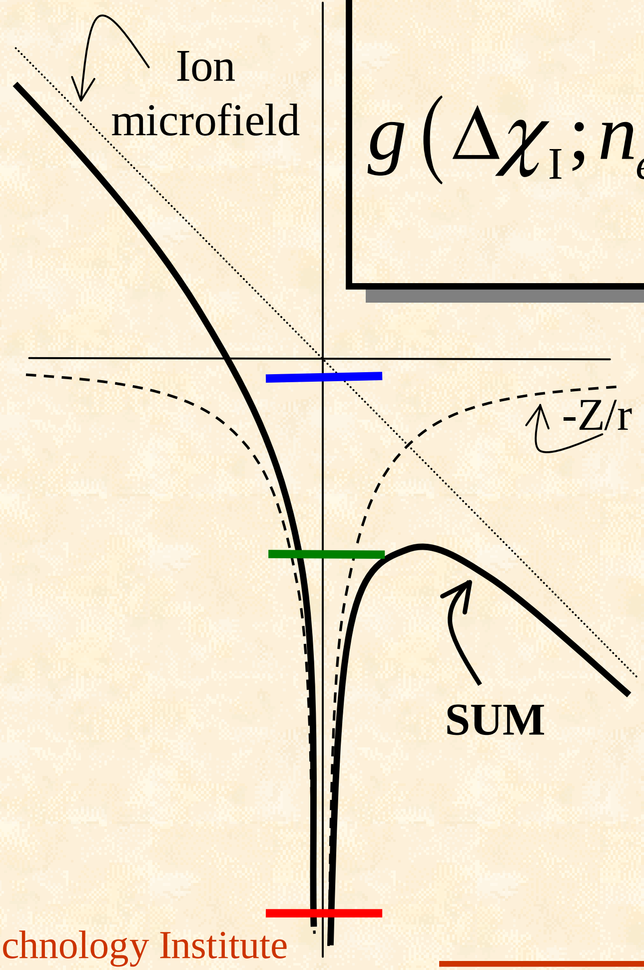
Most probable ion microfield, $\bar{F}$, linear Stark effect

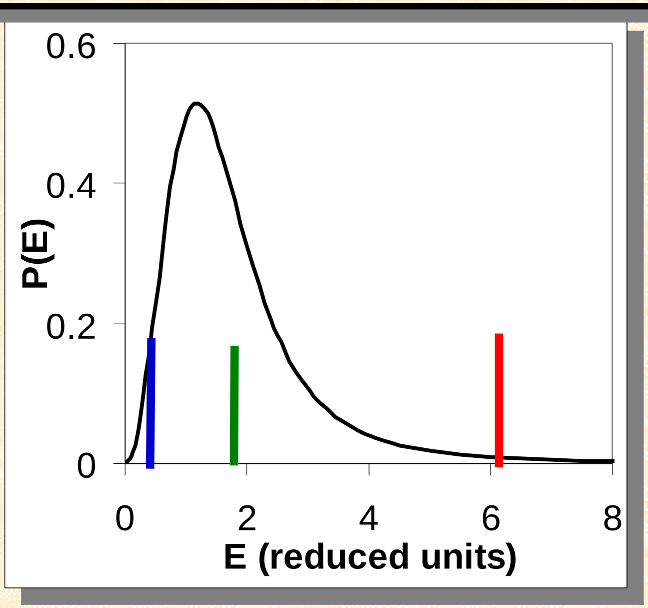
$$\Delta E\left(\bar{F}\left(n_e\right)\right)$$

Given level shifts on the order of the observed line shifts, level population calculations relying on degeneracy lowering models should include the effects of these shifts.

Though the line shifts we have observed are much smaller than kT, level shifts on the order of the observed line shifts will effect temperature inferences from line ratios calculated using degeneracy lowering models.

