UCRL-PRES-225989

Measuring the ionization balance of gold in EBIT plasmas of importance to ICF

Mark J. May

B-Division

Lawrence Livermore National Laboratory

Experiment
P. Beiersdorfer
M. Schneider
S. Terracol
K. Wong
G. Brown

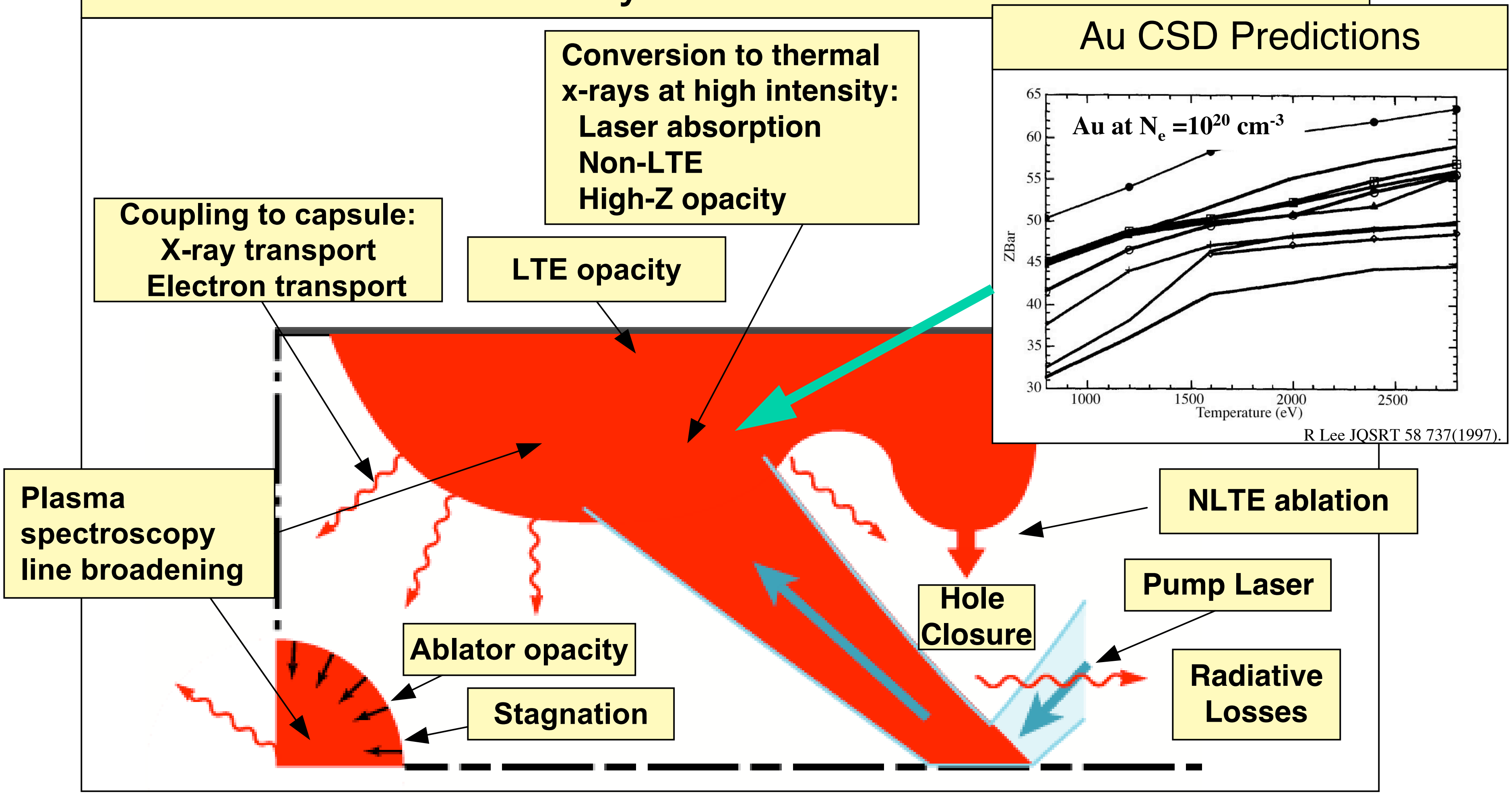
Modeling
S. Hansen
H.K. Chung
M. Gu (Stanford)
K. Fournier
B. Wilson
J. Scofield
K. Reed

GSFC-NASA
F.S. Porter
R. Kelley
C. Kilbourne
K. Boyce

20 Years of Spectroscopy with the Electron Beam Ion Trap
November 12 - 16, 2006 Berkeley, California

Accurate models for non-LTE physics are necessary for ICF

Atomic Physics Needs for ICF

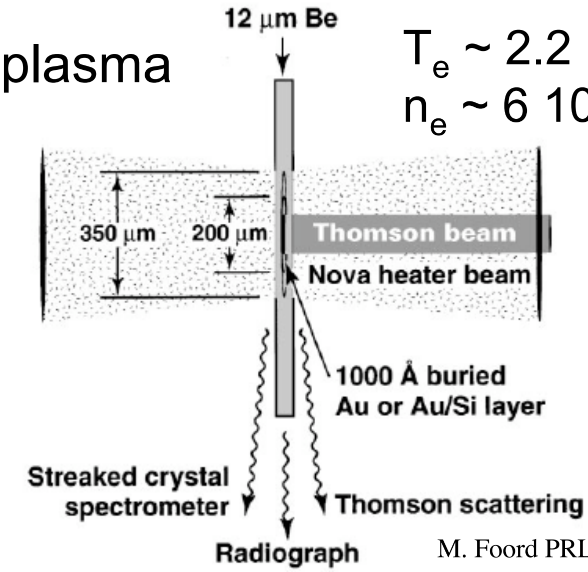


Experiments are required to improve theoretical models

Previous charge balance measurements from NOVA distinguish between models at high density

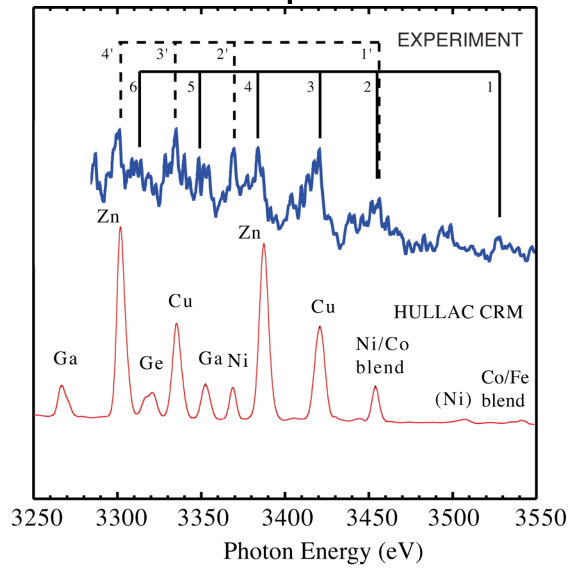
Au plasma

$T_e \sim 2.2$ keV
$n_e \sim 6\ 10^{20}$ cm^{-3}

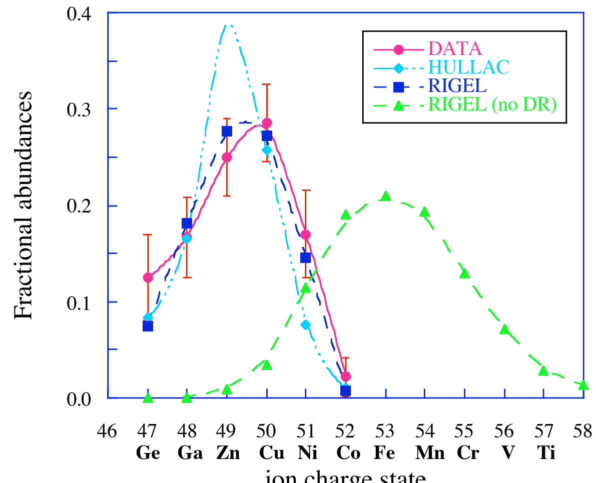


M. Foord PRL **85** 992 (2000)

Nova Spectrum



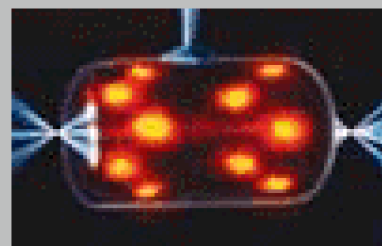
Nova CSD

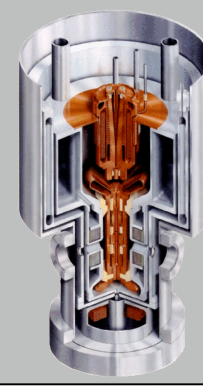


- CSD by fitting detailed HULLAC computations to the measured line emission
  - EA/DR corrections / Optical depth corrections
- Analysis of the complex spectrum is challenging in the high density plasma
  - Many competing atomic physics processes
  - Spatial gradients
  - Transient nature of the experiment
  - Differences between HULLAC and experimental photon energies

