White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 15, 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	
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	**The interplay of continuum and atomic physics**
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Research Frontier: Develop a comprehensive understanding of the ways in which plasma effects alter atomic structure and atomic interaction rates.

The behavior of plasmas containing significant quantities of atoms other than hydrogen is strongly affected by atomic structure and atomic interaction rates. In fundamental terms, the atomic structure determines the equilibrium equations of state and opacities, and the atomic interaction rates determine the dynamic evolution of the system, perhaps toward some steady state. There is substantial energy involved in creating and sustaining the atomic states present in the plasma, and at times the radiation produced can also be substantial. Yet the atoms in the plasma do not exist in isolation. They affect one another, and interact with the electrons, so that the atomic structure itself is coupled to, and affected by, the plasma environment of each atom.

Our present understanding of the impact of the plasma environment on atomic structure and interaction rates is primitive and crude, especially in the "ion-sphere" regime of dense plasmas, where the Debye length is smaller than the inter-atomic spacing. Estimates of the depression of the ionization potential energy, also known as continuum lowering, differ by more than a factor of three. Evaluations of the impact of this on atomic structure and interaction rates in this regime have focused only on the impact on principal quantum number. In reality this is oversimplified, as some states with nonzero orbital quantum number will be excluded even when the principal quantum number is allowed. This has long been

understood with regard to Rydberg atoms, being mentioned for example by Griem in his plasma spectroscopy book. But to my knowledge it has not been explored for atoms in dense plasmas.

The figure illustrates one rate for which these issues have a particularly large impact. Electron-ion recombination is dominated by the three-body, collisional process for most plasmas in the ion-sphere regime. The recombination occurs primarily into the highest available energy levels, with the likelihood of recombining into a level of principal quantum number n scaling as $n^{4.6}$. (This is based on adapting the argument of Hahn[1] to the ion-sphere regime, using a fit to the rate coefficient of Lotz[2] for the high-n states.) The figure shows how the resulting rate coefficient, integrated over all n, depends on the relative value of the continuum lowering. (Shown in the figure is the value of the two-body form of this rate coefficient, which is most sensible to show for plasmas in the ion-sphere regime.) The present uncertainty in continuum lowering corresponds to a 30-fold uncertainty in the rate coefficient. And this result does not consider the effects of orbital quantum number mentioned above, which adds to the uncertainty.

It is thus no surprise that various codes do poorly at predicting the ionization state distribution. This general topic is clearly an area where further research is needed and is likely to produce significant and exciting discoveries.

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

Continuing advances in theory and computations are clearly needed, and need to be supported. It will be more challenging to obtain experimental evidence. The effects in dense plasmas cannot be probed one reaction at a time, and so experimental approaches based on the study of populations will be necessary. This is turn will require the preparation of uniform, well-characterized plasmas that are then in some way perturbed. For example, a heat pulse might be sent through them. From precise diagnosis of the behavior under well-chosen conditions, one will be able to determine rates of interest. This will require research facilities with multiple energy sources to both produce and probe the behavior. Some work can be done at the MEC instrument at LCLS, and indeed has been,[3] but the lasers there have too little energy to go much further. Relevant work also can be done at large lasers, and has been done at Orion,[4] but substantial access to such devices would be needed to make much progress. Pulsed power devices might prove effective at creating relevant plasmas, but would need substantial diagnostic capability to address this area of interest. A new intermediate scale laser facility might be the best tool, if it can provide sufficient beamlines, stable laser conditions, and the necessary diagnostics.

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

Progress in understanding atomic structure in plasmas will improve our predictive understanding of plasma behavior. This fundamental advance will impact a wide range of plasma research and applications. Our present ability to explore phenomena ranging from shock waves to complex hydrodynamics to heat waves to phase transitions is fundamentally limited by our incomplete understanding of this topic, which creates uncertainty in equations of state, opacities, and other quantities. The applications that are affected include x-ray sources and laboratory astrophysics at high energy density, and inertial confinement fusion. They also must extend to lower-density plasmas, although experts in those areas will have to provide the details.