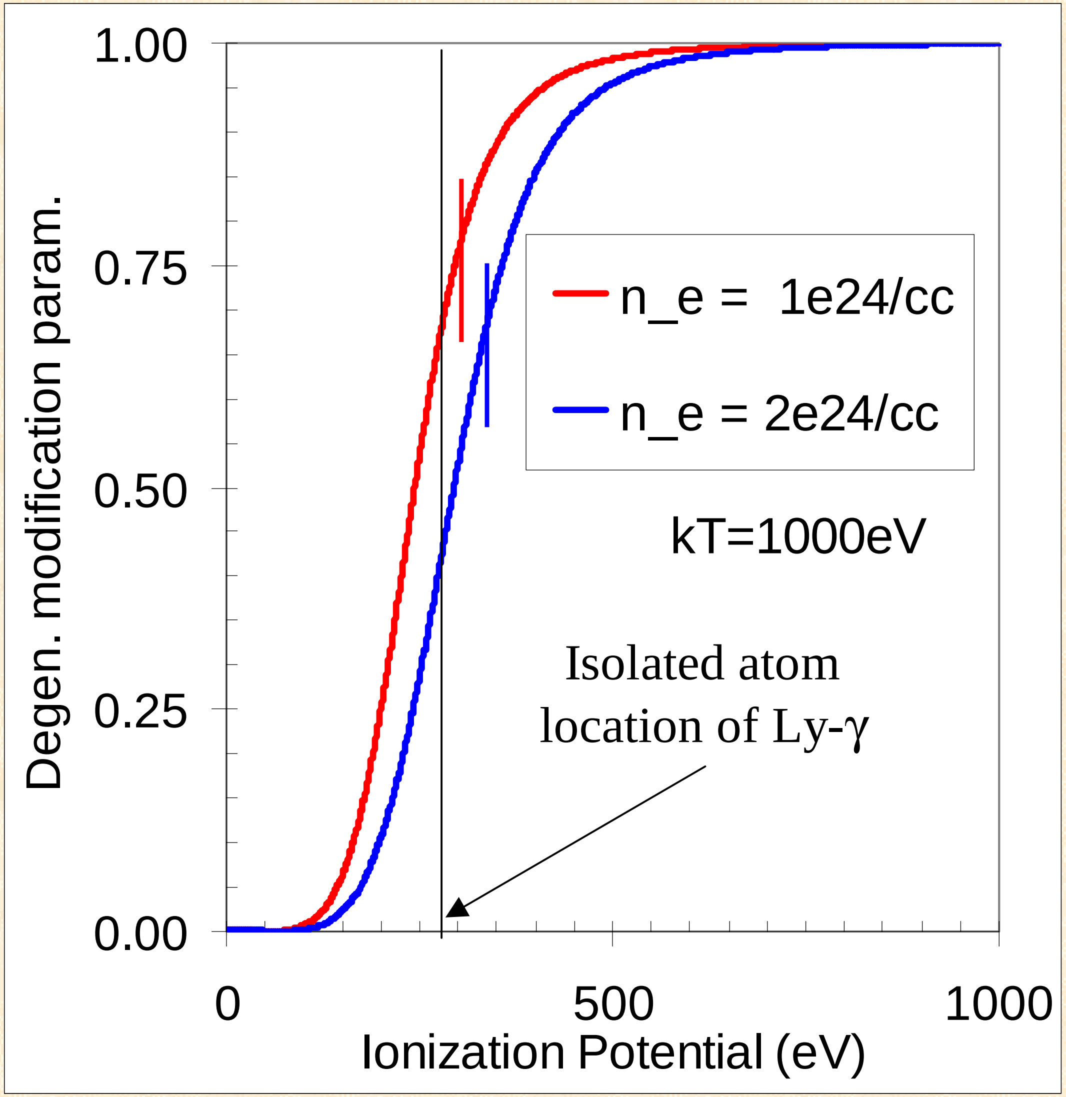
$$g\left(\Delta\chi_{\mathrm{I}};n_e,kT\right)=g_0\left[1-\int_{E\left(\Delta\chi_{\mathrm{I}}\right)}^{\infty}dE\,P\left(E;n_e,kT\right)\right]$$





The dependence of the degeneracy lowering parameter on binding energy in, *e.g.*, the Mihalas-Hummer approximation is sufficiently strong so that shifts ~ 0.1kT can have large effects on the population of the upper states of transitions.

A naïve implementation of plasma-induced line shifts into a CRE population kinetics calculation would change the degeneracy lowering parameter of the n=4 $^3P_{½}$ level by 12% and 33% for plasma with electron densities of 1e24/cc and 2e24/cc, respectively.



Conclusions and Summary

- Observation of plasma-induced line shifts in a variety of systems with charged radiators have been reported.
- These shifts are to lower energy, approximately linear in density, and increase strongly as a function of principal quantum number.
- Line merging calculations and use of the Inglis-Teller limit should include the effects of these shifts.
- For the laser-produced plasmas studied by the UF group, these shifts may have a marked effect on the intensities of the Ar K-shell γ lines, even though the shifts are small with respect to kT.

The observation of plasma-induced line shifts in the K-shell spectrum emitted by hot, dense plasmas necessitates an exploration of the implications of these shifts on line merging and population kinetics.