Au Charge State Distribution Experiments

	Omega and Helen Lasers	Electron Beam Ion Trap



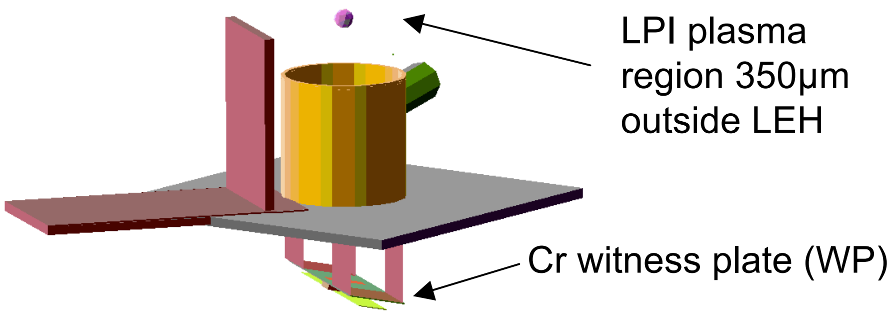


	Omega and Helen Lasers	Electron Beam Ion Trap
T_e(keV)	5 - 10	2 - 3
E_{Beam}(keV)	-	2.5 - 6.5
N_e(cm^{-3})	$3x10^{21}$	$1x10^{12}$

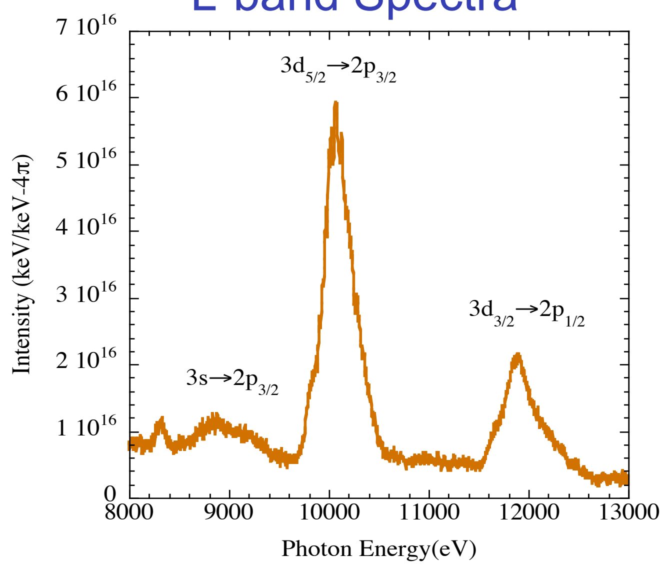
		Omega and Helen Lasers		Electron Beam Ion Trap
Gold Ionization States		Ni - P		Kr - Ar
		51+ - 64+		43+ - 61+
Spectral Regions	M-band:	5f→3d	M-band:	4f→3d & 5f→3d
		3 - 5.0 keV		2 - 6 keV
	L-band:	3d→2p	RR:	n = 4, 5, 6, etc
		8.5 - 12.5 keV		6 - 8 keV
Spectrometers		Space and Time Res.		Time Resolved