References (Maximum 1 page)

[1] Y. Hahn, Plasma density effects on the three-body recombination rate coefficients, Physics Letters A 231, 82 (1997).

[2] W. Lotz, Electron-impact ionization cross sections and ionization rate coefficients for atoms and ions, Astrophys. J. Suppl. S. 14, 207 (1967).

[3] O. Ciricosta, S. M. Vinko, H. K. Chung, B. I. Cho, C. R. D. Brown, T. Burian, J. Chalupsky, K. Engelhorn, R. W. Falcone, C. Graves, V. Hajkova, A. Higginbotham, L. Juha, J. Krzywinski, H. J. Lee, M. Messerschmidt, C. D. Murphy, Y. Ping, D. S. Rackstraw, A. Scherz, W. Schlotter, S. Toleikis, J. J. Turner, L. Vysin, T. Wang, B. Wu, U. Zastrau, D. Zhu, R. W. Lee, P. Heimann, B. Nagler, and J. S. Wark, Direct Measurements of the Ionization Potential Depression in a Dense Plasma, Physical Review Letters 109 (2012).

[4] D. J. Hoarty, P. Allan, S. F. James, C. R. D. Brown, L. M. R. Hobbs, M. P. Hill, J. W. O. Harris, J. Morton, M. G. Brookes, R. Shepherd, J. Dunn, H. Chen, E. Von Marley, P. Beiersdorfer, H. K. Chung, R. W. Lee, G. Brown, and J. Emig, Observations of the Effect of Ionization-Potential Depression in Hot Dense Plasma, Physical Review Letters 110 (2013).

Figures (maximum 1 page)

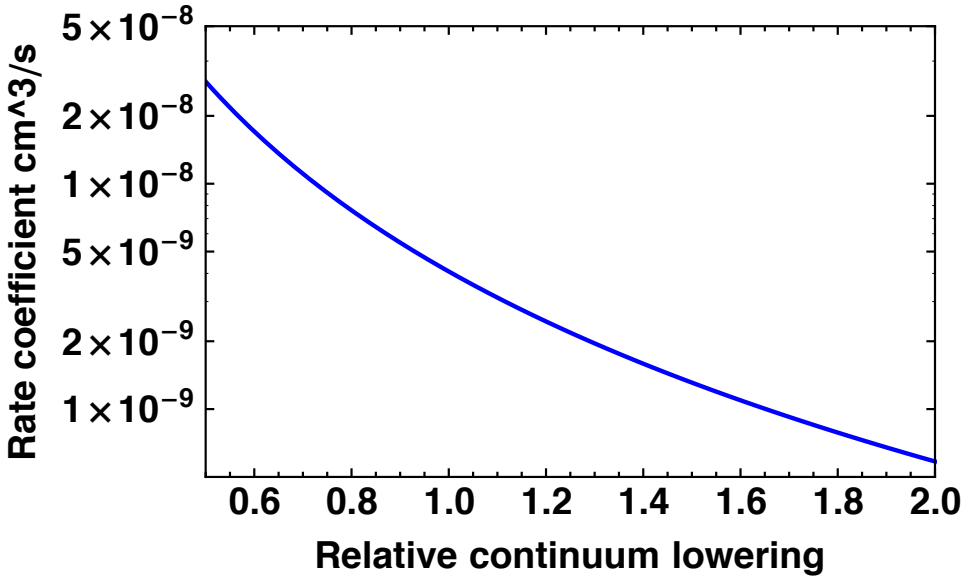

Figure 1. The rate coefficient for three-body recombination of an ion of charge 15, in a plasma of temperature 100 eV, at a density of 10^{20} cm^{-3}, is very strongly sensitive to the amount of continuum lowering, which is uncertain by a factor of 3.