White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/16/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	P
• Turbulence and transport	
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• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	X

Title:	Benchmarking Collisional-Radiative Modeling Against Observed X-ray Spectra from Tokamak Plasmas
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)**

- ***Describe the research frontier* and importance of the scientific challenge.**

Advancements in high wavelength resolution imaging x-ray spectrometers [1,2] have enabled detailed investigations of emission from highly ionized medium and high atomic number ions in high temperature plasmas. This is made possible by corresponding advances in atomic structure codes, which enables individual line identifications to be made [3]. Collisional-radiative (CR) modeling of line intensities then allows for interpretation of the observed spectra [4,5]. Since transition intensities depend upon plasma parameters (electron and ion temperatures, and electron, impurity and neutral densities) through the various population processes for the upper levels, diagnostic applications are possible [5,6]. In tokamak plasmas, robust, independent measurements of the electron density and temperature have enabled validation of CR modeling codes allowing x-ray spectra to be used to determine the temperature and density when other methods are not available, for example in high energy density or astrophysical plasmas. These measurements are essential for understanding of laser-produced plasmas and astrophysical objects.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Tokamak plasmas are equipped with extensive diagnostic suites to measure the electron temperature and density which vary strongly from the boundary to the hot plasma core. This results in spatially varying x-ray emission from the plasma volume, which has traditionally limited the interpretation of line-averaged observations. By leveraging new advancements in hybrid pixel x-ray detectors, high resolution *imaging* x-ray spectrometers can be built which can utilize tomographic approaches to overcome this hurdle and provide complete emissivity profiles. This allows devices like tokamaks, which can operate over a large range in plasma conditions and allow for a wide assortment of atomic species to be introduced, to make strong contributions to the validation of structure and CR codes. For example, the current spectrometers on Alcator C-Mod [1,2] have been used to study x-ray spectra from H- and He-like argon [5,6], calcium [5] and iron, in addition to Ne-like molybdenum. Conditions have been achieved where Ne-like xenon and H-like krypton are expected to be accessible as well. C-Mod has operated with electron density between $10^{19}/m^3$ and $10^{21}/m^3$ with electron temperatures between 1 and 10 keV. Elements which have been injected into C-Mod by laser ablation or through a gas valve include: Si, S, Cl, Ar, Ca, Sc, Fe, Kr, Zr, Nb, Mo, Pd, Xe and W. To continue this work on C-Mod in FY2016 would require a substantial increase in run time above the current plan of 5 weeks. Similar studies could be performed on NSTX-U, which is planning to build an imaging x-ray spectrometer and laser ablation system, and on ADX [7] with a transfer of the C-Mod apparatus. Once the x-ray spectra have been obtained, the first step is to make proper emission line identifications, which requires both an accurate wavelength calibration and a comparison with atomic structure codes. Observed x-ray spectra, in conjunction with measured electron density and temperature spatial profiles, will then be compared with CR modeling from a variety of codes including HULLAC [8], MZ [9], FAC [10] and COLRAD [11]. Examples of this benchmarking, as a function of electron temperature in He-like ions [5,6] and for electron density in Ne-like [4] (see Figs.1 and 2) and H-like [5] ions, has been demonstrated. These studies need to be expanded for larger ranges of plasma parameters, and to other elements of astrophysical relevance or which will be present in fusion reactors.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

Expansion of the benchmarking described above is particularly important for astrophysics or high energy density plasmas where independent electron density and temperature measurements (like those on tokamaks) are not available. Determination of these two very basic plasma parameters is *essential* for proper modeling and basic understanding of astrophysical objects and laser-produced plasmas, and one can see these research activities as a means of 'calibrating' the atomic system to be used via a laboratory plasma. In addition, since future fusion reactors will have tungsten plasma facing components, it is important to investigate the radiation from the large number of charge states across the plasma cross section, especially because of the potential for deleterious radiation losses. With the extremely large number of W emission lines, it will be a challenge for both measurements and atomic structure calculations to make the basic identifications, let alone the CR modeling. Only after line identifications have been made can the CR modeling be assessed.

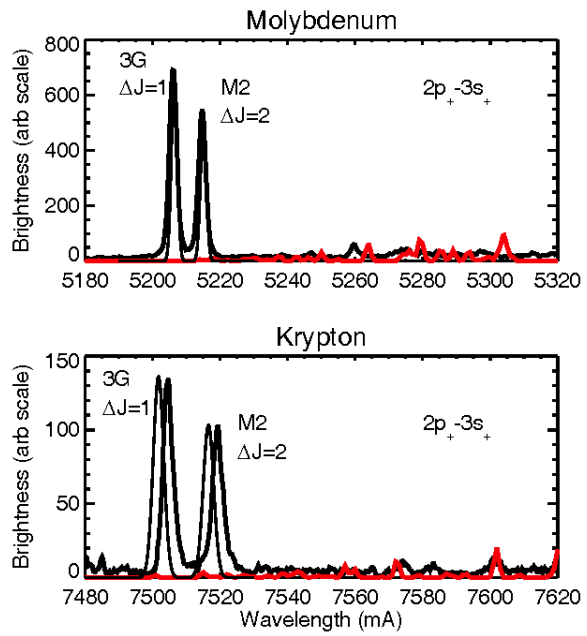

Fig.1 Measured and synthetic spectra of Ne-like molybdenum (top) and krypton (bottom).

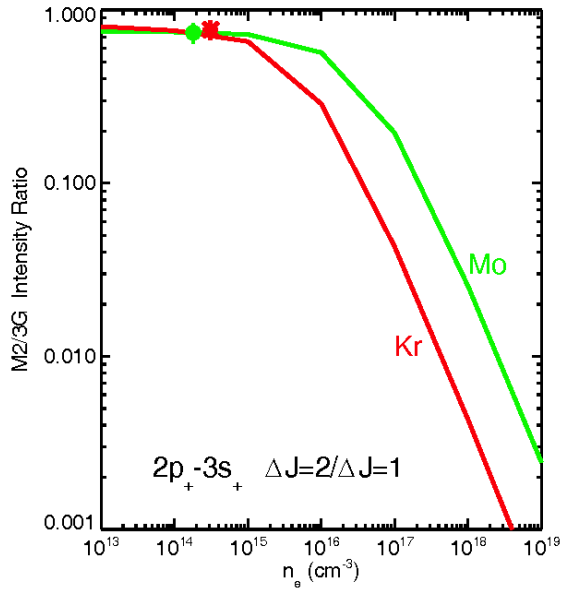

Fig.2 Measured (symbols) and calculated (lines) M2/3G line ratios for Mo and Kr.

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