High Temperature Plasmas in Hot Halfraums at the OMEGA Laser

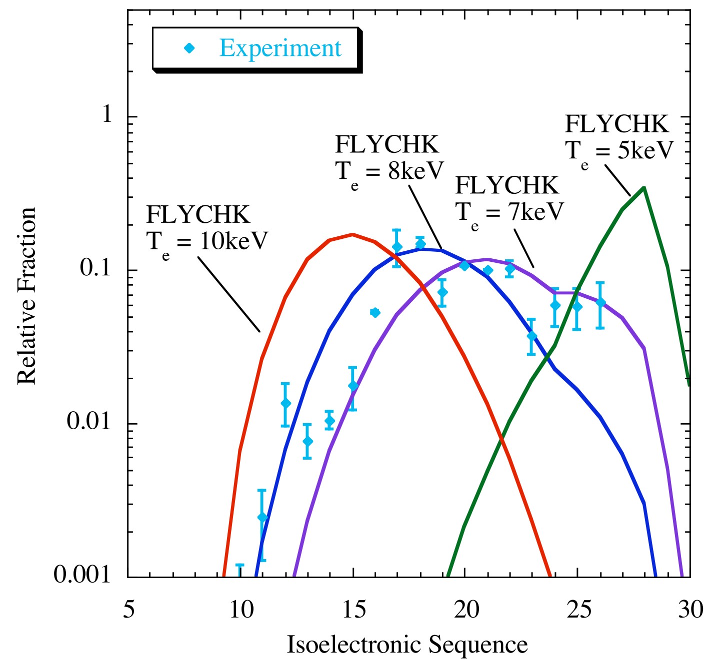
Hot Halfraum Target



L-band Spectra



Inferred Halfraum CSD

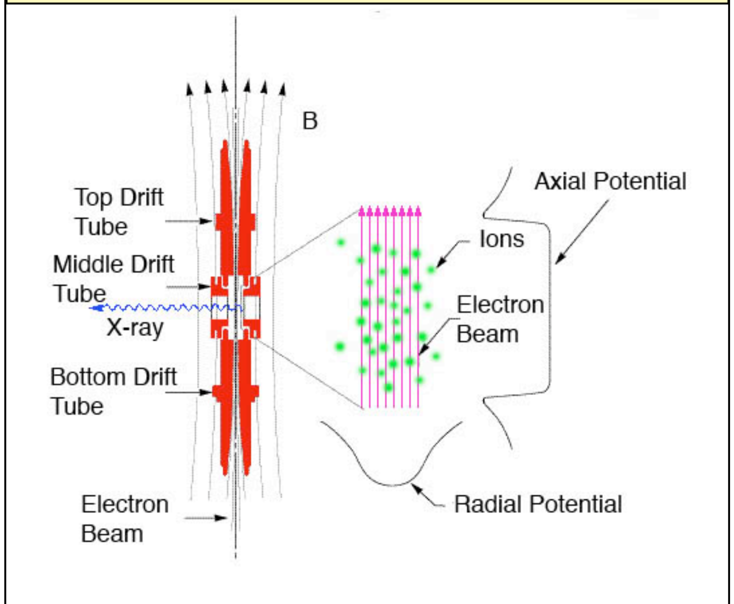


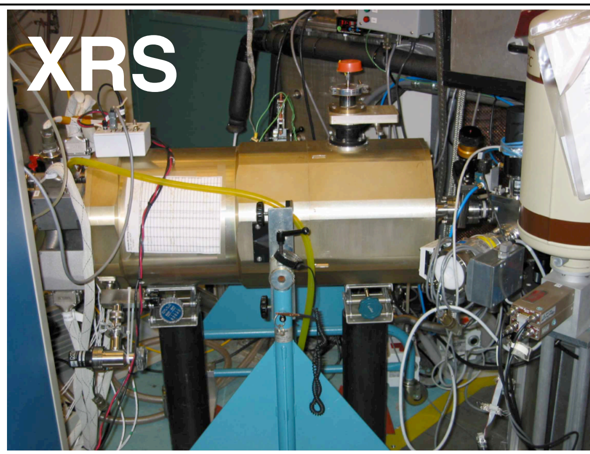
MJ May et al, UCRL-JRNL-214752

Experiments are required at even higher electron temperatures

EBIT measurements test models at low density

Conceptual View EBIT-I

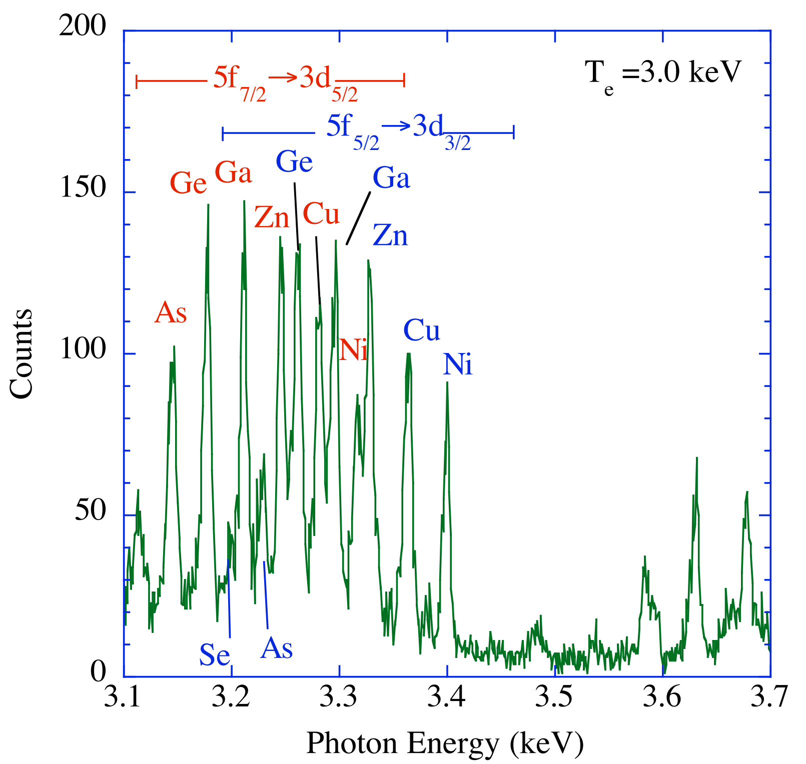




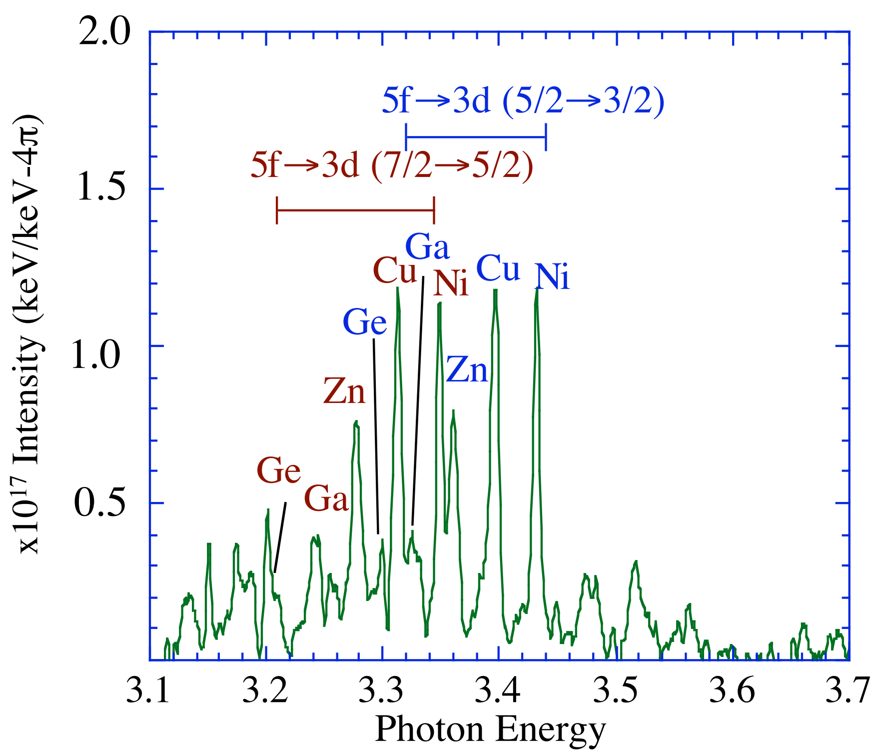
- Electron Beam Ion Trap (EBIT-I and EBIT-II)
  - Gold Plasmas
  - E_{Beam} = 2.75, 3.0, 3.6, 4.6, 5.5, 6.0, 6.5 keV
  - T_e = 2.0, 2.5, 3.0 keV
  - $n_e \sim 1\text{x}10^{12}$ cm^{-3}
  - Fewer active atomic physics processes than in high density plasmas
  - Steady state plasmas
- Gold Measurements/Modeling
  - Ni-like to Kr-like Gold lines (E_{photon} = 0.1 – 8.0 keV)
  - Spectrometers: XRS microcalorimeter (GSFC), Crystal, Grating
  - Collisional line emission (CE) and radiative recombination (RR) measurements
  - CSD inferred from both CE and RR spectral measurements
  - Collisional excitation cross sections inferred from the CE and RR measurements

EBIT spectrum helps interpret Au foil spectrum from laser plasmas

EBIT-I XRS Spectrum



AWE Au Foil Spectrum



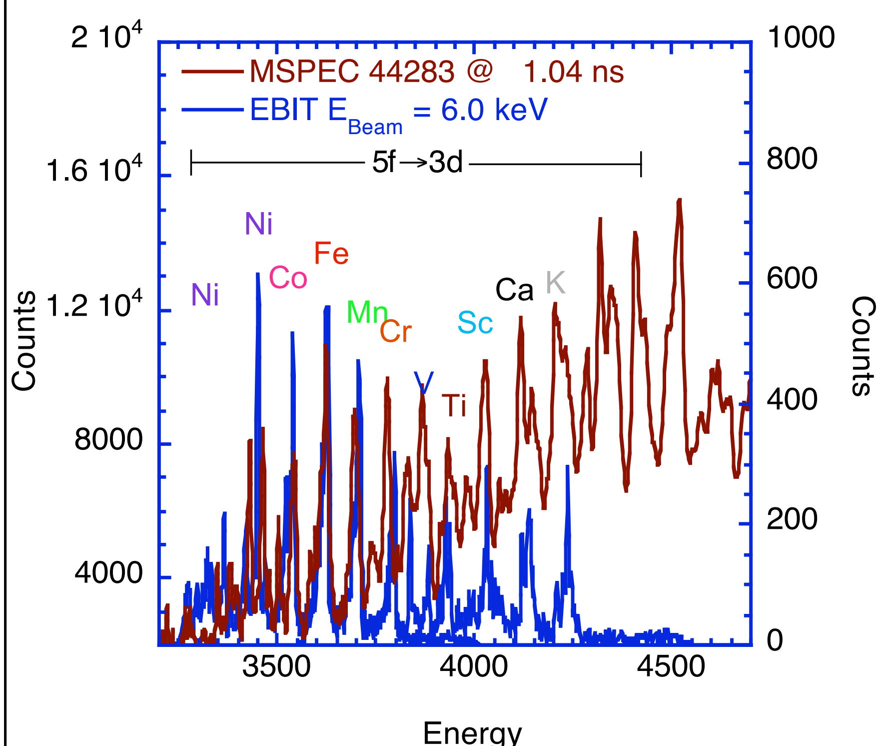
Low density spectrum allows unambiguous line identification of laser spectrum

MJ. May EBIT Nov 2006.

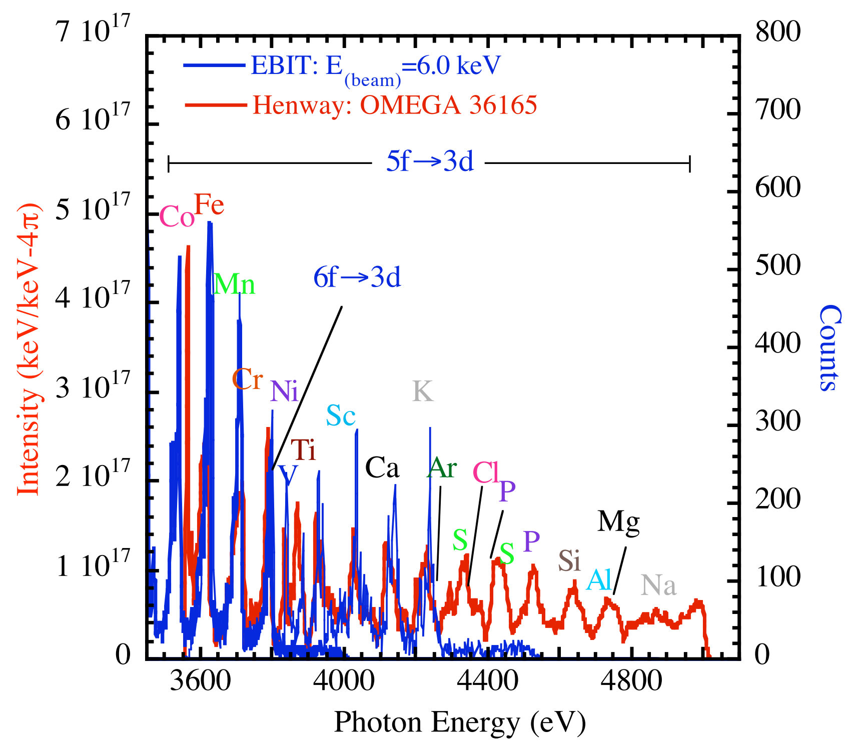
Physical Data Research Program
Nuclear•Atomic•Condensed Matter Physics

Direct Comparisons of EBIT and OMEGA Spectra

EBIT and MSPEC Spectra

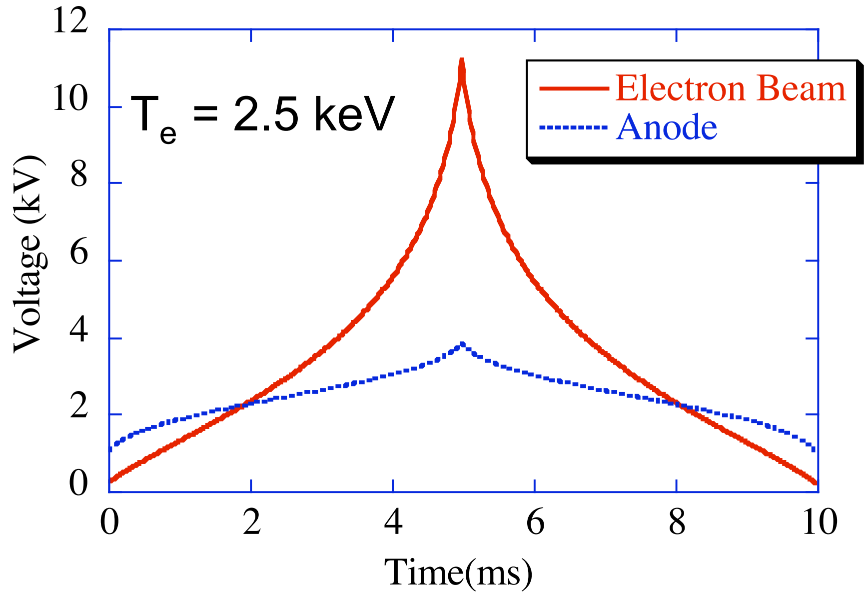


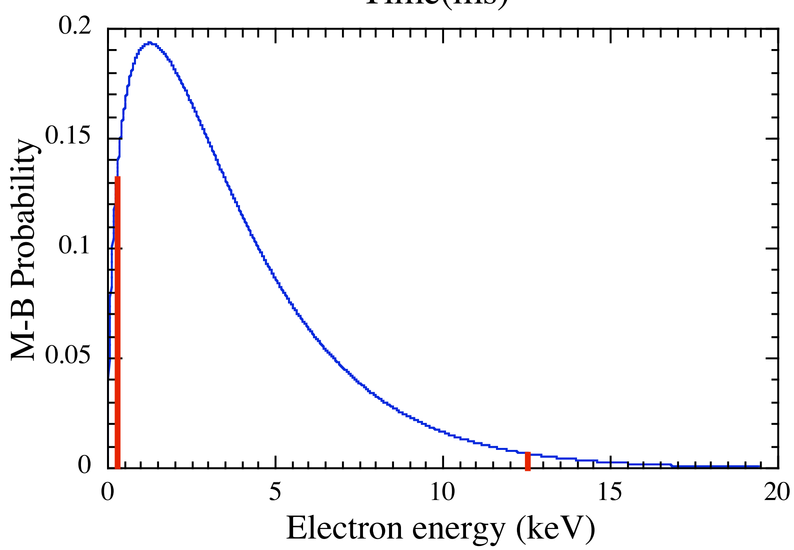
EBIT and Henway Spectra



EBIT spectra useful in identification and energy calibration of OMEGA spectra

LLNL EBIT produces simulated Maxwell-Boltzmann plasmas

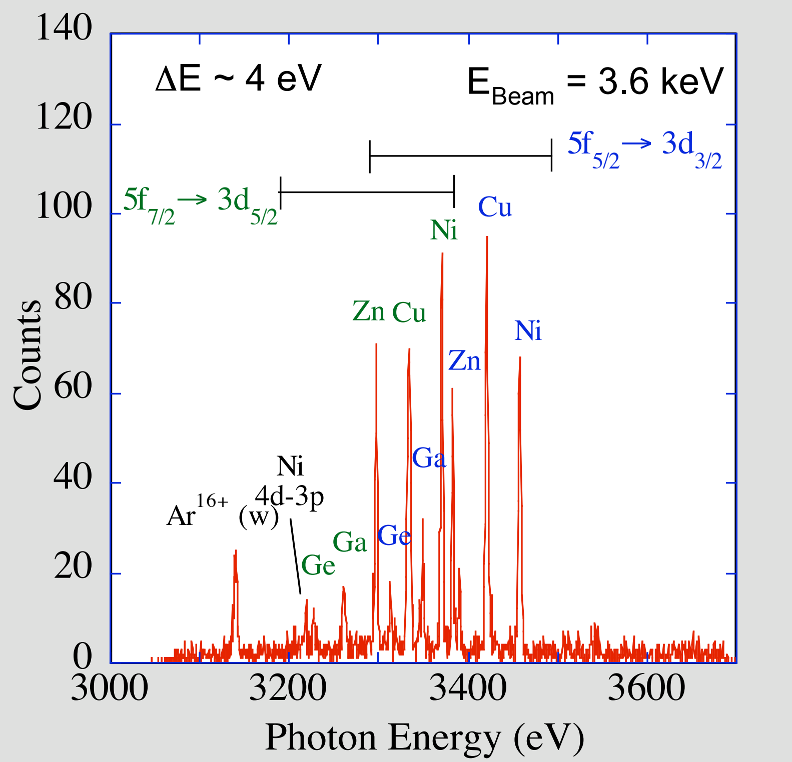




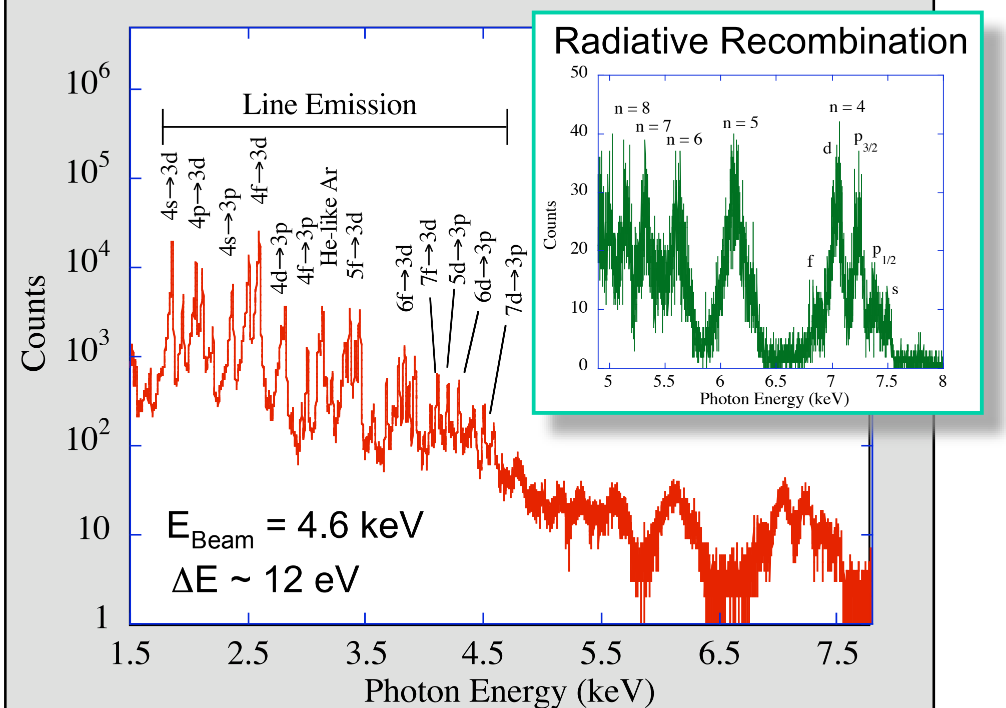
- Simulated a Maxwell-Boltzmann (MB) electron distribution
- Monoenergetic electron beam is swept in time by an arbitrary waveform generator
- Time spent at one beam energy is proportional to the MB distribution at that energy
- Anode Voltage (V_A) swept to maintain constant n_e in beam
- Sample a large fraction of the MB distribution
- Sweep time ~ 5 ms.

Complementary X-ray measurements provide two approaches to measure the CSD in EBIT

Crystal Spectrum



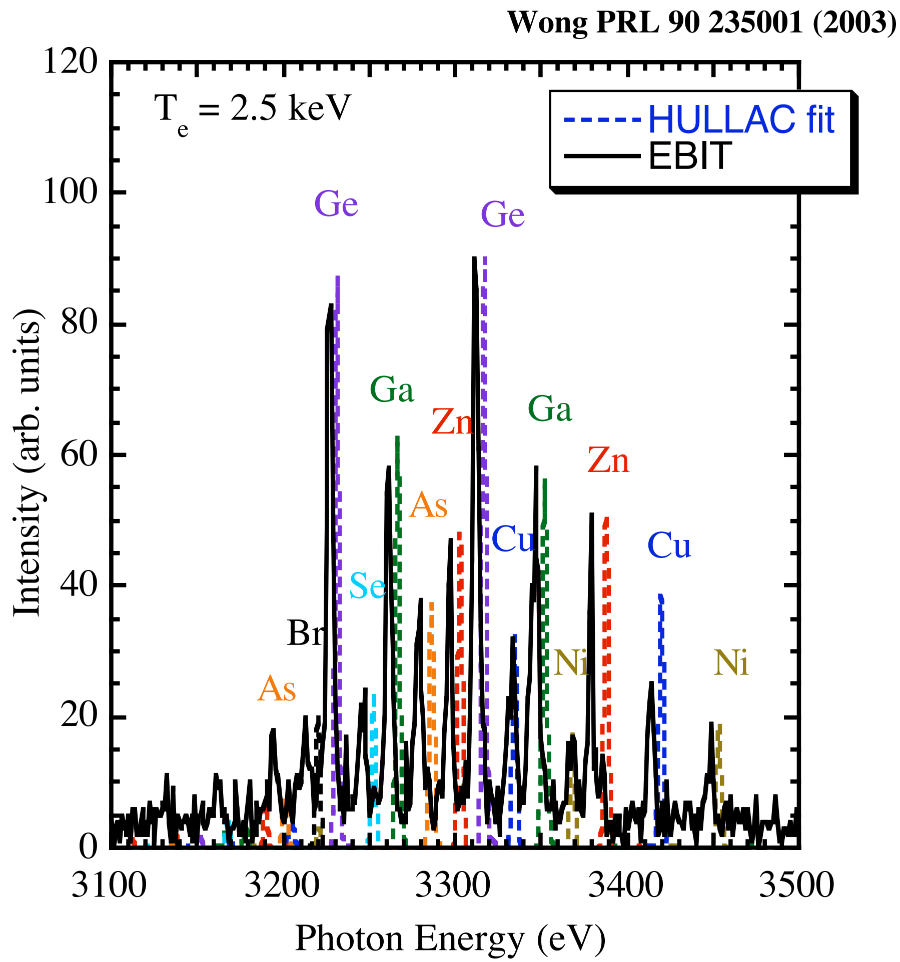
XRS Spectrum



- High resolution allows line spectra to be used to infer charge balance (NOVA approach)

- Broadband spectra used to infer charge balance from RR peaks
- Technique is independent of line excitation models

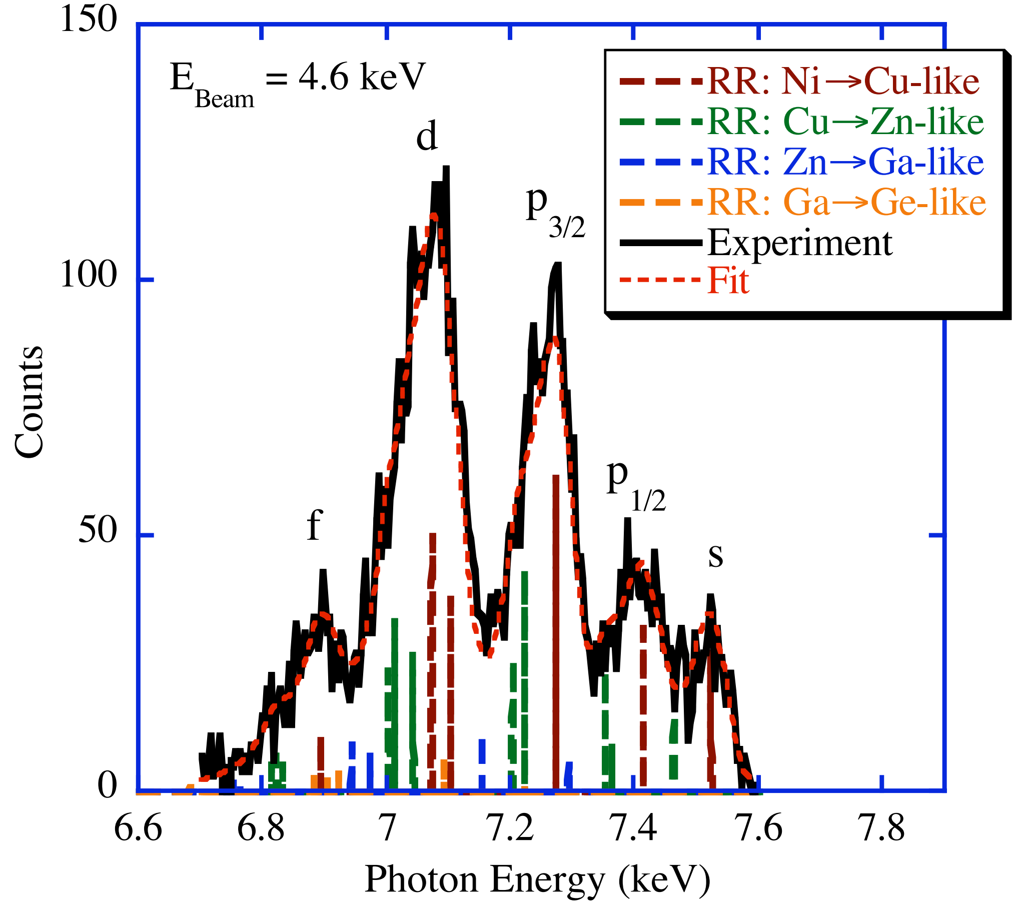
Gold CSD from EBIT inferred from X-ray spectra and fit with HULLAC calculations



- Crystal spectrometer: 5f→3d and 4f→3d transitions
- Each HULLAC charge state is coupled to the higher charge state to include the effects of DR on line intensities
- CSD is inferred by individually fitting each HULLAC charge state model to the measurement

Accurate CSD inferred from the line emission spectra

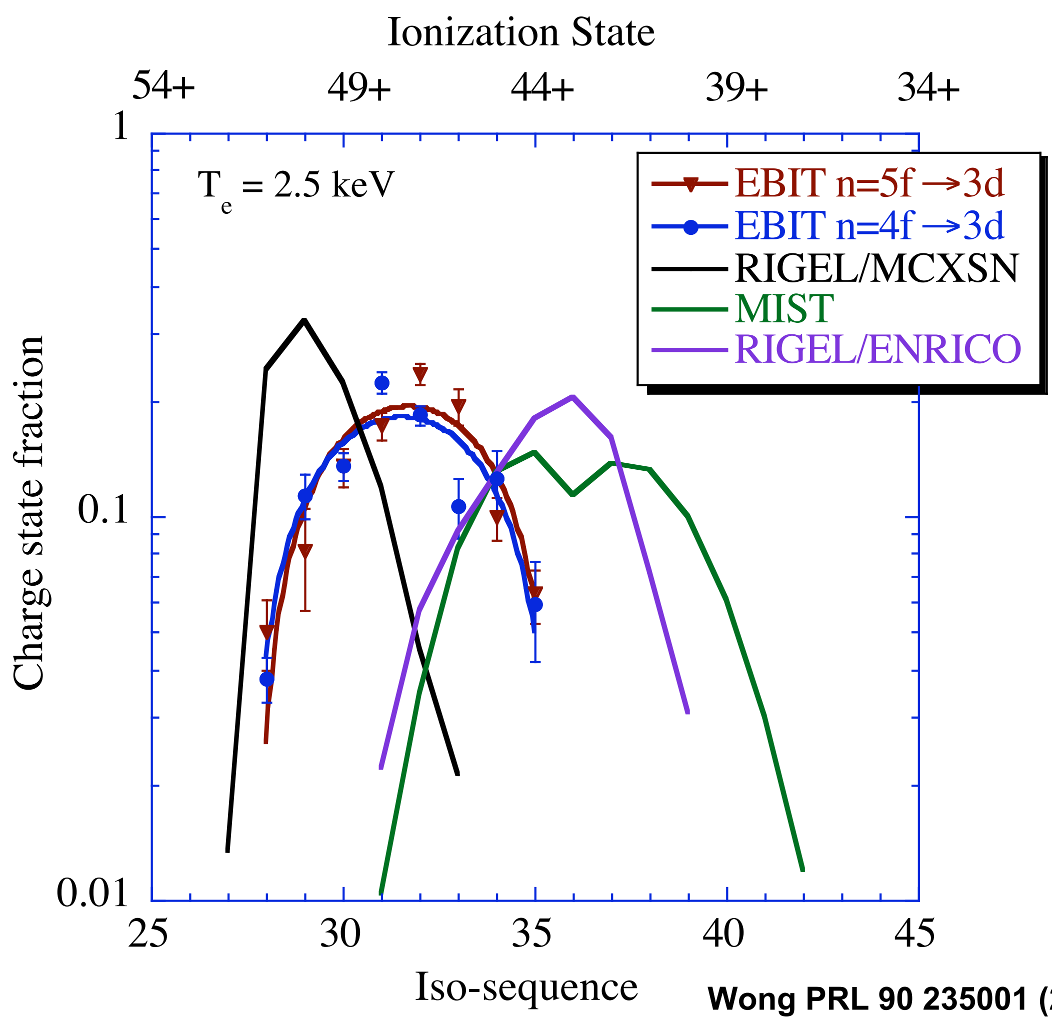
Radiative recombination spectrum from EBIT and fit with GRASP RR calculations



- XRS microcalorimeter: Radiative Recombination (RR) spectrum
- Beam Plasma
- ΔE_{Beam} ~ 70 eV
- CSD is inferred by fitting the RR spectrum with accurate Grasp calculations (Scofield)

Accurate CSD independent of the line emission spectra

Gold CSD from EBIT thermal plasmas compared to simulations



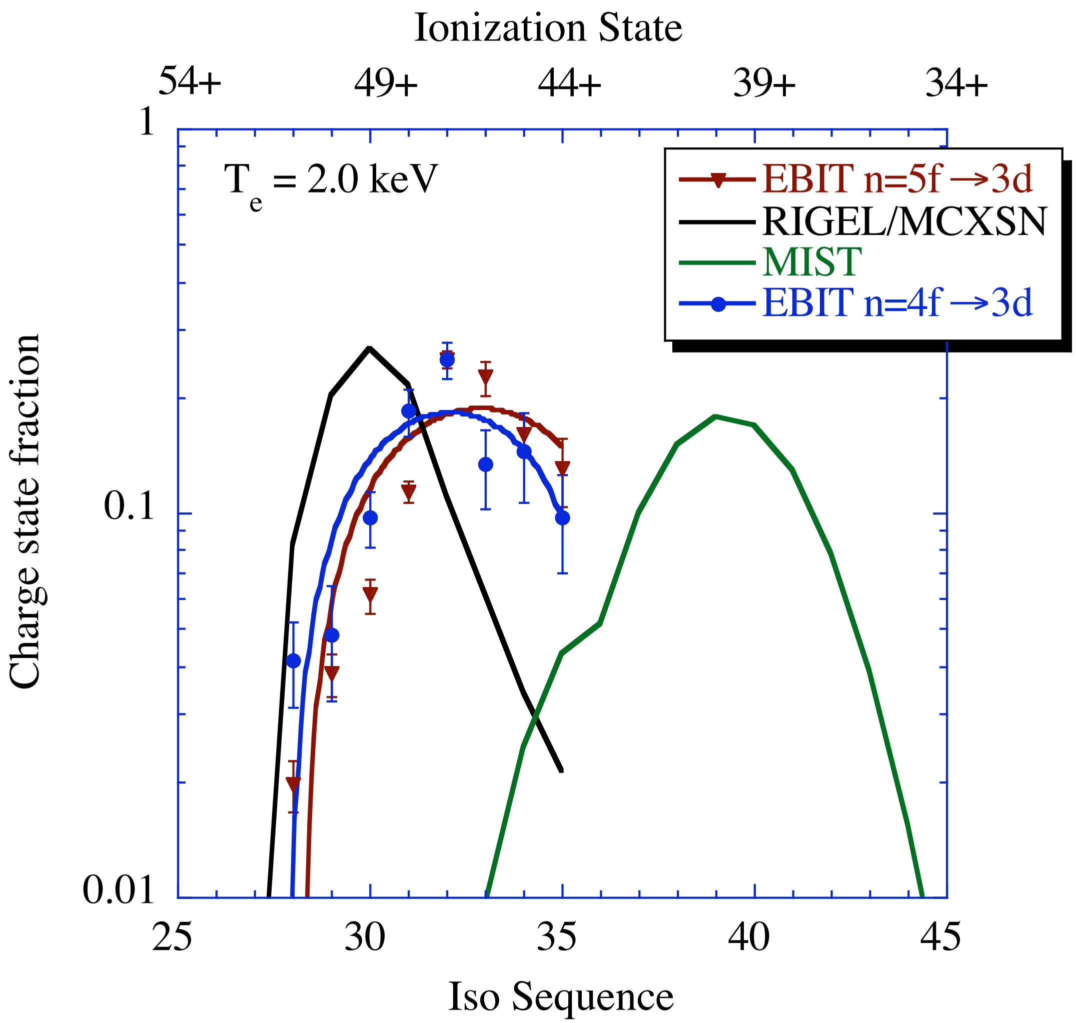
Wong PRL 90 235001 (2003)

- EBIT: Inferred from the n= 5f→3d,4f→3d spectra
- MCXSN/ENRICO: high density code
- MIST: tokamak transport code: low density

Z_{eff} Results	
EBIT (5f→3d)	46.8 ±0.8
EBIT (4f→3d)	47.5±0.3
ENRICO	43.7
MCXSN	49.5
MIST	42.7

Significant discrepancy between experiment and simulation

Gold CSD from EBIT thermal plasmas compared to simulations

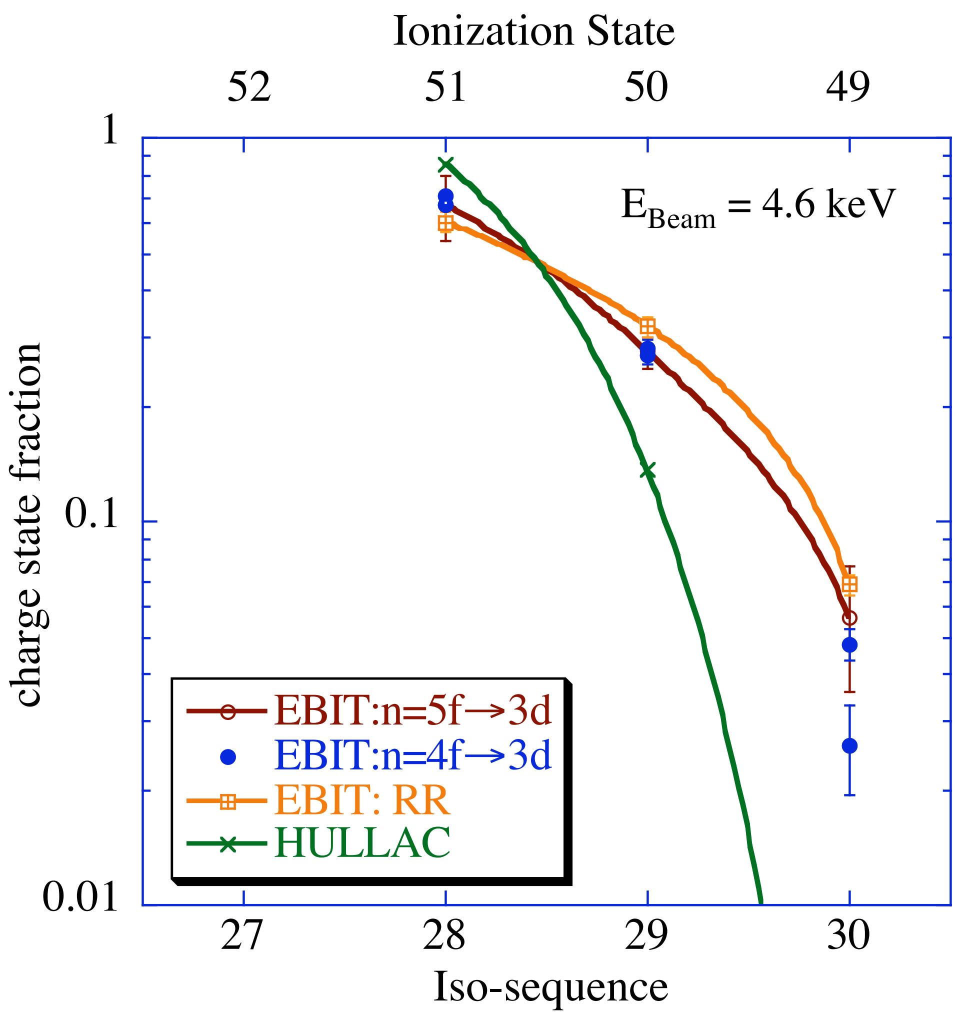


- EBIT: Inferred from the n=5f→3d and 4f→3d spectra
- MCXSN: high density code
- MIST: tokamak transport code: low density

Z_{eff} Results	
EBIT (5f→3d)	46.5±0.9
EBIT (4f→3d)	46.9±0.5
MCXSN	48.5
MIST	39.9

Significant discrepancy between experiment and simulation at other temperatures

Gold CSD from EBIT beam plasmas compared to simulations

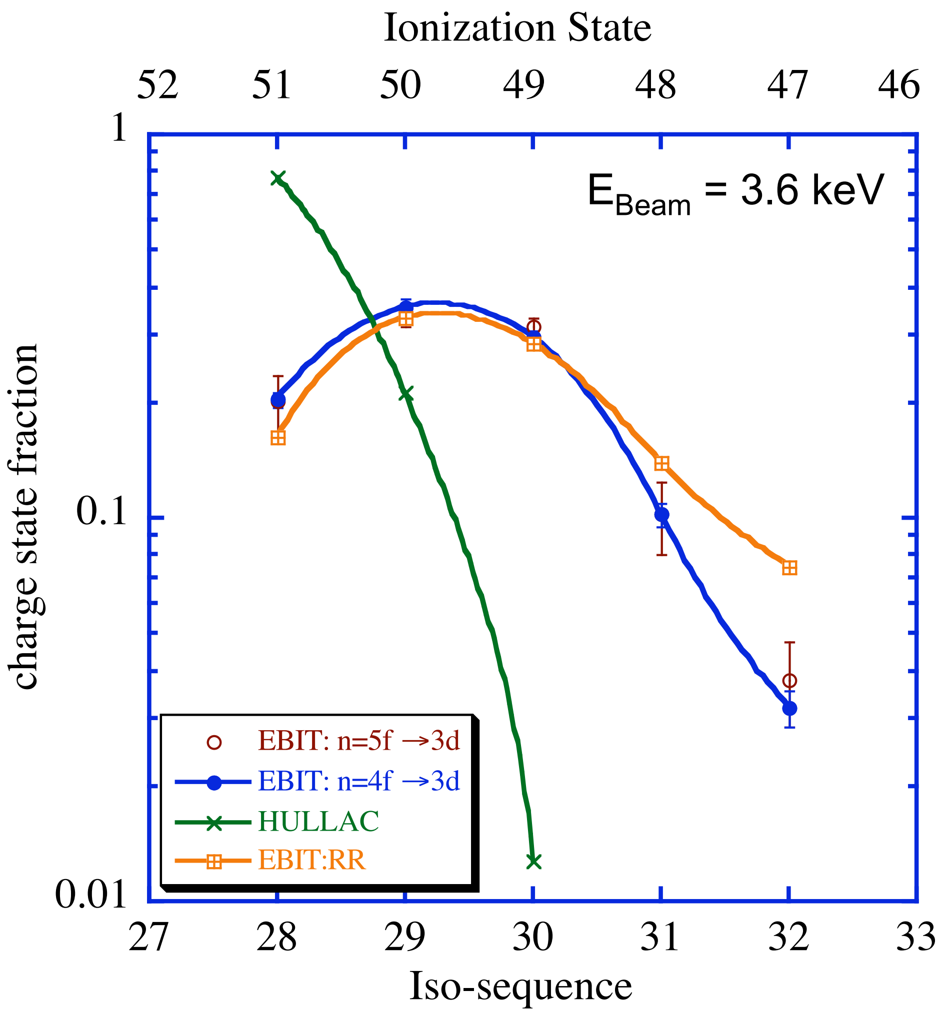


- EBIT: Inferred from both the n = 5f→3d and 4f→3d spectra and the RR spectrum
- HULLAC: modeling CSD
- I_p (Ni-like) ~ 4.9 keV

Z_{eff} Results	
EBIT (5f→3d)	50.7±1.4
EBIT (4f→3d)	50.5±1.0
EBIT (RR)	50.5±1.0
HULLAC	50.9

Experimental results are self-consistent but disagree with HULLAC

Gold CSD from EBIT beam plasmas compared to simulations

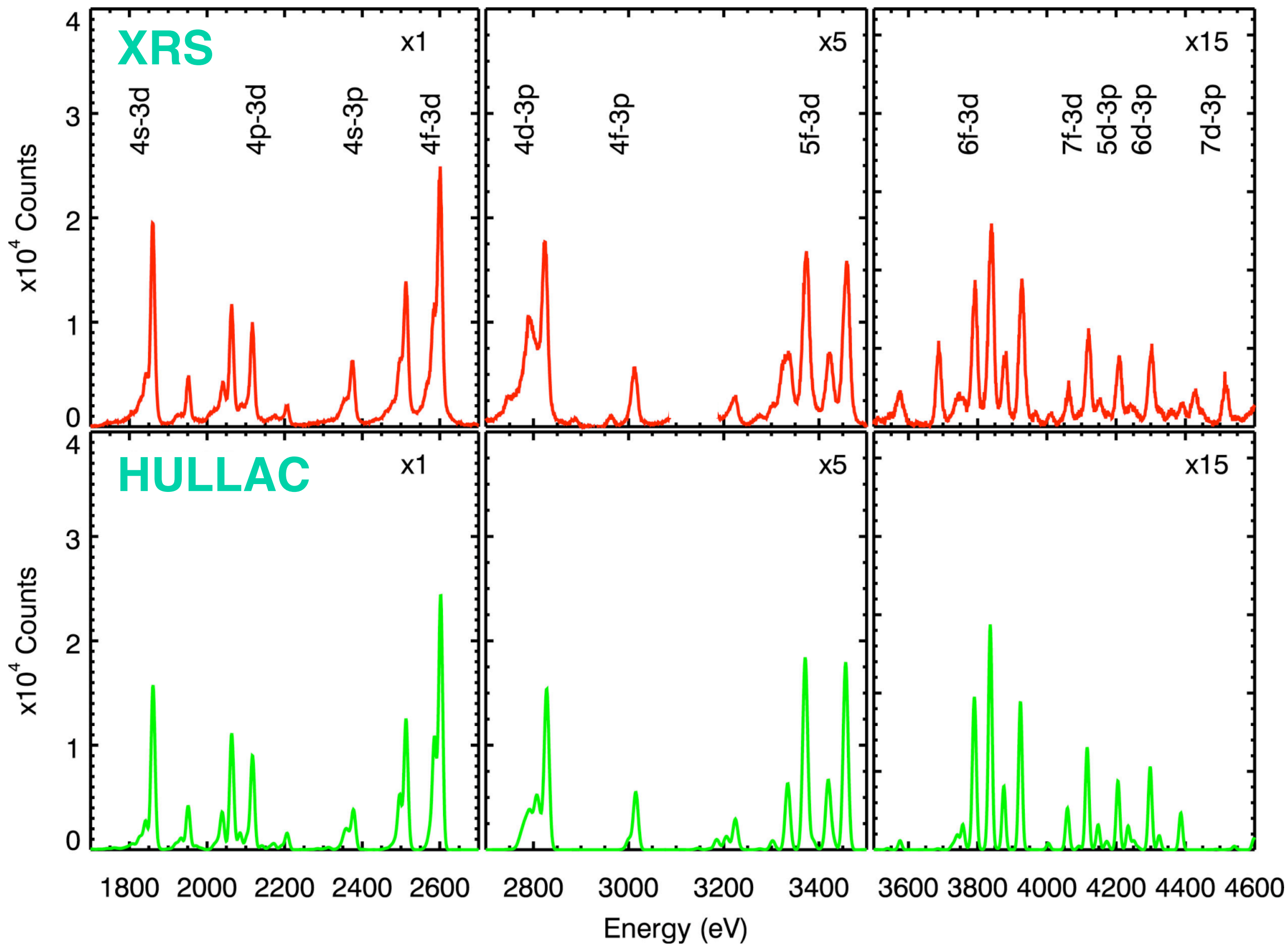


- EBIT: Inferred from both the n = 5f→3d and 4f→ 3d spectra and the RR spectrum
- HULLAC: modeling CSD

Z_{eff} Results	
EBIT (5f→3d)	49.8±1.2
EBIT (4f→3d)	49.8±0.8
EBIT:RR	49.4±0.3
HULLAC	50.8

Experimental results are self-consistent but disagree with HULLAC at other beam energies

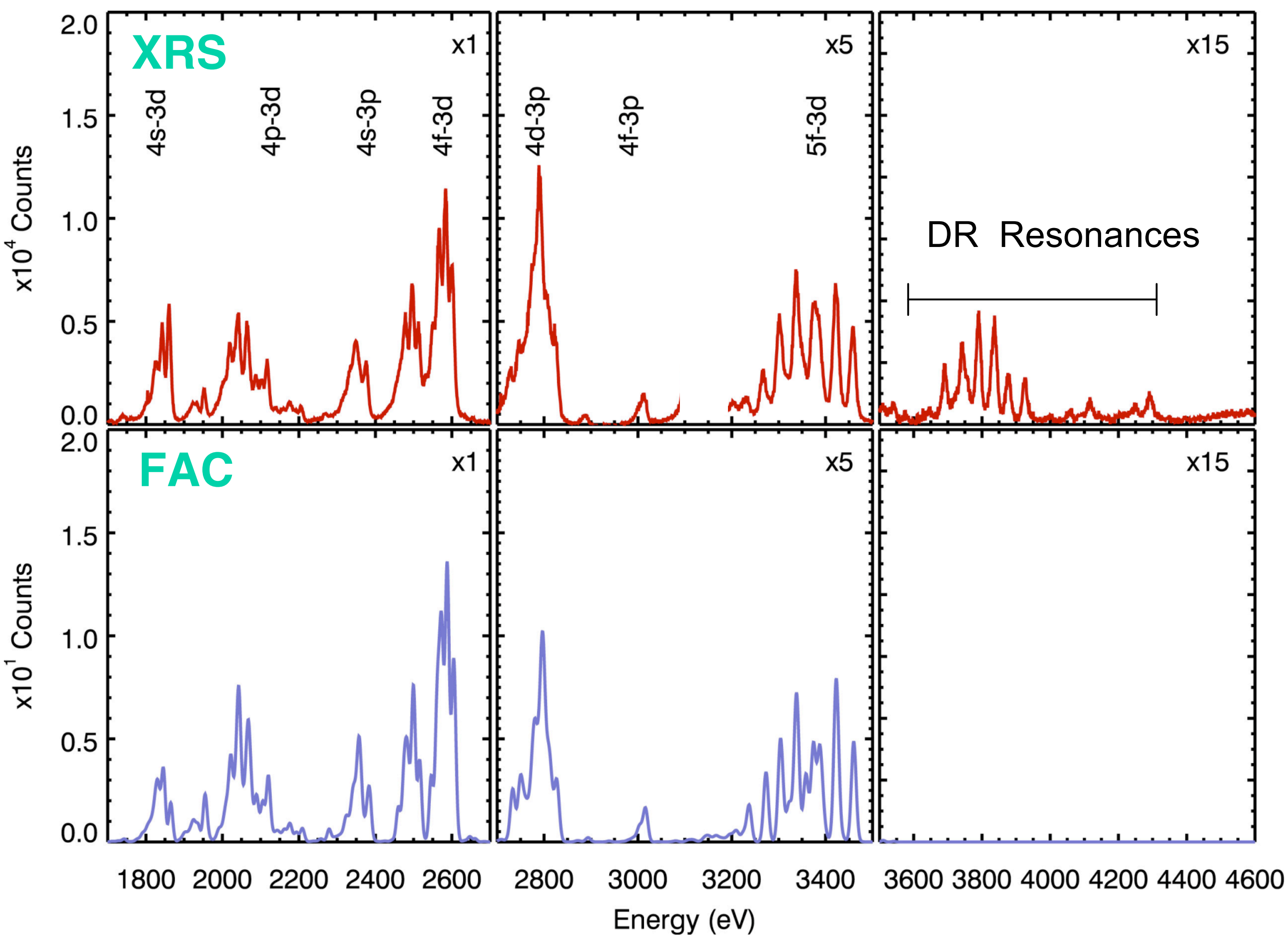
Modeling of XRS Microcalorimeter Spectrum from EBIT with HULLAC



- E_{Beam} = 4.6 keV
- XRS microcalorimeter Spectrum
  - Photometrically Calibrated
  - 1.5 - 5 keV
- HULLAC Modeling
  - Ni,Cu,Zn-like
  - n=4→4, n=4→3 to 7→3
  - Use experimentally Inferred CSD

HULLAC modeling reproduces collisionally excited microcalorimeter spectrum

Modeling of XRS Microcalorimeter Spectrum from EBIT with FAC



- E_{Beam} = 3.6 keV
- XRS Spectrum
  - Photometrically Calibrated
  - 1.5 to 5 keV
- FAC Modeling
  - Ni,Cu,Zn,Ga,Ge-like
  - n=4→4, n=4→3 to 5→3
  - Experimentally Inferred CSD

FAC modeling reproduces collisionally excited XRS spectrum at other beam energies

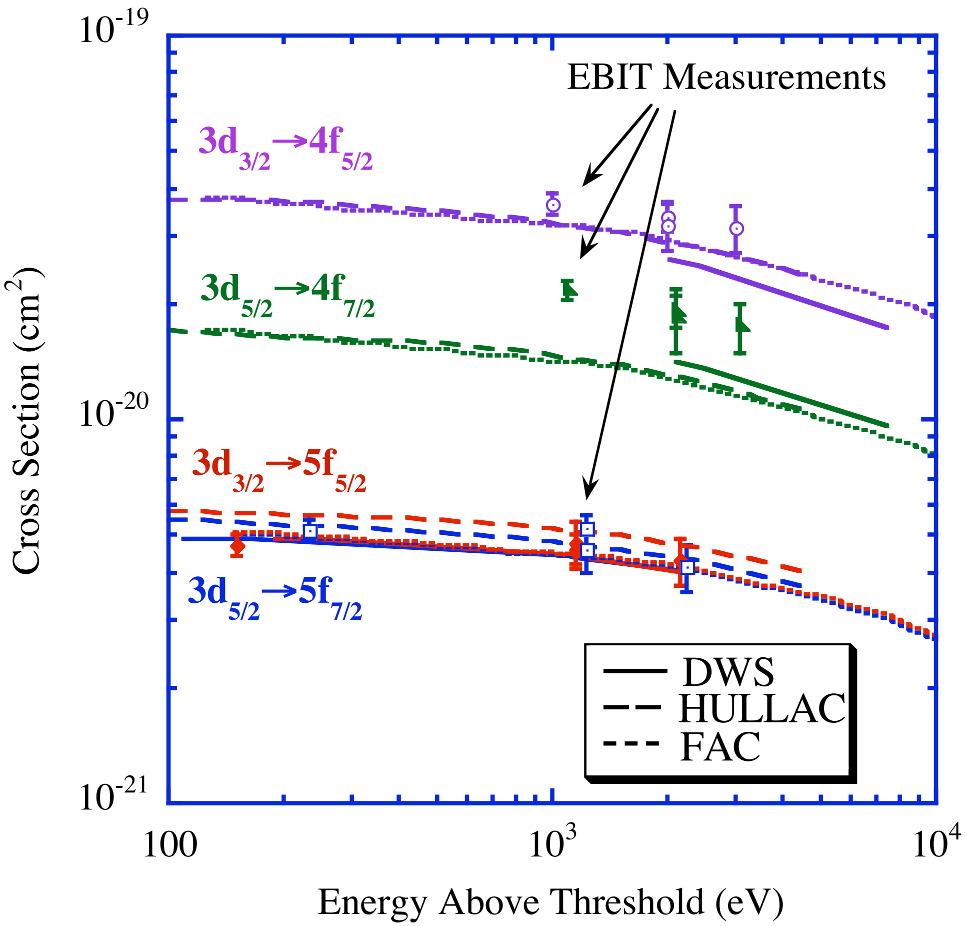
XRS microcalorimeter spectra can be used to infer collisional excitation cross sections

- Verify the electron impact collisional excitation cross sections, σ^{CE}, from HULLAC utilized in the CSD analysis
- Measured the σ^{CE} from the XRS CE line and RR emissions

$$\sigma^{CE} = \frac{\Sigma_j G_j^{RR} \eta_j^{RR} T_j^{RR} \sigma_j^{RR}}{G^{CE} \eta^{CE} T^{CE}} \frac{I^{CE}}{I^{RR}}$$

  - I - intensities, σ - cross section, η - detector efficiency, T - filter transmissions
  - G -angular distribution of the polarization, P
    - Dipole Transition G= 3/(3-P)
- Polarization of the line emission from the EBIT Plasma
  - Magnetic sub-level cross sections provided by K. Reed
  - Ni-like $5f_{5/2} \rightarrow 3d_{3/2}$ (J=1→0)
  - $P = (\sigma_{-1} - 2\sigma_0 + \sigma_{+1}) / (\sigma_{-1} + 2\sigma_0 + \sigma_{+1})$
  - P ~ 0.3; G ~ 0.91 at E_{Beam} = 4.6 keV

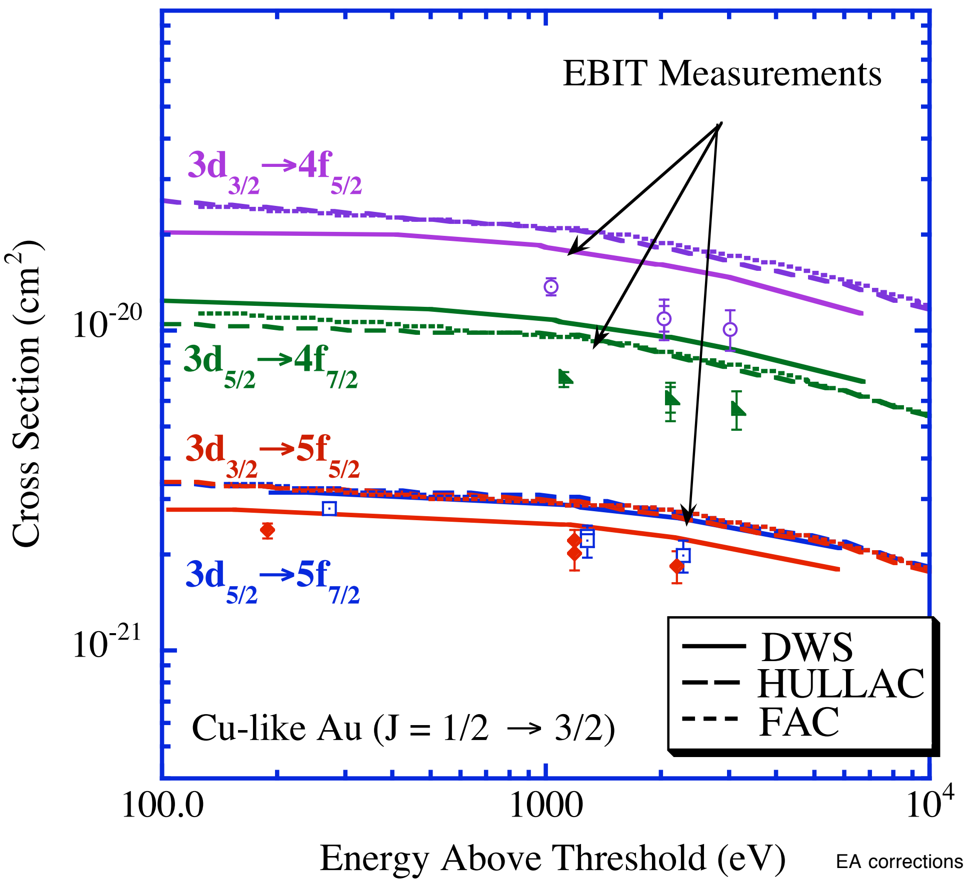
Measured and theoretical collisional impact cross sections: Ni-like Gold



- EBIT: Measured direct impact collisional excitation rates
  - Ni-like Au
  - n = 3d→5f, 3d → 4f
- Theory:
  - HULLAC
  - K. Reed
  - FAC
- 3d→5f:
  - Reasonable Agreement
- 3d→4f:
  - Measurement ~ 1.5 times theory

Measurements demonstrate errors in some excitation rates

Measured and theoretical collisional impact cross sections: Cu-like Gold



- EBIT: Direct impact collisional excitation rates
  - Cu-like Au
  - n = 3d→5f, 3d→4f
- Theory:
  - HULLAC
  - DWS (K. Reed)
  - FAC
- 3d→5f
  - Reasonable Agreement
  - EA Corrections
    - B(5/2→3/2) = 0.832
    - B(7/2→5/2) = 0.800
- 3d→4f:
  - Exp. ~ 0.7 of theory

Errors are larger for some Cu-like cross sections

Conclusions

- CSD Determinations
  - Beam plasmas: CE line emission and RR
  - Simulated thermal plasmas: CE line emission
  - Discrepancies with calculations

- Successfully modeled the EBIT-I beam plasma XRS microcalorimeter spectra

- Measured the collisional excitation cross sections
  - Ni-, Cu- and Zn-like gold n=3d→4f and 3d→5f
    - Some Discrepancies with theory

  → Extend this to Ga - Kr-like Au